Sustainable Real Estate and Resilient Cities

Management, Assessment and Innovations

Edited by
Pierfrancesco De Paola, Francesco Tajani,
Marco Locurcio and Felicia Di Liddo

Printed Edition of the Topics Published in
Sustainability, Buildings and Urban Science

www.mdpi.com/topics

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Felicia Di Liddo

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Editors
Pierfrancesco De Paola
Department of Industrial Engineering, Univeristy of Naples "Federico II", Napoli, Italy

Francesco Tajani
Department of Architecture and Design, Sapienza University of Rome, Rome, Italy

Marco Locurcio
Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Bari, Italy

Felicia Di Liddo
Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Bari, Italy

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Topic published online in the open access journals *Sustainability* (ISSN 2071-1050), *Buildings* (ISSN 2075-5309), and *Urban Science* (ISSN 2413-8851) (available at: https://www.mdpi.com/topics/sustainable_real_estate).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-5831-8 (Hbk)
ISBN 978-3-0365-5832-5 (PDF)

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Editorial

Sustainable Real Estate and Resilient Cities: Management, Assessment and Innovations

Pierfrancesco De Paola [1,*], Francesco Tajani [2,*], Marco Locurcio [3] and Felicia Di Liddo [3]

[1] Department of Industrial Engineering, University of Naples "Federico II", Piazzale Vincenzo Tecchio 80, 80125 Napoli, Italy
[2] Department of Architecture and Design, Sapienza University of Rome, Via Flaminia 359, 00196 Rome, Italy
[3] Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy; marco.locurcio@poliba.it (M.L.); felicia.diliddo@poliba.it (F.D.L.)
* Correspondence: pierfrancesco.depaola@unina.it (P.D.P.); francesco.tajani@uniroma1.it (F.T.)

Citation: De Paola, P.; Tajani, F.; Locurcio, M.; Di Liddo, F. Sustainable Real Estate and Resilient Cities: Management, Assessment and Innovations. *Sustainability* **2022**, *14*, 8984. https://doi.org/10.3390/su14158984

Received: 11 July 2022
Accepted: 15 July 2022
Published: 22 July 2022

1. Introduction

Production and consumption activities have determined a weakness of the sustainable real estate economy. The main problems are the subordination of public decision-making, which is subjected to pressure from big companies, inefficient appraisal procedures, excessive use of financial leverage in investment projects, the atypical nature of markets, income positions in urban transformations, and the financialization of real estate markets with widespread negative effects.

A delicate role in these complex problems is assigned to real estate appraisal activities, called to make value judgments on real estate goods and investment projects, the prices of which are often formed in atypical real estate markets, giving ever greater importance to sustainable development and transformation issues.

Furthermore, during recent decades, the overestimation of demographic growth has highlighted the need for the restructuring of urban planning processes by limiting the area's building potential, mitigating the loss of place identity with high environmental and cultural value, and preventing uncontrolled land use. Restructuring may also occur through the valorisation and recovery of the existing heritage. In this context, economic, social, and environmental demands are combined with uncertainties about the near future, related to the ongoing COVID-19 pandemic.

In the outlined framework, the focus on sustainability issues also has significant relevance in the financial sector: EU Regulation 2019/2088 requires an effort to evaluate the investments risks in relation to their ability to promote environmental and social sustainability. In this sense, the European Commission highlights the stress between a short-term approach based on the exclusive profit pursuit, and the need for long-term investment that is aimed at sustainability objectives. This is referred to as an ESG (Environmental, Social and Governance) investment rating, oriented to assess the contribution of a financial product and/or a real estate project for improving environmental, social and governance quality.

The main topics of this Special Issue include the following: (i) building management, (ii) building costs, (iii) mass appraisal methods, (iv) econometric models, (v) real estate risk management, (vi) economic valuation of real estate investment projects, (vii) real estate market, (viii) social housing, (ix) urban economics, (x) land, (xi) transport economics, (xii) real estate economics and finance, (xiii) sustainable building transformations and economic effects on environment, (xiv) green buildings, (xv) resilient cities, (xvi) COVID-19 pandemic and (xvii) Environmental, Social and Governance (ESG).

A total of one-hundred and one papers written by academic and scholars from universities and research institutes has been submitted. Following a rigorous procedure of peer review, twenty-five papers have been accepted and published: in particular, nineteen papers in *Journal Sustainability*, four in *Journal Buildings*, two in *Journal Urban Science*.

Furthermore, among the total twenty-five papers, twenty-one documents are classified as Article, three as Review, and one is a Commentary.

With reference to the different countries of the authors' affiliation, the Special Issue has been characterized by a strongly international nature, by pointing out the significant role assumed by the overall topic addressed in the Special Issue at global level. In fact, the universities or research institutes affiliations to which the Authors belong are distributed throughout the world: in the Europe the authors come from Spain, France, Portugal, Netherland, Germany, Belgium, United Kingdom, Poland, and Hungary; in Asia from China, Korea, Russia, Malaysia, and United Arab Emirates; in South America from Colombia and Chile; in Africa from Ghana; and in Oceania from Australia.

In Figure 1, the countries affiliations of the Authors of the published papers are reported.

Figure 1. Countries affiliation of the Authors of the published papers.

A more detailed description of the papers is carried out in Section 2 and the conclusions related to the main issues dealt with by the documents collected in the Special Issue are drawn in the Section 3, by including some wide-reaching and general indications for policies, practices and researches on sustainable real estate theme.

2. The Topics of the Published Papers

The main topics discussed in the papers are consistent with the objectives of the present Special Issue. They attest the relevance of disseminating knowledge and innovations related to the most recent real estate evaluation methodologies applied in the fields of architecture and civil, building, territorial and environmental engineering and to the current tools to guide the sustainable urban planning decision-making processes. In particular, in Figures 2 and 3 the two main categories of the topics dealt with and their declinations are defined and the number of papers referred to each is reported.

A brief summary of the contents of each paper is illustrated below.

In "Research on the Evaluation of Resilience and Influencing Factors of the Urban Network Structure in the Three Provinces of Northeast China Based on Multiple Flows", He Liu, Xueming Li, Shenzhen Tian, and Yingying Guan analyze the resilience of the urban network structure and explore the influencing factors of resilience in the three provinces of Northeast China by using the Gephi profiling social network analysis tools based on the Baidu Index, road mileage, statistical data, other multi-source data, construction information, and the transportation, innovation, and economic multiple linkage network, in order to propose suggestions and strategies for the optimization of urban network structure resilience and the healthy development of the territory [1].

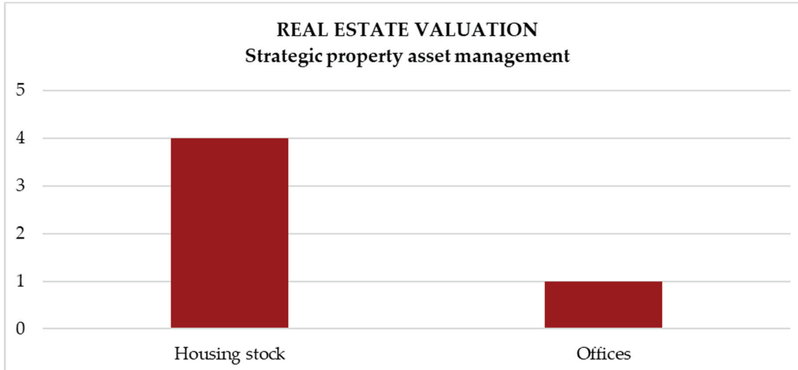

Figure 2. Number of papers concerned the "Real Estate Valuation" issue.

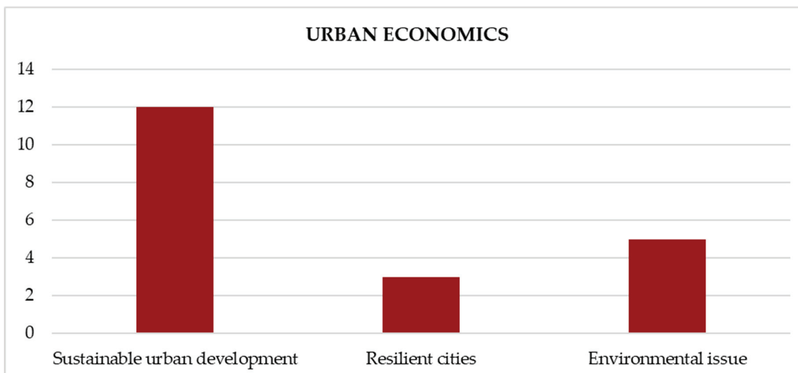

Figure 3. Number of papers concerned the "Urban economics" issue.

The paper by Maarja Meitern, entitled "Does Access to Regulative Exemption Reduce Barriers for Energy Communities? A Dutch Case Study", investigates the set-up of local energy communities issue within the processes of energy transition, by describing the Dutch policy related to local energy initiatives and by providing a starting point for policymakers to define valid energy governance and finance models [2].

The same topic of energy transition connected to the energy resilience is discussed in "Nationwide Evaluation of Urban Energy System Resilience in China Using a Comprehensive Index Method" by Ziyi Wang, Zengqiao Chen, Cuiping Ma, Ronald Wennersten, and Qie Sun: in the paper, 309 Chinese cities are evaluated using a comprehensive Urban Energy System Resilience (UESR) assessment framework composed of 113 indices that measured vulnerability and capabilities of resistance and restoration, by showing that China's UESR is distributed unevenly and that cities in the eastern region generally have higher resilience than those in other regions. The findings of this study may support municipal and provincial decision makers for enhancing overall UESR and its continual assessments could offer policy makers valuable information on energy transition and urban development [3].

With reference to the geographical context of China, Hongqiang Wang, Qiaoyan Lin and Yingjie Zhang in "Risk Cost Measurement of Value for Money Evaluation Based on Case-Based Reasoning and Ontology: A Case Study of the Urban Rail Transit Public-Private Partnership Projects in China" develop a prediction model for estimating the risk cost in the phase of Value for Money (VFM) evaluation through a combination of Case-Based

Reasoning (CBR) and ontology technology. The analysis intends to improve the efficiency of risk cost assessment, by promoting the accuracy and feasibility of the risk cost measurement of VFM evaluation and by proposing several suggestions for risk data accumulation in the process of project management [4].

The cooperation between the public and private sector constitutes the key idea of the research developed by Joanna Węgrzyn and Anna Wojewnik-Filipkowska and entitled "Stakeholder Analysis and Their Attitude towards PPP Success". In particular, in the study the central role played by public-private partnership (PPP) to combine the competencies of the public sector and both the financial and managerial commitment of the private entities in the process of delivering infrastructure, to fulfilling social and economic needs, to rise the quality of life, and to support sustainable development, is recognized and, then, a conceptual model for the identification and classification of stakeholders in this projects typology, is developed and tested [5].

The research entitled "Effect of the Standardization of Service Platforms for High-Involvement PropTech Services" by Jinmin Kim, AhRam Cho and Jaeyoung Kim focuses on the innovation resistance to information technology service acceptance, that is changed after the COVID-19 pandemic, and, on the basis of a survey of property technology (PropTech) service users in Korea, aims at the development of an extended technology acceptance model that implements a standardized service platform by considering the variables of the information system success model and analyzing the effects of specific parameters [6].

In "Environmental Footprint and Economics of a Full-Scale 3D-Printed House" by Hadeer Abdalla, Kazi Parvez Fattah, Mohamed Abdallah and Adil K. Tamimi, the assessment of the eco-efficiency of 3D printing compared to conventional construction methods in large-scale structural fabrication is carried out. By selecting a single-story 3D-printed house in the United Arab Emirates, the authors implement the life cycle assessment (LCA) framework to quantify the environmental loads of raw materials extraction and manufacturing, as well as energy consumption during construction and operation phases; the authors also identify the economics of the selected structural systems through life cycle costing analysis (LCCA). The aggregation of the results obtained shows that houses built using additive manufacturing and 3D printed materials represent the optimum and most eco-efficient alternative [7].

The changes in residential sector due to the modifications in cities inhabitants needs mainly related to the incorporation of technology in spaces and to the remote working spread, accelerated by the COVID-19 crisis, are the focus on which the research "Data-Driven Methodology for Coliving Spaces and Space Profiling Based on Post-Occupancy Evaluation through Digital Trail of Users" by Alicia Regodon, Maxime Armand, Carmen Lastres, Jose De Pedro, and Alfonso García-Santosis is addressed. In particular, the research intends to propose a methodology to understand and improve the use of co-living spaces based on remote Post-Occupancy Evaluation (POE) analysis of the digital trail generated by the users; the authors conclude that the analysis of the available data from the digital infrastructure of co-living buildings can support and upgrade the future design of residential spaces [8].

Weiwu Wang, Jingyi Liang, and Jie Niu use big data analysis technologies including Python and ArcGIS to reveal the distribution characteristics of Co-Working Spaces (CWSs) in Hangzhou (China) and develop an indicator system of factors affecting site selection of this typology of office that innovates the traditional workplace model; to do this, they promote the realization of efficient utilization of office buildings and the sustainable development of spaces and aiming at provide a scientific basis for the rational planning of CWSs [9].

The issue of urban resilience represents a critical aspect for cities and the identification of preliminary elements of attentions for its improvement plays a central role to oppose the rapidly changing world and potential disasters. In this context, Min Chen, Yujie Lu, Yi Peng, Tingting Chen, and Yiye Zhang in "Key Elements of Attentions for Enhancing Urban Resilience: A Comparison of Singapore, Hong Kong and Hangzhou" compare the fundamental elements of attentions for enhancing urban resilience among Singapore, Hong Kong, and Hangzhou (China), by carrying out a questionnaire survey to collect data to assess their significance level and to identify comparison factors [10].

The research "Thinking Critically through Key Issues in Improving the Effectiveness of Waterlogging Prevention and Control System in China's Historic Districts" developed by Shuai Si, Junqi Li, Yuzhen Wang, and Lian Liu analyzes the waterlogging prevention and control system in historic districts in China, considered as a systematic project, which cannot be completely solved only from the engineering and technical aspects, but it involves the cultural relic protection, the planning, the urban construction, the environmental protection, the urban management, the development and reform, in order to promote the protection of existing historical heritage and to support efficient management systems. Starting from the examination of the status quo of drainage systems, the paper proposes a series of countermeasures for the upgrade of the efficiency of waterlogging prevention and the control systems in the context of protection and renewal of historic districts to coordinate the protection of architectural heritage and the improvement of the quality of life of residents [11].

In "Barriers to Offsite Construction Adoption: A Quantitative Study among Housing Associations in England" Andrew Agapiou studies the perceived barriers within Housing Associations (HA) towards the use of Off-Site Construction (OSC) and their comparison with the perceptions in the wider housing sector, with reference to the territorial context of England: a quantitative survey is implemented through a questionnaire submitted by an online platform, by concluding that the cost-related barriers are perceived to be the most significant barriers to OSC use for HAs, followed by the capacity of suppliers and by the end-user preferences for traditional construction [12].

The paper entitled "Determinants of the Economic and Financial Feasibility of Real Estate Development Projects: A Comparative Analysis between Public and Private Development Projects in South Korea" by Heecheoul Shim and Jaehwan Kim analyzes the key factors involved in the selection of a development site to guarantee the financial and economic feasibility of a public development real estate intervention and, in the presence of competing facilities, to avoid duplicate investment issues. Through a direct comparative analysis between private and public projects, the characteristics, similarities and differences between the two types of initiatives are investigated. Given the public and private sectors different goals and business development methods, with the scope of improving operating balance, the measures to increase the economic and financial convenience of development projects are explored [13].

The environmental topic related to the pollution inflicted upon different ecosystems by anthropic activities is dealt with in the research carried out by Mario Fernando Castro Fernández, Ileana Romea Cárdenas Manosalva, Ramón Fernando Colmenares Quintero, Carlos Enrique Montenegro Marín, Yeffer Edilberto Diaz Cuesta, Daniela Escobar Mahecha, and Paula Andrea Pérez Vásquez. The paper is entitled "Multitemporal Total Coliforms and Escherichia coli Analysis in the Middle Bogotá River Basin, 2007–2019". With reference to Bogotá River in the Cundinamarca department of Columbia, highly affected by effluents and uncontrolled domestic, industrial, and/or commercial wastewater, in the paper the quality of its water is assessed using microbiological indicators and data provided by the Regional Autonomous Corporation of Cundinamarca, in order to determine the pollution levels and to highlight the importance of implementing new sustainable treatment alternatives aimed at improving water quality [14].

In "Design of Social Responsibility Incentive Contracts for Stakeholders of Megaprojects under Information Asymmetry" Feng Xue, Guangyu Chen, Shanming Huang, and Huan Xie approach the issue related to the social responsibility for the sustainable development of megaprojects. Through a quantitative method, the goal of the research concerns the comparison and analysis of the single-stage revenue-sharing model under symmetric and asymmetric information from the perspective of incentive contract design, in order to promote a transparent information-sharing mechanism for supporting the general contractors to encourage subcontractors to fulfill responsibility and to improve project efficiency [15].

Within the Russian Federation, the need to develop new strategic management initiatives leads Margarita Panteleeva and Svetlana Borozdina in "Sustainable Urban Development Strategic Initiatives" to propose a strategic roadmap for the sustainable development of housing and communal service facilities, in order to ensure a comfortable living environment for citizens. The developed tool represents a practical reference for the state and municipal authorities on the main reproduction forms of capital construction objects of housing and communal services and allows to make operational management decisions within the framework of identified or anticipated socioeconomic problems of cities, in line with the goal of the strategic development of urban facilities [16].

Starting from the sustainable development goals (SDG) and Local Agenda 21 introduced in Malaysia in 1999, the paper "Indicators of the Public Participation Exercise for Designing Public Parks in Malaysia: A Systematic Review" by Ungku Norani Sonet, Mustafa Klufallah, Michael D. Peters, and Timothy J. Dixon, develops a set of variables and indicators to propose a public participation framework in designing public parks in the Asian country. In this sense, the study aims at tackling two critical issues detected in Malaysia concerned the underutilization of public parks and the weakness of the present top-down development policy, by promoting an innovate integrated design framework [17].

The phenomenon of the shrinking city is examined in "Fading Attraction of the Shrinking City: An Empirical Study from an Urban Resource Perspective" by Yuanping Wang, Mu Lin, Jingxin Gao, and Zhaoyin Zhou, in order to define the Urban Resource Degree (URD) model to measure and select the influencing factors on this urban dynamic. Given the spillover effect and heterogeneity of the influencing factors, a Spatial Durbin Model (SDM) and a Spatiotemporal Geographically Weighted Regression Model (GTWR) are implemented with reference to the context of the Northeast China for proposing policy implications to support the decision-making processes intended to the strengthening of competitive industries, to the implementation of urban transformation and upgrading and to the increase of investment in science and technology [18].

An interesting review of commonly used machine learning (ML) methods use in land use planning along with their advantages and disadvantages is illustrated in "Machine Learning Algorithms for Urban Land Use Planning: A Review" by Vineet Chaturvedi and Walter T. de Vries. In particular, in the comparative study several ML algorithms (Support Vector Machine, neural network, Markov random field, GANS and random forest, etc.) are tested for their performance on different kinds of datasets for land use classification and simulation of territorial planning processes. Moreover, for the purpose of mapping and growth projections of land use, simulation models (Cellular Automata, Statistical modeling, Agent-based modeling, etc.) are described, for modeling, assessing, qualifying, quantifying and predicting the degree/extent/direction of soil exploitation changes and increases [19].

Another paper entitled "Mining the Built Environment: Telling the Story of Urban Mining" gives a general overview of the literature body related to circular economy connected to the reuse and recycling of construction materials that positively impact the natural environment and resource efficiency, leading to sustainable cities. The authors Faisal Aldebei and Mihály Dombi investigate the development of urban mining, i.e., the exploitation of material stock, through an extensive review of reference literature from conception until present day state of the art. They analyze the main researches included in academic databases and classifying them based on research objectives according the categories of waste management, production and consumption, environmental impacts, and urban mining and secondary resources, in order to identify the current research gaps and the potential future studies directions [20].

In "Statistical Modelling of the Market Value of Dwellings, on the Example of the City of Kraków" Elżbieta Jasińska and Edward Preweda analyse a database of 8812 dwellings that are traded on the primary market in Kraków (Poland) through a multivariate analysis to investigate the basic characteristics that influence the transaction property prices. Thus, different methods are implemented to detect outliers, to identify those to be deleted and to validate the results obtained. Moreover, by using the classification tree methods, further analysis allows to distinguish homogeneous urban areas in terms of price dispersion and, for which, a specific set of influencing factors on real estate prices is determined [21].

According to the research by Sally Adofowaa Mireku, Zaid Abubakari, and Javier Martinez, the urban blight phenomenon is investigated through a qualitative method and a case study approach to identify the contextual reasons of degradation in East Legon first-class suburb of Accra-Ghana (Sub-Saharan Africa) and to evaluate its effects on the territorial development. In this sense, the distribution of urban blight in the study area is analyzed and the perceptions of different stakeholders are described, in order to contribute to fill the gap on the root causes of urban blight in the global south, specifically in prime areas, that currently exists in the reference literature [22].

Arlindo Madeira, Teresa Palrão, Alexandra Sofia Mendes, and Ernesto López-Morales, in their study "Perceptions about Tourism and Tourists in Historic Neighborhoods: The Case of Alfama" analyze the tourist-led gentrification, aiming at identifying the local people tourism perceptions in Alfama (Lisbon). In the research, a questionnaire to old long-term residents is defined, to determine the negative and positive effects of overtourism on population everyday experience in the neighborhood. For this purpose, through the questionnaire responses exam, the perceptions that range from a generalized acceptance for the benefits related to an improved safety associated to an increased street-life and a cleaner neighborhood and, on the other hand, the grievance for the loss of a pre-existing community, are observed [23].

In a further paper, Dongyoung Kim, Sungwon Jung, and Yongwook Jeong develop a crime prediction model that reflects the influence of surrounding areas and geographic characteristics on criminal events. With reference to the administrative districts of Seoul, named Dongjak-gu, in South Korea, the study applies the spatial clustering technique to predict the location of crimes more microscopically, using a grid unit, with the wider scope to help to improve the effectiveness of crime prevention by distributing control measures in a more efficient way [24].

Peter Newman, Sebastian Davies-Slate, Daniel Conley, Karlson Hargroves, and Mike Mouritz present a paper entitled "From TOD to TAC: Why and How Transport and Urban Policy Needs to Shift to Regenerating Main Road Corridors with New Transit Systems" that learns from century-old experiences in public–private approaches to railway-based urban development, along with innovative insights from the new integration of historical perspectives, entrepreneurship theory and urban planning, to introduce the concept of a "Transit Activated Corridor" (TAC). Finally, in the study five design principles for delivering a TAC, three principles from entrepreneurship theory and two from urban planning are illustrated [25].

3. Conclusions

The spread of knowledge and innovations through scientific contributions that improve the reference literature field on the most recent real estate assessment methodology approaches and tools for supporting the decision-making processes related to the urban transformation dynamics assumes a key role in this Special Issue. The published papers analyze different aspects of sustainable development of territory (economic, social, environmental), aiming at providing a different point of view on one of the most relevant and current topics dealt with in the debate concerning the effective urban policies definition. The social, economic, cultural, environmental, energy issues [26–31] are fundamental to achieve an always increasing awareness on the importance of developing efficient supporting tool able to analyze and monitor the sustainable urban growth. In all published papers, the city is the main research focus, and the numerous topics dealt with are studied by the authors by implementing different methodological approaches and techniques to investigate specific issues related to the real estate and urban mechanisms in various international geographical contexts, connected to detected phenomena.

During the recent years, the rapid changes observed in the real estate sector connected to the significant variations on urban development have led to a growing need to increase the scientific references in order to define the appropriate investigation of sustainable urban and building evolution processes. The analysis and the interpretation of urban phenomena—on different scales—carried out in the papers included in the Special Issue have allowed us to determine specific methodologies and techniques to support the current debates on sustainable real estate and resilient cities. The prestigious papers, written by international researchers and academics, broaden the frontiers of knowledge on the issues addressed and represent a relevant contribution for effectively pursuing the goals of the 2030 Agenda [32], demonstrating the current interest at a global level, in accordance with the mutable needs of the communities and the international legislative frameworks.

Author Contributions: This note is to assign in equal parts to the four Guest Editors of the Special Issue. The contribution is the result of the joint work of the authors. In particular: conceptualization, P.D.P. and F.T.; contents analysis, F.D.L. and F.T., writing—review and editing, M.L. and F.D.L.; supervision, P.D.P., F.T. and M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: It is our pleasure to thank the reviewers for their exacting and accurate suggestions, all the authors for responding to this Special Issue with alacrity and prestigious scientific contributes, and the team at MDPI for making this Special Issue so efficient and successful.

Conflicts of Interest: The authors declare no conflict of interest.

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A Comparative Analysis of the Competitiveness of Central American Countries Based on the Global Competitiveness Index before the COVID-19 Pandemic

César Melara-Gálvez [1] and Emilio J. Morales-Fernández [2,*]

[1] Department of Operations and Systems, School of Engineering and Architecture, Universidad Centroamericana José Simeón Cañas, San Salvador 0614, El Salvador; cmelara@uca.edu.sv
[2] Department of Business Management, Faculty of Economics and Business Administration, Universidad Loyola Andalucía, 14004 Cordoba, Spain
* Correspondence: emorales@uloyola.es

Abstract: A country's global competitiveness is a fundamental element that facilitates the understanding of why some countries generate more wealth than others, as well as better sources of income in a sustainable manner. With globalization and market integration, governments are reviewing the current values of economic, business, social, and environmental variables that define multidimensional competitiveness indices. Central American countries face difficult economic situations with challenging political and social ramifications. This study presents a comparative analysis of the competitiveness of Central American countries in a globalized environment before the COVID-19 pandemic. For this purpose, multivariate statistical analysis and Cluster analysis have been applied to data from the World Economic Forum (WEF) Global Competitiveness Index 2018, contrasting it with the publication of the same index for 2019. This methodology allows to rank countries with similar levels of competitiveness and shows the relative position of each country about countries belonging to the same group and countries belonging to other groups with different levels of competitiveness. The results show differences in competitiveness at the country level in 12 variables or composite indicators of the Global Competitiveness Index, the most important being Macroeconomic Stability, IT Adoption, and Infrastructure, with the most significant differences between countries. This result contributes to the current policy discussion on measures to achieve sustainable competitiveness of Central American economies.

Keywords: competitiveness; macroeconomic analyses of economic development; comparative studies of countries; Central American countries; classification methods; cluster analysis

Citation: Melara-Gálvez, C.; Morales-Fernández, E.J. A Comparative Analysis of the Competitiveness of Central American Countries Based on the Global Competitiveness Index before the COVID-19 Pandemic. *Sustainability* **2022**, *14*, 8854. https://doi.org/10.3390/su14148854

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 25 April 2022
Accepted: 27 June 2022
Published: 20 July 2022

1. Introduction

During the last decade, the Central American region has shown some economic and social advances that have been insufficient to reverse the global problems and social imbalances that have considerably hindered the development of the region's countries since the end of the 20th century. Before the pandemic, most of the countries in the region presented economic and social situations characterized by certain inequalities in some micro- and macroeconomic indicators related to competitiveness, unbalanced distribution of resources, weak political and social structures, and insufficient promotion of human development, aggravated by some political setbacks, sustained social conflict and social violence that condition the levels of social welfare of their populations [1]. Therefore, this article seeks to incorporate competitiveness into the agendas of the countries of Central America to reduce these shortcomings and thus achieve better development standards.

In the 1990s, exports from the Central American region maintained steady growth with an average annual rate of 13.7%, with coffee and textile products being its main export items [2]. In contrast, between the period from 2006 to 2015, exports from the region to the

United States presented an average annual growth rate of 2.5%, where the competitiveness of Central American countries showed a positive evolution, driven by exports and the establishment of the Central American Common Market (CACM), which subsequently achieved the Central American and Dominican Republic Free Trade Agreement (CAFTA-DR) with the United States, Canada, and Mexico [3]. However, in recent years, all countries except Panama and Costa Rica have experienced stagnation in their competitiveness.

Between 2016 and 2019, before the pandemic, the Central American region presented a declining panorama in terms of economic performance, at the same time that some relevant sectors showed signs of exhaustion and deceleration processes, which directly impacted the labor opportunities of the population. This situation could be associated with the low tax burden in Central American countries, which is lower as a percentage of GDP than the average tax burden in Latin America, and the high budget deficit in all countries [1].

The region's countries have advanced slowly and unevenly in transforming their productive and labor structures, with reduced margins for change explaining the fragility of their socio-economic systems and development. This can be seen by comparing the gaps between countries' GDP per capita, where Panama has the highest GDP per capita in the region, followed by Costa Rica. The disparity is such that, in 2019, Panama's GDP per capita was almost seven times the GDP per capita of Nicaragua, more than five times the GDP per capita of Honduras, and between three and four times the GDP per capita of El Salvador and Guatemala [1].

Based on the relevance of competitiveness as a driver of wealth for countries and the situation in the Central American region, this paper aims to analyze the competitiveness and development of Central American countries.

Competitiveness depends on the ability of countries to produce knowledge, education, and innovation, which function as indicators of growth and globalization [4]. Therefore, there is a need to reduce the gaps between the region's countries by strengthening trade, competitiveness, and productivity in the region. A country's competitiveness plays an essential role in the efforts of the state to achieve sustainable development that impacts the well-being of the population, so its measurement has been addressed in various studies. At the same time, it contributes to the creation of economic policies, both at the country and regional levels, which in turn impacts business, especially in developing strategies that improve nations' micro- and macroeconomic levels [5].

The concept of competitiveness dates back to the Theory of Trade when Adam Smith established that profit maximization, as an absolute advantage, is how a country obtains more significant benefits and trade becomes the generator of world production growth [6]. Later, Heckscher-Ohlin postulated that the intensity or abundance of the factor of production is the variable that drives the difference in comparative advantage [6].

However, it was not until the 1990s that Michael E. Porter [7] presented the basis of the so-called Competitiveness Theory. From this, the definition of competitiveness of the World Economic Forum (WEF) emerges, which defines it as "the set of institutions, policies, and factors that determine the level of productivity of an economy, which in turn sets the level of prosperity that the economy can achieve" [8]. Likewise, and addressing the concept beyond the country level, competitiveness can be understood as the ability of companies, industries, regions, or geographic areas to generate relatively high levels of income and employment on a sustainable basis [9]. Therefore, if the main goal of a nation is to produce a high and sustained standard of living for its citizens, productivity becomes a lever to achieve this goal, being fundamental the ability to measure the state of competitiveness at the country level as a source of information that determines future allocations of public resources to improve it [10]. In addition, Baumann and Pintado [11] proposed the model known as competitive productivity, which seeks the concrete relationship between both concepts and relates attitudes and behaviors aimed at beating the competition.

In this sense, the Central American region and the countries that comprise it present notable inequalities in some micro- and macroeconomic indicators related to competitiveness [12]. Although it is worth noting that the countries of the region showed positive changes in their competitiveness during the 1990s [13], in recent years, they have experienced stagnation on average, only surpassed by Panama [12]. In addition, it should be considered the work done regarding the region's integration, where a process of continuous changes has been experienced concerning trade integration, at the same time on infrastructure and mobility, tourism, environment, and more [14].

Thus, and based on the relevance of the concept of competitiveness as a driver of wealth at the country level and the situation described in Central America, this work aims to perform a comparative analysis of the competitiveness of Central American countries (Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama) in a globalized environment, to deepen the knowledge about their behavior in terms of competitiveness, in addition to visualizing whether these countries present similar traits of competitiveness because they are located in the same region or if there are other countries with similar characteristics.

To this end, this research responds to the problem posed by the fact that the Central American region has considerable difficulties in terms of development. Hence, the objective is, first, to identify significant differences in the competitiveness of Central American countries, and second, to determine the variables with the most important differentiating potential in the region. For this, secondary data from the World Economic Forum's Global Competitiveness Indicator (GCI) for Central America published in 2018 [12] and 2019 [15] are used, this taking into account that the GCI was updated in 2018, incorporating the novelty of the evaluation of variables focused on the fourth revolution, which, at the same time, prevents comparison with previously published indicators but manages to cover current issues and multivariate statistical analysis, mainly cluster analysis by hierarchical clusters. Thus, first, the Central American countries are classified according to the 12 pillars that make up the GCI, considering 139 countries covered by this index, in order to subsequently study only the Central American countries.

Concerning the structure of this paper, after the introductory section, the conceptual framework of the research is presented, followed by a review of the data and the characteristics of the sample. Next, the methodology of analysis is presented, followed by an explanation of the results, ending with the discussion and conclusions.

2. Literature Review

The concept of competitiveness has evolved throughout the history of economic thought, adopting different approaches, from mercantilist theories, which introduced the idea of a rivalry between nations, to Porter's well-known theory of the competitive advantage of nations [5]. Precisely, Smith established that absolute advantage was based on specialization to minimize absolute costs (profit maximization); this became the way for a country to obtain greater profits and trade was the generator of growth in world production. Subsequently, David Ricardo advanced in the theory defined by Smith, establishing that relative costs, and not absolute costs, are determinants for the establishment of the advantage between countries until the contribution of Heckscher-Ohlin appeared by proposing the abundance of production factors as a differentiating variable and generator of comparative advantage [6].

Another important idea in the development of the concept of competitiveness is that of Krugman [16], who mentioned that the competitiveness of countries should not be measured exclusively with macroeconomic factors, this is based on Ricardo's idea, that all countries have a comparative advantage; added to the fact that states cannot go bankrupt, while companies can; also that competition is generated between companies and not between nations so that competitiveness is firmly rooted in the behavior of companies [5].

At the end of the 20th century, Michael Porter presented the Theory of Competitiveness, stating that "the prosperity of a nation depends on its competitiveness, which is based on the productivity with which it produces goods and services. At the same time, he states that macroeconomic policies and solid legal institutions, and stable policies are necessary but not sufficient conditions to ensure a prosperous economy. Competitiveness is grounded in a nation's microeconomic fundamentals: the sophistication of a company's operations and strategies and the quality of the microeconomic business environment in which companies compete. Understanding the microeconomic foundations of competitiveness is vital for national economic policy" [7]. He also mentioned that the main goal of a nation is to produce a high and sustained standard of living for its citizens. In a globalized world, countries face a variety of challenges and opportunities. Figure 1 shows a timeline of the evolution of the concept described in this section.

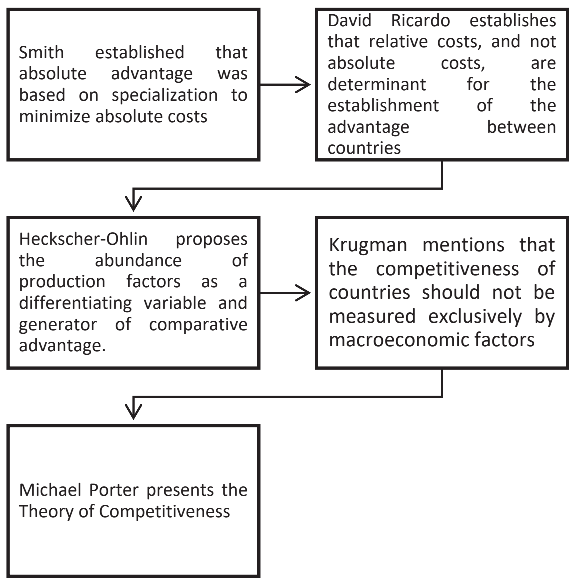

Figure 1. Evolution of the concept of competitiveness.

The constant flow of products and services between nations has increased and become more volatile, with some countries benefiting and others not [5], explaining the growing interest in competitiveness at all levels shown by many governments and industries, which demonstrates the importance of measuring it through productivity [17]. Precisely, D'Alessio stated that the concept of productivity is the "relationship between the results obtained concerning the resources used and the time to achieve them" [18]. This concept was also taken by Porter [10], when he proposed a model that helps understand industries and competition, facilitating the formulation of global strategies.

Taking into account the above concepts, Mahmoo [19], clarified that "The notion of comparative advantage is based on the factor endowment position of a country where no participating firm within an industry has an advantage over another based on its factor endowment (public goods characteristics). Unlike comparative advantage, competitive advantage is created and appropriated by individual firms (private good characteristics). One should not choose between one of the two paradigms, as they are neither mutually exclusive nor explicitly separable. So, we can argue that it is inappropriate to present competitive advantage as an alternative (substitute) to comparative advantage. The two theories must properly be seen as complements rather than competitors in the formulation of trade and industrial policies".

Another idea that emerges is the relationship between competitiveness and GDP, where wealth, prosperity, and economic growth are often referred to as the results of substantial and well-developed intellectual capital. However, GDP has become a questionable indicator of prosperity and economic development, given that national well-being lies beyond GDP, which in turn requires inclusive economies, productivity, and well-functioning markets [20].

From a business perspective, a company's competitiveness is its capacity to supply goods and services that are equally or more effective and efficient than those of its competitors [21]. With the same idea, Labarca [22] mentioned that competitiveness is the determining factor in determining how easy it is for companies to take advantage of the opportunities offered by the international economy. There is evidence to suggest that international trade strongly influences certain sectors of a country to produce the same goods and services they already produce but at a lower cost, through the improvement of technology in their production processes, which becomes a differentiating factor between developed and developing countries [23].

In addition, Esser [24] mentioned that systemic competitiveness constitutes a frame of reference for both industrialized and developing countries. He said that competitiveness is the product of the interaction between a nation's four economic and social levels. A first micro- or business-level simultaneously seeks efficiency, quality, flexibility, and speed of reaction of companies. A second meso-level, which corresponds to the state and social actors responsible for the development of specific support policies, encourages the formation of structures and articulates learning processes at the societal level. A macro-level, which exerts pressure on companies through performance requirements. In addition, there is a final target level, which is structured with solid basic patterns of legal, political, and economic organization, and the social capacity for organization and strategic integration [24]. Thus, and thanks to the increase in intraregional trade among the nations that make up a region, regional economic integration has positively impacted the national economies of the countries that make up the region as a whole [25].

In this concept, two elements differentiate it from others. A first element, such as the distinction of the four levels (meta, macro, meso, and micro), emphasizes the importance of the meta-level where the factors related to the capacity of society for integration and strategic action are examined, and a meso-level where the action of an environment capable of promoting and multiplying the company's efforts is studied. In addition, a second difference is related to linking elements to industrial economics, innovation theory, and industrial sociology [24].

The adoption and evolution of concepts such as regional innovation systems, and the recognition of subnational regions as critical units in globalization, have given rise to increasing attention to regional competitiveness policies, a common factor strengthening the conditions for innovation. Designing effective competitiveness policies is a complicated, dynamic, innovative process [26].

In a complementary manner, the Economic Commission for Latin America and the Caribbean (*CEPAL*) considers that national competitiveness is the "capacity of a country to increase or maintain its participation in international markets, which in turn translates into an increase in the standard of living of the population" [27].

Along the same lines, Wienert [17] defined competitiveness as the ability of firms, industries, regions, or specific geographic areas to generate relatively high levels of income and employment on a sustainable basis. He also mentioned that the Organization for Economic Cooperation and Development (*OECD*) has four different classifications for competitiveness studies:

- Engineering, which defines a country's competitiveness based on its companies, is understood as its capacity to maximize its productivity to obtain higher income.
- Environment/systemic, which considers competitiveness to be directly linked to the productivity of companies, but considering environmental factors such as incentives, quality of inputs, and infrastructure.
- Capital development, understanding competitiveness as the ability of firms to accumulate physical, human, and technological capital to modify long-term performance or, also, the ability of firms to obtain income from factor differentiation in international markets.

- Eclectic/Academic considers competitiveness a complex concept composed of specific and selective factors and elements, such as the pillars of competitiveness that make up the World Economic Forum's global competitiveness model.

Likewise, and considering the contribution of Porter [10], Baumann and Pintado [11] proposed the beginnings of the model known as competitive productivity (CP), which in essence relates attitudes and behaviors aimed at beating the competition. This approach considers that productivity can be separated from competitiveness. In contrast, a pure focus on competitiveness can overlook productivity, so a nation, company, or individual could be very productive but not necessarily competitive [28].

Later, Baumann, Cherry, and Chu [28] added a broader look to the concept of the competitive productivity model, adjusting the concepts of productivity and competitiveness at different levels. The first is at the national level (NCP), which considers the geography, political stability, culture, and institutions, as well as the economic policy of each country. A second level, at the enterprise or meso-level (FCP), considers variables related to talent management, resource management, corporate culture, and brand management. In addition, a third level, at the individual or micro-level (ICP), considers the individual's genetics, personality, motivation, education, nature, and life experience.

The literature review on the definitions and concepts of competitiveness shows a diversity of nuances. However, they share the idea that competitiveness should have an impact on improving a country's prosperity [29]. Complementarily, the different theoretical foundations of the concept of competitiveness have generated various forms and measurement instruments, such as, for example, the Global Competitiveness Index of the Institute for Management Development (IMD); the World Bank's Doing Business Index, or the International Competitiveness Index of the Mexican Institute for Competitiveness (IMCO). However, Ordóñez [29] mentioned that, possibly, the best-known competitiveness evaluation reference is the Global Competitiveness Index, prepared and published annually and since 1979 by the World Economic Forum, which defines competitiveness as "the set of institutions, policies and factors that determine the level of productivity of a country" [20], and considers that the level of competitiveness has a direct relationship with the ability of countries to achieve sustained growth and long-term prosperity.

3. Data and Methodology

3.1. Data

This research was based on the concept of competitiveness of Porter [10], the World Economic Forum [12], and Baumann, Cherry, and Chu [28], previously commented, where the focus is on the influence of the state and companies to generate conditions for competitiveness, well-being, and human development. Thus, to perform the comparative analysis of the competitiveness of Central American countries, the Global Competitiveness Index (GCI) published by the organization mentioned above for 2019 was used [12]. This index is designed to measure micro- and macroeconomic variables associated with the competitiveness of each country, constituting one of the most widely used references for measuring competitiveness [30].

The Global Competitiveness Index published in 2018 [12] incorporates a new methodology by including concepts associated with the Fourth Industrial Revolution (4IR) and evaluates a set of variables that collectively determines the level of a country's productivity, which nowadays influences the long-term improvements in living standards of millions of people around the world [12].

This version is a compilation of 98 indicators or observed variables that capture concepts that matter for productivity and long-term prosperity. These indicators are collected and grouped into 12 pillars or latent variables (Institutions, Infrastructure, ICT adoption, Macroeconomic stability, Health, Skills, Product market, Labor market, Financial system, Market size, Business dynamism, and Innovation capability). These 12 pillars are grouped into four categories or components (Enabling environment, Human capital, Markets, and Innovation ecosystem) [12]. This structure of indicators, pillars, and categories or components is shown in Figure 2.

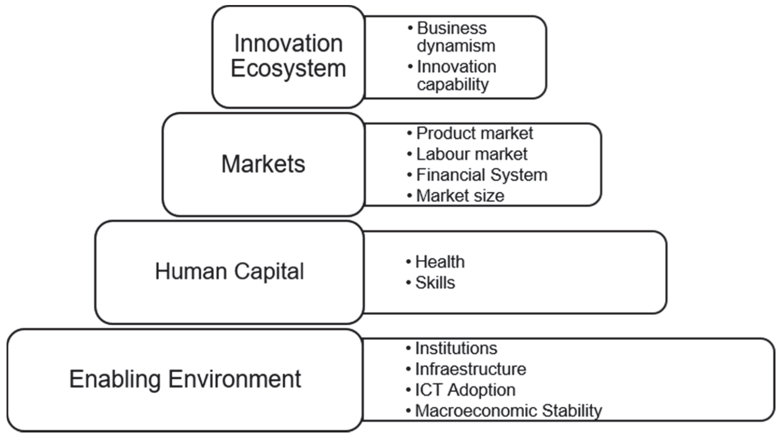

Figure 2. Composite indicators comprise the Global Competitiveness Index. Source: Framework adopted from WEF, modified by authors.

The first category or component, Enabling Environment, ensures an environment conducive to economic activity in each country, reducing transaction costs and accelerating the exchange of information, thereby increasing business confidence and productivity. The second component, Human Capital, measures how the physical, mental, and productive capabilities of individuals, as well as interpersonal skills and the ability to think critically and creatively, influence the competitiveness of countries. The third component, Market, measures the characteristics that enable the arrival of new products to a market while attracting, incentivizing, and retaining talent while providing an efficient payment system. Finally, the Innovation Ecosystem component is responsible for creating innovative products and services, fostering collaboration, creativity, diversity, confrontation; and the ability to turn ideas into new goods and services [12].

In addition, the calculation of the Global Competitiveness Index is based on successive aggregations of scores, from the indicator level (the most disaggregated level) to the overall GCI score (the highest level), thus in each aggregation level, there are different variables, being the score of each aggregation the arithmetic average of the variables that compose it and the overall GCI score will be the average of its 12 pillars [12]. In addition, each variable individually, before aggregation, presents values ranging from 0 to 100, with 100 being the highest value, as well as the ideal state of each variable. This score coincides with the highest level (GCI).

In turn, the Global Competitiveness Index comes from different sources. Of the 103 indicators composing the GCI, part of these is based on statistics provided by reliable external sources suppliers that adequately capture the identified concepts, is derived from external statistics from reputable organizations that collect high-quality data that will be regularly updated in the future, and have wide geographical coverage and are available for at least 75% of the economies covered by the GCI. Another part of the indicators is sourced from the Executive Opinion Survey (EOS), which for almost 40 years has been fundamental in providing critical aspects of the indicator for variables that are impossible or extremely difficult to measure statistically. The goal of the survey is to capture reality as best as possible, and business leaders are arguably the best at assessing these aspects [12,13].

For the 2019 publication, the opinion of 16,936 business executives in 41 different languages was taken between January and April 2019. In turn, the EOS comprises 78 questions divided into 10 sections, where most of the questions are answered on a scale of 1 to 7, with

7 being the highest and therefore considered the best in the world on specific aspects of the business environment of the country where the respondent operates [15].

Thus, and as previously commented, this research uses the Global Competitiveness Index data published in 2019 by the World Economic Forum [15]. Specifically, 139 records were selected and utilized corresponding to countries that did not present missing data in any pillar, including most Latin American countries and countries in the Central American region. Although the analysis focuses on the Central American countries (Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama), it was necessary to use the complete information of the countries mentioned to have a sufficient sample size to apply the analysis and classification methods to analyze the competitive differences and similarities between countries.

Table 1 presents the values of the descriptive statistics for the 12 composite indicators or pillars that make up the 2018 and 2019 GCI for the countries in the sample.

Table 1. Descriptive statistics of the 12 composite indicators of the 2018 and 2019 GCI.

GCI Composite Indicators	Year	Average	Median	Std. Deviation	Min.	Max.	Skewness Coef.	Kurtosis Coef.
1. Institutions (INST) *	2018 2019	55.399 55.074	53.561 53.893	11.495 11.957	29.466 25.721	81.554 81.216	0.436 0.241	−0.426 −0.451
2. Infrastructures (INFRA)	2018 2019	65.359 65.397	66.987 67.839	16.049 16.702	28.574 26.878	95.704 95.448	−0.309 −0.350	−0.607 −0.617
3. ICT Adoption (ADOP_ICT)	2018 2019	52.049 55.330	54.029 55.394	19.813 19.381	12.772 10.769	81.255 92.836	−0.129 −0.185	−0.975 −0.840
4. Macroeconomic Stability (MAC_STAB) *	2018 2019	79.967 80.083	74.648 75.000	16.155 17.625	31.063 0.000	100.000 100.000	−0.287 −1.019	−0.546 2.373
5. Health (HEALTH) *	2018 2019	75.224 75.406	79.985 80.545	19.667 18.138	11.933 21.728	100.000 100.000	−0.815 −0.716	−0.180 −0.360
6. Skills (SKILLS)	2018 2019	60.613 61.262	61.698 63.161	14.924 14.513	28.248 29.039	87.878 86.721	−0.289 −0.353	−0.743 −0.681
7. Product market (PRO_MAR)	2018 2019	56.561 55.262	55.700 54.632	8.183 8.595	37.517 35.433	81.230 81.613	0.242 0.206	0.307 0.377
8. Labour market (LAB_MAR)	2018 2019	59.384 59.980	59.176 59.822	9.166 8.753	37.607 40.905	81.885 81.229	0.245 0.180	−0.219 −0.374
9. Financial system (FIN_SYS) *	2018 2019	61.469 62.441	58.797 59.791	13.726 14.185	37.170 29.035	92.117 91.411	0.577 0.351	−0.583 −0.615
10. Market size (MAR_SIZE)	2018 2019	53.987 54.504	52.229 53.500	17.740 17.428	15.992 17.125	100.000 100.000	0.213 0.235	−0.467 −0.418
11. Business dynamism (BUS_DYN)	2018 2019	59.499 59.955	58.330 59.795	11.285 11.411	14.897 14.071	86.489 84.210	−0.322 −0.589	1.170 1.398
12. Innovation capability (INNO_CAP) *	2018 2019	42.433 42.981	36.408 37.984	17.588 17.066	16.782 17.967	87.522 86.829	0.998 0.961	−0.118 −0.134
Global Competitiveness Index	2018 2019	60.162 60.639	59.861 60.929	12.604 12.427	35.520 35.085	85.641 84.784	0.106 0.058	−0.751 −0.741

Note: * Non-normal distributions according to the Kolmogorov–Smirnov test. Source: Authors' calculation.

The descriptive statistical values of the Global Competitiveness Index 2019 of the 139 countries have the following descriptive statistical values: Average = 60.639, Median = 60.929, Standard Deviation = 12.427, Skewness coefficient = 0.058, Kurtosis coefficient = −0.741. The average 2019 GCI indicates a medium level of competitiveness.

From this brief characterization, it became evident that the latent variable with the highest average value corresponds to the Macroeconomic stability pillar (80.083), followed by Health (75.406), Infrastructure (65.397), and Financial system (62.441) pillars, with performance levels at the international level above the average value of the 2019 GCI (60.639).

While the pillars ICT adoption (55.330), Product market (55.262), Institutions (55.074), Market size (54.504), and Innovation capability (42.981) present not only values below the average value of the 2019 GCI but are the pillars with low performance in terms of competitiveness for the set of countries analyzed.

3.2. Multivariate Analysis

A cluster analysis [31] was performed to group countries with similar values and behaviors in terms of competitiveness and in order to differentiate from other countries with different values and behaviors [32]. A clustering proposal was made, and as previously mentioned, using the 12 pillars or latent variables of the 2018 GCI as evaluation variables, applying the inter-group linkage method through the squared Euclidean distance, different analyses were obtained (grouping in 4, 5, 6, and 7 clusters, respectively). The analysis with grouping in 5 clusters was selected because it shows better values of intragroup linkage and intergroup differences, at the same time that the natural association observed with the dendrogram shows that using 5 clusters will allow a positive interpretation of the results [33]. The dendrogram, or tree diagram, is a graphical representation of the clustering procedure, where the nodes represent the clusters. The stem lengths represent the distances at which the clusters are joined [34]. In addition, this number of clusters allows associating the countries in such a way that in each group, some observations statistically can be worked with other methodologies used later.

The ANOVA statistical technique and the Bonferroni and Games–Howell tests were applied to evaluate the existence of statistically significant differences between the five groups of countries. The ANOVA technique is a method for analyzing the equality of means of variables with normal distributions between different populations through the analysis of sample variances [35], determining the influence of some variables on others and their significance [36]. The Kruskal–Wallis non-parametric test [37] was used to analyze differences in the means of variables with non-normal distributions. Complementarily, the Bonferroni and Games–Howell tests were applied to determine, more concretely, the differences between the four groups [38].

Finally, the non-parametric Mann–Whitney–Wilcoxon test was applied to the subsample of data from the Central American countries to compare the cluster analysis results and determine whether differences exist [39]. The influence of the variables on the grouping of the countries was also evaluated, based on the geometric means of each variable, which is the average of the rate of change of a variable [40], averaging percentages, indices, or relative figures. From the results of the Mann–Whitney–Wilcoxon test, the variables with the greatest differences were identified.

The statistical analysis described was conducted using IBM SPSS Statistics (v. 26) and Microsoft Excel (v. 2019) software. Figure 3 summarizes the statistical analysis performed throughout the paper.

Thanks to the identification of significant differences in the competitiveness of Central American countries, groups with similar characteristics to the countries of the region are identified and the variables with the most significant potential for differentiation among the countries are identified, which in turn can have an impact on support when making decisions on public policy issues.

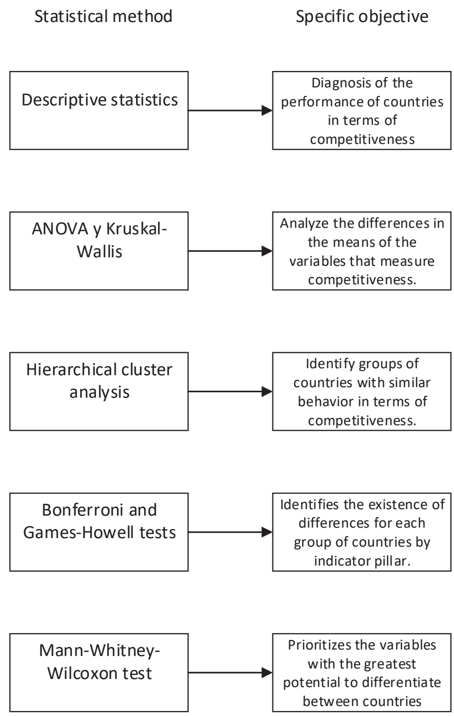

Figure 3. Summary statistical analysis.

4. Results

The hierarchical cluster analysis performed on the 139 countries in the sample, considering the values of the 12 composite indicators of the 2019 GCI, formed five groups or clusters (Table 2).

Table 2. Distribution of countries by the group.

Cluster	Countries
1 (26 countries)	ANGOLA, BENIN, BURKINA FASO, BURUNDI, CAMEROON, CHAD, CONGO, CÔTE D'IVOIRE, ETHIOPIA, GUINEA, HAITI, LESOTHO, LIBERIA, MALAWI, MALI, MAURITANIA, MOZAMBIQUE, NIGERIA, PAKISTAN, SIERRA LEONE, SWAZILAND, TANZANIA, UGANDA, YEMEN, ZAMBIA, ZIMBABWE.
2 (55 countries)	ALBANIA, ALGERIA, ARGENTINA, ARMENIA, AZERBAIJAN, BANGLADESH, BARÉIN, BOLIVIA, BOSNIA AND HERZEGOVINA, BOTSWANA, BRAZIL, BRUNEI, CAMBODIA, CAPE VERDE, COSTA RICA, CROATIA, CYPRUS, DOMINICAN REPUBLIC, ECUADOR, EGYPT, EL SALVADOR, GAMBIA, GEORGIA, GHANA, GREECE, GUATEMALA, HONDURAS, IRAN, JORDAN, KENYA, KYRGYZSTAN, LAOS, LEBANON, MACEDONIA, MALDIVES, MAURITIUS, MONGOLIA, MONTENEGRO, NAMIBIA, NEPAL, NICARAGUA, PARAGUAY, RUANDA, SENEGAL, SERBIA, SEYCHELLES, SRI LANKA, TAJIKISTAN, TRINIDAD AND TOBAGO, TUNISIA, TURKEY, UKRAINE, URUGUAY, VIETNAM.
3 (31 countries)	BULGARIA, CHILE, CHINA, COLOMBIA, CZECH REPUBLIC, ESTONIA, HUNGARY, INDONESIA, ITALY, KAZAKHSTAN, KUWAIT, LATVIA, LITHUANIA, MALAYSIA, MALAYSIA, MALTA, MEXICO, MOROCCO, OMAN, PANAMA, PERU, PHILIPPINES, POLAND, PORTUGAL, QATAR, ROMANIA, SAUDI ARABIA, SLOVAK REPUBLIC, SLOVENIA, THAILAND, UNITED ARAB EMIRATES.
4 (25 countries)	AUSTRALIA, AUSTRIA, BELGIUM, CANADA, DENMARK, FINLAND, FRANCE, GERMANY, HONG KONG, ICELAND, IRELAND, ISRAEL, JAPAN, LUXEMBOURG, NETHERLANDS, NEW ZEALAND, NORWAY, SINGAPORE, SOUTH KOREA, SPAIN, SWEDEN, SWITZERLAND, TAIWAN, UNITED KINGDOM, UNITED STATES OF AMERICA.
5 (2 countries)	INDIA, SOUTH AFRICA.

Cluster 1 is mainly made up of countries from the African region. Precisely 23 of the 26 countries belong to the region mentioned above, while only 2 Asian countries (Yemen and Pakistan) and one from the Central America and Caribbean region (Haiti) are included in the group. It is also important to note that the performance of the countries belonging to this cluster is lower than the others concerning the GCI. The cluster shows an average score of 42.48 points in the GCI, a value below the world average. Therefore, this cluster is made up of the countries with the lowest competitive levels. Slightly improving cluster 1, in terms of competitive levels, is cluster 2, comprising 16 Asian countries, 13 African countries, 10 from the rest of Europe, eight from Central America and the Caribbean, six from South America, and two belonging to the European Union. This country has an average GCI score of 56.03, slightly below the world average.

Cluster 3 shows a better picture than the two previous clusters, with an average score of 66.63 in the GCI. This cluster is made up of 13 countries from the European Union, 11 Asian countries, three from South America, and one from Africa, North America, Central America and the Caribbean, and the rest of Europe.

On the other hand, cluster 4 has the highest average score in the study, with 79.49 ICG points. This cluster is mainly made up of countries belonging to the European Union (12 countries), followed by 6 Asian countries, three from the rest of Europe, and two from North America and Oceania.

Finally, cluster 5 is made up of only two countries, South Africa and India, with an average score of 61.39 in the GCI. This cluster presents a particular behavior. It can be inferred that these countries are characterized by trade, having on average a good debt management (79.08) and a relatively low inflation rate (4.92).

With the above, it is corroborated that the behavior of the countries in terms of competitiveness presents different nuances, visualized in various groupings, which show better standards than others in terms of competitiveness. Thus, according to this analysis, the Central American region presents differences in the behavior of its countries, since they were classified into two groups or clusters. Panama belonged to one group (cluster 3) along with 30 other countries, which presented similar characteristics in terms of competitiveness. On the other hand, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua presented similar characteristics, belonging to the same cluster (cluster 2) that they shared with 50 other countries.

Table 3 provides the average values of the composite indicators of the global competitiveness of the five clusters.

Table 3. Average values of the composite indicators of 2019 GCI in each cluster.

GCI Composite Indicators	Cluster				
	1	2	3	4	5
1. Institutions (INST)	42.658	51.427	58.164	73.929	55.833
2. Infrastructures (INFRA)	40.946	62.550	74.050	85.889	68.651
3. ICT Adoption (ADOP_ICT)	23.781	48.593	63.512	76.039	37.032
4. Macroeconomic Stability (MAC_STAB)	62.804	69.741	91.307	97.680	88.251
5. Health (HEALTH)	43.270	76.479	84.104	95.970	51.118
6. Skills (SKILLS)	38.570	58.646	67.057	80.212	56.444
7. Product market (PRO_MAR)	47.425	54.295	59.457	67.737	53.062
8. Labour market (LAB_MAR)	50.294	56.901	60.756	72.581	59.638
9. Financial system (FIN_SYS)	45.756	56.508	65.175	82.984	75.818
10. Market size (MAR_SIZE)	40.511	46.775	62.904	69.207	80.524
11. Business dynamism (BUS_DYN)	47.654	55.431	63.583	75.563	61.279
12. Innovation capability (INNO_CAP)	25.924	33.882	45.409	74.199	49.042

Source: Authors' calculation.

The performance of cluster 4 stands out in 11 out of 12 pillars, concerning the other clusters, thus being the cluster made up of the most competitive countries analyzed. Cluster 2 (Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua) shows a medium level in the variables that make up the GCI; however, its competitive performance is surpassed by cluster 3 (Panama) in all the latent variables or pillars of the GCI.

Figure 4 shows, graphically, the comparison of the values of the composite indicators of the five groups, where the differences mentioned above can be observed.

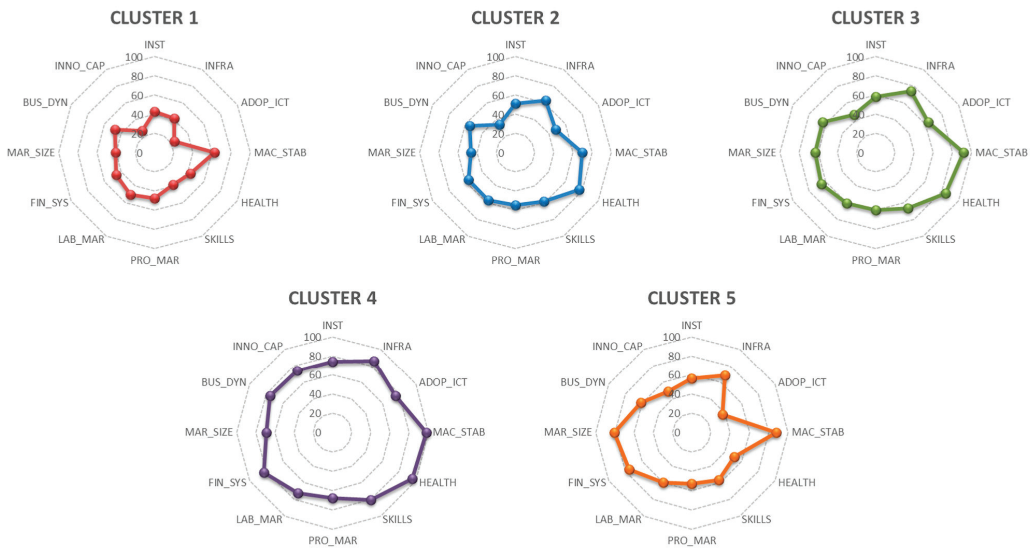

Figure 4. Graphical profiles of average 2019 GCI of the groups. Source: Authors' elaboration.

In turn, the Bonferroni and Games–Howell tests [39] show the significant differences of each composite indicator of the 2019 GCI and determine the pillars that present the highest degree of heterogeneity among the defined groups. The values obtained are presented in Table 4.

Table 4. Bonferroni and Games–Howell test the composite indicators for the groups or clusters.

GCI Composite Indicators	Cluster 1	2	3	4	5
1. INST	42.658 ^{C2,C3,C4}	51.427 ^{C1,C3,C4}	58.164 ^{C1,C2,C4}	73.929 ^{C1,C2,C3}	55.833
2. INFRA	40.946 ^{C2,C3,C4,C5}	62.550 ^{C1,C3,C4}	74.050 ^{C1,C2,C4}	85.889 ^{C1,C2,C3,C5}	68.651 ^{C1,C4}
3. ADOP_ICT	23.781 ^{C2,C3,C4}	48.593 ^{C1,C3,C4}	63.512 ^{C1,C2,C4}	76.039 ^{C1,C2,C3}	37.032
4. MAC_STAB	62.804 ^{C2,C3,C4,C5}	69.741 ^{C1,C3,C4,C5}	91.307 ^{C1,C2}	97.680 ^{C1,C2}	88.251 ^{C1,C2}
5. HEALTH	43.270 ^{C2,C3,C4}	76.479 ^{C1,C3,C4}	84.104 ^{C1,C2,C4}	95.970 ^{C1,C2,C3}	51.118
6. SKILLS	38.570 ^{C2,C3,C4}	58.646 ^{C1,C3,C4}	67.057 ^{C1,C2,C4}	80.212 ^{C1,C2,C3,C5}	56.444 ^{C4}
7. PRO_MAR	47.425 ^{C2,C3,C4}	54.295 ^{C1,C3,C4}	59.457 ^{C1,C2,C4}	67.737 ^{C1,C2,C3}	53.062
8. LAB_MAR	50.294 ^{C2,C3,C4}	56.901 ^{C1,C3,C4}	60.756 ^{C1,C2,C4}	72.581 ^{C1,C2,C3,C5}	59.638 ^{C4}
9. FIN_SYS	45.756 ^{C2,C3,C4}	56.508 ^{C1,C3,C4}	65.175 ^{C1,C2,C4}	82.984 ^{C1,C2,C3}	75.818
10. MAR_SIZE	40.511 ^{C3,C4}	46.775 ^{C3,C4}	62.904 ^{C1,C2}	69.207 ^{C1,C2}	80.524
11. BUS_DYN	47.654 ^{C2,C3,C4}	55.431 ^{C1,C3,C4}	63.583 ^{C1,C2,C4}	75.563 ^{C1,C2,C3,C5}	61.279 ^{C4}
12. INNO_CAP	25.924 ^{C2,C3,C4}	33.882 ^{C1,C3,C4}	45.409 ^{C1,C2,C4}	74.199 ^{C1,C2,C3}	49.042

Note: Ci: Significant differences at 5% according to Bonferroni and Games–Howell tests with clusters 1 to 5. Source: Authors' calculation.

Thus, differences are observed between cluster 1 and cluster 2 in 11 of 12 pillars, being Market size the only one that does not show significant differences. In comparison, cluster 1 and cluster 3 have different behavior in the 12 pillars, as well as with cluster 4. Comparing cluster 1 with cluster 5, significant differences are observed in the macroeconomic stability and infrastructure pillars.

When doing the same analysis with cluster 2, significant differences are found in the 12 pillars, both with clusters 3 and 4, and significant differences are observed in the Macroeconomic Stability pillar with cluster 5.

While cluster 3 and cluster 4 present significant differences in the pillars of Macroeconomic Stability and Market Size. In addition, cluster 4 compared to cluster 5 presented significant differences in 4 pillars, Infrastructure, Skills, Labor market, and Business dynamism.

This result confirmed the division in competitive terms among the Central American countries. In addition, the same is visually ratified in Figure 5, where a comparison between clusters 2 and 3 is presented.

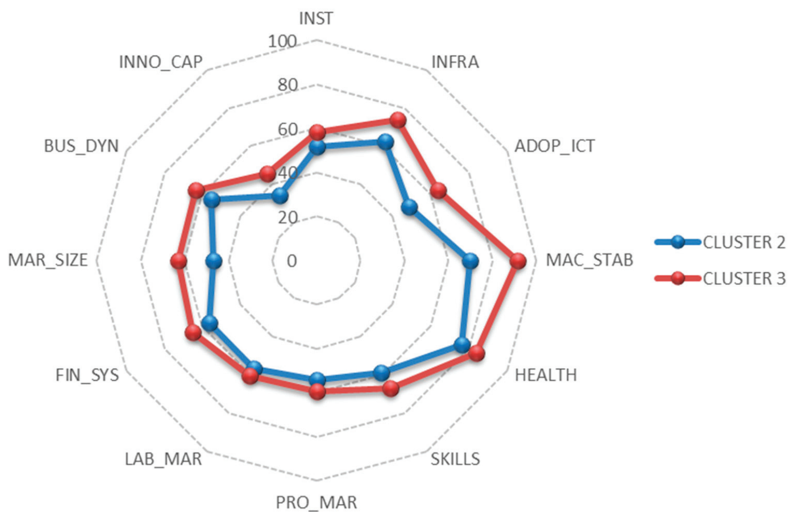

Figure 5. Comparative performance between clusters 2 and 3. Source: Authors' elaboration.

The descriptive statistical values of the Global Competitiveness Index 2019 for the two groups, including the seven Central American countries, have the following descriptive statistical values:

- Panama (PAN *, Panama spot values), belonging to cluster 2. Average = 61.639, Median = 58.608, Standard Deviation = 16.226, Skewness coefficient = 0.837, Kurtosis coefficient = 0.396.
- Costa Rica (CRI), El Salvador (SLV), Guatemala (GTM), Honduras (HND), Nicaragua (NIC) belong to cluster 3. Average = 54.448, Median = 52.626, Standard Deviation = 14.585, Skewness coefficient = 2.084, Kurtosis coefficient = 4.475.

To carry out a comparative analysis exclusively among the Central American countries, Table 5 provides the average values of the composite indicators of the global competitiveness of the Central American countries.

The purpose of this is to find the variables with the greatest potential for differentiation in the region, without considering the other countries in each respective cluster, and to better approximate the study problem.

Table 6 presents the geometric means and the Mann–Whitney–Wilcoxon test for each set of countries' pillars or latent variables, where the largest statistically significant differences are found. This is to compare the cluster analysis results and evaluate the importance of the variables that most influence the grouping of countries in a given way since this test allows the binary comparison of two independent samples to determine the existence of differences between the populations.

Table 5. Average values of the composite indicators of 2018 and 2019 GCI in each Central American country.

GCI Composite Indicators	Year	Central American Countries					
		Costa Rica (CRI)	El Salvador (SLV)	Guatemala (GTM)	Honduras (HND)	Nicaragua (NIC)	Panama (PAN)
1. Institutions (INST)	2018 2019	59.0590 57.1262	40.6698 39.8444	43.5226 42.4459	44.6730 43.7889	43.9360 41.8889	50.8569 51.4129
2. Infrastructures (INFRA)	2018 2019	65.0822 68.7386	59.7500 61.0201	58.3029 55.8500	58.0190 57.3979	55.2416 55.5954	68.3043 69.4727
3. ICT Adoption (ADOP_ICT)	2018 2019	59.6071 59.9677	39.4859 40.6399	31.0734 37.7340	28.1220 30.1710	31.9802 35.8776	47.5176 50.0603
4. Macroeconomic Stability (MAC_STAB)	2018 2019	72.9971 74.3482	74.8716 69.7430	74.3768 74.8058	74.1620 74.6734	74.0424 73.5053	89.8051 90.0000
5. Health (HEALTH)	2018 2019	97.3820 93.2328	82.7442 78.1180	74.5727 73.9648	75.8393 77.8311	90.3676 90.0059	91.8050 92.0125
6. Skills (SKILLS)	2018 2019	69.0822 68.9541	48.2658 48.4393	52.5752 51.3830	48.2499 49.5189	45.5488 46.7982	58.1668 58.4650
7. Product market (PRO_MAR)	2018 2019	60.4175 59.3794	54.0008 53.9390	61.1210 58.9903	56.9334 55.3169	53.7589 51.3914	57.9514 59.2315
8. Labour market (LAB_MAR)	2018 2019	59.7191 59.0925	52.2354 53.4133	51.3272 50.9283	56.3724 55.9451	52.7885 53.2354	56.4554 56.2813
9. Financial system (FIN_SYS)	2018 2019	59.7935 60.0613	60.0994 62.2506	57.3572 57.5215	59.7968 59.7914	54.0079 53.1308	66.8837 67.6324
10. Market size (MAR_SIZE)	2018 2019	46.1955 46.5381	43.1644 42.8516	50.8351 51.2039	41.9480 42.4852	39.6580 39.1523	48.8838 49.0378
11. Business dynamism (BUS_DYN)	2018 2019	55.8959 56.3278	51.6279 52.6886	54.5500 55.8112	53.9064 53.9574	49.6468 49.8266	58.2861 58.7510
12. Innovation capability (INNO_CAP)	2018 2019	40.4334 40.3006	26.9207 27.9165	30.7385 31.5489	31.5131 30.6355	27.0373 27.8485	37.4883 37.3077
Global Competitiveness Index	2018 2019	62.1387 62.0056	52.8196 52.5720	53.3627 53.5156	52.4613 52.6261	51.5012 51.5213	61.0337 61.6388

Source: Authors' calculation.

Table 6. Prioritization of the 2019 GCI composite indicators for the two groups containing Central American countries.

GCI Composite Indicators	Cluster 2 (PAN) **	Cluster 3 (CRI, SLV, GTM, HND, NIC)	Difference in Averages	Sig. Mann–Whitney–Wilcoxon ***
1. INST *	51.4129	45.019	6.394	0.000
2. INFRA	69.4727	59.720	9.752	0.000
3. ADOP_ICT *	50.0603	40.878	9.182	0.000
4. MAC_STAB	90.0000	73.415	16.585	0.000
5. HEALTH	92.0125	82.631	9.382	0.002
6. SKILLS *	58.4650	53.019	5.446	0.000
7. PRO_MAR	59.2315	55.803	3.428	0.000
8. LAB_MAR *	56.2813	54.523	1.758	0.009
9. FIN_SYS	67.6324	58.551	9.081	0.000
10. MAR_SIZE	49.0378	44.446	4.592	0.000
11. BUS_DYN *	58.7510	53.722	5.029	0.000
12. INNO_CAP	37.3077	31.6500	5.658	0.000

Note: * Variables prioritized according to ANOVA, Mann–Whitney–Wilcoxon, and Kruskal–Wallis tests in the complete groups. ** Panama point values for the 12 pillars of the 2019 GCI. *** Test conducted with all countries belonging to clusters 2 and 3. Source: Authors' calculation.

From the above, it is observed that there are statistically significant differences between the means of the two groups of Central American countries in the 12 composite indicators of the 2019 GCI, with higher mean values for all indicators associated with Cluster 2, and therefore with Panama, compared to the mean values for Cluster 3, to which Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua are associated.

In addition, it is possible to prioritize certain pillars of the 2019 GCI according to the Mann–Whitney–Wilcoxon test and the difference between the geometric means of the Central American countries, whereby the pillars with the largest significant differences are Macroeconomic stability (16.585), Infrastructure (9.752), Health (9.382), IT Adoption (9.182), and Financial system (9.081). Therefore, these can be considered key factors determining Panama's best performance in terms of competitiveness.

5. Discussion

This research confirms the existence of different patterns of association in the Central American region in terms of the drivers that characterize competitiveness so that the existence of competitive differences can be affirmed. This can be associated with a difference in the level of economic development, which seems to be corroborated by the United Nations/ECLAC [41], when it mentions that Latin America and the Caribbean are not the poorest regions in the world but the most unequal. This organization also comments on the difficulties of this region to develop as such, which is caused by gaps in different areas such as low productivity, poor infrastructure, segregation, and problems in the quality of services such as health and education, in addition to persistent gender gaps and territorial inequalities, adding to environmental problems and the significant risks of climate change. The region has experienced a complicated situation recently, with economic recessions in Argentina and Brazil. Venezuela has been experiencing critical social and economic conditions for several years, which can easily be replicated in other countries in the region [25]. The Central American area is an example of a region that presents problems of inequality, with competitiveness being a fundamental factor that has been measured in the region for years.

The result of this research confirms the existence of a significant gap in competitiveness between two groups of Central American countries. Thus, Panama presents a better competitive performance at the country level than Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua in the 12 composite indicators analyzed from the Global Competitiveness Index published in 2018 and 2019. The result coincides with the region's GDP growth rate, where Panama maintained an average growth rate of over 5% between 2015 and 2017, decreasing in 2018, compared to El Salvador, which held growth rates below 3% over the same period [42]. As well as a GDP per capita higher than the rest of the countries in the region, where Panama reaches values of US $15,545 million, followed only by Costa Rica with US $12,485.4 million for the year 2018, against Guatemala, El Salvador, Honduras, and Nicaragua whose value of GDP per capita does not exceed US $5000 million in the same year [43]. At the same time, Panama presents the lowest inflation rate value for 2018, slightly reaching the value of 0.8%, contrasting with countries such as Guatemala, Honduras, and Nicaragua, whose inflation is around or above 4% [44].

Another relevant factor is exports, where Panama has the highest merchandise exportation levels, reaching US $11.48 million in 2018, followed by Costa Rica with US $11.34 million for the same year [45]. This behavior is repeated with imports, where Panama reached values of 23.01 million dollars for 2018, followed by Guatemala with 19.7 million dollars for the same year [46]. Another influential factor is maritime container traffic, where Panama shows itself to be enormously superior in the region, presenting values of 7,014,700 TEUs (20-foot equivalent units) in 2018, followed by Guatemala with 1,530,596 TEUs [47].

The importance of these competitiveness indicators is corroborated by works such as those of Von Krogh, Nonaka, and Rechsteiner [48], which state that companies must generate and acquire new knowledge in a continuous and sustained manner, in addition to improving their technological readiness to achieve and maintain satisfactory competitiveness values and sustainable growth levels. Precisely this relationship points to an important challenge for Central American countries.

Thus, one aspect that has the potential to influence both competitiveness and development is infrastructure. The IDB [49] states that “infrastructure is essential for economic growth and productivity. Especially in developing countries, infrastructure contributes to (i) expanding markets, (ii) raising private investment, and (iii) lowering production costs”. Therefore, investment in infrastructure is a facilitating element for the growth of countries that has positive effects and increases private investment, promotes the expansion and sophistication of markets, and favors the efficiency of the productive sector, so that the growth in quantity and quality of infrastructure in Central American countries has an impact on higher levels of development and competitiveness of their economies.

On the other hand, UNESCO [50] explains the link between education, competitiveness, and development by pointing out that “the educational progress of countries is but one component of the process of improving the living conditions of societies, that is, of their development, and has a reciprocal relationship of influence with the latter: while more and better education is expected to contribute to general progress, the very absence of progress is, in turn, an obstacle to the expansion of educational opportunities”. The close relationship between development and education is an important challenge for the Central American region.

The achievements and efforts in education in the region occur too late, responding when opportunities have passed or have been replaced by other realities with greater demands. This has generated a secular delay that places the region at a disadvantage against other countries worldwide.

This is shown graphically in Figure 6, which shows per capita public social spending on education, where Costa Rica stands out in the region [51].

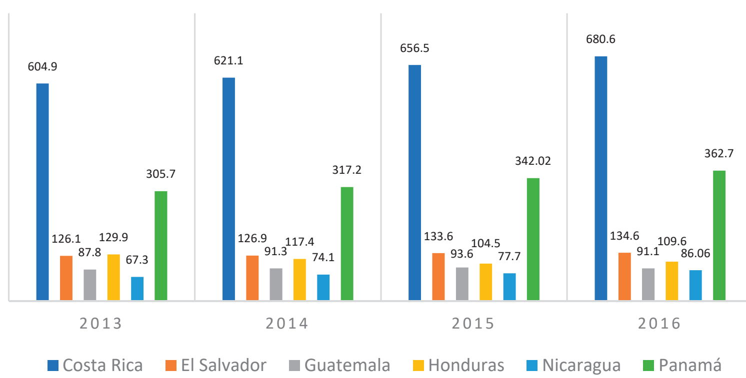

Figure 6. Public social spending on education in Central American countries.

Furthermore, the importance of science, technology, and innovation in the sustainable growth of the Central American region has been emphasized. Precisely, Casalet [52], mentions that the greatest challenge for the region consists of “increasing the macro and micro-complexities of their respective productive and innovation systems to continuously boost the development of capabilities that promote changes in productive and institutional processes aimed at greater complementarity”. To this, it is essential to add that the constant and rapid technological changes, such as cloud computing, the internet of things, and the generation of computer applications, considerably affect economic science since it is one of the social sciences most sensitive to changes in the environment. Therefore, policymakers should consider technological evolution as a relevant factor when creating policies that affect the development of nations [4].

Innovation is a relevant and necessary factor in facing the challenges generated by the COVID-19 pandemic, where new solutions must be implemented to respond to the current problems. Thus, governments must be faster and more transparent while at the same time cooperating with other social actors to develop new technologies and tools that generate and increase collective benefits [53].

This can be seen graphically in Figure 7, which shows the public spending, as a percentage of GDP, on research and development in the countries of the Central American region, in which a notable difference between Costa Rica and the other countries of the region between 2007 and 2017 can be seen.

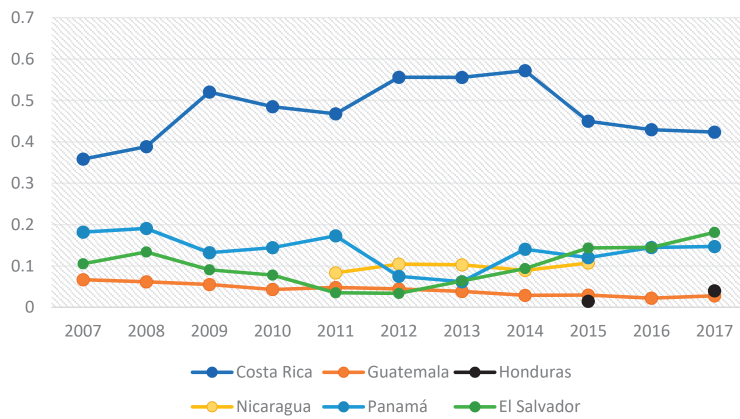

Figure 7. Research and development spending (measured as a percentage of GDP) year 2007 to 2017.

In a complementary manner, UNDP [54] points out that the successful management of the development processes of some nations is closely linked to aspects related to the institutional and governance framework. Evans [55] clarifies that the understanding of development requires an institutional approach and points out that the differences in the levels of investment and technological progress of countries are key differentiating factors and cannot be understood without the institutional context. Furthermore, although the context is open and globalized, development processes are constrained by specific local conditions, with the institutional aspect being a fundamental part of the social fabric determining development [56].

In addition, and according to Martínez [14], regional integration will allow achieving more significant benefits in terms of competitiveness than those obtained by each country separately. Therefore, the importance of the participation of the Central American Integration System (SICA) in the development of the region is fundamental, since, according to Martínez [14], it faces the challenge of creating instruments for collaboration in the region, in addition to the creation of regional agreements that guarantee thresholds of well-being and development, this promoting the participation of all actors, as well as equality, security, and social support networks. The integration of markets can achieve a higher degree of productive specialization, generating competitive advantages in international markets [57]. In the particular case of Central America, regional integration presents an additional advantage that could contribute to solving some challenges, facilitating the decoupling of economic growth and the increase of negative externalities and consolidating a structural change with high rates of equality, as proposed by the Goals of the 2030 Agenda for Sustainable Development [58].

In the Central American region, significant progress has been made concerning the integration plan [57]. However, the region faces enormous challenges due to high poverty levels originating from income inequality and lack of social inclusion. Therefore, it is necessary to stimulate growth and competitiveness in the region's countries in an economic and social context threatened by frequent episodes of social violence, the action and effects of organized crime, and increasing vulnerability to threats arising from climate change [55].

6. Conclusions

This research demonstrates the existence of significant differences in the competitiveness of Central American countries, five different groups of countries have been identified, and each grouping presents particular characteristics. The Central American region is characterized by having a low competitive level, except for Panama, which is incorporated into a different group where it shows a better competitive outlook.

At the same time, this research identifies the variables with the most significant differentiating potential in the Central American region, where, as previously mentioned, Panama shows a better competitive outlook. The pillars with the most remarkable significant differences, and therefore the pillars where it is necessary to prioritize state intervention through public policies, are macroeconomic stability, infrastructure, health, adoption of information technologies, and the financial system. Therefore, these can be considered key factors that determine Panama's better performance in terms of competitiveness with other countries in the region.

Without wishing to enter into controversy about the leading roles that governments should assume in favoring and defining the political, social, and economic conditions that favor competitiveness and development, it seems reasonable to specify the status of governments as depositaries of this responsibility in the exercise of the same, given the influence they have in determining and ensuring the conditions necessary for the country's companies and economies to be competitive [16], being able to affect productive conditions directly or indirectly through the formulation of economic and industrial policies [59]. However, it is crucial to consider that the design and implementation of competitiveness policies are highly complex, being a constantly evolving and innovative process in itself. This complexity offers learning opportunities throughout the process, so the participation of various agents in the territory is necessary [60].

The factors of competitiveness that favor and facilitate the economic and social development of countries can be used as evaluation instruments to guide the definition of political measures and laws that serve governments to stabilize markets and promote the growth and development of countries. In other words, this research presents findings that revolve around the fact that the reduction of the gaps between the elements that differentiate Central American countries in terms of competitiveness is transcendental for the region's development. For this reason, they should not be seen as separate elements of political or governmental action but as related elements that, if properly implemented, can facilitate and promote the improvement of a country's productivity, competitiveness, and prosperity on a sustainable basis.

The limitation of this study lies in the performance of a single comparative analysis through the cluster methodology, which is an exploratory technique, finding the need to extend the research beyond the analysis of the Global Competitiveness Index. At the same time, it is necessary to perform a comparative analysis with more years of study. Still, it is required to clarify that having a new methodology since the 2018 publication and due to the influence of the pandemic generated by COVID-19, it is necessary to wait for recent publications of the World Economic Forum. Finally, it is required, in the first place, to perform an in-depth statistical analysis to visualize the influence of time on the behavior of the competitiveness of the countries in the region, taking this role as the study's hypothesis. In addition, it is necessary to perform a separate analysis of the competitive behavior of the countries under study where the influence of the pandemic is a variable.

Author Contributions: Conceptualization, C.M.-G. and E.J.M.-F.; methodology, C.M.-G. and E.J.M.-F.; software, C.M.-G.; validation, C.M.-G. and E.J.M.-F.; formal analysis, C.M.-G. and E.J.M.-F.; investigation, C.M.-G. and E.J.M.-F.; resources, C.M.-G. and E.J.M.-F.; data curation, C.M.-G. and E.J.M.-F.; writing—original draft preparation, C.M.-G. and E.J.M.-F.; writing—review and editing, C.M.-G. and E.J.M.-F.; visualization, C.M.-G.; supervision, E.J.M.-F.; project administration, C.M.-G. and

E.J.M.-F.; funding acquisition, C.M.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: All personal data obtained in this study are confidential and will be treated in accordance with the Organic Law on Data Protection and Guarantee of Digital Rights (LOPDGDD) 3/2018.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data used in this article are from the World Economic Forum and were obtained from https://es.weforum.org/reports/the-global-competitveness-report-2018 and https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2019.pdf (accessed on 7 November 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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Research on the Evaluation of Resilience and Influencing Factors of the Urban Network Structure in the Three Provinces of Northeast China Based on Multiple Flows

He Liu [1,2], Xueming Li [1,2,*], Shenzhen Tian [1,2] and Yingying Guan [1,2]

1 Geographical Sciences School, Liaoning Normal University, Dalian 116029, China; liuhe1581@163.com (H.L.); tsz999@lnnu.edu.cn (S.T.); gyy9418@126.com (Y.G.)
2 Human Settlements Research Center, Liaoning Normal University, Dalian 116029, China
* Correspondence: lixueming@lnnu.edu.cn

Abstract: An important indicator for measuring the resilience and ability of urban networks to recover under external environmental shock, which is essential for the healthy development of the region, is urban network structure resilience. Herein we analyzed the resilience of the urban network structure and explored the influencing factors of resilience in the three provinces of Northeast China. We accomplished this by utilizing the Gephi profiling social network analysis tools based on the Baidu Index, road mileage, statistical data, other multi-source data, construction information, and the transportation, innovation, and economic multiple linkage network. This analysis enabled us to propose relevant suggestions and strategies to optimize urban network structure resilience. Our results indicate that (1) in 2019, the multi-city network structure in the three provinces of Northeast China contains both commonalities and characteristics. Overall, each network demonstrates a spatial distribution pattern of "dense in the north and sparse in the south." (2) There exist evident hierarchical differences in the resilience characteristics of the multi-city network structure in the three provinces; each provincial capital city and sub-provincial city possesses greater advantages, the innovation network exhibits the most evident hierarchy, the mismatch of the information network is the highest, and the transmission and agglomeration of the economic network are the most prominent. (3) The resilience of the urban network structure of the three provinces is the result of the interaction of several factors. Political and economic factors such as government capacity, economic status, and urban vitality are the main factors affecting the resilience of the network structure.

Keywords: network structure resilience; multiple flows; influencing factors; optimization strategy; three provinces of Northeastern China

Citation: Liu, H.; Li, X.; Tian, S.; Guan, Y. Research on the Evaluation of Resilience and Influencing Factors of the Urban Network Structure in the Three Provinces of Northeast China Based on Multiple Flows. *Buildings* **2022**, *12*, 945. https://doi.org/10.3390/buildings12070945

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 7 June 2022
Accepted: 30 June 2022
Published: 2 July 2022

1. Introduction

Resilience originated in the field of ecology, and its primary meaning is the ability of the ecosystem to develop steadily and sustainably [1]. The term "resilience" was gradually applied to other fields such as sociology and psychology [2]. With the continuous acceleration of globalization, industrialization, and urbanization, the disturbance and impact caused by many uncertain factors on urban development are gradually increasing, such that the scale of resilience research has expanded, and resilience is now being explored in urban and regional research. As such, scholars consider theoretical studies and empirical analysis of regional resilience [3–5]; some even believe that a close relationship between urban network structure and regional resilience exists [6,7]. As a new urban geographic system, an urban network constitutes a group of cities in a particular region among which there is a flow of information, material, and energy, thereby making these cities nodes [8]. A typical form of spatial characteristics of resilience is the resilience of the urban network structure; hence, the analysis of the ability of the urban network systems to resist, adapt, recover, and maintain their original state under external environmental shocks via inter-city collaboration in ecological, social, economic, and engineering fields is essential [9,10].

A networked urban geographic system is a prerequisite for exploring the resilience of the urban network structure. The spatial organization of cities has changed with the development of an information-based society, and economic globalization has made the relationship among cities increasingly complex. The "space of place" has been replaced by "space of flow," and the urban networks have gradually become a new perspective for studying urban systems [11,12]. Scholars have explored the structural characteristics, evolutionary trends, and influencing factors of urban networks, including enterprise networks [13–15], airline networks [16,17], logistics networks [18], freight networks [19], and information networks [20–22]. Presently, the increasingly complex social environment, urban connectivity, and diverse economic structures have made it essential to enhance the capability of urban networks to cope with shocks for maintaining sustainable regional development [23]. Existing studies have shown that indicators such as network efficiency, diversity, and connectivity can effectively characterize the resilience of urban network structures [24–26]. Unpredictable, uncertain, and frequent natural and man-made disasters can affect urban nodes to a certain extent or can even fail, which can lead to the failure of urban networks and affect the sustainable development of a region [27]. In this regard, building and strengthening the resilience of urban nodes for coping with external environmental shocks has become a key issue that needs to be addressed urgently [28]. Presently, the gradual spread of COVID-19 in the urban network has significantly impacted the healthy development of the region, such that the sudden virus outbreak has reinforced the importance of strengthening the construction of resilient cities and enhancing the structural resilience of urban networks. Meanwhile, the regional cooperation mechanism adopted by China to cope with COVID-19 demonstrates that mutual collaboration among cities in response to external environmental shocks can create a good network synergy [29].

Previous studies provide few empirical results on the resilience of the urban network structure, which still needs to be explored and improved. Meanwhile, most of the existing studies focus on assessing the resilience of the urban network structure and the analysis of optimization strategies, and the discussion on the influence mechanism of urban network structure resilience is insufficient [30]. As the three provinces of Northeast China are located in the center of Northeast Asia and occupy an important strategic position in the development pattern of China, it is significant to analyze the resilience of the urban network structure in the three provinces of Northeast China. In light of this, we take the three provinces as our study area to construct a multi-linkage network through multi-source data and evaluate the characteristics of the resilience of the urban network structure from the four perspectives of hierarchy, matching, transmission, and agglomeration. We explore the influencing factors of urban network structure resilience and propose appropriate optimization strategies as relevant references and theoretical bases for enhancing the resilience of urban networks by adjusting the spatial organization of cities and optimizing the allocation of resources.

2. Research Data and Methods

2.1. Study Area

We selected the three provinces of Northeast China as the research area to conduct empirical research. The primary reasons for choosing this area are as follows: (1) As one of the four major economic sectors in China, the regions are connected by the three provinces by relying on the development axis of "Harbin–Changchun–Shenyang–Dalian". As such, affected by geographical proximity and collective rooting, these provinces have close ties with each other. Simultaneously, certain exchanges and cooperation are maintained among them, such that socio-economic ties among the prefectures are characterized by crossover, overlap, and integration, and have strong characteristics of regional integrity. (2) As a complete and independent economic zone, the regional development of the three provinces of Northeast China occupies an important position, and as the window for China's opening to Northeast Asia, coping with the impact of the external environment in the context of the unstable growth of trade globally, is an important challenge for the urban network structure of the three provinces. Hence, we selected the three provinces of Northeast China as our study area, including Heilongjiang, Jilin, and Liaoning Provinces. Among them, the Daxinganling region of Heilongjiang Province and the Yanbian Korean Autonomous Prefecture of Jilin Province were not included in the research due to missing data. Therefore, a total of 34 prefecture-level cities were considered (Figure 1).

Figure 1. Study area.

2.2. Data Source

The data in this article mainly include four parts (Table 1): (1) Baidu Index data, mainly from the official website of Baidu Index search (http://index.baidu.com, accessed on 20–23 June 2021). We used the 34 prefecture-level cities as search keywords to obtain the attention data between two cities at a time in the three provinces from 1 January to 31 December 2019. On this basis, the daily average value was obtained by sorting the data, which was used to characterize the strength of information connection among cities; (2) mileage data, including highway mileage and train and railway mileage, where highway mileage data were searched through the official website of Baidu Map (https://map.baidu.com, accessed on 26 June 2021) to obtain the highway mileage among 34 cities, and railway mileage data were retrieved based on the railway mileage search website of the train ticket network (http://www.huochepiao.com/licheng/, accessed on 28 June 2021) to obtain the railway mileage between two cities; (3) Paper co-author data, mainly from the Web of Science database (http://webofscience.com, accessed on 3–5 July 2021), were retrieved from the number of co-authored journal papers between two cities in 2019 to characterize the intensity of innovation linkage among cities; (4) statistical data, mainly from Liaoning Province Statistical Yearbook 2020, Jilin Province Statistical Yearbook 2020, and Heilongjiang Province Statistical Yearbook 2020.

Table 1. Multi-source data information used in the research.

Data	Date	Data Sources	Corresponding Urban Network Type
Statistical data	2019	Statistical Yearbook of Liaoning Province, Jilin Province, and Heilongjiang Province	Economic network
Baidu Index	January 2019–December 2019	Baidu Index search platform (http://index.baidu.com, accessed on 20–23 June 2021)	Information network
Mileage data	-	Baidu Map official website (https://map.baidu.com, accessed on 26 June 2021), train ticket and railway mileage inquiry website (http://www.huochepiao.com/licheng/, accessed on 28 June 2021)	Transportation network
Paper co-author	2019	Web of Science database (http://webofscience.com, accessed on 3–5 July 2021)	Innovation network

2.3. Multi-City Network Construction Method

A prerequisite for exploring the resilience of the urban network structure is the construction of multiple urban networks. In general, regional resilience contains four major domains: ecological, economic, social, and engineering [31–33]. Furthermore, because the research object of this study is the urban network, the ecological domain is considered a substrate of urban construction and development without considering the construction of the corresponding urban network [9]. In addition, cities are the spatial carriers of innovation, such that the innovation cooperation among cities can effectively reflect the regional development capacity [34,35]. Therefore, the innovation domain is considered to be included in the construction of urban networks. To sum up, based on the four domains of economy, society, engineering, and innovation, we constructed the connection network of economy, information, transportation, and innovation. We measured the hierarchy, matching, transmission, and agglomeration of multiple urban network structures. This enabled us to evaluate the resilience of the urban network structure in the three provinces of Northeast China (Figure 2).

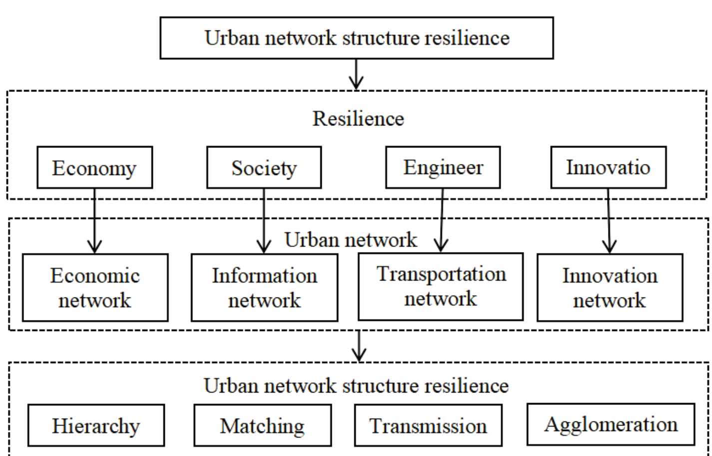

Figure 2. Multi-city network construction framework.

2.3.1. Information Network

The information connection network among cities is represented in the form of the Baidu Index product between cities, the formula for which is [36]:

$$I = I_{ij} \times I_{ji} \tag{1}$$

where I is the information connection strength, I_{ij} is the Baidu attention value of city i to city j, and I_{ji} is the Baidu attention value of city j to city i.

2.3.2. Transportation Network

Considering that roads and railroads are the primary modes of transportation among cities in the three provinces of Northeast China, we constructed the transportation connection network based on the law of gravity with the formula [10]:

$$T = K_{ij} \times \left(\sqrt{P_i N_i} \times \sqrt{P_j N_j} \right) / D_{ij}^2 \tag{2}$$

In the formula, T is the strength of transportation connection, K_{ij} is the gravitational coefficient, which takes the value of 1, P_i and P_j are the number of economically active populations in city i and city j, N_i and N_j are the GDP of city i and city j, and D_{ij} is the sum of the highway and railway mileage between city i and city j.

2.3.3. Economic Network

Referring to previous research [37], the employed population G in the urban area is chosen to represent the urban functional capacity, and the value of location entropy of a sector's employees in a city determines whether the city has an outward function, and the location entropy Lqij of employees in department j in city i is presented as follows:

$$Lq_{ij} = \left(G_{ij} / G_i \right) / \left(G_j / G \right) \quad (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, m) \tag{3}$$

where, if $L_{qij} < 1$, the department does not have an export-oriented function and $E_{ij} = 0$. If $L_{qij} > 1$, the department has an export-oriented function, and, at this time, the export-oriented function E_{ij} of department j in city i is as follows:

$$E_{ij} = G_{ij} - G_i^* \left(G_j / G \right) \tag{4}$$

Total outward function E_i of m departments in city *i:*

$$E_i = \sum\nolimits_{j=1}^{m} E_{ij} \tag{5}$$

Functional efficiency N_i of city i:

$$N_i = GDP_i / G_i \tag{6}$$

The amount of outward function impact of city i:

$$F_i = E_i \times N_i \tag{7}$$

On this basis, the economic network is constructed based on the gravity model:

$$R = \left(F_i \times F_j \right) / D_{ij}^2 \tag{8}$$

where R is the strength of economic connection, F_i and F_j are the amounts of the outward functional influence of city i and city j, and D_{ij} is the linear distance between city i and city j.

2.3.4. Integrated Network

The TOPSIS method based on the entropy weight method combines the entropy weight method with the TOPSIS method to avoid the influence of subjective weight assignment on analysis structure. Therefore, we chose the entropy weight TOPSIS method to construct the integrated network [38].

2.4. Urban Network Structure Resilience Measure

Based on relevant research [25,39,40], with the help of the complex network analysis method, the resilience of the urban network structure in the three provinces of Northeast China was assessed from the perspectives of hierarchy, matching, transmission, and agglomeration (Table 2).

Table 2. Evaluation indicators of urban network structure resilience.

Dimension	Index	Spatial Significance
Hierarchy	Weighted degree	Externally connected degree of urban nodes
	Weighted degree distribution	Urban node level
Matching	Weighted average nearest-neighbor degree	Correlation degree among urban nodes
Transmission	Average path length	Urban node communication capability
Agglomeration	Local weighted clustering coefficient	Agglomeration degree of urban nodes and their neighboring nodes

2.4.1. Hierarchy

Hierarchy can characterize the rank of urban nodes in the network and degree, whereby degree distribution can measure the hierarchy of nodes in the urban network structure [41]. Nevertheless, this has the drawback of ignoring the functional relationship among urban nodes. Therefore, the weighted degree and weighted degree distribution are used to measure the hierarchical resilience of the urban network structure considering the urban network weights. The formula for this is [32]:

$$W_i = C(W_I^*)^a \tag{9}$$

The formula is processed as follows:

$$ln(W_i) = ln(C) + aln(W_i^*) \tag{10}$$

where W_i is the weighted degree of city i, W_i* is the ranking of the weighted degree of city i in the network, C is a constant, and a is the slope of the weighted degree distribution curve. The higher the slope, the more evident the hierarchy of the urban network [32].

2.4.2. Matching

Matching reflects the degree of correlation among urban nodes. As the degree of connection among urban nodes is not equivalent, preferential attachment makes the connection among urban nodes correlated. Based on the results of hierarchical calculation, the urban nodes with a large weighted degree tend to "clump" together, which indicates that the network is homogeneous; however, in reality, it is heterogeneous [32]. This is also the case with the homogeneity network relative to the different distribution of the network; it is more easily affected by curing the contact path. Its innovation, low permeability, and external shocks make it difficult to guarantee a quick update and change, leading to increased risk. Hence, the structure's resilience in the matching of urban networks is lower [42]. On this basis, the weighted degree correlation is applied to measure the matching resilience of the structure of the urban network. The formula is as follows [30]:

$$\overline{NW_i} = \frac{1}{K_i}\sum_{i \in G_i} W_k \quad \overline{NW_i} = D \times W_k^b \tag{11}$$

where $\overline{NW_i}$ is the neighbor-weighted average degree (NWAD) of city i, W_k is the weighted degree of neighbor node k of city i, K_i is the degree of city i, G_i is the set of neighbor nodes of city i, D is a constant, and b is the weighted degree correlation coefficient. Among them, if $b > 0$, it indicates that the network has homogeneity; however, the network has heterogeneity.

2.4.3. Transmission

Transmission measures the ability of urban nodes to spread and diffuse in the network through path length, such as the shortest path length [43]. Combined with existing research, this study uses network efficiency to measure the transmission resilience of urban network structures. The formula is [44]:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{D_{ij}} \tag{12}$$

where E is the network efficiency, D_{ij} are all the shortest paths from city i to city j, N is the number of nodes in the network, and G is the set of the remaining nodes in the network after removing the nodes.

2.4.4. Agglomeration

Agglomeration can characterize the nature of grouping urban network nodes. Generally, the stronger the connection among urban nodes, the larger the value of the clustering coefficient of urban nodes. The local clustering coefficient ignores the importance of urban nodes in the weighted network; thus, we consider using the local weighted clustering coefficient to measure the structure agglomeration resilience of the urban network. The formula for this is [45]:

$$C_i^w = \frac{1}{k_i(k_i-1)} \sum_{j,k} \left(\hat{w_{ij}} \hat{w_{ik}} \hat{w_{jk}} \right)^{\frac{1}{3}} \tag{13}$$

where C_i^w is the local weighted clustering coefficient, k_i is the number of neighbors of node i, and w_{ij}, w_{ik}, and w_{jk} are the weights of the edges among nodes, which are processed using the network maximum weight standardization method. The more urban transmission among nodes and the stronger the interaction capabilities, the higher the dependence among nodes, the less "robust" the network is, the less the city's ability to resist interference from the outside world is, and the more network connections will be disrupted in the event of any local outage; as such, the local weighted clustering coefficient's numerical size and the network structure are inversely proportional to the level of resilience [46].

3. Evaluation of Urban Network Structure Resilience in the Three Provinces of Northeast China

3.1. Spatial Pattern of the Urban Network Structure

Based on the information of the connection matrix, transportation connection matrix, innovation connection matrix, and economic connection matrix, the multiple connection networks were classified according to the natural breakpoint method. Further, ArcGIS was used to realize spatial visualization and draw the multiple network connection distribution maps (Figure 3). Through the Quadratic Assignment Procedure (QAP) correlation analysis in UNICET (Table 3), we found that the correlation coefficients among the information network, transportation network, innovation network, and economic network are significantly correlated at the 1% level, indicating that the multiple urban networks in the three provinces of Northeast China exhibit strong correlation characteristics. Among them, the correlation between the transportation network and the economic network is the highest (0.610), and the correlation between the innovation network and the economic network is the lowest (0.307); this indicates that there are certain similarities among the multiple urban networks in the three provinces, but, at the same time, high differences also exist. Hence, it is necessary to further explore the structure resilience characteristics of each network.

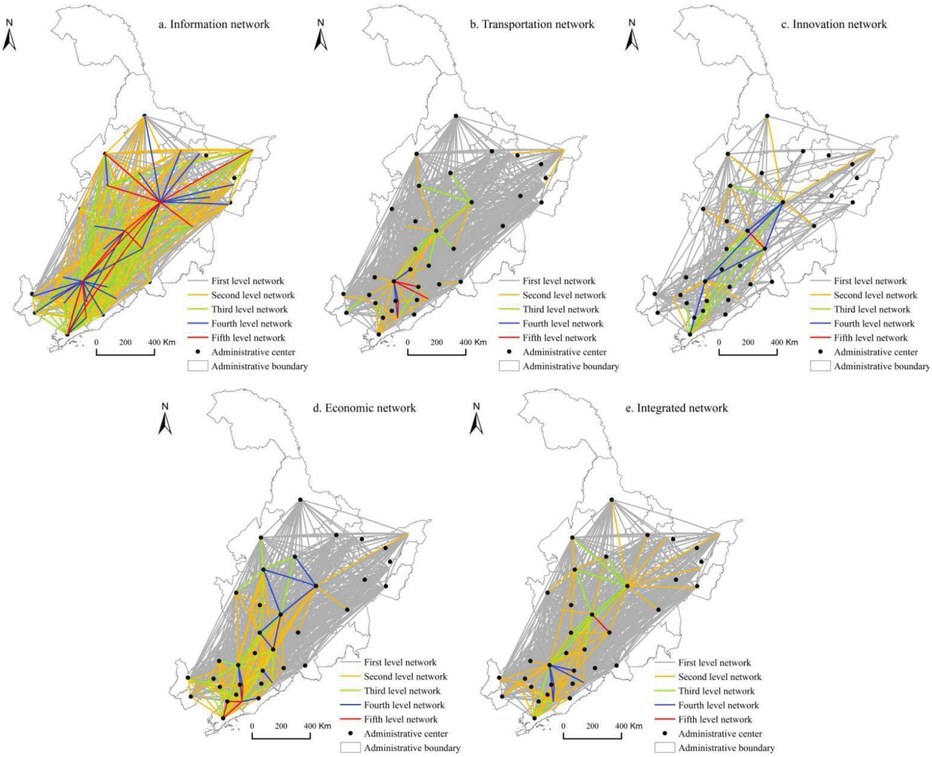

Figure 3. Distribution of the network connection strength of multiple cities in the three provinces of Northeast China.

Table 3. Correlation coefficients of multiple connection networks in 34 cities in the three provinces of Northeast China.

Multiple Network	Information Network	Transportation Network	Innovation Network	Economic Network
Information network	-	0.497 ***	0.387 ***	0.428 ***
Transportation network	0.497 ***	-	0.390 ***	0.610 ***
Innovation network	0.387 ***	0.390 ***	-	0.307 ***
Economic network	0.428 ***	0.610 ***	0.307 ***	-

Note: *** indicates passing the 1% significance test.

In order to reflect the urban network spatial pattern of the three provinces in Northeast China more clearly, the natural breakpoint method is used to classify the element connections between cities, and ArcGIS is used to visualize them [10]. The urban networks in the three provinces demonstrate an overall spatial pattern of "dense in the north and sparse in the south", but each network also has different characteristics (Figure 3). The urban information network has a multi-center network structure with Shenyang, Dalian, Harbin, and Changchun as the core (Figure 3a), whereby the first level constitutes a "cross" spatial pattern, showing a more complex network pattern than other networks. The difference of the urban transportation network is more evident (Figure 3b), influenced by spatial proximity, such that the first level of the transportation network is mainly the connection among Shenyang-Fushun, Anshan-Liaoyang, and Shenyang-Benxi, and the fifth level mainly constitutes the connection among urban nodes. The overall connection of the urban innovation network is looser than that of other networks, and the connections among city nodes are relatively weak (Figure 3c). The intra-provincial linkage of the innovation network is closer, and the cross-provincial linkage is mainly between provincial capital cities and sub-provincial cities. The first level of the urban economic network in Liaoning Province presents an "N"-shaped structure, with closer intra-provincial ties and closer inter-provincial ties than the transportation network and innovation network (Figure 3d). The connections among urban nodes in the integrated network are more complicated than those in other networks, and the connections among cities are closer, and the urban network structure is more robust (Figure 3e).

3.2. Urban Network Structure Resilience

3.2.1. Network Hierarchy

Urban nodes with strong radiation and dispersal capabilities in the information network and transportation network are mainly Harbin, Changchun, Shenyang, and Dalian, indicating that the provincial capital cities and sub-provincial cities are leading in terms of socio-economic development, and the rest of the cities are dependent on them owing to their spatial proximity and radiation-driven effects, resulting in a high hierarchy of city nodes around them (Figure 4a,b). The cities with a high hierarchy in the innovation network are Changchun and Jilin, which form a single core pattern in space with evident polarization characteristics (Figure 4c). The spatial distribution of economic network hierarchy shows a "ridge-type" trend with "Harbin–Changchun–Shenyang–Dalian" as the axis, decreasing from the middle to both ends (Figure 4d). In the integrated network, the urban nodes located at the fifth level are mainly Harbin, Changchun, Shenyang, Dalian, and Anshan, and a spatial axial development trend is evident (Figure 4e).

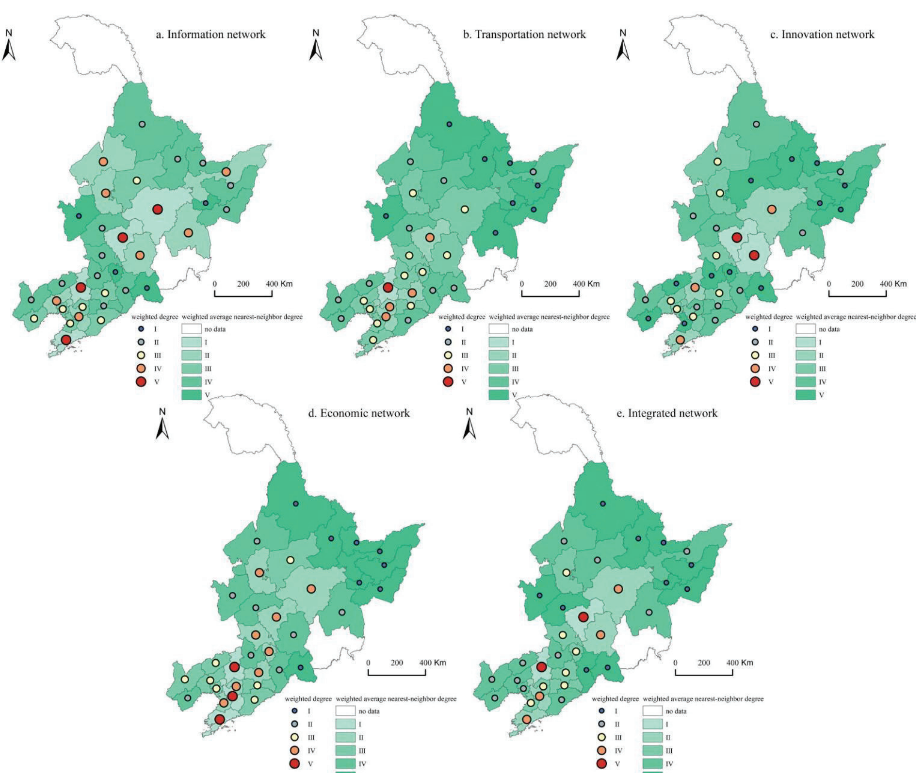

Figure 4. Spatial distribution of weighted degree and weighted average nearest-neighbor degree of the multi-city linkage network in the three provinces of Northeast China.

We drew the weighted degree distribution fitting curve according to the weighted degree calculation results of each urban node (Figure 5). From the slope of each curve (0.883 < ∣a∣ < 3.235), we can determine that all kinds of networks have strong hierarchical characteristics. Among them, the curve slope of the innovation network has the largest value (∣a∣ = 3.235), which indicates that the innovation network has the highest hierarchical level, the core position of the urban node is more prominent, and the three-dimensional development trend of the innovation network is evident. The curve slope of the economic network has the second highest value (∣a∣ = 1.603), indicating that the network has a more evident hierarchical structure of urban nodes. The transportation network (∣a∣ = 1.431) and the information network are less hierarchical (∣a∣ = 0.883), and the high-value areas are mainly provincial capitals and sub-provincial cities, which show spatial homogeneity. The slope of the integrated network curve (∣a∣ = 1.117) is relatively smooth compared with that of the innovation, economic, and transportation networks, indicating that the degree of external connection of urban nodes under the integrated network is relatively reasonable, and the difference in the hierarchical level among urban nodes is not significant; relatively speaking, the integrated network shows a flat development.

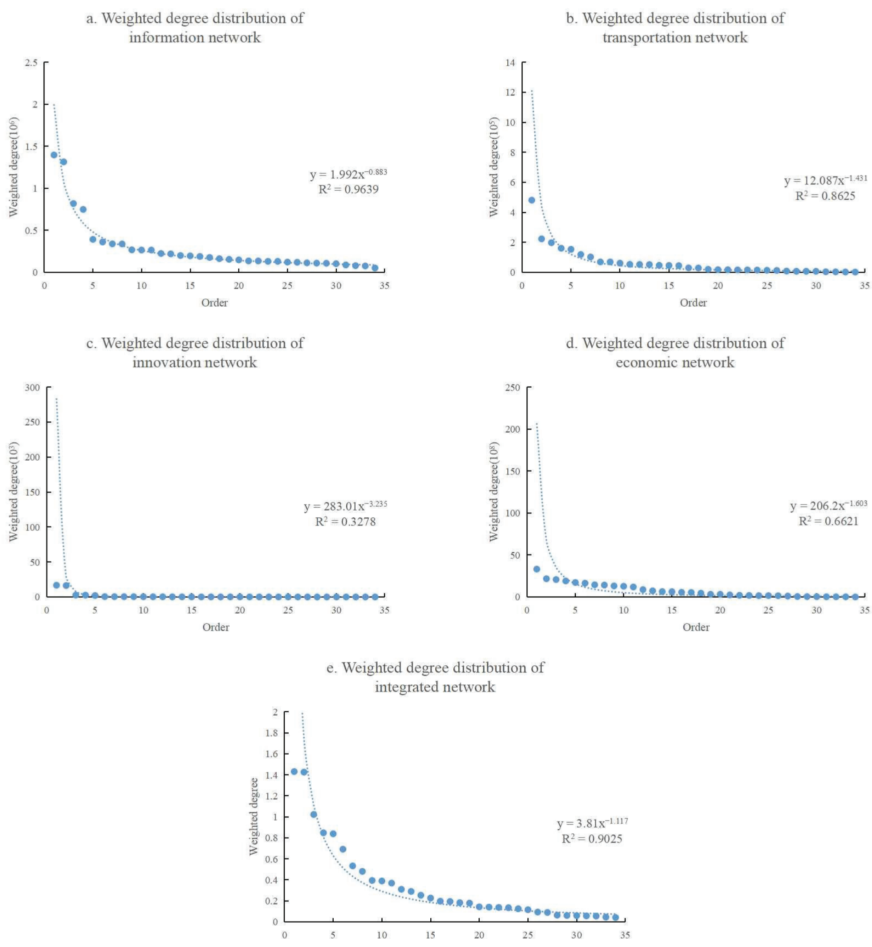

Figure 5. Distribution of the weighted degree of the urban network in the three provinces of Northeast China.

3.2.2. Network Matching

The NWAD values of urban nodes with higher hierarchy in each urban network are smaller (Figure 4). In the integrated network, the number of urban nodes with NWAD in the first group is the largest, and they are mainly the urban nodes with higher values of weighting degree, which, to some extent, indicates that there are more communication and contact paths between the core urban nodes and other urban nodes, which is more conducive to the flow of elements among nodes.

The weighted degree correlation of all five types of network coefficients is negative ($-0.041 < b < -0.008$), indicating that the information, transportation, innovation, economic, and integrated networks all have heterogeneous characteristics. Among them, the information network has the most evident heterogeneity ($b = -0.041$), and the urban nodes with higher weighted values can maintain good interaction with the nodes at the same level and can also communicate and cooperate with the urban nodes at different levels. The transportation network has strong heterogeneity ($b = -0.027$), and the city nodes with evident transportation advantages have a radiating and driving effect on their neighboring cities. In addition, the well-connected transportation network also contributes to the development of regional linkages, and the path connections among city nodes tend to be heterogeneous. The heterogeneity characteristics of the economic network are weak ($b = -0.015$), with strong mobility of economic factors among core cities but weak mobility of economic factors among peripheral cities, with significant spatial differences in the intensity of the flow of economic factors and the low structural resilience of the economic network. The heterogeneity of the innovation network is not evident compared with other networks ($b = -0.008$), and the phenomenon of homogeneous grouping exists, the connection among nodes in core cities and nodes in peripheral cities is weak, and the cross-regional exchange and cooperation regarding the innovation factor flow are restricted. The combined network heterogeneity is lower than that of the information network and higher than that of the transportation, economic, and innovation networks ($b = -0.025$), indicating that there may be a certain degree of bias in measuring the structural resilience of urban networks based on a single factor flow. The combined effect of multiple factor flows can enhance the "robustness" of the connection paths among urban nodes to some degree and jointly improve the level of the urban network.

3.2.3. Network Transmission and Agglomeration

The spatial difference of the economic network transmission is the most evident, followed by that of information, integrated, and transportation networks. Meanwhile, the innovation network transmission has the smallest spatial variability (Figure 6), in which the information network transmission shows an overall hierarchical structure that increases from south to north. Moreover, the spatial pattern of the transportation, economic, and integrated network transmission has a certain similarity, and the innovation network transmission has a multi-core distribution pattern. Shenyang exhibits the most significant influence on the transmission of the information and innovation networks. In the information network, there are three groups that have the same degree of influence on the network transmission after the failure of city nodes: Songyuan and Baicheng, Qiqihar and Jixi, and Mudanjiang and Heihe; the degrees of influence are 0.3808, 0.3818, and 0.3836, respectively. Two groups of cities in the innovation network have the same impact on the innovation network transmission: Anshan and Jinzhou, Baishan and Jixi; the network efficiency after the failure of the city node is 0.4363 and 0.4484, respectively, and the network efficiency after the failure of city nodes in Changchun contributes the most to the transport network transmission, while Anshan, Suihua, Fushun, Tieling, Yingkou, Benxi, Tonghua, and Mudanjiang have the same degree of influence on the network efficiency, at 0.1467, 0.1485, 0.1488, and 0.1491, respectively. The urban node that bears the main transmission function in the economic network is Harbin, in which, the cities of Tonghua-Dandong and Jilin-Jixi-Hegang have equivalent influence on the transmission of the economic network, and the network efficiency after the failure of the city node is 0.6139 and 0.6169, respectively.

In the integrated network, Shenyang is the city node that undertakes the main transmission function, and Qitaihe and Baishan have the lowest transmission function.

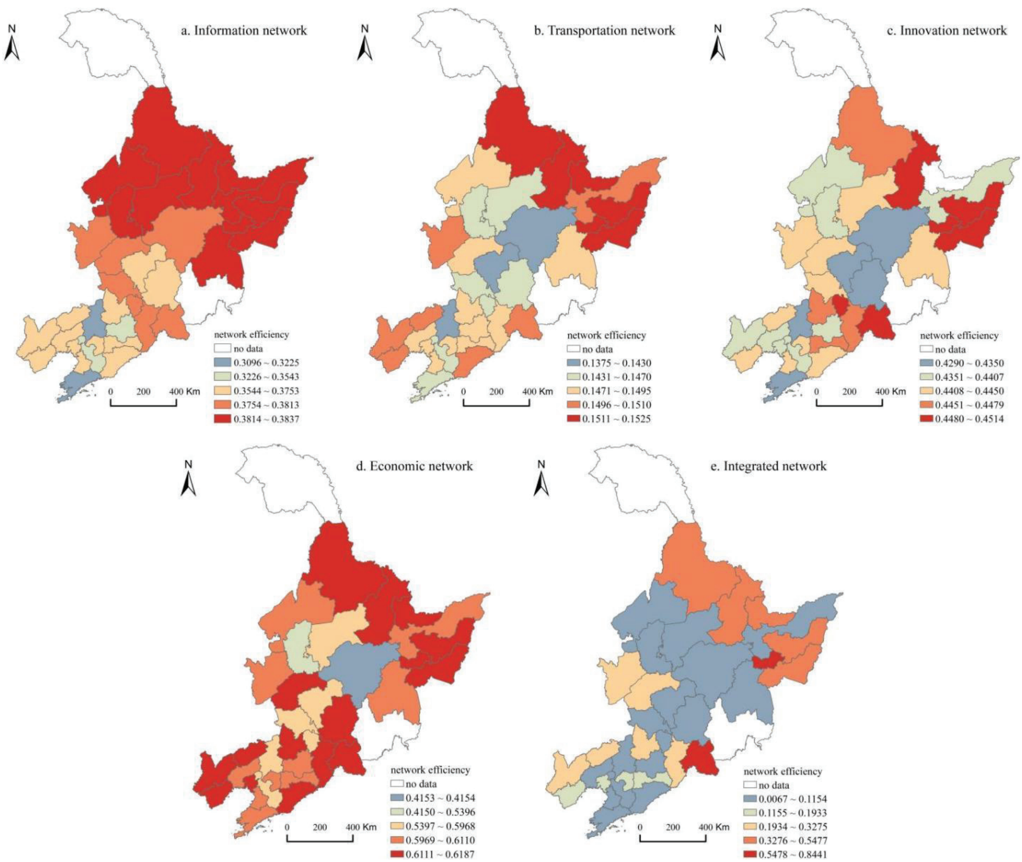

Figure 6. Spatial distribution of the transmission efficiency of the multi-city connection network in the three provinces of Northeast China.

The average weighted clustering coefficients of the information, transportation, innovation, economic, and comprehensive networks are all approximately 0.2, indicating that the clustering characteristics of each type of network are weak, and with the expansion of the network scale, the core urban nodes have a wider radiation range, and other city nodes rely on the core city nodes to achieve cross-regional cooperation. The local weighted clustering coefficients of the rest of the networks except the transportation network show that the local weighted clustering coefficients of provincial capital cities and sub-provincial cities are in the first group (Figure 7). This indicates that the relationship between provincial capital cities and sub-provincial cities and other cities is not very close, but rather, there is a one-way connection between other city nodes and core city nodes, whereby there is less interactive cooperation among other city nodes, such that the node is not yet evident. The interaction and cooperation among other city nodes are lower, and no evident network has been formed. From the perspective of network structural resilience, the weak connection between core city nodes and other city nodes facilitates the penetration of external information, thereby enhancing the "robustness" of the city network in response to external information interference.

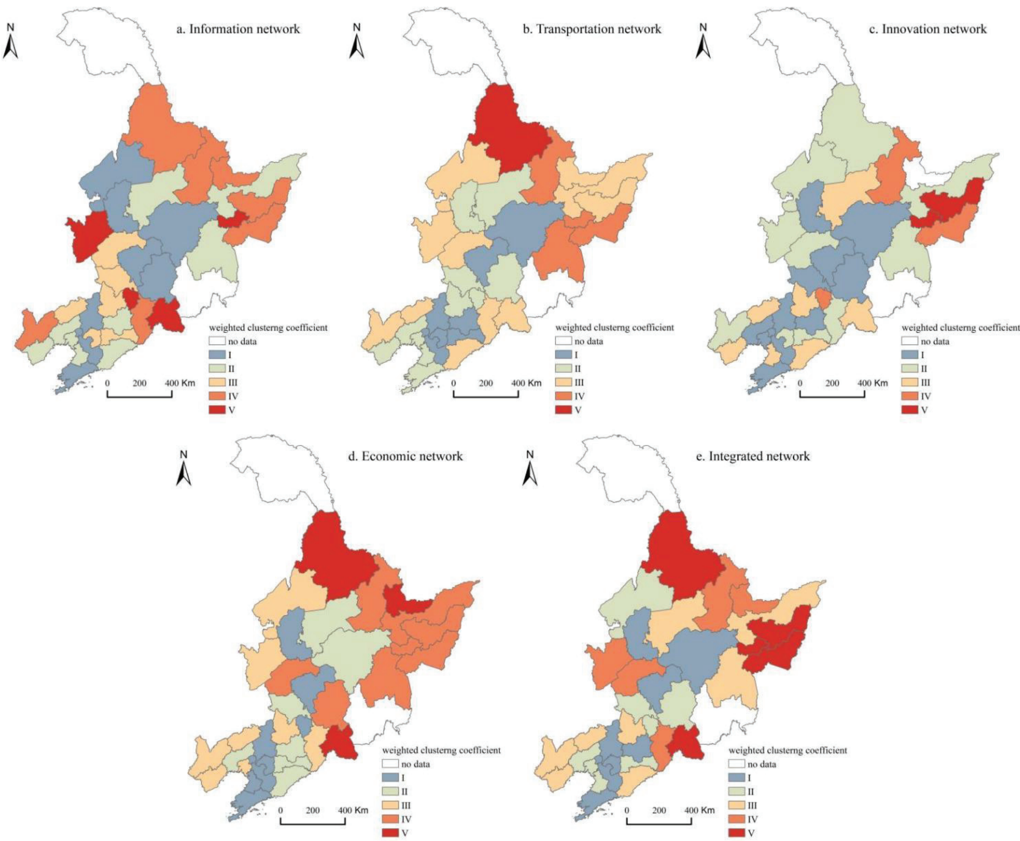

Figure 7. Spatial distribution of the local weighted clustering coefficients in the multi-city connection network of the three provinces of Northeast China.

3.2.4. Urban Node Type Identification

The city nodes whose transmission and agglomeration are located in the first and second groups are regarded as dominant city nodes. There are five city nodes, which are provincial capital cities (Harbin, Shenyang, and Changchun), sub-provincial cities (Dalian), and resources-based cities (Daqing and Anshan). The cities in this category are in prominent positions in diverse networks, with strong comprehensive strength, leading the construction and development of the neighboring cities. The city nodes with both transmission and agglomeration in the fourth and fifth groups are considered as vulnerable city nodes, such that there are nine city nodes in total, namely, Songyuan, Tonghua, Baicheng, Jixi, Yichun, Heihe, Hegang, Shuangyashan, and Baishan, all of which are located in Jilin Province and Heilongjiang Province; most of them are peripheral cities with a low level of socio-economic development and imperfect public service facilities (Figure 8). Under the effect of administrative barriers, vulnerable city nodes are distant from provincial capital cities. As such, in considering future construction and development, it is necessary to heed and support the development of such cities and enhance their capability to cope with unexpected risks.

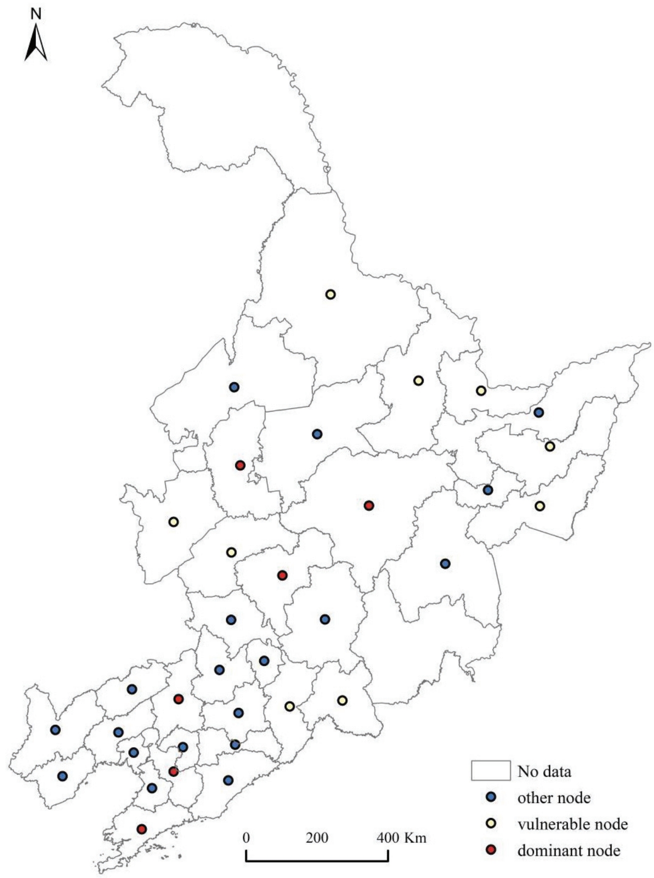

Figure 8. Spatial distribution of the types of urban nodes in the three provinces of Northeast China.

4. Influencing Factors of Urban Network Structure Resilience in the Three Provinces of Northeast China

4.1. Variable Selection

Exploring the factors influencing urban network structure resilience can provide relevant references for optimizing the resilience of the urban network structure. Presently, research on urban network structure resilience is still in the exploration stage, and there are few studies on the factors influencing urban network structure resilience. The resilience of the urban network structure is the result of multiple factors interacting and working together, combined with existing research results on the urban network structure and urban resilience [47–51]. The four properties of comprehensive urban network structure resilience are used as dependent variables. Economic scale, knowledge thickness, political status, geographic conditions, urban vitality, government capacity, openness, labor wages, and science and education level are used as the drivers affecting the resilience of the urban network structure (Table 4).

Table 4. Influencing factors of urban network structure resilience.

Variable	Index	Unit	Max	Min	Mean	Std. Dev.
Economic scale	Gross National Product per capita	Yuan (RMB)	99,996	21,045	42,314.471	21,207.168
Knowledge thickness	Total number of patent applications	Piece	37,313	6	4260	8765.050
Political status	1 for provincial capital cities and sub-provincial cities and 0 for the rest of the cities	-	1	0	0.118	0.327
Geographic conditions	1 for cities in eastern provinces and 0 for cities in central and western provinces	-	1	0	0.412	0.500
Urban vitality	Population density	Person/km^2	587.869	22.785	194.313	132.818
Government capacity	Proportion of public financial expenditure in GDP	%	59.056	12.300	32.589	12.186
Openness	Proportion of total exports to GDP	%	27.711	0.003	4.605	5.888
Labor wages	Average salary of on-the-job employees	Yuan (RMB)	100,781	44,953	65,556.941	12,364.777
Science and education level	Proportion of science and education expenditure in total expenditure	%	16.283	6.521	11.780	2.203

4.2. Regression Results

The least-squares method was used to analyze the influencing factors of urban network structure resilience, and the regression results are shown in Table 5. These results show that the R2 is between 0.455 and 0.793, which can explain 45.50% to 79.30% of urban network structure resilience. Overall, the fitting effect of the least-squares method is more suitable.

Table 5. Regression results of influencing factors.

	Hierarchy	Matching	Transmission	Agglomeration
Economic scale	0.0005	0.0011	0.0003	0.0003
Knowledge thickness	−0.0002	0.0023	−0.0006 *	−0.0005 *
Political status	0.5396 ***	−0.0164 ***	0.1184 ***	0.0578
Geographic conditions	−0.1932	0.0059	0.0935	0.0141
Urban vitality	0.0015 ***	−0.0045 ***	−0.0006	−0.0005 **
Government capacity	−1.5922 **	0.0482 **	0.9966 *	0.9603 *
Openness	−1.0181	0.0309	−0.2738	0.1490
Labor wages	0.0004 ***	0.0005	−0.0001	−0.0007
Science and education level	−0.6303	0.0191	−2.1147	−1.0740
Intercept	0.860	0.326	0.153	0.107
Sample size	34	34	34	34
R^2	0.793	0.715	0.543	0.455

Note: *, **, *** indicate passing the 10%, 5%, and 1% significance test, respectively.

The best fit for the hierarchical nature of the city network structure, by controlling the other variables, denotes that political status, urban vitality, and labor wages can have a significant positive effect on enhancing its hierarchical characteristics, and all pass the 1% significance level test. The improvement of government capacity also has an effect, albeit to a lesser extent, but passes the 5% significance level test, consistent with the results for provincial capital cities and sub-provincial cities as core city nodes. Under the interaction of political status, urban vitality, labor wages, and government capacity, the non-heterogeneous pattern of the urban network structure is evident.

In terms of urban network structure matching, the regression results of its influencing factors are similar to those of hierarchy, in which government capacity, political status, and urban vitality significantly impact it negatively. Hence, it is necessary to focus on the interaction and cooperation between provincial capital cities and sub-provincial cities through the macro-regulatory role of the government, enhance the radiation capacity of core city nodes, and promote the development of other urban nodes through core urban nodes.

The transmission of the urban network structure is significantly affected by political status, government capacity, and knowledge thickness, and the transport function of the provincial capital cities and sub-provincial cities occupies a significant position in the entire network. After the failure of such city nodes, the transmission of the urban network structure will be significantly affected, and the network efficiency will decrease. Therefore, it is necessary to enhance the transmission efficiency of other urban nodes to ensure that the urban network can maintain regular operation in unexpected situations.

The agglomeration of the urban network structure is mainly related to urban vitality, government capacity, and knowledge thickness. The local weighted clustering coefficient of urban nodes with a large number of urban residents and a large total number of patent applications is lower, which is consistent with the results of the previous analysis. Therefore, we need to emphasize improving the level of science and technology within the region and strengthening the construction of transportation infrastructure to promote the flow of information, transportation, innovation, economy, and other factors among city nodes to realize regional interaction and cooperation.

5. Conclusions

The structural resilience of urban networks is one of the important factors affecting regional sustainable development. Through studying the structural resilience of urban networks in three provinces of Northeast China, the weak links in regional network structures are found, and the network structure is adjusted to promote the rational flow of regional factors, so as to promote the overall high-quality development of the region. To provide relevant references for optimizing the urban network structure resilience at home and abroad, we measured urban network structure resilience and the influencing factors in the three provinces of Northeast China in 2019. This was accomplished through the construction of urban information, transportation, innovation, economy, and integrated networks in the study provinces. As a result, the following conclusions can be drawn:

(1) There are certain similarities among the multi-city networks in the three provinces of Northeast China; nevertheless, there are also major differences. Overall, information, transportation, innovation, economy, and the integrated network show a spatial distribution pattern of "dense in the north and sparse in the south", with closer intra-provincial ties than inter-provincial ties. Nonetheless, the spatial structure differences are evident: The information network shows a multi-core spatial pattern. The main levels have a cross-shaped spatial structure in space, which breaks the limitation of regional spatial distance and presents a more complex networked state. The transportation network is evidently affected by geographical spatial proximity, and the flow of transportation elements in neighboring regions is strong. The overall connection of the innovation network is looser, and the connection among urban nodes is relatively weak. The first level of the economic network presents an "N"-shaped structure in Liaoning Province, and the flow of economic factors decreases with increasing spatial distance. The integrated network is more complex than other networks, and the network structure is more robust.

(2) There are evident differences in the resilience characteristics of the multi-city network structure in the three provinces of Northeast China. The information network exhibits the highest heterogeneity, the transmission and agglomeration are at the medium level, and the hierarchy exhibits the lowest. Hence, overall, the information network structure has limited resilience. The hierarchy and heterogeneity of the transportation network are at the medium level, with low transmission and lower agglomeration, and are limited by urban traffic conditions. Hence, the resilience level of the transportation network is low. The innovation network has a high level of hierarchy, with higher transmission, low agglomeration, and the lowest heterogeneity, such that the local network with high resilience has low capability to drive its surrounding network. The economic network has high transmission, agglomeration, higher hierarchy, and low heterogeneity. Hence, its overall resilience is higher. The integrated network is affected by the interaction of multiple networks, and the characteristics of network structure resilience are complicated. Triggering the radiation-driven effect of dominant urban nodes and focusing on the construction and development status of vulnerable urban nodes have important implications for improving the resilience of urban network structures.

(3) The resilience of the multi-city network structure in the three provinces of Northeast China is affected by the interaction of multiple factors. In terms of hierarchy, under the interaction of government capacity, political status, urban vitality, and labor wages, the urban network structure demonstrates a phenomenon of heterogeneity. In terms of matching, the urban network structure of the three provinces exhibits high heterogeneity owing to government capacity, political status, and urban vitality. In terms of transmission, government capacity, political status, and knowledge thickness together shape the transmission resilience of the urban network structure, resulting in a more prominent transmission function of core urban nodes. In terms of agglomeration, government capacity, urban vitality, and knowledge thickness are the main factors influencing the agglomeration of the urban network structure; hence, we need to focus on the construction of urban vitality, government capacity, and knowledge thickness to enhance the connection among urban nodes.

6. Discussion

6.1. Optimization Strategies

With the gradual strengthening of the globalization trend, cities are no longer simple individual units, and the diversified flow of elements connects cities. Hence, it is crucial to maintain a coordinated and stable resilience capacity during the disturbance of the external environment. On this basis, based on the four aspects of hierarchy, matching, transmission, and agglomeration, we propose countermeasures for optimizing the resilience of the urban network structure.

The hierarchy of the urban network structure in the three provinces of Northeast China is evident, and there is a significant trend of heterogeneity, which is significantly influenced by government capacity and political status; which results in the prominent core positions of provincial capital cities (Shenyang, Changchun, and Harbin) and sub-provincial cities (Dalian). Therefore, cross-provincial exchanges and cooperation among core cities to realize the linkage development of the three provinces of Northeast China need to be emphasized. In addition, the radiation function of the nodes of core cities should be allowed to drive the development of surrounding areas, realize the synergistic development between core cities and edge cities, promote the flat development of the urban network structure, and enhance the integrity and rationality of the urban network as well as its resistance to the disturbance of the external environment.

Concerning the matching of the urban network structure, enhancing the flow of elements among urban nodes can improve the “robustness” of the linkage paths among nodes and improve the resilience of the urban network structure. Regarding the transportation network, we should improve the construction of the transportation system, focus on strengthening the advantages of national highways, focus on the construction of the “Harbin–Changchun–Shenyang–Dalian” transportation axis, improve the urban transportation conditions, and strengthen the connections among the municipalities in the provinces and among provinces. In terms of the economic network, we must adjust the economic development model, build industrial clusters, promote the development of manufacturing industries, and realize cross-regional economic exchanges and cooperation. The innovation network is affected by regional barriers and has the lowest heterogeneity and resilience. Therefore, it is necessary to eliminate the restrictions of regional conditions, strengthen exchanges between universities and scientific research institutions, cultivate scientific and technological bases, develop regional knowledge bases, and enhance the diversity and flexibility of innovation links among cities.

The transmission and agglomeration of the urban network structure are closely related to the knowledge thickness in the region. In this regard, we should focus on building science and technology centers with regional characteristics, enhancing regional innovation strength, breaking administrative barriers, and strengthening the construction of emergency response plans while promoting the flow of innovation among cities. Furthermore, we should promote the formation of effective two-way links between core city nodes and other city nodes and enable the radiation-driven role of core urban nodes while enhancing exchanges and interactions among other city nodes to improve and realize an efficiently networked state.

According to the type screening of urban nodes, the dominant urban nodes are essential for influencing the resilience of the urban network structure. When it fails, the resilience of the urban network structure will be seriously damaged; hence, an emergency system of dominant urban nodes should be built to enhance the resilience to cope with external environmental shocks to ensure that urban nodes can operate safely and stably. For vulnerable urban nodes, the construction of public infrastructure should be improved to enhance the resilience of urban nodes to cope with external environmental shocks, and the factor flow between vulnerable urban nodes and other urban nodes should be enhanced to strengthen regional connections.

6.2. Academic Contributions

The impact of COVID-19 and other uncertainties on cities has had a serious impact on the sustainable development of the region. As a relatively complete and independent economic zone, the three provinces of Northeast China have important material value for the interpretation and clarification of the structural resilience of the entire regional network. In addition, the research can also provide relevant reference for the sustainable development of other similar regions. Therefore, taking regional resilience as the starting point, we introduced multiple data such as the Baidu Index, highway mileage, railway mileage, Web of Science, and other data, and integrated them with traditional statistics to build multiple urban networks based on information, transportation, innovation, and economy for a comprehensive assessment of the structural resilience of urban networks; this, to some degree, avoids the one-sidedness of measuring the resilience of the urban network structure based on single factor flow. In addition, considering that the factor flows among urban nodes are not equal, to reflect the real urban network structure more realistically, weighted network structure resilience is analyzed by giving weights, which enriches and expands the theoretical study of urban networks and resilient regions.

6.3. Potential Bias and Future Steps

Although this study is valuable in constructing multiple urban connection networks based on multi-source data, it also has some limitations that need to be mitigated by future studies. First, the study only evaluated the resilience of urban networks within 34 cities in the three provinces of Northeast China, without considering the impact of the external environmental factors on the network structure resilience in the study area. Second, due to the limitations of a large amount of data and a time-consuming cleaning process, the study only statically measured the resilience of the urban network structure in 2019. As such, the dynamic evolution characteristics of the resilience of the urban network structure can be analyzed in the future. Finally, because the research on the resilience of the urban network structure is still in the exploratory stage, this study only conducts a preliminary analysis of the factors influencing urban network structure resilience, which needs to be further studied and discussed in the future.

Author Contributions: Conceptualization, H.L.; methodology, H.L.; software, H.L.; validation, H.L. and X.L.; formal analysis, H.L.; investigation, H.L.; resources, H.L.; data curation, H.L.; writing—original draft preparation, H.L.; writing—review and editing, S.T. and X.L.; visualization, H.L. and Y.G.; supervision, X.L.; project administration, X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 41671158).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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Does Access to Regulative Exemption Reduce Barriers for Energy Communities? A Dutch Case Study

Maarja Meitern

Social Sciences and Solvay Business School, Vrije Universiteit Brussels, Pleinlaan 2, 1050 Brussel, Belgium; maarja.meitern@vub.be

Abstract: European policymakers are encouraging national lawmakers to grant citizens a larger role in the process of energy transition. One way to achieve this is to promote the set-up of local energy communities. This article describes the impact of a particular policy approach, the Dutch regulative exemption, on an energy community. A comparison is made with the traditional barriers that energy communities encounter. The results indicate that, overall, the Dutch regulative exemption is a beneficial policy tool that can support the creation of local energy communities. The exemption enables the community to explore governance and finance models that will allow it to stack revenue streams, while keeping the initial investment costs to a minimum. However, the improved conditions do not allow for a significant improvement in the financial business case. In particular, costs of organising an energy community and the uncertainty of long-term organisational stability remain prohibitive barriers to the roll-out of scaled communities. The study provides a starting point for policymakers investigating how regulative freedom could be of help for local energy communities. The lessons learnt can be applied by policymakers across Europe to support citizen-led energy initiatives.

Keywords: energy communities; regulative exemption; local energy market; Dutch energy policy

Citation: Meitern, M. Does Access to Regulative Exemption Reduce Barriers for Energy Communities? A Dutch Case Study. *Sustainability* **2022**, *14*, 5608. https://doi.org/10.3390/su14095608

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 10 February 2022
Accepted: 20 April 2022
Published: 6 May 2022

1. Introduction

The energy infrastructure of Europe has been on the verge of transformation since the EU authorised itself, in the Treaty of Lisbon (2007), to establish harmonised measures relating to Member States' energy policy (TFEU Art. 194(1)). European policy aims to transform the energy markets to more consumer-centric and decentralised models (EC, 2018). One way of achieving decentralisation is to promote the set-up of local energy communities. Towards this goal, in 2019, the European Parliament adopted two directives (Renewable Energy Directive (RED II) and Internal Electricity Market Directive (EMD)) that for the first time recognise "certain categories of community energy initiative as ¨energy communities¨" [1]. Furthermore, collective energy initiatives have been in practice in Europe for several decades [2]. Therefore, several different terms and interpretations are used to describe the term "energy communities" [3]. A broader definition of energy communities is derived from their democratic and local governance model as organisational structures around collective local energy actions that provide value for their participants or the local community [1].

In addition to changes in policy direction, a paradigm shift is also occurring at a social level. Compared with the year 2000, the willingness of citizens in 2020 to contribute to sustainability initiatives seems to have increased [4]. Until 2020, the prevailing community models had been similar to those of the 1980s, when local energy communities acquired common ownership of a few large generation assets [5]. The new wave of sustainable local energy initiatives is capable of involving "organisational forms, technology uses, skills, infrastructures, markets, and other institutional requirements maladapted and challenging to conventional regimes" [6]. Community initiators now find that cheaper and more efficient technology combinations are available but, due to regulative constraints and industry push back, not applied. In this context, it is important to understand what changes would occur if/when regulative constraints are minimised. Would additional regulative freedom allow community initiators to exploit the opportunities available in the 2020s?

The initiation and management of an energy community in the age of digitalisation is a complex process. When establishing energy communities, local authorities and community initiators encounter various economic, technical and institutional barriers [2]. This may in the long run result in systems of low public value [7]. Studies of energy communities confirm that they will be unstable if "heavily burdened by inefficient governance, complex legal requirements and high transaction costs" [8]. In the policy realm, sustainable innovation is desirable but it often faces the reigning structural power, especially in the field of niche development [6]. The academic literature further confirms that institutions favouring centralised energy systems constitute the largest barrier to local energy initiatives [9,10].

Even as EU Member States are introducing the energy communities concepts from RED II and EMD into their national legislation, some countries in Europe are already providing the possibility to test a potential new system set-up. For example, in 2015, the Dutch government published an administrative "sandbox" decree that exempts certain innovative local energy projects from the Dutch Electricity Law [11]. This exemption allows the local community to take control of its energy system management while pursuing goals to increase renewable generation and energy savings, while reducing CO_2 emissions [11]. Under the regulative exemption, projects can combine energy production, supply and network operations within one organisation and provide energy to members without supplier licence requirement [12]. One such exemption has been granted to an energy cooperative within the municipality of Eemnes.

This article describes how the Dutch regulative exemption has impacted the process of setting up a new type of local energy community market in Eemnes and compares this experience with the common barriers that other energy communities face. Numerous articles have explored the general barriers that energy communities face and analysed the opportunities that communities could exploit. However, no paper has attempted to combine these two branches of research and analyse a real-life case that uses state-of-the-art technologies and operates in a relaxed, regulative space. This study is the first to examine how additional regulative space could support the set-up and running of an innovative, citizen-led, local energy community, in particular, investigating whether the common barriers that energy communities encounter can be overcome with the help of the regulative freedom offered by the Dutch government. The lessons learnt can serve as an important example for European policymakers in understanding better the impact of the new policies on citizen-led energy initiatives.

The paper is organised as follows: Section 2 presents an overview of the Dutch policy context. Section 3 describes the case study and explains the methodology employed in this paper. Section 4 comprises the main part of the study. It presents the results of the meta-analysis and then contrasts these results with the results of the case study. Section 5 presents the conclusions and policy implications of the research.

2. Policy Background: Dutch Energy Policy Related to Local Energy Initatives

2.1. Policy Context

The overarching aim of the Dutch energy policy is to contribute to the European ambition for a sustainable, reliable and affordable energy supply [13]. From 2008 to 2020, to support local sustainable energy production, three new policies were adopted: the net metering scheme (*saldering*), the collective form of net metering (*postcoderoseregeing*) and regulative exemption (*ontheffing Besluit Experimenten decentrale duurzame elektriciteitsopwekking*) [11]. Compared with the energy communities established in the 1980s, the new energy communities have been encouraged to engage in broader activities at a local level, such as the resale of local renewable energy or providing advice on energy savings [2]. The new branding of the sale of local green energy and new services offered has increased consumer interest while allowing the cooperative to earn extra profit [2]. In conjunction with falling PV panel prices, this has fomented a surge of energy cooperatives. In 2018, approximately 500 energy communities were active in the Netherlands [3]. However, while the Dutch government has enacted policies to support local initiatives, some authors have argued that national policies are still primarily concentrating on supporting partnerships in traditional energy sectors and are paying little attention to citizen-led projects [2,12].

2.2. Legal Framework

The Netherlands Enterprise Agency (*Rijksdients voor Ondernemende Nederland* (RVO)), operating under the Ministry of Economic Affairs and Climate Policy, defines energy communities as legal voluntary entities with open participation whose primary purpose is to provide local environmental, economic and social benefits while promising not to make a profit [14,15]. (Communities are expected to provide diverse energy-related services to their members [14]. The applicable legislation for energy communities in the Netherlands is the Electricity Act 1998. In Article 1ar, the law defines provisions for different forms of energy self-consumption [16]. Furthermore, since 2014, the law has permitted a regulatory exemption space for experiments that contribute to developments in the production, transport and delivery of locally generated sustainable electricity or electricity generated in a cogeneration installation [16]. The regulative exemption clause was further defined in the Dutch Experimentation Decree of 2015 [11]. This administrative decree (*Besluit experimenten decentrale duurzame elektriciteitsopwekking*) exempts cooperatives from complying with certain provisions of the Dutch Electricity Act for a period of 10 years [1].

2.3. The Dutch Regulative Exemption

The experimentation decree for renewable energy projects allows project-based exemptions to energy cooperatives wanting to take over the majority of tasks undertaken by the grid operator and electricity supplier that are otherwise forbidden [17].

The exemption holder can become the producer, supplier and manager of the community electricity grid, eliminating the current strict division in the rest of the energy market [12]. Another requirement is that 80% of the end users must be consumers. In principle, the grid will be transferred back to the grid operator after the end of the exemption [11]. All these provisions enable an energy community to test a new technical system that could lower electricity bills for end users while incentivising renewable energy take-up.

The exemption holder must decide which roles they will take over and which will be performed by partner organisations and communicate these decisions beforehand to RVO [18]. In addition, the cooperative must have an internal governance structure in place, along with complaint management procedures. Finally, the exemption holders must prove to RVO that they have announced in writing the rates and delivery conditions to the customers in the network and obtained approval from the Authority Consumer Market (ACM) (the Dutch business regulation agency responsible for competition oversight, sector specific regulation, and consumer protection) for the methods employed to calculate the tariffs and tax rates [18]. Note that an exemption does not change the energy tax to be paid but allows the cooperative to discuss the matter with the ACM and possibly agree on a new rate [19].

The experimentation rules also set a maximum generation capacity for the community, which is equal to the maximum electricity consumption of the consumers participating in the experiment (+/−5%) [20]. Several other conditions and limitations apply, including the limitation of geographic scope, remaining approval of installation of generation capacity with the DSO, and bankruptcy provisions.

2.4. Policy Incentives

2.4.1. Net Metering

Since 2004, the Dutch government has established a net metering scheme (*saldering*) that has made solar panels a popular investment among homeowners. The net metering scheme allows private prosumers to feed locally produced energy back to the grid. In exchange, the utility subtracts the energy that was fed back from the total electricity bill without adding tax [21]. The scheme incentivises self-consumption, as the netted amount is capped by the maximum consumption of the individual prosumer [22]. From 1 January 2023, the netting scheme will be gradually phased out [23]. By 2031, the prosumers will only receive a net feed-in price from the energy company for the returned solar power [23]. This will increase the payback time for homeowners investing in solar power by approximately 5 years [22].

2.4.2. Zip Code Regulation

In 2014, the zip code regulation came into force (*postcoderoosregeling*), allowing community energy initiatives to share the ownership of electricity generation assets in a geographically delimited area. The policy was designed for citizens without access to their own installation site, such as a roof, but who wanted to participate in local renewable energy projects. The scheme incentivises citizens in an energy community to collectively set up a PV park or a windmill in the same postcode area [24]. Zip code regulation is a form of distant net metering or collective net metering [25] and even has a similar limitation: the collective project generation capacity must not exceed the maximum of 10.000 kWh/year, or the equivalent of members' yearly collective electricity consumption [26]. The policy mechanism was upgraded from collective self-consumption to a direct subsidy scheme in April 2021.

3. Method

3.1. The Case Study

This study analysis the set-up and operation of an innovative energy community project in the municipality of Eemnes. With 3600 households, Eemnes is located in the centre of the Netherlands, roughly 35 km from Amsterdam. The municipality has set a goal of meeting its energy demand entirely through renewables by 2030 [27,28]. Therefore, the municipality is supporting local citizen efforts to install more renewable energy assets in Eemnes [29]. In 2018, the municipality helped the Eemnes Energy Cooperative (EEC) apply for a Dutch regulative exemption experiment on decentralised sustainable electricity generation, which the EEC received in 2018 [17]. Furthermore, the project concept received support from the European Commission's H2020 programme as part of the project RENAISSANCE [30].

The Eemnes experiment aims to establish, based on flexible pricing, a consumer-centric centrally handled electricity market [30], i.e., a peer-to-pool community market where an ICT-based community manager enables local trading [4,30].The market is today only for electricity, thus other energy vectors are not part of the experiment. The physical community consists of homeowners with or without their own renewable generation assets. EEC conducts consumer onboarding, billing and site management. The community will also trade energy with the wholesale energy market [30]. The experiment begins with 10 homeowners; the ambition is to scale this up over a period of 10 years to approximately 1500 households. During the project set-up phase, the name of the pilot was changed from Micro Energy Trading Eemnes to LEF in Eemnes. The experiment of LEF in Eemnes is not the only activity the EEC is promoting among its members. The EEC is promoting a national green energy provider contract and providing advice on energy savings and joint investment options in renewables that takes advantage of the zip code regulation.

3.2. The Use of Barriers as an Analytical Tool

This paper employed barrier analysis as an analytical assessment tool [31] to compare an energy community set-up in Eemnes under regulative freedoms and an energy community set-up under traditional energy market rules. The academic literature details a number of barriers local energy initiatives face under the present energy market rules, identified in a meta-analysis of the literature. First, several overall key barriers were identified. To narrow the scope of the barrier analysis, the SCOPUS database was used to search for articles. The most widely cited articles focusing on energy community barriers between 2014 and 2020 were taken into consideration, given that it was during that time that the most recent and significant policy schemes were adopted. A literature search was thus performed for the period between January 2014 and December 2020 using only the keywords “energy community”, “energy communities” and “community energy”. The results were organised in descending order, from the most cited to the least cited works. Two main criteria were used for choosing articles from the search results. First, the articles had to include a section where barriers were analysed; secondly, the articles had to analyse more than one community in order to cover a variety of issues. The key articles contributing to the analysis were those by Brummer [10], who compared and analysed the barriers for 62 energy communities; Koirala [9], who conducted a literature analysis of 1285 articles mentioning terms relating to community energy systems; and Caramizaru and Uihlein [1], who reviewed 24 energy community case studies in Europe. The literature provides a long list of individual barriers that can fit under several theoretical categories of barrier [31]. However, for the purpose of this paper, the barriers are categorised into three broad groups: institutional barriers, technology related barriers and socio-economic barriers [9,32]. Regarding institutional barriers, this paper analyses the obstacles that derive directly from policies or regulation [33]. Technology-related barriers pertain to the selection, use and accessibility of technology. Socio-economic barriers are broadly related to the monetary issues that surround energy communities [9].

3.3. Empirical Data Collection

For the empirical research element, qualitative methods were employed to compare state-of-the-art literature on the common barriers energy communities face, with a real-life case study. The RENAISSANCE project deliverables and minutes of the meetings describe the process and results of the pilot set-up and operations. The barriers were contrasted with the evidence from these documents. The study has one limitation, namely the energy community is using a novel energy market model. The innovative nature of the project may have added new barriers and difficulties that were not present before.

4. Analytical Findings

In this section, traditional barriers for energy communities are compared with the exempted case study results. Three broad types of barriers identified in the literature are compared with the empirical evidence from LEF in Eemnes. The key barriers that energy communities encounter are broadly related to institutions, technology and socio-economics [9,32]. Although divided in this paper to enhance readability, the three categories are empirically intertwined [31]. For example, the institutional context defines the legal form that an energy community may take [9], which determines the business models that can be used in the community. The business model impacts the economic return that a community can generate. Similarly, technology barriers influence the ability to design different energy sharing models, impacting the business model. Following this logical pathway, this section first analyses the institutional barriers, then discusses technology and finally examines the socio-economics.

4.1. Institutional Barriers

The growth of local energy initiatives in Europe derives, to a large extent, from the fact that many citizens are not satisfied with the progress in greening our energy systems

[2,9]. Since the 1970s, different forms of energy initiatives have emerged in Europe as alternatives to the incumbent energy companies [5]. Nonetheless, sudden surges in the number of consumer-centric grassroot initiatives have emerged following legislative or policy changes [1,2]. For example, in Germany, the re-municipalisation of the grid has accelerated the growth of energy communities [5]. Similarly, in the Netherlands, following the liberalisation of the energy market, the number of energy cooperatives increased over a 6-year period, from approximately 40 initiatives to over 360 initiatives [2,34].

4.1.1. Frequently Changing Policies

Unclear, complex and frequently changing policies make it difficult for energy communities to grow [5,10]. Quickly changing policies do not allow communities to plan their activities securely [10]. The inability to construct clear plans limits the growth of the community because energy communities depend on the interpersonal trust between community members and initiators [9].

In the case of LEF in Eemnes, the exemption has been granted for a period of 10 years [17]. The exemption period starts from the moment the implementation commences, and thus the years spent preparing the experiment are not counted. In the case of the EEC, the exemption was granted to the cooperative at the beginning of 2018 and the implementation was anticipated to start in mid-2021. This allowed the EEC to take the time needed to prepare the experiment for implementation and build trust within the community [35]. The clear 10-year implementation period and flexible starting date have allowed community initiators to build internal trust and establish a clear timeline for future developments.

4.1.2. Organisational Form

Institutions determine the legal form that an energy community can take. In some cases, the models permitted can pose a barrier to community growth. For example, a not-for-profit nature may limit the long-term financial stability of the organisation, rendering the community dependent on voluntary work [10].

The 2015 regulative exemption was granted only to cooperatives and associations of owners [11]. On the one hand, this means that the EEC is an energy cooperative and thus its primary goal is not profit generation. On the other hand, the exemption affords the EEC the right to manage its own grid, making it possible for the cooperative to test new energy market models, such as peer to pool, as well as experiment with different business models [20]. Thus, the barrier related to limitations in the organisational model has not been resolved; but the possibilities under the same organizational model to stack up more revenue streams (Section 4.1.3) has increased. Thus, some of the pains from the barrier have been relieved. The community has more opportunities to breakeven in terms of cost and reduces the dependency on voluntary work in the long run.

4.1.3. Roles in the Energy Market

The regulator defines the roles an energy community is allowed to take in the energy market [5,9]. The energy market regulations limit the options for community energy trading models or access to the grid [4]. With limited possibilities to access certain energy markets, such as wholesale or ancillary services, the community has limited ability to stack up revenue streams [5,10]. Moreover, for any kind of energy sharing within the energy community, the law requires the organisation to have a supply licence, acquiring which is complex and costly procedure [20]. Similarly, rules regarding balancing responsibility activities and connecting new assets to the energy communities can “present a challenge for small energy communities” [5].

In terms of administrative barriers, the greatest benefit of the exemption is the ability to be freed from the supply licence, which helps to avoid various administrative procedures [17,20]. However, to fulfil the balancing responsibility requirement and have access to wholesale energy markets, the cooperative had to purchase these services from a white label energy supplier. This procedure has been used before by Dutch local energy cooperatives because it helps to reduce their administrative burdens [2]. Thus, although the EEC has the ability to take on the balancing responsibility role, the process is still too complicated for local initiators to manage on their own. However, due to the exemption, the community is able to offer new services to its members, with hope of lowering their electricity bills.

4.1.4. Additional Observations on Institutional Aspects

In the context of wider policy, RVO does not provide structured support for activating the exemption and helping communities to better understand all the administrative and legal provisions that need to be fulfilled before local trading can start. Furthermore, there seems to be a mismatch between the policy support that the Dutch government is offering and recognition of the Eemnes experiment as an innovation project by other governmental organisations. The experimentation proposal was submitted to both European and Dutch innovation subsidy programmes, and though two European grant requests were approved, the Dutch innovation subsidy granting agency did not provide a positive evaluation.

4.2. Technology-Related Barriers

Technological innovation has the potential to reduce the initial set-up costs of energy communities, but only if deployed wisely. The energy grid involves generation, distribution, storage and control technologies, which have become cheaper and increasingly sophisticated over the last decade, making real-time grid management technically and financially possible for local citizens [36]. New technologies can increase system reliability and transparency while paving the way for new services that can increase revenue streams within the community [4]. An increased number of flexible assets at the household level, such as heat pumps and smart appliances, provide an opportunity to exploit local flexibility, which can be traded within the community and with the national grid with the assistance of innovative technology platforms [9]. This provides an opportunity for energy communities to offer their members services such as energy efficiency, energy savings, energy storage, management of local distribution networks, aggregation and flexibility management [5]. All these opportunities have only become available in the last decade, meaning that in most small-scale initiatives, these opportunities have not yet materialised. Therefore, lack of support regarding technical skills and a limited access or ability to use technologies hinder the take-up of energy communities [2].

4.2.1. Lack of Expertise

Community "initiatives are often started by non-experts" [10], so there could be a lack of technical understanding within the community [9,10]. This could result in choosing hardware or software options that are not optimal for the community, resulting in a technology lock-in or situations where technologies with low payback are chosen.

RVO, before granting the exemption to a cooperative, requires the community to describe in its application which technologies and business models will be employed in the project. Therefore, the EEC has to demonstrate to RVO the innovative aspects and technical soundness of the community approach before being granted the exemption right [37]. Furthermore, already in the exemption application, RVO requires the cooperative to demonstrate that a number of experts will be supporting the project [37]. This reduces the chances that the community will be unsuccessful because of a lack of expertise. Overall, these mandatory provisions and a certain degree of flexibility make energy community projects less prone to the risk of failure than initiatives without exemption.

4.2.2. Barriers to Combining New Technologies

Although hardware and software prices are reducing, the small size of the communities and the lack of initial financing mean there is limited access to these technologies (e.g., community batteries or neighbours' PV panels). Furthermore, energy communities experience difficulties in accessing different ancillary service markets, not only because of institutional constraints, but also because of their limited size.

In the case of Eemnes, the regulative exemption enables the Eemnes community to manage its own grid [17], allowing the EEC to take better advantage of the assets that its community members already own (rooftop PV, heat pumps), lowering the initial investment costs and potentially improving the business case [38]. On the other hand, managing a grid requires smart software, adding to operational costs of running the community. In Eemnes, energy is traded between citizens with their own PV and community members without generation assets. In a later stage, flexible energy assets could be added [38], providing additional benefits. The exemption is, therefore, alleviating this barrier.

4.3. Socio-Economic Barriers

One way of reducing socio-economic issues is to establish the energy community by using new innovative electricity market models. The new prosumer models where citizens can trade energy among themselves, such as peer-to-peer or peer-to-pool models, are expected to generate profits [4]. Innovative business models, in conjunction with new ICT, are more likely to find ways to optimise old assets and reduce the up-front costs, as discussed in Section 4.2. In addition, energy communities should be able to generate income near the energy generation site, which will confer local economic benefits by creating local jobs (maintenance, management, etc.), keeping the generated value local [10,39].

4.3.1. Initial Set-Up Costs

One huge obstacle local energy communities face is the lack of initial financing and funding options when setting up [5,9,10]. Energy communities are unable to guarantee revenue streams, and their non-profit nature does not allow them to build up reserves [10], making the up-front expenditure of an energy community higher for local citizens and community members, compared with existing national grid alternatives. This impacts the long-term stability of the organisation [1].

The potential to create an energy community using innovative market models and technologies made the Eemnes project a more appealing candidate for consortiums seeking state-of-the-art pilot projects, such as RENAISSANCE. The ambition and the ready-to-go concept helped Eemnes receive two European funding opportunities, showcasing its European-level innovation [30,40,41]. Furthermore, the exemption reduced the initial set-up costs from a technology perspective, as discussed in Section 4.2.2.

However, the exemption does not provide better financing terms. Nonetheless, Eemnes has been in discussion with battery providers willing to provide support in the form of technical expertise and the organisation of a community-financed battery, partly due to the innovative nature of the project [42]. Therefore, this one-off exemption has helped the EEC obtain access to initial funds and financing, although the financial cost and uncertainty of organising these may outweigh the benefits and may not be replicable.

4.3.2. Uncertainty with Respect to Financial Success

It is difficult for municipalities and citizens to lead initiatives that promise green local energy but at a much higher cost. Financial benefits, such as shares or cheaper electricity prices, are among the most important factors motivating citizens to join energy communities [1]. Nonetheless, small community projects are considered "high risk projects with uncertain probability of success" [10]. Beyond having difficulties attracting new members, this uncertainty further lessens the probability of a community receiving initial financing and building up reserves.

More important than the initial set-up costs has been the impact of the regulative exemption on the potential for increasing the revenue streams of the community using an innovative peer-to-pool energy trading model. The LEF in Eemnes business model is built around two core energy transactions. Firstly, energy will be traded on the internal peer-to-pool community market, where prosumers and consumers are engaged in a mutual exchange of energy [30]. Secondly, the community will also be trading energy with the wholesale energy market. Before the project began, a simulation of this business case was created based on the PV and consumption data were collected from 50 households. Initial estimates indicate that the costs of consumed electricity in the electricity bill account for only 18% of the entire utility costs [42]. Estimates suggest that households in the community without PV installation would on average receive a lower electricity bill each year if they participate in the peer-to-pool model as they can take advantage of lower local energy prices [42]. At the same time, households with PV would have slightly higher electricity bills than usual as long as the current net metering rule remain in place, given that these offer higher compensation for surplus energy than the local pool market. Once the net metering starts to reduce (as of 2023), the prosumers of the community will also receive gradually lower electricity bills compared with the current bills when acting in the community, with maximum savings expected in 2031 (LEF in Eemnes minutes 2021). The project has also attracted the interest of the local Distribution System Operator (DSO), which announced that it would grant financial incentives to a community member if the community exercises local balancing and acts on the energy market as one connection point [43]. The community is projected to be able to offer lower electricity bills to its members as of 2023, while covering the gap prior to 2023 with the incentives from the local DSO [43]. Without the exemption, this type of local energy trading business model would not be possible.

4.3.3. Split Incentive

Split incentive barrier can appear in an energy community when costs and benefits are allocated unfairly between members. This issue can arise when the social housing sector is involved or if rental properties are part of the community. In such cases, landlords would need to make the initial investments in PV but the tenant would reap all the benefits [9]. Similarly, split incentive problem is present when designing the local electricity market price for a community that composes of individual prosumers and consumers, the latter having not contributed with capital investments into the communally used energy generation assets.

The split incentive barrier in Eemnes from the housing provider perspective was raised as the housing provider is not an active participant in the community and no tenant has raised the question. The problem might arise later, when Eemnes wishes to exploit economies of scale and reach a higher number of participants, given that there are various social housing properties in the municipality [28]. The second, split incentive issues have come out from the simulations of the yearly electricity bills, where the consumer had with peer-to-peer model a higher savings compared to the prosumer (Section 4.3.2). This issue has been solved by a final balanced electricity bill calculation at the end of the year on community level to have more equal compensation.

4.3.4. Economies of Scale

The reduced bankability of assets decreases the size of the community, preventing economies of scale. The local transactions that keep revenue local could also encourage "reinvestments in additional renewable generation" [39], increasing the size of the energy community, which increases the benefits accrued from economies of scale.

Economies of scale are not overcome in Eemnes. After 9 months of being operational the community has 10 active members who are billed through EEC and 135 households who share their energy consumption data with the project. Nonetheless, the regulative exemption is not a barrier here as with the provision EEC could expand up to 10,000 connections, which in the case of Eemnes would cover all the 3600 households registered in the municipality.

4.3.5. Other Observations

Given the goal set by Eemnes to reach 1000+ connections [30], community managers will need to hire professional day-to-day managers for the local grid in the long run or outsource this activity to a commercial party. In the project preparation phase, the cooperative members have been working on a voluntary basis to design the local market set-up with support from external experts [30]. At an early stage, instead of an external installation company, cooperative members who were installing the gateways for the community took up some of the engineer-related monetary jobs [30].

5. Conclusions and Policy Implications

This paper has analysed the extent to which common barriers energy communities face could be removed through the provisions set in a specific policy support tool such as the Dutch regulative exemption. The lessons learned in this paper be transferred to most European member states as the energy regulations across Europe follow similar principles due to the common market.

Regarding, socio-economic barriers, the removal of regulative barriers in Eemnes made it possible to stack more revenue streams and lowered initial set-up costs, this was not enough to confidently defend this as being a more competitive business case compared to traditional utilities. The margins of producing centralised energy versus decentrally produced and managed energy are not yet big enough to sustain the costs of running a community. Thus, testing new models and providing support for early initiatives are key to later replication of the community models elsewhere. Policymakers should consider providing financial support to community initiatives, whether in the form of tax incentives or direct financial support.

In addition, market access rules and grid usage rules could be made more transparent and beneficial for energy communities. In Eemnes, the DSO grid is used for local trading and additional revenue streams could be secured through participation at the DSO balancing market. This has increased the willingness of citizens to join the community and act as a grid balancing node for the remaining grid. Thus, regulators should think of ways in which regional grid operators could remunerate energy communities if the latter offer flexibility services to the grid. This approach would allow citizens to invest in renewable energy production locally while lowering the grid investments for the grid operator and the society as a whole.

Though the exemption opened the possibility for the energy cooperative to act as a utility, taking up DSO and BRP roles, it was not used in practice. The case study confirms that if regulators eliminate some of the institutional barriers, such as access to the grid or exemption from a supply licence, the community can solve technological and socio-economic barriers only if the necessary technical expertise is available. Therefore, national policymakers need to ensure that local energy innovation is combined with technical knowledge support, either in the form of financial aid or by providing expertise. The lack of such an option can negatively impact the business case, and the regulative changes set out in the two directives will have a limited impact in practice.

In the case of Eemnes, the regulatory exemptions were not combined with financial support for innovation. This meant that nationally recognised innovative local experiments had to be self-funded or make a significant effort to obtain grants. A lack of initial financing is an issue, as those taking initiatives lack the capability to access technical experts and new technology platforms. This further weakens the business case for the community and creates distrust and frustration among the community initiators. All in all, this could lead to a contrary impact on national energy markets, to the policymakers' initial ambition of boosting the energy communities' growth in Europe.

The Clean Energy Package directives [44] force Member States to provide energy communities in Europe more enabling conditions similar to the Dutch regulative exemption. It is in this framework that the Eemnes case study highlights the barriers that remain in place even if regulative constraints are removed. The Eemnes case study demonstrates that additional regulative freedoms can help the community set-up but, on their own, are not sufficient to address the key barriers the removal of which would allow energy communities to blossom. This demonstrates that providing only additional degrees of freedom to energy community initiators is not enough and that policymakers must also put in place an additional supporting framework of policies to support the growth of local energy communities.

Funding: This research was funded by the European Union's H2020 Research and Innovation Programme under grant agreement no. 824342, RENAISSANCE.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to thank the LEF in Eemnes team for the collaboration in setting up the pilot. I would like to express my gratitude to my primary supervisors, Sebastian Oberthür and Thierry Coosemans from VUB and to Rolf Bastiaanssen from Bax & Company for constructive criticism and paper reviews.

Conflicts of Interest: The author declares no conflict of interest.

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Risk Cost Measurement of Value for Money Evaluation Based on Case-Based Reasoning and Ontology: A Case Study of the Urban Rail Transit Public-Private Partnership Projects in China

Hongqiang Wang [1,*], Qiaoyan Lin [1] and Yingjie Zhang [2,*]

[1] School of Management, Shanghai University, Shanghai 200444, China; linqiaoyan608@163.com
[2] School of Management, University of Shanghai for Science and Technology, Shanghai 200093, China
* Correspondence: whqsl@shu.edu.cn (H.W.); alina_sh@163.com (Y.Z.)

Citation: Wang, H.; Lin, Q.; Zhang, Y. Risk Cost Measurement of Value for Money Evaluation Based on Case-Based Reasoning and Ontology: A Case Study of the Urban Rail Transit Public-Private Partnership Projects in China. *Sustainability* **2022**, *14*, 5547. https://doi.org/10.3390/su14095547

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 4 April 2022
Accepted: 2 May 2022
Published: 5 May 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: Risk is demonstrated as one of the most crucial drivers of value for money (VFM) in public–private partnerships (PPP), but in previous studies, the risk cost estimation of the quantitative evaluation of VFM was still a dilemma that strongly depended on specialist discretion or had low methodological operability. This paper establishes a prediction model for estimating the risk cost in the phase of VFM evaluation through a combination of case-based reasoning (CBR) and ontology technology. PPP information ontology was established to provide the technical basis of knowledge representation for the CBR cycle. Then, according to whether the information data were quantitative or qualitative, similarity calculation methods were used for the retrieval of similar cases. The conceptual semantic similarity algorithm based on the ontology tree structure was well implemented to compare abstract information. After the most similar cases were extracted, a revision mechanism was followed when there were deviations in the similar cases. Finally, the risk costs of the target case were obtained by weighting the extracted similar cases based on the similarity. An empirical analysis was performed with 18 historical projects from the China Public–Private Partnerships Center. The results showed that the relative errors between the estimated and actual costs of total risk and retained risk were 11.05% and 2.41%, respectively. This indicates that the estimation model could achieve a better risk cost prediction with small errors, which validates the availability of the model. Based on the proposed model, this research establishes an extensible PPP information ontology model. It promotes the integration and interoperability of information knowledge in the PPP domain, which can be further expanded according to the requirements. Coherent accuracy is provided by the whole CBR-based measurement process, which has offered a systematic and objective method for the risk costs measurement of PPP projects.

Keywords: public–private partnerships; risk cost; case-based reasoning; ontology

1. Introduction

Public–private partnership (PPP), as a significant institutional innovation in infrastructure investment and public service delivery [1], is a long-term cooperation mechanism that advocates a relationship of "complementary advantages, benefit, and risk-sharing" between government and private departments [2]. Since 2014, PPP has experienced a new boom under marked motivation from the central government [3]. After seven years of rapid development in China, PPP has become an effective approach for stabilizing growth, facilitating innovation, regulating strategy, and increasing the welfare of individuals, promoting the integral expansion of the economy. According to the latest statistics from the China Public–Private Partnerships Center, as of January 2022, a totally of 10,254 projects, with a total investment volume of RMB 16.2 trillion, are collected in the management database, of which 7714 projects with an investment of RMB 12.8 trillion have been contracted and landed, with an implementation rate of 78.9%. China has become one of the largest markets of PPP in the world. However, various stakeholders are involved in the PPP projects, as well as huge investments and long construction cycles. It is easy to encounter problems such as the irrational allocation of risks, the creation of explicit shares but real debts, an emphasis on construction while neglecting operation, and excessive financing leverage. Thus, a dialectical perspective should be taken in the practical application of PPP to clarify that it is not an almighty tool that is feasible for all projects.

Value for money (VFM) is defined as "the optimum combination of whole life costs and quality (or fitness for purpose) to meet the user requirement" [4]. In practice, the VFM of a PPP project can be expressed as the difference between the net present value (NPV) of the whole life-cycle cost (LCC) of a project procured by a traditional method (LCC_{PSC}) and the NPV of the LCC of the same project procured through a PPP approach (LCC_{PPP}) [5]. Ultimately, VFM is generated when the total net present value of PPP is less than the NPV of traditional procurement, indicating that the whole life cost of the proposed project can be reduced [6]. For both NPV of PPP and PSC, risk costs are engaged as the crucial issue and dilemma in the quantitative evaluation of VFM. At the early stages of popularization of VFM, there is a complete system, but not yet an established sophisticated information platform that can accumulate specific data for types of projects, leading to the assessment and allocation of risk being widely dominated by experts whose subjective and unilateral nature properly induce some bias in the entire measurement of VFM. In addition, the topics of risk assessment and allocation have aroused a research fever that has facilitated the emergence of substantial-excellent studies during the period of rapid expansion of PPP. Almost of them are based on experts, but further mitigate the influence of individual subjectivity by employing different techniques that do not fundamentally improve the independence of specialists, and some methodologies are complex and not operable in practical projects. Moreover, many characteristics have emerged in China's PPP market, such as quantity reduction but quality increase, more sophisticated systems, stronger supervision, more transparent information, etc. These have provided a stable environment for PPP development, which considerably enhanced the general quality and maturity of PPP projects in the official database. Consequently, some items with high availability are accumulated in municipal engineering, transportation, and other PPP areas, creating friendly conditions to offer guidance for subsequent new projects. However, the utility has failed to be effectively utilized by existing accounts, especially in the risk cost estimation. Based on the current situation, this study seeks to explore a valid way to adopt useful historical projects to estimate risk costs in VFM evaluation, in parallel, decreasing the reliance on experts.

In this research, a risk costs estimation model for VFM evaluation was developed based on previous similar cases. The risk costs include the retained costs undertaken by governments and the transferable costs incurred by private sectors. An objective of this research is to improve the efficiency of risk cost assessment, as well as the utilization of old cases in the VFM evaluation phase, and to propose several suggestions for risk data accumulation in the process of project management. The accuracy of the VFM value determines whether the PPP can be successfully applied to an infrastructure project, while a more sophisticated data system will contribute greatly to industry development. The research was carried out as follows. A combination of case-based reasoning (CBR) and ontology is used to set up the estimation model, while the information from the China Public–Private Partnerships Center is used as an instruction in the process. The model has been organized into the following four submodules: (1) ontology model development, (2) attributes weighting, (3) similarity calculation, (4) VFM risk cost measurement. More specifically, an information ontology model for risk cost calculation was first developed from previous PPP projects that contained a series of attributes. Second, the ID3 algorithm of the decision tree was adopted in attributes weighting to identify similarities between the target and old cases. Third, similarities were calculated by the semantic similarity algorithm incorporated with principal component analysis (PCA) based on the ontology tree structure. Additionally, more than three most similar cases for the target case were retrieved, and the contributions were prioritized according to the degree of similarities. The extracted cases were utilized to predict the risk cost of the target case. Deviations of data in similar cases which induced uncertain predicted values were considered in the process. A data revision step was taken to improve the accuracy of the estimation of risk costs. Finally, the retained cost and the transferable cost of risk were predicted from the revised data of similar historical projects. The outcomes were compared to the actual risk costs of the target cases documented in the official database for validation. This approach can increase the computational performance and availability for estimating costs of potential risk for government and private sectors in the phase of VFM evaluation. Therefore, experts can be freed from repetitive work and devote their time to better implementing projects to optimize the application of the PPP model.

2. VFM Risk Cost of PPP Project

Risk is demonstrated as one of the most crucial drivers of VFM by numerous academics [7–10]. One of the most prominent tasks of PPP is to invite the private departments to share risks. It is necessary to confirm the risks and the risk costs borne by the governments and social capitals in the evaluation phase of VFM, thereby facilitating more detailed risk control in the subsequent steps. Compared to traditional procurement, where the governments take all the risks, PPP plays an effective role in sharing some of the risks with the private sector, called transferable risks, while the remaining risks taken by the government itself are called retained risks. Furthermore, the associated costs of both are directly related to the achievement of value for money which requires accurate risk identification, assessment, and allocation. Optimization studies surrounding the evaluation are continuously active in the PPP field. There is extensive research on risk identification in all areas of PPP. Song et al. investigated ten key risks of PPP waste-to-energy (WTE) incineration projects in China [11]. Zhang et al. combined the 2-tuple linguistic representation model and DEMATEL to examine the risk factors and their interrelationships of EVskCI-PPP projects [12]. Similarly, the identification of other PPP fields, such as water supply, urban underground pipe gallery, sponge city, and construction projects is well undertaken by various surveys and academics [13–16]. Additionally, this determination is often done along with assessing the principal risks and classifying the related risks into different levels by using a series of methods. The Mann–Whitney U test was adopted to seek out the most important risk factors for PPP projects in China, including government intervention, government corruption, and poor public decision-making processes [17]. A combination of two-dimension linguistic variables and the cloud Choquet integral (CCI) is used to mitigate the subjectivity of experts [18]. Multi-organization fuzzy rough sets (MGFRSs) are incorporated with an improved DEMATEL method to deal with the influence of interrelationships on the ranking of risks [19]. Structural equation modeling (SEM) has been applied in ranking risks and identifying several risk paths by focusing on risk interaction and stakeholders' expectations [20]. Interpretative structural modeling (ISM), along with MICMAC analysis, were used to prioritize PPP risks [21]. Related research likewise provides valuable references for risk assessment, but they were all conducted on the premise of specialists' opinions. Specifically, the cost assessment is usually calculated by occurrence and impact, which heavily depend on expert judgments. Risk allocation, as an extremely significant part of VFM evaluation, affects the effective supervision and control of risks in the subsequent process of each PPP project. Optimal risk allocation, with its aim to achieve VFM [22], is perceived as the key to the success of the PPP model [23,24]. Thus, there are numerous studies on this theme. The Delphi questionnaire survey is conducted as the most prevalent tool [25,26] used to reduce the subjectivity of individuals; fuzzy synthetic evaluation, game theory, the artificial neural network, and other multi-attribute decision-making methods and intelligent technologies are used to obtain more precise results. Ke et al. found that the public sector preferred to retain most of the political, legal, and social risks, and share most of the microlevel risks and force majeure risks; the majority of microlevel risks were preferred to be retained by the private sector [27]. Ameyaw et al. adopted the fuzzy-set approach to examine the allocation of five key risk factors related to PPPs in water supply infrastructure projects [26]. Li et al. proposed a bargaining game theory to prioritize risk allocation that considers the probability, severity, and impact of risk factors [28]. Artificial neural network (ANN) models were built up for risk allocation decision making based on the industry-wide questionnaire survey [29]. A neuro-fuzzy decision support system (NFDSS) was developed to assist the sharing process [30]. A genetic algorithm (GA) was applied to enhance efficiency [31]. Valipoura et al. presented a SWARA-COPRAS approach to utilize qualitative linguistic terms in the allocation of risks [32]. Parallelly, some relevant studies were carried out from particular perspectives. A framework with a deeper understanding of risk was afforded by the principal–agent theory (PAT) to ensure a more complete and optimal risk allocation across the whole life cycle of PPP projects [33]. Project finance contracts were also considered [34].

As we can conclude, it is no longer a dilemma to identify and reasonably allocate the risks owing to proven methodologies, in addition to estimating the risk costs borne by different parties. Deviations always arise due to the irregularity of data and the dependence of commonly used methods on experts when calculating the occurrence and degree of risk. In the past, the accumulation of historical data was not mature enough to apply to risk cost estimation in China. Currently, however, as the database keeps optimizing and expanding, it has often been overlooked as an important resource to be used in this field. While historical cases are used to predict total project costs and risk response strategies, the increasingly available data has the potential to be a valuable asset for risk costs calculation. This paper employed CBR and ontology to achieve the above purpose, while at the same time, enhancing the efficiency of using historical cases, supplementing the information on risk pre-management, and providing more useful support for later regulation.

3. Case-Based Reasoning and Ontology

CBR, or case-based reasoning, is an approach to problem-solving that originated from cognitive science [35,36] and which emphasizes solving new problems by reusing and if necessary, adapting the solutions to similar problems that were solved in the past [37]. As a computerized approach, CBR has a wide range of applications in various areas, such as fault detection, chemical prediction, disease inference, and rehabilitation practice [38–41]. In particular, it is commonly applied in cost prediction, accident pre-control, and strategic decision making in construction [24,42–44]. However, it has not been popularly applied because of the initial poor accumulation of available data. Now that the PPP mode in China has entered a stable development stage, as the information management of the PPP official database has been strengthened, historical projects are expected to become powerful tools for new PPP projects, and applying CBR in this field is conducive to improving the efficiency of historical knowledge reuse.

Aamodt [45] stated that a case-based reasoning process can be represented by the three tasks of retrieval, reuse, and learning, which collapse several steps compared to the subsequent definition by the author. The full process is shown in Figure 1; the CBR consists of four primary processes: retrieval, reuse, revision, and retention. Case retrieval is responsible for looking for the most similar cases in the established case base that indicate corresponding data or solutions for the target case to reuse. If the proposed solutions are not well matched, it is necessary to make some revisions to obtain more credible results based on the initial solution generated from old similar cases. The revised solutions are then retained as useful old cases in the case base. Among the whole cycle, retrieval, as well as revision, are the critical steps to ensure the successful application of CBR [46,47]; an accurate retrieval method guarantees the availability of extracted historical cases with high similarity, while an effective revision process improves the accuracy of the final results.

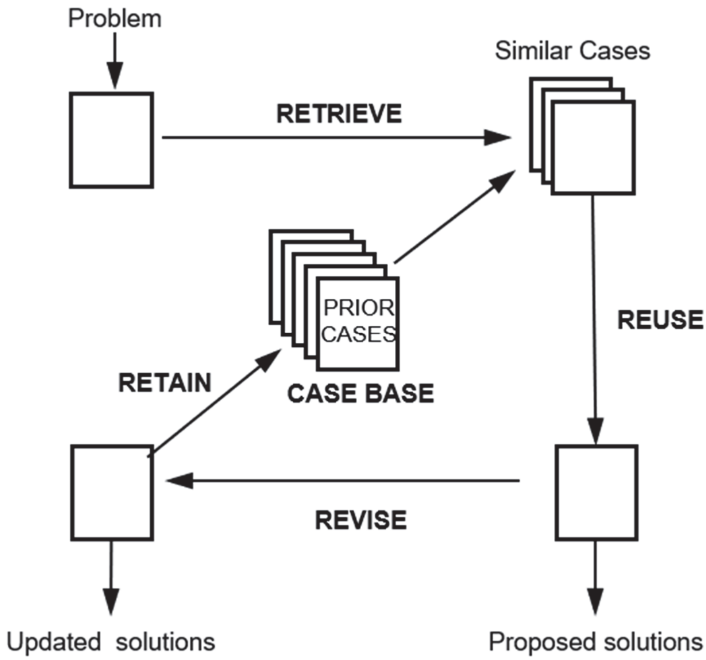

Figure 1. The CBR cycle. Adapted from ref. [45].

Before implementing CBR, the most crucial task is the representation of case knowledge. The ontology technology, as one of the case knowledge representation approaches, is an explicit formal specification of a shared conceptual model with the goal to capture the knowledge of related domains, forming a consensus in a field, and improving the efficiency of information interchange [48]. While the ontology uses a hierarchical tree structure to represent the concept sets, as well as the semantic relationships, of the concepts [49]. The nodes of the tree are called classes, with edges between the nodes representing semantic relationships between concepts. From the top-down, concepts are classified from large to small, and the lower-level concepts are a subdivision of the upper-level concepts. It supports the definition of new concepts based on the existing vocabulary in a way that does not require the revision of the existing definitions [50].

Ontology has structured some mature knowledge models for biomedical science that contain substantial complex information and which are constantly being expanded. A comprehensive resource of computable knowledge about genes and their products, Gene Ontology (GO), has been established and developed by the Gene Ontology Consortium and is widely used in the biomedical community [51,52], while a human phenotype ontology (HPO) was introduced to bring together a standardized vocabulary of phenotypic abnormalities associated with more than 7000 diseases that were presented [53]. The Cell Ontology (CL) is an OBO Foundry candidate ontology covering the domain of canonical, natural biological cell types [54]. Given the better inherent capability of knowledge representation, ontology has been broadly used in other areas, such as multilingual interoperability, document management, and industrial resource forecasting [55–57], as well as construction engineering [49,58,59], where there are many stakeholders, complex situations, and considerable information. Previous studies reflect that ontology technology is competent to support more sophisticated information expressions in various domains. Furthermore, as a kind of knowledge integrator, it contributes to achieving a consensus of knowledge in different industries and effectively realizes easy interoperability of information, offering excellent backup for CBR.

Simultaneously, an excellent similarity estimation method, conceptual semantic similarity, is provided by the structure of the ontology model. Based on this structure, the ID3 algorithm is allowed to be well applied in attribute weighting that directly influences the overall similarity between target and old cases. With these conveniences, the objectivity of the entire CBR cycle can be substantially improved, and the reliance on experts can be effectively minimized, to some extent.

4. VFM Risk Cost Measurement of a PPP Project Based on CBR and Ontology

4.1. Ontology Development

In this paper, we used Protégé, an ontology development tool, to create the PPP information ontology model using a seven-step approach, whose detailed steps are illustrated in Figure 2.

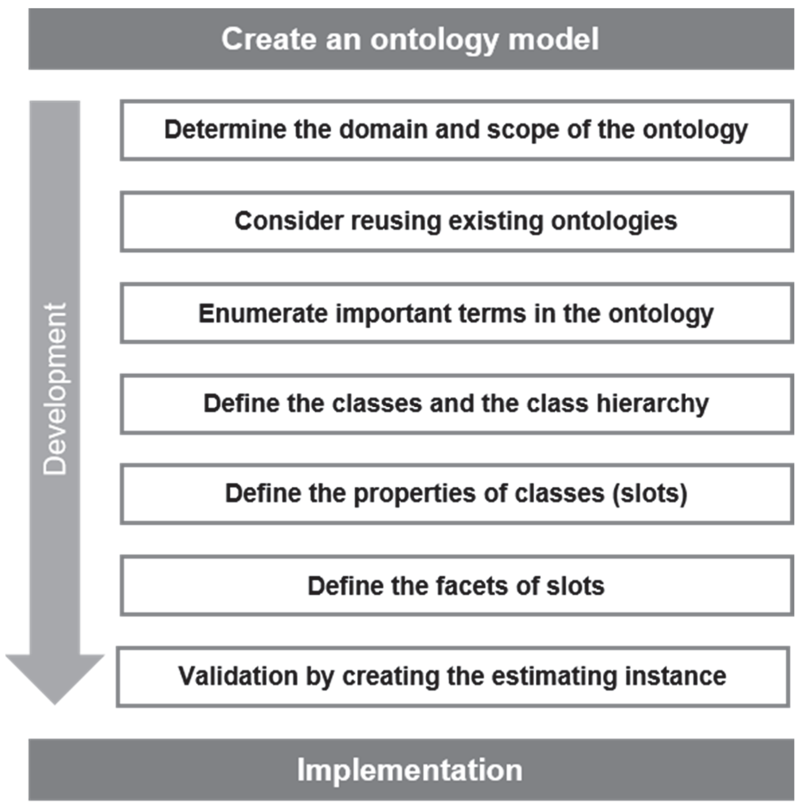

Figure 2. Ontology Development Process.

1. The domain and scope of the ontology created in this paper was PPP project information, which was derived from the PPP project management database of the China Public–Private Partnerships Center.
2. There are few existing ontologies in the PPP field and no available ontology models that could be used in the VFM evaluation. Thus, we reconstructed an ontology model based on the information from the PPP project management database. According to the information listed in the database, eight major classes were defined, namely "district," "invest count," "demonstration levels and batches," "return mode," "co-operation term," "procurement mode," "operation mode," and "risk factors." The

above classes were applicable for all PPP industries and were allowed to be further expanded or subtracted according to the actual industries studied.

3. Define classes and the hierarchy structure. The classes "district," "return mode," "demonstration levels and batches," "operation mode," and "procurement mode" were commonly perceived attributes in the PPP project management database, and their hierarchies (subclass and individuals) were created based on the different property values they contained. For example, the "procurement mode" consists of open tendering, selective tendering, competitive consultation, competitive negotiation, and single-source procurement, which cannot be further subdivided; therefore, they are regarded as individuals of the "procurement mode." For the distinctive classes such as "invest count" and "cooperation term," whose values were different in different PPP projects, hierarchies were created according to every practical case. For "risk factors," since there was no unified risk factor index system for each industry, this part of the ontology model would be established based on a complete index system that was created according to the actual industry studied; it will be introduced in the validation section.
4. Define the properties of classes. The role of properties in ontology models is to connect "class to class," "class to individual," or "individual to individual." There is no obvious correlation between the major classes, which were considered mutually exclusive. Each major class and the subclasses (or individuals) are related to each other as "Has" and "Part of." For "individual to individual," it must be created according to the actual situation. For example, if the procurement mode of project A is B, then A and B can be connected with the property "has procurement mode." On this basis, this paper created the hierarchical structure of PPP project information ontology and its relationships. Due to the massive amount of information, only the foundational structure is exemplified, as shown in Figure 3.

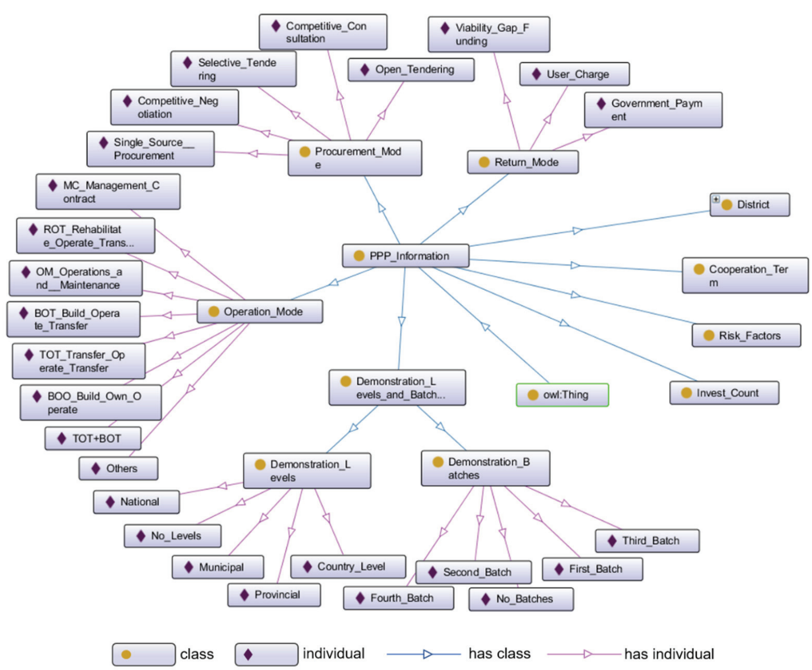

Figure 3. Major Classes of PPP Projects Information Ontology.

4.2. Similar Case Retrieval

4.2.1. Attribute Weighting

It is necessary to assign weights to each major class, while every class in a PPP project information ontology has a different influence on VFM risk cost, which definitely shows the relative importance of each class. Given the tree structure of the ontology model, we applied the ID3 algorithm of decision tree [60] to determine class weights, whose core ideology is to measure feature weights by information gain. The larger the information gain is, the more information it contains, and the more important the attribute is.

Before calculating the information gain, it is first necessary to understand the concept of information entropy. In 1948, Shannon [61] defined information entropy as the probability of the occurrence of discrete random events; the more orderly a system is, the lower the information entropy, while the more chaotic the system is, the higher the information entropy. Its calculation formula is:

$$H(v) = -\sum_{i=1}^{n} P(u_i) log_2 P(u_i) \tag{1}$$

$$P(u_i) = \frac{|u_i|}{|v|} \tag{2}$$

where v = a set of cases; the $P(u_i)$ represents probability of the occurrence of symbol i; $|u_i|$ = number of cases in symbol i; and $|v|$ = a number of cases in the set v.

The information gain is specific from different attributes; for an attribute, the difference of information between the system with it and without it is the information gain, so the formula for calculating information gain is:

$$Gain(v, a) = H(v) - \sum_{s \in value(a)} \frac{|v_s|}{|v|} H(v_s) \tag{3}$$

where a represents an attribute of a case; $value(a)$ = a set of values taken by attribute a; v is a value of attribute a; v_s = a set of cases with value s in v; and $|v_s|$ indicates the number of cases contained in v_s.

4.2.2. Conceptual Semantic Similarity

The PPP project information ontology contained both quantitative and qualitative information, which dictated that different methods should be applied for calculating similarities. For quantitative information, a concrete calculation mathematical formula was used. For qualitative information, it is difficult to compare two abstract concepts using a typical formula; therefore, this paper adopted the conceptual semantic similarity which is based on the tree structure of the ontology model to achieve the comparison of abstract concepts.

(1) For quantitative information, the similarity calculation formula is shown below:

$$sim(w_N, w_j) = 1 - \frac{|w_N - w_j|}{w_{\max} - w_{\min}} \tag{4}$$

where w_N = value of an attribute for the target case; w_j = value of an attribute for the j-th old case u; and $w_{\max}$, $w_{\min}$ represent the maximum and minimum values for all the old cases included in the database.

(2) For qualitative information, we used an improved domain ontology similarity algorithm, which integrated a total of four dimensions of semantic similarity: semantic distance, node depth, node density, and semantic coincidence [62]. This algorithm ensured that the calculated value of each influencing factor was between [0, 1] and

the combined semantic similarity was always in the range of [0, 1], while the result was always 1 for the similarity calculation of the same node.

① The formula for calculating similarity based on semantic distance is:

$$distance\_sim(A,B) = \frac{2 \times (H-1) - L}{2 \times (H-1)} \tag{5}$$

where H = maximum depth of the ontology tree, while the depth of root node is defined as 1, and which increases by one unit for each additional level; and L = semantic distance between concepts A and B.

② Similarity based on node depth incorporates the nearest common ancestor, which is calculated as:

$$depth\_sim(A,B) = \frac{2 \times N_{LCS}}{N_A + N_B + 2 \times N_{LCS}} \tag{6}$$

where N_A, N_B = number of edges passed by concept A and B to the nearest common ancestor node, respectively. N_{LCS} = a number of edges passed by the nearest common ancestor node to the root node.

③ Similarity based on node density takes into account the effect of node density in the ontology tree structure, and its similarity is calculated by the formula:

$$density\_sim(A,B) = 1 - \frac{|2 \times wid(LCS) - wid(A) - wid(B)|}{\max(wid(Tree))} \tag{7}$$

where $wid(LCS)$ = number of sibling nodes of the nearest common ancestor of concept A and B; $wid(A)$, $wid(B)$ = number of sibling nodes of concept A and B (including themselves); and $\max(wid(Tree))$ = a maximum number of children nodes owned by each node in the concept tree.

④ Similarity based on semantic coincidence considers the effect of the number of common ancestor nodes possessed by the two concepts, which is calculated as follows:

$$coincidence\_sim(A,B) = \frac{\sum_{C \in T_A \cap T_B} F_{A,B}(C)}{\sum_{C \in T_A \cap T_B} F_{A,B}(C) + \sum_{C_A \in T_A - T_B} F_A(C_A) + \sum_{C_B \in T_B - T_A} F_B(C_B)} \tag{8}$$

$$F_{A,B}(C) = \frac{2 \times Dep(C)}{Dep(A) + Dep(B)} \tag{9}$$

$$F_A(C_A) = \frac{Dep(C_A)}{Dep(A)} \tag{10}$$

$$F_B(C_B) = \frac{Dep(C_B)}{Dep(B)} \tag{11}$$

where T_A, T_B = set of nodes passed by concept A or B to the root node; $Dep(A)$, $Dep(B)$, $Dep(C)$ = depth of concepts A, B, C, while C is the common ancestor of A and B; and C_A, C_B represent the ancestor nodes of A, the ancestor nodes of B, but excluding the common ancestor nodes of A, B, respectively.

⑤ Integrating the similarity of the above dimensions to find the combined similarity of each attribute is then calculated by the formula:

$$\begin{aligned} semantic\_sim(A,B) = \; & \alpha \cdot distance\_sim(A,B) + \beta \cdot depth\_sim(A,B) + \\ & \gamma \cdot density\_sim(A,B) + \phi \cdot coincidence\_sim(A,B) \end{aligned} \tag{12}$$

where α, β, γ and ϕ are the impact weights of semantic distance, node depth, node density, and semantic coincidence on the semantic similarity of the concepts, respectively, satisfying the condition $\alpha + \beta + \gamma + \phi = 1$. Generally, these four parameters are set manually; in order to overcome individual subjectivity and to allow flexible adjustment depending on the practical situation of different domains, principal component analysis (PCA) is introduced.

It takes the contribution of principal components as the parameter value for weighting the semantic similarity in aggregate, which removes the artificial influence.

(3) Since the similarity between concept sets in qualitative information, it can be calculated based on the above four dimensions of similarity. Since a PPP project always contains multiple and variable numbers of "risk factors," the calculation of this attribute's similarity between two cases is actually a comparison between two sets of concepts of different sizes. In this paper, we use the "mean-maximum" algorithm to calculate the semantic similarity between concept sets, as proposed by Wang et al. [63] in Gene Ontology. It defines the semantic similarity between a concept t and a concept set T as the maximum semantic similarity between a concept t and any concept in the set T. That is

$$Sim(t,T) = \max semantic\_sim(t,t') \ t' \in T \tag{13}$$

Therefore, given two concept sets S and T annotated by $S = \{s_1, s_2, \ldots, s_m\}$ and $T = \{t_1, t_2, \ldots, t_n\}$, respectively, the similarity between the concept sets is defined as:

$$Sim(S,T) = \frac{1}{m+n}\left(\sum_{1\le i\le m} Sim(s_i,T) + \sum_{1\le j\le n} Sim(t_j,S)\right) \tag{14}$$

4.3. Risk Cost Measurement

4.3.1. Preliminary VFM Risk Cost Calculation

After obtaining the weights of each attribute and the similarities between the target with each historical case in all attributes, the general similarity can be figured out based on the following equation:

$$Sim(V_N, V_{Sj}) = \sum_{i=1}^{n} \omega_i (sim_i(V_{Ni}, V_{Sji})) \tag{15}$$

where ω_i = weight of the i-th attribute; $Sim(V_N, V_{Sj})$ = similarity between the target case and the j-th historical case; and $sim_i(V_{Ni}, V_{Sji})$ = similarity between the target case and the j-th historical case in the i-th attribute. According to the general similarity between the target case and the historical cases, the nearest historical cases can finally be selected as the candidates using these principles:

① The general similarity between selected historical cases and the target case should not be less than 70%;

② The number of selected historical cases should not be less than three;

③ The higher the similarity between historical cases and the target cases, the higher their contribution to the target case.

When selecting the moderate historical cases, the retained cost of risk and the total cost of risk for the target case can be estimated from Equations (16) and (17); the difference between R and R_0 is the transferable cost of risk.

$$R_0 = \sum_{j\ge 3} R_{j0} Sim(V_N, V_{Sj}) \quad Sim(V_N, V_{Sj}) \ge 70\% \tag{16}$$

$$R = \sum_{j\ge 3} R_j Sim(V_N, V_{Sj}) \quad Sim(V_N, V_{Sj}) \ge 70\% \tag{17}$$

4.3.2. Case Revision

Considering that China's PPP project management database is still in the process of perfection, and there is no normative constraint on the measurement of risk cost, the data in some cases may deviate from reality. Therefore, after retrieving several cases with high similarity, some formula revisions were required for those historical cases that have highly similar characteristics of each attribute, but large variations with other extracted cases in risk costs, and the corrected risk costs were used to calculate the final risk cost of the target project.

The revision was based on the PPP value after deducting the retained cost of risk, the PSC value after deducting the total cost of risk, as well as the contribution of each case to improve the accuracy of the result; the formula is shown as follows:

$$R_{i0r} = \sum_j \frac{PPP_i - R_{i0}}{PPP_j - R_{j0}} R_{j0} * \frac{\omega_j}{\sum_j \omega_j} \tag{18}$$

$$R_{ir} = \sum_j \frac{PSC_i - R_i}{PSC_j - R_j} R_j * \frac{\omega_j}{\sum_j \omega_j} \tag{19}$$

where R_{i0}, R_i, PPP_i, PSC_i are retained cost, total cost, PPP value and PSC value of the i-th historical case that need to be revised; R_{i0r}, R_{ir} = revised value of retained cost and total cost; R_{j0}, R_j, PPP_j, PSC_j are retained cost, total cost, PPP value, and PSC value of the j-th historical case that stand still, while ω_j = weight of the j-th historical case. After the revisions for the selected historical cases are completed, the risk costs with higher degrees of acceptance for the target case can be measured by the following formulas

$$R_0 = \sum R_{i0r} Sim(V_N, V_i) + \sum R_{j0} Sim(V_N, V_j) \quad i + j \geq 3 \tag{20}$$

$$R = \sum R_{ir} Sim(V_N, V_i) + \sum R_j Sim(V_N, V_j) \quad i + j \geq 3 \tag{21}$$

5. Validation

5.1. Data Collection

To verify the effectiveness of the model for predicting the risk cost of PPP projects in the VFM evaluation stage, the urban rail transit PPP project was taken as an example. We screened out a total of 18 projects from the official management database that was in the implementation stage and had completed a quantitative VFM evaluation, which included comprehensive risk identification and an allocation framework. Simultaneously, according to the profile of urban rail transit projects, a total of 11 major classes were ultimately defined; 3 unique attributes of “route length,” “unit investment,” and “station quantity” were added as new classes to the original ontology model in Section 4.1, while the individuals of each class were added, respectively. Then, details of the 18 projects under the 11 classes were summarized.

Specifically, for the class of “risk factors,” a standardized description or a normative index system that was applicable for multiple practical projects was absent in urban rail transit PPP projects. Consequently, it was not conducive to the establishment of an ontology model. To solve this problem, we formed a risk index system that was available for these 18 projects by aggregating the risks of 18 cases, and finally divided all risks into two groups by type and by occurrence stage. The whole system contained a total of 10 primary risks and 101 secondary risks, some of which may also have tertiary and quaternary risks. The more the layers of risk indexes could be subdivided, the more integrated the corresponding ontology model was, and the more significant the differences between risks would be, which was more efficient to improve the accuracy of the whole process. Since the entire risk index system is relatively huge, only primary risks, some secondary risks, and subdivided risks in the ontology model are shown in Figure 4.

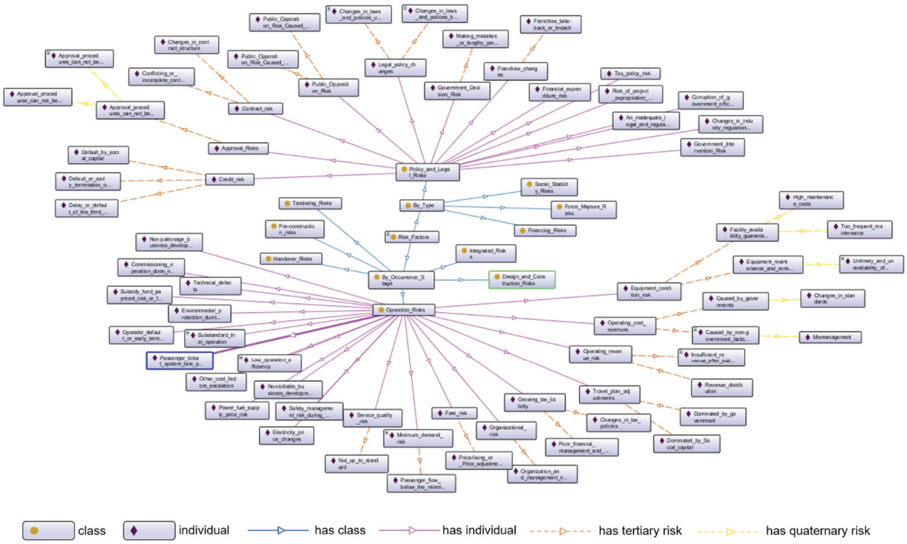

Figure 4. Risk Factor Hierarchy.

After all the information from the 18 cases was completely collected, we chose the project of Dalian Metro Line 5 to be the target case to be tested, and the rest were used as historical cases for empirical analysis. As there were huge amounts of data for the 18 cases, we only listing the details for Dalian Metro Line 5 in Figures 5 and 6; they reflect how to build the information of a project into the ontology structure. Eventually, the individual data under each property of each case would correspond to the unique node in the PPP information ontology model.

5.2. Similarity Calculation between Cases

5.2.1. Attribute Weighting

Before measuring the similarity between the target and historical cases, the weights of classes should first be evaluated. According to the information of 18 projects whose "return modes" are total "viability gap funding," the "return mode" is temporarily removed from this validation and will be considered when more projects are available in the future. Thus, the contributions of the remaining 10 classes could follow the rules of the ID3 algorithm where each class was assigned a distinct weight according to the definition that the greater the information gain, the greater the impact on the ontology system. Results are shown in Table 1.

Table 1. Class weights calculation.

Class	Information Gain	Weight
District	0.3494	0.0230
Invest count	0.2404	0.0158
Unit investment	0.2404	0.0158
Station quantity	0.2404	0.0158
Route length	0.2404	0.0158
Demonstration levels and batches	0.3767	0.0248
Cooperation term	0.4747	0.0312
Procurement mode	0.1833	0.0121
Operation mode	0.1689	0.0111
Risk factors	12.6859	0.8346

Note: Self-organized by the authors.

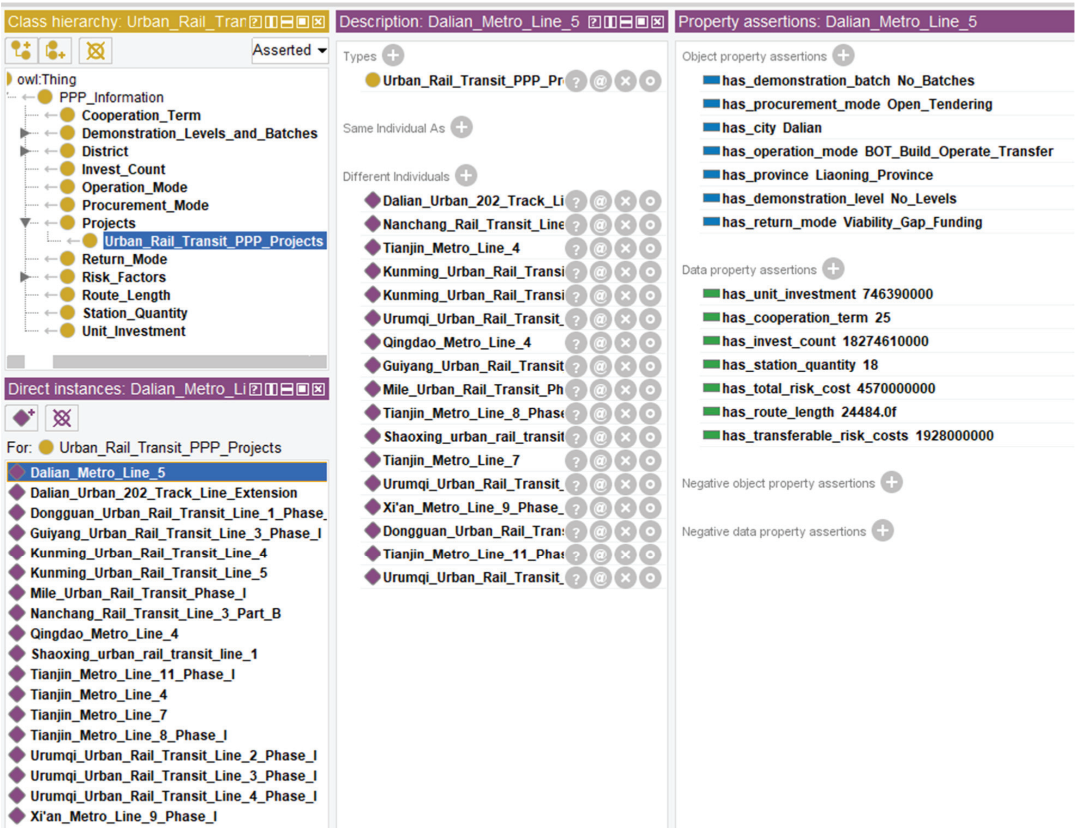

Figure 5. Ontology Creation of Dalian Matro Line 5.

As we could easily conclude from the results, the "risk factors" class brought the highest information gain, which meant that its weight was also the highest. Given that "risk factors" had the most subdivision levels which directly determined the depth of the ontology tree, and further indicated that with the expansion of the "risk factors," its contribution to the whole ontology would be increasing and the risk cost prediction of VFM evaluation would be more reliable.

5.2.2. Cases Similarity

When the index weights calculation has been completed, the similarity between the Dalian Metro Line 5 and the historical cases in terms of each attribute can be completed based on the information ontology model.

(1) For quantitative information, take the "invest count" as an example. The maximum value of total project investment in the historical database was RMB 31,300 million and the minimum was RMB 1457.30 million, while the total project investment of Dalian Metro Line 5 was RMB 17,670.5 million and that of Tianjin Metro Line 4 was RMB 18,274.61 million, then the similarity between the two was $sim = 1 - \frac{|17670.50 - 18274.61|}{31300.00 - 1457.30} = 0.98$.

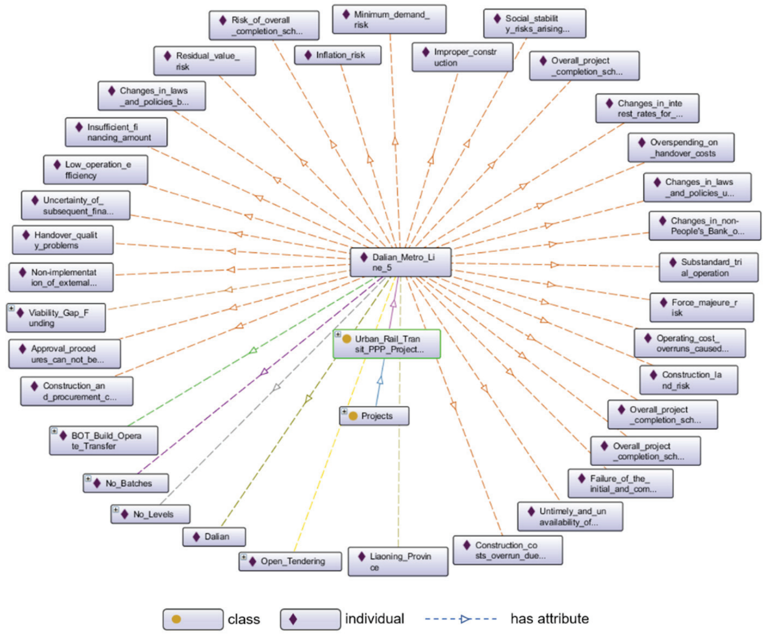

Figure 6. Dalian Metro Line 5 Ontology Structure Diagram.

(2) For qualitative information, all the calculations were based on the conceptual semantic similarity of the ontology.

① First, clarify the weights of the four dimensions of semantic distance, node depth, node density, and semantic coincidence. In this paper, we employed a computer program to derive the similarity values of the four dimensions between Dalian Metro Line 5 and each historical case under all classes, with a total of 14,287 datasets, which were imported into SPSS version 23.0 for principal component analysis, and the contribution rate of the four principal components was taken as the final weight of the four dimensions. Ultimately, $\alpha = 0.7215$, $\beta = 0.2410$, $\gamma = 0.02925$, and $\phi = 0.00825$.

② Measure the combined similarity under each class. For example, the "procurement mode" of Dalian Metro Line 5 was "public bidding," while Qingdao Metro Line 4 adopted "competitive negotiation" as the "procurement mode." The similarities of the four dimensions under the class were 0.875, 0.5, 0.929, and 0.333, respectively, so the combined similarity of the two projects was $0.875 \times 0.7125 + 0.5 \times 0.2410 + 0.929 \times 0.02925 + 0.333 \times 0.00825 = 0.7817$.

③ Evaluate the similarity of the risk sets. The target and historical cases contained multiple risk factors, so the calculation of their similarity was a comparison between two sets of concepts, which required calculating the combined similarity of each risk factor in one case against another case in sequence, and then exchanging the positions of two cases to make the second round of calculation. After that, extract every maximum value in every comparison to acquire a string of values whose quantity was equal to the number of risk factors in the two projects, and their average was the semantic similarity of the two cases under the class of "risk factors." Because of the workload and complexity, the whole process was implemented with the support of a computer program. Table 2 shows an example of the semantic similarity of "risk factors" between Dalian Metro Line 5, which owned 28 risk factors, and Qingdao Metro Line 4, which owned 25 risk factors.

Table 2. Similarity calculation of "risk factors" between two projects.

No.	Dalian-Qingdao	Qingdao-Dalian	Similarity of "Risk Factor"
1	0.8728	0.7299	
2	0.8728	0.7299	
3	0.9134	0.7746	
4	0.9134	0.8714	
5	0.8714	1.0000	
6	0.8120	0.8120	
7	0.7767	0.7735	
8	1.0000	0.7143	
9	0.6657	1.0000	
10	0.7819	0.7850	
11	0.7819	0.7299	
12	0.7102	0.7850	
13	0.6557	0.7850	
14	0.7102	0.7850	(23.4045 + 20.8964)/(28 + 25) = 0.8359
15	1.0000	1.0000	
16	1.0000	0.7102	
17	0.7752	0.9336	
18	0.7756	1.0000	
19	0.9336	0.8120	
20	1.0000	0.8120	
21	0.8120	0.7819	
22	0.8120	0.9134	
23	0.6657	0.8728	
24	0.7819	1.0000	
25	0.8392	0.7850	
26	0.8571	-	
27	1.0000	-	
28	0.8141	-	
Total	23.4045	20.8964	

Note: Self-organized by the authors.

If all the above measurements were completed, then the general similarity between Dalian Metro Line 5 and each historical case could be obtained by weighting the semantic similarities under all classes using the contribution rates which was calculated by the ID3 algorithm. Finally, all the general similarities were greater than 80%. However, under the principle restriction of identifying no less than 3 cases, similar historical cases with an overall similarity above 85% were selected, while five items actually met the requirement. The detailed similarity values are shown in Table 3; moreover, the contribution degree of each item was determined by the general similarity, which is listed in Table 4.

As presented in Table 4, the risk costs of Tianjin Metro Line 8 Phase I and Tianjin Metro Line 4 were extremely different from those of Tianjin Metro Line 7 and Tianjin Metro Line 11 Phase I, which were all located at Tianjin and were highly similar to the two projects for every class. Additionally, no extra efforts to reduce the risk costs were detected after further studying the complete information and report of the VFM evaluation of these two cases. This demonstrated that there was likely some bias in the forecasting process. Therefore, the calculated preliminary total risk cost and retained cost of Dalian Metro Line 5 deviated drastically from the actual amount of RMB 45,70 hundred million and RMB 19.28 hundred million. To obviate this situation, some revisions were required.

Table 3. Calculation of the similarity of each class.

Project	District	Invest Count	Unit Investment	Station Quantity	Route Length	Demonstration Levels and Batches	Cooperation Term	Procurement Mode	Operation Mode	Risk Factors	General Similarity
Urumqi Urban Rail Transit Line 2 Phase I	0.6417	0.9325	0.8899	0.619	0.8742	0.6699	0	1	1	0.8323	0.8016
Kunming Urban Rail Transit Line 4	0.6428	0.7196	0.6136	0.5714	0.8415	0.6699	0.5	1	1	0.8362	0.8115
Mile Urban Rail Transit Phase I	0.6428	0.4365	0.6854	0.5238	0.2972	1	0.5	1	1	0.8425	0.8122
Urumqi Urban Rail Transit Line 3 Phase I	0.6417	0.9703	0.9267	0.9524	0.8974	0.6699	0	1	1	0.84	0.8148
Dalian Urban 202 track line extension	1	0.5409	0.6749	0.8095	0.241	1	1	0.7817	0.8248	0.8189	0.8168
Nanchang Rail Transit Line 3 (Part B)	0.6417	0.6265	0.9179	0.8095	0.4051	1	0.7	1	1	0.8304	0.8212
Urumqi Urban Rail Transit Line 4 Phase I	0.6417	0.9321	0.9226	0.9048	0.9537	1	0	1	1	0.84	0.8225
Qingdao Metro Line 4	0.6417	0.9665	0.8872	0.8571	0.7956	0.6699	1	0.7817	1	0.8359	0.8225
Kunming Urban Rail Transit Line 5	0.6428	0.9643	0.9976	0.8571	0.9523	0.6699	0.5	1	1	0.8362	0.8277
Xi'an Metro Line 9 Phase I	0.6417	0.853	0.9854	0.8571	0.7659	0.6699	0.5	1	1	0.8524	0.8362
Dongguan Urban Rail Transit Line 1 Phase I	0.6417	0.7305	0.3146	0.8571	0.6492	1	0.9	1	0.7097	0.8489	0.8364
Guiyang Urban Rail Transit Line 3 Phase I	0.6428	0.5635	0.6209	0.4762	0.9774	1	0.5	1	1	0.8637	0.8409
Shaoxing urban rail transit line 1	0.6417	0.9521	0.8504	0.7619	0.848	1	0.5	1	1	0.8741	0.8618 *
Tianjin Metro Line 8 Phase I	0.7128	0.9781	0.8797	0.9524	0.759	1	0.9	1	1	0.8574	0.8645 *
Tianjin Metro Line 7	0.7128	0.9669	0.9582	0.8571	0.9577	1	0.9	1	1	0.8543	0.8645 *
Tianjin Metro Line 4	0.7128	0.9798	0.9492	0.9524	0.9319	1	0.9	1	1	0.8574	0.8683 *
Tianjin Metro Line 11 Phase I	0.7128	0.9964	0.9615	0.8571	0.931	1	0.9	1	1	0.8864	0.8915 *

Note: Self-organized by the authors. "*" is the overall similarity value of the final selected cases.

Table 4. Weight calculation of similar cases.

Project	Risk Cost		Similarity to Target Case	Weight	Preliminary Risk Cost of Target Case	
	Retained	Total			Retained	Total
Shaoxing Urban Rail Transit Line 1	27.41	58.78	0.8618	0.1981	11.21	32.29
Tianjin Metro Line 8 Phase I	0.98	9.82	0.8645	0.1987		
Tianjin Metro Line 7	13.10	26.35	0.8645	0.1987		
Tianjin Metro Line 4	1.07	10.62	0.8683	0.1996		
Tianjin Metro Line 11 Phase I	13.51	55.35	0.8915	0.2049		

Notes: Self-organized by the authors. The currency unit is RMB 100 million.

5.3. Cases Revision and Result

By adopting Equations (16) and (17) to adjust the retained risk cost and total risk cost of Tianjin Metro Line 8 Phase I Project and Tianjin Metro Line 4, the correction process is listed in Table 5.

Table 5. Revision of historical cases.

Project	Original Risk Cost		PPP	PSC	*PPP	*PSC	Revised Risk Cost		Weight	Risk Cost of Target Case	
	Retained	Total					Retained	Total		Retained	Total
Tianjin Metro Line 8 Phase I	0.98	9.82	198.48	218.73	197.50	208.91	14.98	44.08	0.1987	17.15	46.80
Tianjin Metro Line 4	1.07	10.62	223.86	243.82	222.79	233.20	16.90	49.20	0.1996		
Shaoxing Urban Rail Transit Line 1	27.41	58.78	271.31	281.18	243.90	222.40	-	-	0.1981		
Tianjin Metro Line 7	13.10	26.35	219.33	222.36	206.23	196.01	-	-	0.1987		
Tianjin Metro Line 11 Phase I	13.51	55.35	271.12	292.22	257.61	236.87	-	-	0.2049		

Notes: Self-organized by the authors. The currency unit is RMB 100 million.

As the final results presented in Table 5, four of the five selected similar cases of Dalian Metro Line 5 were also urban rail transit PPP projects located in Tianjin, while the remaining one was Shaoxing Urban Rail Transit Line 1. Moreover, the contribution weights of Tianjin Metro Line 11 Phase I, Tianjin Metro Line 4, Tianjin Metro Line 8 Phase I, Tianjin Metro Line 4, and Shaoxing Urban Rail Transit Line 1 were 0.2049, 0.1996, 0.1987, 0.1987, and 0.1981, respectively. This showed that the contributions of the four similar cases belonging to Tianjin were the most similar. According to conventional cognition, the projects located in the same district, implementing the same urban management and planning policies, owning virtually the same construction technology and investment, etc., are relatively similar to each other. The retrieval mechanism based on the ontology model has achieved the objective of identifying the similar projects in the same district with high priority. It indicated that the ontology model has realized the structured representation and completed the sharing and interoperability of project information. Meanwhile, the conceptual semantic similarity algorithm was feasible to guarantee the usability of the extracted similar cases. These advantages have been validated in previous accounts. Im et al. [64] enhanced the cost management efficiency of construction projects by developing an ontological knowledge structure. Xiao et al. [65] used the ontological knowledge representation to improve access to information for construction noise control. In addition, a conceptual similarity based on ontology has been proven to be more accurate to support the retrieval measure [66]. Ontology provided a good boost to the whole process of CBR.

After case revision, the risk costs of Tianjin Metro Line 8 Phase I and Tianjin Metro Line 4 were more reasonable compared with the original cases, and their deviations from the other two projects of Tianjin were further reduced. Ultimately, the retained risk cost of Dalian Metro Line 5 was calculated to be RMB 17.15 hundred million, and the total risk cost was RMB 46.80 hundred million, while the actual cost measured in the VFM evaluation was

RMB 19.28 hundred million and 45.70 hundred million, with relative errors of 11.05% and 2.41%, respectively. The accuracy was greatly improved in comparison with the preliminary risk costs calculation. Furthermore, the results were more acceptable where the risk costs of the target case were basically at the same level as all projects in Tianjin. Ji et al. [46] likewise established a more sophisticated revision mechanism to improve the accuracy of estimating housing costs by using CBR. They verified that an effective revision could make a great difference by comparing the results before and after the revision. Fan et al. [42] used CBR to generate the desirable risk response strategies, and further, through the analysis of the strategy-risk response relationships, to revise the inapplicable strategies. These all revealed that positive revision improved the utilization and validity of the case data.

6. Discussion

Risk is demonstrated as one of the most important drivers of VFM in the PPP field [7–10]. Research on its identification and allocation is well advanced, but the cost assessment was still difficult to address. It was usually conducted based on specialists' opinions whose subjective bias cannot be completely eliminated. The CBR-based measurement model developed in this paper compensated for this deficiency by employing the expert problem-solving ideology, but removing its subjective influence [35–37]. In addition, the knowledge representation capability and hierarchical structure of ontology provided useful support for the promotion of CBR performance [49].

In this paper, a foundational ontology structure containing eight major classes was initially established, which was applicable to all industries in the PPP area. In the validation section, three extra classes of "route length," "station quantity," and "unit investment" were expanded independently according to the features of the urban rail transit PPP industry under study, and the individuals were created based on practical cases. The results showed that the expanded ontology model performed well in the whole process, which verified that the scalability of the ontology [50]. Other classes or individuals can be extended on the basis of this ontology with characteristics of many other PPP industries. A comprehensive knowledge system can be further improved by the development of PPP information ontology in the future.

Ultimately, the entire validation process demonstrated accurate results that are in line with reality. In the creation of the risk index system, 10 primary risks and 101 secondary risks were included, with some of them further subdivided, as shown in Figure 5. In the future, the risk index system can be continuously refined to provide clearer knowledge for the ontology model. Thus, it became the most detailed class of the ontology model, serving as the basis for risk costs estimation. While using the ID3 algorithm to weight the major classes, "risk factors" as the key to risk costs received the highest weight, as shown in Table 1. This not only conformed to practical perception, but also showed that the ID3 algorithm could intuitively reflect the amount of information carried by each node of the tree structure [60]. The algorithm is suitable for the ontology model. Moreover, the ontology-based conceptual semantic similarity provided an excellent comparison method for abstract qualitative information, especially the concept set of "risk factors" [62,63]. Based on the series of complementary calculations, the final extracted cases are the most similar to the target case, as shown in Tables 4 and 5. The cases located in the same district as the target were retrieved with priority, which indicated that the established model has complied with the computational requirements. The retrieval mechanism has delivered an effective and efficient extraction of similar cases. After revision, the total risk cost and the retained risk cost of the target case were better estimated, with reasonable relative errors; therefore, we believed that the effectiveness of the whole measurement cycle was well tested. Nevertheless, there is still room for improvement in the revision method of this research. The formula approach may be rigid for some cases with fortuities. Other methods are welcomed to assist in the elimination of the contingency of cases and to promote the extensive application of the measurement model.

7. Conclusions

When the PPP mode stepped into a steady development period in China, the VFM evaluation system similarly entered into a mature era, acting as a solid foundation for the construction of PPP projects. However, it is still slightly inadequate in risk assessment, which relies heavily on domain specialists, and the corresponding academic research has poor practicality, leading to an unbalanced development between academics and practitioners. Considering to promote the accuracy and feasibility of the risk cost estimation of VFM evaluation and to increase the probability of reusing PPP historical cases, we combine the CBR and ontology technology to facilitate the overall efficiency of the process. Using the ontology model to structure and integrate the PPP information knowledge for the CBR cycle, based on the ontology tree structure, the overall efficiency of CBR is improved by using the conceptual semantic similarity algorithm. The revision mechanism was established to ensure the accuracy of the results of the entire measurement process. Simultaneously, more objective weighting algorithms are adapted in the entire process to alleviate the reliance on experts. Ultimately, the proposed estimation model was tested using a total of 18 urban rail transit PPP projects in the official database. Results show that the five most similar cases of the target case were efficiently extracted. The total risk cost and retained risk cost are successfully estimated, with the relative errors of 11.05% and 2.41%, respectively. Therefore, it can be concluded that the VFM risk costs measurement which involved ontology and CBR is feasible and reliable. Based on the historical cases, it has great accuracy, which increases the independence from experts in the quantitative evaluation of VFM. It further demonstrates that the sources involved in the PPP information ontology model established in this paper can accommodate the computational requirements of the whole process, strengthening the information integration and interoperability of PPP information, particularly the abstract qualitative information. The combination of CBR with ontology has maximized the usage and efficiency of valuable information concerning past projects from the perspective of problem-solving by human beings. We believe that the cooperation of both is going to be more satisfactory as the database is expanded and updated to be more comprehensive in the future.

However, this study has several limitations that are expected to be improved in future work. First, for an ontology to have application capabilities, it must build a consensus among users on how the world is codified [67]. For better cognition, more valid historical cases are required to be used as an information source for a more complete ontology. Additionally, a comprehensive model that integrates more categories of projects, such as wastewater treatment, elderly care facilities, ecological construction, the environment, etc., is expected to be developed in order to achieve holistic knowledge management without redundancy. Third, the risk index system in the ontology model is expected to be perfected in the future. We suggest that every PPP industry ought to affiliate with its own specific and normalized risk index system that unifies the description of risk factors. Finally, CBR requires valid retrieval and revision [46,47]. The revision method established in this paper may be too absolute for the target cases. The fact that the revised results still deviate from the practical situation is still not well explained. Other methodologies are expected to be explored for assistance in the revision process. Therefore, we continue to seek a better combination to improve the accuracy of results and avoid contingency in the process.

Author Contributions: Conceptualization, H.W.; investigation, Q.L.; supervision, Y.Z.; validation, Q.L.; writing—original draft, Q.L.; writing—review and editing, Q.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://www.cpppc.org:8082/inforpublic/homepage.html#/projectPublic/ (accessed on 1 April 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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Effect of the Standardization of Service Platforms for High-Involvement PropTech Services

Jinmin Kim [1], AhRam Cho [2] and Jaeyoung Kim [1,*]

[1] Department of Corporate Management, Korea University, Seoul 30019, Korea; tristan1031@korea.ac.kr
[2] Global Income Strategy Division, Miraeasset Global Investments, Seoul 03159, Korea; ahram.cho@miraeasset.com
* Correspondence: korean4u@korea.ac.kr

Abstract: In this study, we focus on the innovation resistance that has appeared in the process of accepting changed information technology services after the COVID-19 pandemic. Based on a survey of property technology (PropTech) service users in Korea, this study proposes an extended technology acceptance model that considers the antecedent variables of the information systems success model to implement a standard PropTech service platform, and analyzes the influence of the selected parameters. Service quality was applied as the antecedent variable to define system quality and service standards, considering the establishment of the service standards process suggested by the company. The selected parameters were the demand for the personalization of the service and the resistance to innovation, which implies the degree to which consumers refuse to accept new technologies. To this end, we conducted a questionnaire survey of 524 PropTech users from 11 October 2021 to 15 November 2021. This study analyzes the factors affecting consumers' continued use intention in order to derive the service standardization of PropTech operations, and presents the mediating effects of innovation resistance and personalization to derive the implications for service standardization. The implications of this study are as follows: first, the possibility of innovation resistance in the PropTech service sector and its mechanisms are presented. Second, the necessity of redefining the quality dimension is proposed. Finally, we identify that additional research on innovation resistance to PropTech services is needed.

Keywords: innovation resistance; personalization; PropTech; service platform; service standardization

Citation: Kim, J.; Cho, A.; Kim, J. Effect of the Standardization of Service Platforms for High-Involvement PropTech Services. *Sustainability* **2022**, *14*, 5036. https://doi.org/10.3390/su14095036

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 12 March 2022
Accepted: 20 April 2022
Published: 22 April 2022

1. Introduction

Owing to the COVID-19 pandemic, the use of information systems in purchasing activities has become widespread. In the early stage of Amazon's e-commerce business, books that were low-involvement products were selected as trading products. As consumers have become accustomed to purchasing products online, the role of e-commerce has expanded, reaching even to the selection of several high-involvement products, such as insurance, jewelry, medical services, and real estate. Low-involvement products with relatively low anxiety levels vis à vis purchase results can be sold continuously through marketing methods with repetitive exposure. However, many factors influence the selection process of the consumer when making purchase decisions regarding high-involvement products with high consumer interest and high perceived risk [1]. Thus, consumers' innovation resistance (IR) to the purchasing decision-making process increases for high-involvement products. Considering that failure to make good purchasing decisions for high-involvement products causes great losses, it is natural for consumers to engage in progressive information searching activities. In addition, the consumers of high-involvement products tend to research the product in detail; thus, they educate themselves with detailed explanations of the product or recommendations from experts [2,3].

Service standards are a set of guidelines that reflect different situations in customer management and help to reduce the errors caused by individual customers [4]. Setting this guideline is effective in achieving consistency in service quality. When a customer purchases a service, the potential risk associated with the purchase may be higher than expected. This discrepancy can be attributed to the characteristics of service as a purchase. Service quality is highly dependent on people; therefore, the accompanying risks when providing services should be minimized through service production quality. Moreover, service standardization facilitates communication by providing a clear outline of the roles and responsibilities of an organization. Standardization encourages the better performance of both management of employees and, by maintaining service quality, it helps to acquire customers' trust. Therefore, it is imperative to conceptualize an effective and systematic service quality standardization method [5].

This study focuses on the IR to information technology (IT) service acceptance, which has changed since the onset of the COVID-19 pandemic. In addition, personalization has been considered as another variable that contrasts with IR. Considering both system and service quality as antecedent factors that influence IR and personalization, a research model on the continuous intention to use IT services for high-involvement products has been suggested. Accordingly, we collected samples of people who use property technology services to acquire property.

This study proposes an extended technology acceptance model (TAM) that considers the preceding variables of the information systems (IS) success model to implement the standard platform for services. We believe that data analysis based on service users can verify the mediating effects of the proposed variables (i.e., IR and personalization). This study particularly observes system quality, the establishment of service standards processes proposed by companies, and service quality-defining standards. The demand for the personalization of services and IR, which is the degree to which consumers refuse to accept new technologies, have been proposed as mediating variables. In this study, we discuss innovation in a traditional service wherein IT is not internalized. Therefore, we focus on the situation wherein users who are familiar with the conventional service must be accommodated to the new service. In this respect, it can be understood that IR increases against system quality improvement. Considering that traditional real estate brokerage services center on real estate property, rather than on stakeholders, we believe that personalized services could be a differentiating factor moving in a different direction to innovation. This is because personalized services that offer user-centered information sharing, e.g., providing customized information to buyers and sellers, are important for sales.

This study explores three questions:

(1) What are the influencing factors of the standardization of service platforms for high-involvement products (i.e., real estate) on continuous intention to use?
(2) What is the mediating effect of innovation resistance on service platforms?
(3) What is the mediating effect of personalization on service platforms?

This study aims to identify the factors that influence the standardization of service platforms for high-involvement products in connection with the continuous intention to use IT services. The remainder of this paper is organized as follows: Section 2 explores the existing literature to build hypotheses anchored on previous studies, and Section 3 presents the research model and methods. Section 4 presents the results analyzed via partial least squares structural equation modeling (PLS-SEM) and, in Section 5, conclusions and implications based on the study are presented.

2. Literature Review and Hypotheses

2.1. Service Standardization

Service innovation is achieved by organizing innovation as a systematic process [6]. A systematic process is required to ensure sustainable service quality. Furthermore, various recent technology approaches are required, such as IT. More importantly, customers should accept new services and the disruption should propagate. It is imperative that sustainable innovation is achieved so that both the customer and service provider can accept the innovative infrastructure [7].

The use of digital technology is not only innovative but also the most efficient and reliable method of managing risk. Turning a product into a service requires the use of digital technology. Sklyar et al. [8] analyzed the effects of digital services on the manufacturing industry and found that, at a macroscopic level, efforts to maximize the utility of digital technology in line with service application strategies are important. Sklyar et al. [9] analyzed the effect of the digitization of services on the participants of the service network. Immonen et al. [10] proposed scenario-based service requirements engineered to establish the sustainability of digital services. Digitizing services reduces inefficiency in the market and enables environment optimization for both service providers and customers.

The standardization of services enables a detailed comparison and contrast of services, thus providing a structural and realizable service framework [11]. A visible service platform adequately reflects the application of IT in addition to environmental changes. Smedlund [12] classified service platforms as business models, provided a categorization of such service platforms, and proposed a sustainable service construction plan. Löfberg and Åkesson [13] also analyzed the groundwork of successful service platforms and proposed a service framework comprising a service module, the integration of resources, and value creation. Not only do firms participate in service platforms, but service providers, consumers, and all related personnel also work together to create value in the process. Aulkemeier et al. [14] conducted research to establish service platforms on the Internet. They suggest the importance of an e-service platform that integrates both physical and intangible services. Moreover, they emphasized the specialization and division of work through extended research in the e-service supply chain field.

2.2. Service Platforms

Several methods should be considered for a service platform using IT. Some studies have focused on the application of IT to service platforms [15] or online-to-offline e-commerce service platforms that consider standardization in an online business platform [16]. Further studies on service standardization have led to reappraisals of service quality. Service standardization needed for service quality enhancement identifies the rate of satisfaction, and is utilized as a resource for establishing a sustainable business ecosystem [17]. Finally, the service platform is evaluated by customers, and satisfied customers remain loyal to the service platform [18]. It is important to identify the factors that satisfy customers in a standardized service platform and reflect such changes in the process. The service platform, in particular, simultaneously needs to meet both the customer's and service provider's needs.

Based on the extended TAM, we aim to analyze the specificities of the system and ascertain service quality. System quality reflects the standardized platform provided by the producer, and it aims to quantify the level of service that the customer individually recognizes. When the producer proposes innovation, the model selects certain parameters, such as the rate of customers' resistance to new technology and customers' personalization needs, in order to frame an efficient service platform. This research takes the TAM as a baseline model, (1) adds a leading variable to propose an extended TAM, and (2) analyzes the effect of the subordinate parameters. The leading variable is derived from the IS success model, and system quality and service quality are chosen as extra parameters.

2.3. TAM

The TAM, proposed by Davis [19], explains the process of customers' acceptance of new technology based on the rational theory of action. The TAM takes recognized utility and recognized accessibility as independent parameters, and analyzes their effects on behavioral intent. This study considers the complexity of the model and selects the leading variable. After further reviewing the factors in the previous literature, system quality adopts security and data co-ownership, while service quality elects IR and efficiency as contributing factors.

Delone and Mclean's [20] IS success model recognizes service, system, and information quality as the preceding variables. The IS success model is currently being applied in various research fields, particularly as the mobile environment expands [21]. This model is used to evaluate the effect of mobile commerce on consumer satisfaction by analyzing the service process [22,23] and its effect on user satisfaction by improving the education service system [24] to enhance the IT service quality of the enterprise [25].

A simplified model was constructed with two variables (i.e., system quality and service quality) including the information quality of system and service quality and, based on this model, an integrated relationship was derived [26]. Focusing on system quality and service quality is useful for enhancing the understanding of service processes and performing systematic analysis. Xu et al. [27] analyzed the effects between e-service variables and the causes of intention to use, while Pratiwi and Mujadilah [28] analyzed user satisfaction with banking services in mobile environments. Thus, this study identified the system quality and service quality for the standardization of service providers as antecedent variables; subsequently, we derive the following hypotheses:

Hypothesis 1 (H1). *System quality influences perceived usefulness.*

Hypothesis 1a (H1a). *Security influences perceived usefulness.*

Hypothesis 1b (H1b). *Information sharing influences perceived usefulness.*

Hypothesis 2 (H2). *System quality influences perceived ease of use.*

Hypothesis 2a (H2a). *Security influences perceived ease of use.*

Hypothesis 2b (H2b). *Information sharing influences perceived ease of use.*

Hypothesis 3 (H3). *Service quality influences perceived usefulness.*

Hypothesis 3a (H3a). *Innovativeness influences perceived usefulness.*

Hypothesis 3b (H3b). *Efficiency influences perceived usefulness.*

Hypothesis 4 (H4). *Service quality influences perceived ease of use.*

Hypothesis 4a (H4a). *Innovativeness influences perceived ease of use.*

Hypothesis 4b (H4b). *Efficiency influences perceived ease of use.*

2.4. Extended TAM

The TAM has been studied extensively and is evolving in several areas. To enforce changes in corporate work processes through the adoption of IT, research on the TAM has been widely conducted. The TAM is used by organizations to analyze the impact of changes made to improve the efficiency of e-procurement [29,30] and derive strategies to improve consumer satisfaction with e-commerce and increase revisits [31]. This model has also been applied to understand the use of mobile applications to attain service process efficiency [32] and to comprehend the digital behavior of various consumers in relation to the spread of financial technology services [33,34].

The TAM has been extended and utilized in various forms. Through extended studies on the propensity and characteristics of individual students in e-learning services, researchers have attempted to derive an efficient educational method for introducing new technologies [35,36].

The extended TAM has been studied in various service fields; it has been suggested, for example [37], to help adopt and utilize social media consumers, and to create an extended model [38] considering the characteristics of the service field for virtual reality. Researchers have conducted research on telemedicine, including additional variables considering the characteristics of the medical service [39], and have attempted to introduce mobile-based monetary services in developing countries [40]. In this study, the TAM is used as a basic model to extend system quality and service quality and analyze the influence of mediators. Therefore, the following hypotheses have been established:

Hypothesis 5 (H5). *Perceived usefulness influences continuous intentions of use.*

Hypothesis 6 (H6). *Perceived ease of use influences continuous intentions of use.*

2.5. Mediating Variables

In this study, two variables that were expected to have opposite effects were considered as mediators (i.e., personalization (hereafter, PER) and innovation resistance (hereafter, IR)). Notably, IR is a personal reaction to consumer services and arises from various causes, such as the type of product, environment, and individual tendencies. Furthermore, IR affects an individuals' rational choice, regardless of satisfaction in the context of consumer service acceptance [41]. Individual differences occur in tendencies to resist innovation, and service providers must consider the individuals who adopt new services [42]. In particular, the spread of new services based on new IT has a significant influence on the market entry of companies. Considering that there is a need to induce the rapid introduction of services to consumers, it is very important to consider how to tackle IR.

Lukkanen et al. [43] analyzed the differences in opinions according to the age of consumers using mobile banking. They suggested that the perception of the value of new technology was independent of consumers' age, but that the acceptance of information on new technology differs according to age. Matsuo et al. [44] studied consumers' IR to Internet banking services, showing that consumer experiences can reduce IR. Kaur et al. [45] analyzed the reasons why consumers do not adopt services even when there are many benefits, such as the convenience of mobile payment solutions.

Recently, new services in the digital environment have been widely introduced, and research is being actively conducted to analyze the barriers to new businesses owing to consumer IR. Tang and Chen [46] conducted a study on the obstacles to new market opportunities of resale commerce. Some studies that have identified IR as a barrier to the spread of new services suggest the adoption of massive open online courses [47], the acceptance of users' online shopping in e-commerce [48], and the provision of food delivery applications [49] as potential solutions.

Therefore, we expect that IR as a mediator will have a negative effect on the introduction of new services.

Hypothesis 7 (H7). *Innovation resistance will mediate the relationship between system quality/service quality and perceived usefulness/perceived ease of use.*

Hypothesis 7a-(1) (H7a-(1)). *Security influences innovation resistance.*

Hypothesis 7a-(2) (H7a-(2)). *Information sharing influences innovation resistance.*

Hypothesis 7b-(1) (H7b-(1)). *Innovativeness influences innovation resistance.*

Hypothesis 7b-(2) (H7b-(2)). *Efficiency influences innovation resistance.*

Hypothesis 7c (H7c). *Innovation resistance influences perceived usefulness.*

Hypothesis 7d (H7d). *Innovation resistance influences perceived ease of use.*

In contrast to IR, PER is a mediator that is expected to have a positive effect on the introduction of new services. Notably, PER increases consumer service satisfaction and delivers greater value to consumers. [2]. The personalization of services is a powerful way to retain customers by increasing customer loyalty [50]. The advent of Internet-based services has enabled the use of various types of personalized services, such as online shopping activities [51] and the personalization of services in the field of Internet banking [3]. Recently, research has been conducted on the personalization of services in the smart environment of mobile technology [52], including mobile banking [53] and online retail convenience facilities [54] that offer extended personalization services. With the development of IT, personalized services are being provided in various data-based mobile environments. However, previous studies on this topic lack an analysis of the level and degree of personalization, and do not reflect the characteristics of individual service users. Personalization can be a powerful tool to satisfy consumers, but it cannot solve every issue; thus, various environments, factors, and consumer characteristics must be considered [55]. The hypotheses that consider personalization as a mediator are listed as follows:

Hypothesis 8 (H8). *Personalization will mediate the relationship between system quality/service quality and perceived usefulness/perceived ease of use.*

Hypothesis 8a-(1) (H8a-(1)). *Security influences personalization.*

Hypothesis 8a-(2) (H8a-(2)). *Information sharing influences personalization.*

Hypothesis 8b-(1) (H8b-(1)). *Innovativeness influences personalization.*

Hypothesis 8b-(2) (H8b-(2)). *Efficiency influences personalization.*

Hypothesis 8c (H8c). *Personalization influences perceived usefulness.*

Hypothesis 8d (H8d). *Personalization influences perceived ease of use.*

Figure 1 shows the proposed conceptual model and eight hypothesized relationships. Figure 1 also represents an integrated conceptual model constructed to evaluate the relationships between the constructs and mediation effects.

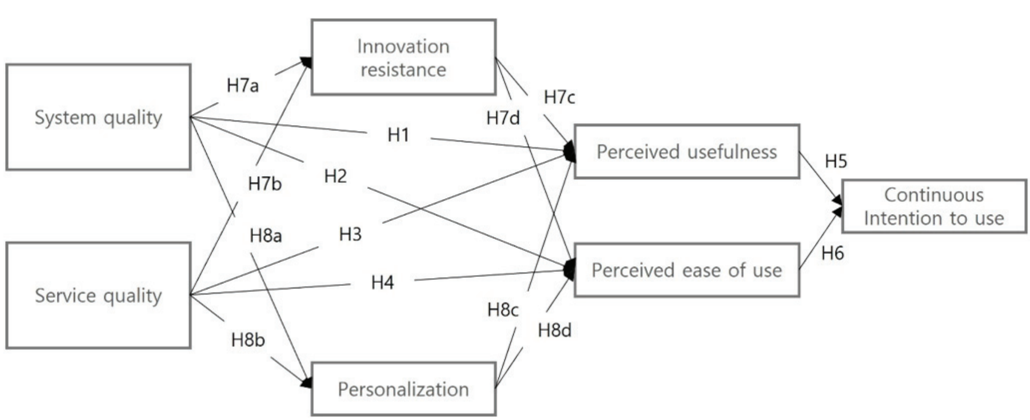

Figure 1. Research model.

3. Research Methodology

3.1. Research Design

In this study, a structural equation model was used to determine the effect between variables through statistical analysis. Structural equation models are generally useful for examining the influence between several variables. In this study, the standardization factors of the service platform were derived and the effect of the mediating variables affecting the consumer's acceptance of new services was confirmed.

This study was designed using PLS-SEM platform for the standardization of services. Based on the extended TAM, the variables of the IS success model were used to explain the relationships between the variables, and the effects of the mediating variables were analyzed. The study procedure was as follows: first, we checked the preliminary considerations such as latent variables, the path of the model, and the number of samples required. Second, we evaluated the reflective measurement models such as the indicator loadings, internal consistency reliability, and discriminant validity. Third, we evaluated formative measurement models such as convergence validity, indicator collinearity, statistical significance, and relevance of the indicator weights. Finally, the structural models and robustness levels were checked.

3.2. Case Study

In Korea, PropTech services have emerged since 2018, and more than 300 service providers currently deliver services to customers. PropTech services combine advanced technology and real estate, and their use has increased as a result of the extensive implementation of social distancing [56]. PropTech services, originating from a platform that provides real estate information, have diversified from real estate development to building design and construction, and the numbers of service providers and investments in this area are also rapidly increasing [57]. Although PropTech has not yet reached the level of developed countries, many people know and have experience in using PropTech services [58]. Since the PropTech service platform can provide personalized services [59] based on a standardized system, it was considered the most suitable field for the purpose of this study.

3.3. Sample and Research Instruments

In order to determine the minimum sample size, the inverse square root method proposed by Kock and Hadaya [60] was used.

$$n_{min} > \left(\frac{L_{se}}{|p_{min}|}\right)^2$$

According to the formula for the minimum sample size proposed by Kock and Hadaya [60], the minimum number of samples required would be 155 considering a significance level of 5% and a minimum path coefficient of 0.2.

In order to derive a more accurate sample number, we used the software G*power 3.1.9.7 (Jochen Grommisch, Düsseldorf, Germany) to calculate sample size [61]. The minimum sample size is provided with the following settings: F^2 = 0.15; a = 0.05; number of predictors = 4; and power set to 80% [62]. The sample size required to test this model was found to be 85. In the PLS-SEM, 524 respondents satisfied the minimum sample size for the survey [63,64].

Based on the expanded TAM, the model was expanded by adding the variables of the IS success model, and the effect of the mediating variables of innovation resistance and personalization on the acceptance of new services was analyzed. There are few empirical studies surrounding PropTech and, therefore, this study proposed an extended model to analyze the effect on the continuous intentions of use by analyzing the path coefficient to derive the standardization factors of the service platform. In addition, the mediating variables were added and studied to analyze the impact on the acceptance of service platforms using new technologies.

The survey was based on the related previous literature [65–67]. Some of the phrases were edited and amended according to the PropTech service. Specifically, the study tried to refine the survey tool by eliminating questionnaires with low correlation. The final survey comprised topics on security (four items), information sharing (six items), innovativeness (four items), efficiency (eight items), innovation resistance (four items), personalization (three items), perceived usefulness (six items), perceived ease of use (six items), and continuous intention to use (seven items) (Table 1).

To achieve the most accurate response, a pilot study was carried out on 38 academic personnel and PropTech service experts. The pilot group completed the survey and suggested a slight modification to the survey language used. After integrating the proposed modifications, we finalized the survey with a 7-point Likert scale and decided to use closed answers. Moreover, we found that the respondents had already used PropTech services in the past, which contributed to a better alignment of the survey.

3.4. Analysis

After explaining the characteristics of the respondents via descriptive statistics, we analyzed the survey using the recently introduced PLS-SEM approach. Notably, PLS-SEM is a powerful tool that has minimum requirements for estimation parameters, and it is effective in modeling latent parameters in a non-normal distribution [68]. PLS-SEM is a suitable research method for path analysis with variables that are indirectly measured through other variables. Indirectly measured variables are common latent variables, and this approach uses latent variables for path coefficient analysis [59,69].

In PLS-SEM, we substantiated the validity of the model and implemented a non-recursive least squares method to retrieve the external weights and structural model relations. Finally, we used bootstrap resampling to evaluate the statistical significance. The collected data were programmed in SPSS 20 before PLS-SEM. To verify the hypotheses we used SMART PLS 3.0, an SEM tool. Using SmartPLS 3.0, this study tested the model with a path weight scheme. We evaluated model fit and reliability, and the heterotrait/monotrait ratio of correlations (HTMT) to confirm discriminant validity. Finally, we were able to provide the results of the structural model.

Table 1. Questionnaire source and number of items.

Constructs	Number of Items	Sources
Security (SEC)	4	[65,70,71]
Information sharing (INS)	6	[65,70,71]
Innovativeness (INN)	4	[65,70,72]
Efficiency (EFF)	8	[65,70,72]
Innovation resistance (INR)	4	[42,44,46,49]
Personalization (PER)	3	[51,55,73]
Perceived usefulness (PEU)	6	[66,67,74]
Perceived ease of use (PEE)	6	[66,67,74]
Continuous intention to use (CIU)	7	[67,75–77]

4. Results

The model developed in this study is a tool for analyzing customers using PropTech services. Between 11 October 2021 and 15 November 2021, the mobile survey application registered 992 responses in total. After thoroughly examining the survey, we screened 524 valid and usable samples and calculated a 58.94% response rate. Table 2 lists the demographic information of the 524 respondents.

Table 2. Demographic information.

Respondents' Demographic Information	Variables	Usable Responses	Percentage (%)
Gender	Male	212	40.5
	Female	312	59.5
Age	Below 19	9	1.7
	19–30	138	26.3
	31–40	188	35.9
	41–50	129	24.6
	Above 50	60	11.5
Marital status	Married	283	54.0
	Never married	241	46.0
Household income (in a month, USD)	Below 1000	64	12.2
	1000~2000	65	12.4
	2000~3000	215	41.0
	3000~4000	77	14.7
	4000~5000	50	9.6
	Above 5000	53	10.1

To test the model, we used SmartPLS 3.0 with a path weight scheme. The bootstrap procedure drew 524 cases and 5000 samples using the unsigned option. When evaluating and reporting results [64,78], the measurement model was evaluated before the structural model.

SmartPLS uses SRMR and GOF to evaluate model fit. The GOF is obtained by multiplying the average value of R2 by the average value of the average variance extracted (AVE) and taking the square root again. The GOF value of this research model was 0.694, which constitutes a good goodness of fit [68,79]. The SRMR value is calculated based on standardized residuals [80]. When the model's goodness of fit is complete, SRMR becomes 0, and if it is less than 0.08, it is judged that the model's goodness of fit is good. It can be judged that the SRMR of this research model had a high goodness of fit of 0.051. In addition, an RMS_theta value of 0.116 indicates that the model is appropriate, with higher values indicating lower levels of appropriateness [81].

Table 3 shows the results of the reliability and definitive factor analysis. In general, an item can be considered valid if its standard loading value is 0.5 or greater. If the mean AVE value is also greater than or equal to 0.5, the grouping factor can be considered as a reliability valid [78] composite, as was the case for the five reflectively measured constructs in our study ranging from 0.93 to 0.96, as these exceeded the minimum requirement of 0.70.

In this study, the variance inflation factor (VIF) was identified as a potential factor proposed by Knock [82] to investigate the common method variance (CMV) that may occur in PLS-SEM. As a result of checking for multicollinearity in the path between latent variables, the VIF did not exceed the threshold of 5, with minimum and maximum values of 1.442 and 3.456, respectively. The CMV was not an issue in the present study. In addition, the possibility of the CMV was low because the correlation coefficient between the variables was not high [69].

The Fornell and Larcker [83] criterion showed that all the AVE values for the specular construct were higher than the squared cross-construct correlation, indicating discriminant validity. Similarly, all the indicator loadings were higher than their respective cross-loadings, thus providing further evidence of discriminant validity. Table 4 shows the diagonal AVE values and the diagonal squared cross-composition correlations.

Table 3. Validity and reliability of measures.

Measures	Item	Loading Weights	Cronbach's Alpha	Composite Reliability	AVE
Security (SEC)	SEC1 SEC2 SEC3 SEC4	0.859 0.885 0.925 0.907	0.917	0.923	0.800
Information sharing (INS)	INS1 INS2 INS3 INS4	0.857 0.896 0.847 0.865	0.889	0.923	0.751
Innovativeness (INN)	INN1 INN2 INN3 INN4	0.856 0.881 0.887 0.887	0.901	0.931	0.771
Efficiency (EFF)	EFF1 EFF2 EFF3 EFF4	0.879 0.853 0.869 0.865	0.889	0.923	0.751
Innovation resistance (INR)	INR1 INR2 INR3 INR4	0.855 0.895 0.925 0.889	0.914	00.939	0.794
Personalization (PER)	PER1 PER2 PER3	0.896 0.896 0.907	0.882	0.927	0.809
Perceived usefulness (PEU)	PEU1 PEU2 PEU3 PEU4 PEU5	0.875 0.872 0.817 0.897 0.895	0.937	0.950	0.760
Perceived ease of use (PEE)	PEE1 PEE2 PEE3 PEE4 PEE5 PEE6	0.864 0.869 0.885 0.874 0.869 0.868	0.937	0.950	0.760
Continuous intention to use (CIU)	CIU1 CIU2 CIU3 CIU4	0.867 0.892 0.859 0.702	0.853	0.900	0.694

Table 4. Discriminant validity results.

	SEC	INS	INN	EFF	INR	PER	PEU	PEE	CIU
SEC	0.894								
INS	0.523	0.867							
INN	0.416	0.519	0.878						
EFF	0.445	0.617	0.719	0.867					
INR	0.09	−0.122	−0.026	−0.134	0.891				
PER	0.409	0.622	0.668	0.756	−0.155	0.891			
PEU	0.385	0.663	0.631	0.762	−0.224	0.766	0.872		
PEE	0.42	0.658	0.655	0.762	−0.209	0.798	0.815	0.872	
CIU	0.444	0.565	0.595	0.644	−0.156	0.683	0.664	0.723	0.833

To confirm discriminant validity, the heterotrait/monotrait ratio of correlations (HTMT) was evaluated, as suggested by Henseler et al. [84] (Table 5). Discriminant validity was established if the HTMT value was less than 0.90. In this study, the HTMT value was found to be between 0.144 and 0.891, thereby confirming the safety of the discriminant validity.

Table 5. Heterotrait/monotrait ratio of correlations.

	SEC	INS	INN	EFF	INR	PER	PEU	PEE	CIU
SEC									
INS	0.567								
INN	0.451	0.578							
EFF	0.484	0.694	0.802						
INR	0.103	0.13	0.052	0.144					
PER	0.448	0.702	0.747	0.853	0.166				
PEU	0.408	0.732	0.691	0.843	0.237	0.85			
PEE	0.443	0.72	0.712	0.834	0.219	0.878	0.878		
CIU	0.506	0.638	0.676	0.732	0.229	0.777	0.732	0.792	

The structural model of the results is shown in Figure 2. R-squares were also used to judge the path coefficients of the endogenous latent variables. Most of the path coefficients with significance were found to be related at a level of $p \leq 0.01$. The path coefficient of $p \leq 0.05$ (ease of use -> user satisfaction and information quality -> intention to use) and the path coefficient of $p \leq 0.10$ (system quality -> intention to use and service quality -> intention to use) showed a statistical relationship and indicated that meaningful analysis was possible. Table 6 lists all of the calculated values.

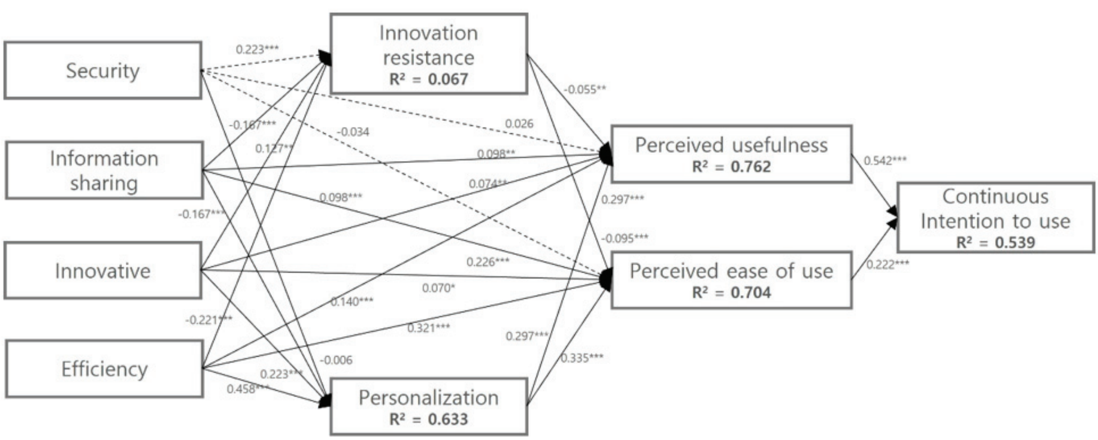

Figure 2. Structural equation model. Notes: *** $p \leq 0.01$; ** $p \leq 0.05$; and * $p \leq 0.10$. Dashed lines represent non-significant relationships.

In Smart PLS, one can substantiate the effect of specific individual effects; the resulting analysis is as follows.

As shown in Table 7, "Security -> Innovation resistance" describes the situation wherein system quality enhancement calls for resistance. Security-related aspects entail not only product quality but also social quality; thus, quality enhancement before ensuring perfect security might undermine a consumer's trust in service quality. Information sharing has a negative effect on IR and a positive effect on PER. When asking questions about information sharing with security, personal information security is excluded, and only the effect of information sharing is evaluated. Therefore, to enhance convenience, information sharing reduces IR, but could positively contribute to PER.

Table 6. Hypothesis testing results.

Hypothesis		Relationship	Total Effect	T-Value	*p*-Value	Status
H1	a	Security -> Perceived usefulness.	0.026	0.847	0.397	Reject
	b	Information sharing -> Perceived usefulness.	0.098	2.541	0.011	Accept
H2	a	Security -> Perceived ease of use.	−0.034	1.042	0.298	Reject
	b	Information sharing -> Perceived ease of use.	0.226	4.813	0	Accept
H3	a	Innovativeness -> Perceived usefulness.	0.074	1.987	0.048	Accept
	b	Efficiency -> Perceived usefulness.	0.14	2.458	0.014	Accept
H4	a	Innovativeness -> Perceived ease of use.	0.07	1.774	0.077	Accept
	b	Efficiency -> Perceived ease of use.	0.321	5.408	0	Accept
H5		Perceived usefulness -> Continuous intention to use.	0.542	7.938	0	Accept
H6		Perceived ease of use -> Continuous intention to use.	0.222	2.785	0.006	Accept
H7	a-(1)	Security -> Innovation resistance.	0.223	4.558	0	Accept
	a-(2)	Information sharing -> Innovation resistance.	−0.167	2.799	0.005	Accept
	b-(1)	Innovativeness -> Innovation resistance.	0.127	2.135	0.033	Accept
	b-(2)	Efficiency -> Innovation resistance.	−0.221	3.307	0.001	Accept
	c	Innovation resistance -> Perceived usefulness.	−0.055	2.475	0.014	Accept
	d	Innovation resistance -> Perceived ease of use.	−0.096	3.713	0	Accept
H8	a-(1)	Security -> Personalization.	−0.006	0.181	0.856	Reject
	a-(2)	Information sharing -> Personalization.	0.226	5.361	0	Accept
	b-(1)	Innovativeness -> Personalization.	0.223	4.851	0	Accept
	b-(2)	Efficiency -> Personalization.	0.458	8.688	0	Accept
	c	Personalization -> Perceived usefulness.	0.297	4.795	0	Accept
	d	Personalization -> Perceived ease of use.	0.335	5.892	0	Accept

Table 7. Mediation test results.

Hypothesis Path	Path Coefficient	T Value	*p* Value	95% Beta Coefficients	$p < 0.05$
SEC -> INR -> PEU -> PEE	−0.007	2.408	0.016	[−0.015, −0.003]	yes
SEC -> INR -> PEU	−0.021	2.684	0.008	[−0.04, −0.01]	yes
SEC -> INR -> PEU -> CIU	−0.005	1.782	0.075	[−0.011, −0.001]	no
SEC -> INR -> PEE	−0.012	2.01	0.045	[−0.028, −0.003]	yes
SEC -> INR -> PEU -> PEE -> CIU	−0.004	2.465	0.014	[−0.009, −0.002]	yes
SEC -> INR -> PEE -> CIU	−0.007	1.818	0.07	[−0.017, −0.002]	no
SEC -> PER -> PEU	−0.002	0.173	0.862	[−0.023, 0.02]	no
SEC -> PER -> PEE	−0.002	0.166	0.868	[−0.026, 0.016]	no
SEC -> PER -> PEU -> CIU	0	0.154	0.877	[−0.006, 0.005]	no
SEC -> PER -> PEU -> PEE	−0.001	0.171	0.865	[−0.008, 0.007]	no
SEC -> PER -> PEU -> PEE -> CIU	0	0.174	0.862	[−0.004, 0.004]	no
SEC -> PER -> PEE -> CIU	−0.001	0.166	0.868	[−0.014, 0.008]	no
SEC -> PEU -> CIU	−0.008	0.947	0.344	[−0.028, 0.005]	no
SEC -> PEU -> PEE -> CIU	−0.006	1.036	0.301	[−0.021, 0.004]	no
SEC -> PEU -> PEE	−0.012	1.048	0.295	[−0.036, 0.008]	no
SEC -> PEE -> CIU	0.014	0.787	0.432	[−0.018, 0.051]	no
INS -> INR -> PEE	0.009	1.594	0.112	[0.001, 0.024]	no
INS -> INR -> PEU -> PEE -> CIU	0.003	1.923	0.055	[0.001, 0.007]	no
INS -> INR -> PEU -> PEE	0.006	1.898	0.058	[0.001, 0.013]	no
INS -> INR -> PEU	0.016	2.01	0.045	[0.002, 0.034]	yes
INS -> INR -> PEU -> CIU	0.004	1.499	0.134	[0.000, 0.009]	no
INS -> INR -> PEE -> CIU	0.005	1.481	0.139	[0.000, 0.014]	no
INS -> PER -> PEE	0.067	3.207	0.001	[0.034, 0.114]	yes
INS -> PER -> PEU -> PEE -> CIU	0.014	3.66	0	[0.008, 0.024]	yes
INS -> PER -> PEU -> PEE	0.026	3.779	0	[0.015, 0.043]	yes
INS -> PER -> PEU -> CIU	0.017	2.225	0.027	[0.005, 0.034]	yes

Table 7. *Cont.*

Hypothesis Path	Path Coefficient	T Value	p Value	95% Beta Coefficients	$p < 0.05$
INS -> PER -> PEE -> CIU	0.036	2.838	0.005	[0.017, 0.071]	yes
INS -> PER -> PEU	0.076	4.316	0	[0.047, 0.121]	yes
INS -> PEU -> CIU	0.05	2.554	0.011	[0.012, 0.091]	yes
INS -> PEU -> PEE -> CIU	0.043	3.536	0	[0.024, 0.07]	yes
INS -> PEU -> PEE	0.078	3.921	0	[0.043, 0.124]	yes
INS -> PEE -> CIU	0.053	2.506	0.013	[0.015, 0.099]	yes
INN -> INR -> PEU -> PEE	−0.004	1.629	0.104	[−0.012, −0.001]	no
INN -> INR -> PEE -> CIU	−0.004	1.537	0.125	[−0.011, 0.000]	no
INN -> INR -> PEU -> PEE -> CIU	−0.002	1.67	0.096	[−0.006, 0.000]	no
INN -> INR -> PEE	−0.007	1.609	0.108	[−0.017, −0.001]	no
INN -> INR -> PEU -> CIU	−0.003	1.365	0.173	[−0.008, 0.000]	no
INN -> INR -> PEU	−0.012	1.747	0.081	[−0.03, −0.002]	no
INN -> PER -> PEE -> CIU	0.036	3.113	0.002	[0.018, 0.065]	yes
INN -> PER -> PEU	0.075	4.004	0	[0.047, 0.119]	yes
INN -> PER -> PEU -> PEE	0.026	3.246	0.001	[0.015, 0.049]	yes
INN -> PER -> PEE	0.066	3.453	0.001	[0.035, 0.112]	yes
INN -> PER -> PEU -> PEE -> CIU	0.014	3.301	0.001	[0.008, 0.027]	yes
INN -> PER -> PEU -> CIU	0.017	2.097	0.036	[0.005, 0.036]	yes
INN -> PEU -> CIU	0.016	1.414	0.158	[−0.002, 0.041]	no
INN -> PEU -> PEE	0.024	1.663	0.097	[−0.004, 0.053]	no
INN -> PEU -> PEE -> CIU	0.013	1.63	0.104	[−0.002, 0.03]	no
INN -> PEE -> CIU	0.04	1.971	0.049	[0.005, 0.083]	yes
EFF -> INR -> PEU -> PEE	0.007	2.083	0.038	[0.003, 0.016]	yes
EFF -> INR -> PEU	0.021	2.35	0.019	[0.008, 0.044]	yes
EFF -> INR -> PEE	0.012	1.95	0.052	[0.002, 0.027]	no
EFF -> INR -> PEU -> PEE -> CIU	0.004	2.087	0.037	[0.001, 0.009]	yes
EFF -> INR -> PEE -> CIU	0.007	1.725	0.085	[0.001, 0.017]	no
EFF -> INR -> PEU -> CIU	0.005	1.709	0.088	[0.001, 0.012]	no
EFF -> PER -> PEE -> CIU	0.074	3.765	0	[0.041, 0.118]	yes
EFF -> PER -> PEU -> CIU	0.034	2.179	0.03	[0.009, 0.071]	yes
EFF -> PER -> PEU -> PEE	0.053	3.478	0.001	[0.028, 0.089]	yes
EFF -> PER -> PEU -> PEE -> CIU	0.029	3.502	0.001	[0.015, 0.048]	yes
EFF -> PER -> PEE	0.136	4.331	0	[0.077, 0.202]	yes
EFF -> PER -> PEU	0.153	4.725	0	[0.095, 0.214]	yes
EFF -> PEU -> PEE	0.111	4.432	0	[0.07, 0.172]	yes
EFF -> PEU -> CIU	0.071	2.518	0.012	[0.012, 0.123]	yes
EFF -> PEU -> PEE -> CIU	0.06	4.165	0	[0.037, 0.097]	yes
EFF -> PEE -> CIU	0.076	2.302	0.022	[0.017, 0.143]	yes
INR -> PEU -> CIU	−0.021	2.141	0.033	[−0.042, −0.004]	yes
INR -> PEU -> PEE	−0.033	3.02	0.003	[−0.056, −0.015]	yes
INR -> PEU -> PEE -> CIU	−0.018	3.028	0.003	[−0.031, −0.008]	yes
INR -> PEE -> CIU	−0.03	1.979	0.048	[−0.07, −0.007]	yes
PER -> PEU -> PEE -> CIU	0.063	4.199	0	[0.04, 0.099]	yes
PER -> PEU -> PEE	0.116	4.203	0	[0.071, 0.177]	yes
PER -> PEU -> CIU	0.074	2.351	0.019	[0.021, 0.147]	yes
PER -> PEE -> CIU	0.161	3.939	0	[0.089, 0.255]	yes
PEU -> PEE -> CIU	0.188	5.559	0	[0.132, 0.262]	yes

PropTech innovation is addressed before IT is implemented across the traditional services. Therefore, IR is enhanced, and users are required to adapt to the new service, which has a positive effect on PER. In traditional real estate-related services, the valuation of properties and the provision of information on the surrounding areas are the primary activities. However, PropTech can supply personalized information about the surroundings and provide a personalized service experience.

Efficiency is a key PropTech service feature that provides a new interface for data searching and transactions. Therefore, IR becomes more important when one needs to accept a new IT service; however, PER is positively affected.

Innovation resistance (efficiency) acts as a partial parameter in information sharing (perceived usefulness and perceived ease of use). It can be concluded that information sharing and efficiency contribute positively towards enhancing perceived usefulness and perceived ease of use by reducing innovation resistance. However, it has been shown that, by increasing IR, complementation and innovation may negatively affect perceived usefulness and perceived ease of use. Innovation has a direct positive effect on perceived usefulness and perceived ease of use; however, it has a negative effect in relation to some factors.

For PER, all independent variables except security showed positive partial factor effects between utility and accessibility.

Regarding the analysis of the parameters, the obtained results are as follows: (1) security takes IR as a parameter and reduces customer use intention through perceived usefulness and perceived ease of use; (2) information sharing takes PER as a factor and increases the users' use intentions despite IR; however, its effects are limited; (3) innovation resistance takes PER as a factor and positively contributes towards enhancing the continuous intention to use. This does not exhibit a negative effect on IR. In particular, PER takes perceived usefulness and perceived ease of use as parameters; (4) innovation resistance affects the customers' continuous intention to use the product without perceived usefulness, and a relationship exists between IR and perceived ease of use, but disruption does not accompany perceived ease of use; (5) efficiency shows a general positive effect via PER, as well as a negative effect via IR; and finally, in general (6), IR unfolds the most efficient process for aligned positive effects and does not exhibit a negative effect. Even with information sharing, the IR effect is limited. Any procedure to enhance security has been shown to have a negative effect on CIU (continuous intention to use), which is the ultimate goal of this study.

5. Discussion

This study focuses on the IR shown during the adoption process of a newly introduced IT service and considers PER as a contrasting feature. Considering these two features of product quality as system and service quality factors, we aimed to investigate the effects of such product quality components on IR and PER during the adoption process. As demonstrated by the results of our study, the results of IR during the adoption process of high-involvement products were similar to those previously seen when assessing low-involvement products [41,42].

For the study, we selected the PropTech service. This service is gaining prominence as a high-involvement real-estate IT platform service. We suggested three implications for the product quality adoption process. First, we identified how the PropTech service could be met with IR and described the underlying mechanisms of such a process [26,27]. The real estate properties that are evaluated and traded on PropTech services are high-involvement products, and it has been suggested that if more information on such products is supplied at an accessible level, a more detailed valuation of such products would be provided. In this study, we demonstrate that the IR shown during the valuation of low-involvement products is similar to that exhibited towards PropTech services, which process the information of high-involvement products.

Furthermore, IR has been demonstrated to have negative effects on service platforms [41]. The previous research of Matsuo et al. [44] demonstrated a similar discovery that, when a customer accepts a new service, he or she focuses more on rationality than on the satisfaction that follows from the service. Here, we note the need to reconsider the definition of product quality dimensions. To select the independent variables, we divided system quality and service quality, and suggested two product quality factors. In the real output, we discovered that data sharing and efficiency demonstrated consistent effects [25], while security and innovation contributed positively to IR [47,49]. This suggests the need for a better strategy regarding product quality dimensions than that used by traditional frameworks considering product quality versus process product quality.

Lastly, we discovered that personalization is an important parameter that has a very positive impact on the adoption of a new service, in contrast to IR [2]. Previous research has also demonstrated that personalization is an important factor in service satisfaction and user retention, proving that it is an important factor for high-quality products [52,53]. In our results, we discovered that the components of data sharing and efficiency had a consistent effect on high-involvement products [55], while security contributed positively to innovation resistance [47]. This signifies that better strategies are needed to maintain product quality than the traditional methods. The effect of PER (0.223) was higher than that of IR (0.127), and the explanatory variable of IR was lower, signifying that it is important to address the side effects caused higher IR after adopting innovation [45]. Lastly, the product quality effect of security is not singular, but should address the hygiene factor of product quality; if this dimension is prematurely recognized before reaching perfection, it may be met with the disruptive resistance of the user.

This study was limited to the PropTech service platform, and thus further research into high-involvement products is needed.

6. Conclusions

In this study, based on a survey of service platform users, we proposed an extended technology acceptance model that implemented a standardized service platform by considering the variables of the information system success model and analyzing the effects of the selected parameters. The effect of innovation resistance in the process of accepting information technology services was analyzed.

We discovered the need for additional research into the IR of PropTech services. While the suggested independent variables explained 63.3% of PER, they explained only 6.7% of IR. This highlights the need for research into the driving factors that affect IR in PropTech services.

The operational implications of this study are as follows: first, we believe that our efforts regarding product quality enhancement with DS and efficiency are consistent and reliable. Two quality dimension factors reduce IR and enhance PER, producing a positive effect on utility and extensibility. Second, it is imperative to consider the double-sided effect when introducing innovation into a situation. Innovation or disruptive changes have a simultaneous positive effect on PER and IR, resulting in conflicting effects on utility and extensibility.

Notwithstanding the contributions above, this study has some limitations that should be addressed in future research. First, although this study analyzed IR and the analysis of contrasting PER comprised an adequate approach, the interpretation of the empirical results explains more about PER than IR. As illustrated, the effect of IR was less explainable, thus giving rise to the need for further research into the leading variables IR. Second, while this research evaluated system and service quality, it did not properly identify the specificities of PropTech services. As PropTech services are integrated into various ISs, transactions, and qualitative information strategies, different results may ensue depending on the services used.

In future studies, a specific PropTech service should be adopted to evaluate the identified service. Lastly, we did not consider the fact that PropTech services may be used rather sporadically. While traditional information services are gradually integrated into the system, data on real estate properties on PropTech services are intermittent and occur less frequently. This reduces customers' familiarity with the service, and system enhancement during the same period could require a new interface, which may result in the customer becoming unfamiliar with the existing service. Such characteristics of PropTech services should be amended so that the customer base can be extended and transaction efficiency can be continuously sustained.

Author Contributions: Project administration, J.K. (Jaeyoung Kim); Writing—original draft, J.K. (Jinmin Kim); Writing—review & editing, J.K. (Jinmin Kim), A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the BK21 FOUR (Fostering Outstanding Universities for Research) funded by the Ministry of Education (MOE, Korea) and National Research Foundation of Korea (NRF).

Conflicts of Interest: The authors declare no conflict of interest.

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Key Elements of Attentions for Enhancing Urban Resilience: A Comparison of Singapore, Hong Kong and Hangzhou

Min Chen [1], Yujie Lu [2,3,4], Yi Peng [5,*], Tingting Chen [6] and Yiye Zhang [5]

[1] School of Transportation and Civil Engineering, Nantong University, Nantong 226019, China; chen.min@ntu.edu.cn
[2] Department of Building Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China; lu6@tongji.edu.cn
[3] Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, Shanghai 200092, China
[4] Shanghai Institute of Intelligent Science and Technology, Tongji University, Shanghai 200092, China
[5] School of Public Administration, Zhejiang University of Finance & Economics, Hangzhou 310018, China; zhangyiye@zufe.edu.cn
[6] Department of Urban and Regional Planning, Sun Yat-sen University, Guangzhou 510275, China; chentt53@mail.sysu.edu.cn
* Correspondence: pengyihz@zufe.edu.cn

Abstract: Urban resilience is an attractive concept among academies and governments with the increasing severity of climate change and relevant disasters in cities. Few studies have been conducted to compare the key elements of attentions for enhancing urban resilience among Asian cities, although resilience is context-dependent. This study aims to compare the key elements of attentions for enhancing urban resilience among Singapore, Hong Kong and Hangzhou. A comprehensive literature review and expert interview validation were used to solicit the preliminary elements of attentions for enhancing urban resilience. Planners and researchers in the field of urban planning were surveyed to assess the significance level of the preliminary elements in the three case cities, as professional knowledge is required in the survey. Statistics were used to identify the key elements of attentions in the three case cities. Results demonstrate that the three cities have various elements of attentions for enhancing urban resilience despite sharing many similarities, which also demonstrate the guidance limitation of the general urban resilience framework. It also provides a reference for other international comparisons.

Keywords: urban resilience; elements of attentions; comparison; Asian cities

Citation: Chen, M.; Lu, Y.; Peng, Y.; Chen, T.; Zhang, Y. Key Elements of Attentions for Enhancing Urban Resilience: A Comparison of Singapore, Hong Kong and Hangzhou. *Buildings* **2022**, *12*, 340. https://doi.org/10.3390/buildings12030340

Academic Editor: Francesco Tajani

Received: 2 January 2022
Accepted: 1 March 2022
Published: 11 March 2022

1. Introduction

1.1. Research Background

Urban resilience is a popular topic with the rapid development of cities, which are the key spaces for human activities around the world. How to cope with uncertainty and risk, including the rapid development of technology [1], social crisis [2], financial crisis [3], climate change [1], and disasters [4,5], is critical for cities to realize sustainable development goals. Urban resilience is proposed as an ideal guideline for urban development and governance, frequently discussed in the government and academe. Godschalk [6] pinpointed that a resilient city is a sustainable network of physical systems and human communities. Campanella [7] defined urban resilience as the ability of a city to recover from destruction. Wu and Wu [8] interpreted urban resilience from the ability of a city to persist without qualitative changes in its structure and function, despite the disturbances. Lhomme et al. [9] defined urban resilience as the ability of a city to absorb disturbance and recover its functions after a disturbance. Meerow et al. [10] defined urban resilience as "the ability of an urban system to maintain or rapidly return to desired functions in the face of a disturbance, adapt to change, and quickly transform systems that limit current or future adaptive capacity". The resilience of what to whom is the key basis to comprehend disruptions and concerned systems regarding urban resilience, even though the consensus of defining urban resilience is still not achieved [10].

Various studies have investigated how to achieve urban resilience. For example, Jha et al. [11] emphasized that urban resilience depends on the resilience of sub-systems, which comprise infrastructure resilience, institutional resilience, economic resilience and social resilience. Ahern [12] proposed a suite of strategies for building urban resilience capacity: multifunctionality, redundancy and modularization, (bio and social) diversity, multi-scale networks and connectivity, and adaptive planning and design. Ribeiro and Gonalves [13] concluded that urban resilience is realized through redundancy, robustness, connectivity, independence, efficiency, resources, diversity, adaptation, innovation, inclusion and integration. Shamsuddin [14] determined that the characteristics of a resilient system include extensive coordination, maintaining adaptability, divergent time horizons and diverse outcomes. Xu and Shao [15] asserted that robustness, efficiency, diversity, redundancy and physical connection are important for physical resilience, while social connectivity, social capital construction, sustainable paths, flexibility and convertibility are the keys to social resilience.

Many cities have formulated strategies to enhance urban resilience. The Rockefeller Foundation launched the first Global 100 Resilient Cities project in 2013, which further advanced the programs of enhancing urban resilience. For example, New York proposed 13 initiatives in the field of neighborhoods, buildings, infrastructure and coastal defense to enhance urban resilience to withstand the impacts of climate change and other 21st century threats in the "One New York Strategy". Specific indicators, which include eliminating disaster-related long-term displacement (more than one year) of New Yorkers from homes by 2050, reducing the Social Vulnerability Index for neighborhoods across the city and reducing average annual economic losses resulting from climate-related events, are proposed to effectively advance the mission of building a resilient New York [16]. Sydney conducted a report called "Resilient Sydney: A strategy for city resilience" and listed five directions in a five-year action plan of 35 actions classified into the flagship, supporting and aligning actions to enhance urban resilience. It is emphasized that the government organizations and communities should understand the risks and respective responsibilities, collaborate with each other, and invest resources to take actions [17]. London formulated the "London City Resilience Strategy 2020" and proposed 21 action plans under the resilience projects of people, place and processes to realize urban resilience by considering both immediate risks and a wider range of shocks and stresses [18].

Comparative studies have also been conducted in terms of urban resilience, as different cities may face different systems and disruptions. For example, Muñoz-Erickson et al. [19] used data from a survey of nine US and Latin American and Caribbean cities to explore how the concept of urban resilience was framed across multiple governance sectors, which include governmental, non-governmental, business, research, and hybrid organizations. Framings converge with definitions of resilience as the ability to resist, cope with, or bounce back to previous conditions, whereas sustainability, equity, and social-ecological-technological systems' perspectives are rarely associated with resilience. Woodruff et al. [20] compared policies and programs of the 101 largest cities in the US that tangibly affect resilience. It was found that different dimensions, such as funding and the level of needed commitment, may explain the empirical patterns of policy adoption of urban resilience better. Nedaei et al. [21] compared the resilience of Tehran and Mashhad to identify the strengths and weaknesses of these two cities and found that both the cities are weak in terms of resilience indicators and sub-indicators, but Mashhad is more resilient than Tehran. However, few studies have been conducted to compare the key elements of attentions for enhancing urban resilience among Asian cities. This insufficiency presented barriers for comprehensively understanding the practices or needs for enhancing urban resilience in the rapid development of Asian cities.

1.2. Research Objective

This study aims to compare the key elements of attentions for enhancing urban resilience among Singapore, Hong Kong and Hangzhou. The three cities were chosen partly due to the convenience of collecting relevant data by the authors and partly due to certain representations. Singapore and Hong Kong are usually model cities in Asia, while Hangzhou is an emerging first-tier city in China, which has the responsibility of exploring various Chinese strategies, e.g., demonstration zone for common prosperity. The research is organized as follows. Section 2 identifies the preliminary elements of attentions for enhancing urban resilience through a literature review. Section 3 introduces the research method. Section 4 presents the results. Section 5 conducts in-depth discussions with regard to the results to ensure clear understandings. Section 6 concludes this research, specifies the limitations of this study and presents potential directions for future study.

2. Literature Review and Preliminary Elements of Attentions for Enhancing Urban Resilience

City, as a complex social ecosystem, is vulnerable to various shocks and disturbances from the outside world and itself. As priorities rapidly evolve and change due to technological advances, climate change and population growth, systematic planning under the concept of resilience can contribute to the sustainable development of cities. However, Klein et al. [22] determined that the previous research does not have a clear and operational definition of resilience. Therefore, one way to achieve sustainable development is through resilience frameworks. The purpose of the resilience framework is to identify factors, such as the types, characteristics and spatial distribution of disturbances faced by the city, as well as to guide the future of the city with the concept of adaptability.

The existing research on the urban resilience framework is mainly divided into two directions. One is a comprehensive resilience framework research based on multiple dimensions. The Resilience Alliance, as an early international organization that conducts urban resilience research, proposes four priority themes for urban resilience: governance networks, metabolic flows, built environment and social dynamics [23]. The Rockefeller Foundation and ARUP proposed the city resilience framework (CRF) in 2014, which includes Health & Wellbeing, Economy & Society, Infrastructure & Environment and Leadership & Strategy [24]. Cutter et al. developed the disaster resilience of place (DROP) and baseline resilience indicators for communities (BRIC) to provide the baseline of measuring community resilience from the perspective of community capital [25,26]. Jabareen attempted to establish a multidisciplinary conceptual framework to support urban resilience, thus proposing the resilient city planning framework (RCPF) [27]. This framework mainly includes four parts: vulnerability analysis matrix, urban governance and prevention and uncertainty oriented planning, with each part comprising three to four elements. By analyzing 20 urban cases, Desouza et al. proposed a conceptual framework of urban resilience, which includes design, planning and management, and divided cities into physical systems and social systems at the macro level [28]. The pressure faced by cities comprises natural, technological, economic and human pressure. Moreover, the disaster resilience scorecard developed by UNISDR assessed community resilience from the perspective of ten key tasks of disaster prevention and mitigation [29]. A quick risk evaluation tool developed by UNISDR assessed community resilience from the perspective of required abilities to cope with common disasters derived from the Sendai Framework for Disaster Risk Reduction 2015–2030 [30]. The other direction is an urban resilience framework based on specific risks or a single system. Joerin et al. proposed a climate disaster resilience index (CDRI) model based on five dimensions of the economy, institution, nature, material and society [31]. Sun et al. developed a seismic resilience evaluation model for the electrified community based on system dynamics [32]. Hernández et al. developed a typhoon risk index to measure community resilience from the perspective of disaster risk and vulnerability [33]. Müller et al. proposed a model to measure rural community resilience based on the carbon cycle [34]. Previous studies have provided good references to understand the concept of urban resilience, relevant impact factors and measurement methods. Table 1 summarizes the general resilient city frameworks covered in this literature review.

Table 1. Summary of general resilient city frameworks.

Framework	Organization/Author (s)	Country Applied	Latest Publication Year
City Resilience Framework	The Rockefeller Foundation [24]	Multiple Countries	2014
Disaster Resilience of Place (DROP)	Cutter [25]	USA	2008
Baseline Resilience Indicators for Communities (BRIC)	Cutter [26]	Multiple Countries	2014
Resilient City Planning Framework (RCPF)	Jabareen [27]	Multiple Countries	2013
Community Based Resilience Assessment (CoBRA)	United Nations Development Programme [35]	Multiple Countries	2014
EnRiCH Community Resilience Framework	Canadian Centre for Security Science, Defence Research and Development [36]	Canada	2014

Note: The authors only highlighted the more comprehensive frameworks. Do note that there are other resilient frameworks that focuses on specific areas, such as hazards or social aspects. Specific indicators are not listed due to the page limit. The detailed information of each framework can be found in the corresponding reference.

Through the analysis, various countries and organizations have different perceptions of the characteristics of resilience, resulting in a different focus of various frameworks. For example, Jon and Reghezza-Zitt found that Seattle resilience planning encourages neighborhood-driven sub-systems that can enhance social cohesion and information sharing, while Paris' resilience planning is becoming a channel that fosters dialogues across various institutions [37]. Chelleria and Baravikova found that the US (similarly to Asia) prefers a "bouncing back" approach with an emphasis on robustness as a key characteristic of resilience, while both researchers and practitioners across the EU tend to define urban resilience as linked to bouncing forward or a concept integrating bouncing forward and back approaches [38]. A detailed analysis of the selected frameworks helps in identifying the key themes, as shown in Table 2. These themes highlighted what the key city stakeholders perceive to be key city functions that are relevant to enhancing urban resilience.

Most urban resilience frameworks cover a few topics: resilience planning, environment, community, social, disaster risk management, governance and economy. However, in the context of climate change and urbanization development, the importance of energy, water, material and waste, green building and green transportation, and innovation in resilient cities has gradually become prominent. Natural resources, such as energy, water and material resources, are the basis for human production, life and wealth creation [38]. With the advancement of industrialization, urban construction and economic development have an increasing demand for natural resources [39]. The increasing natural disasters and environmental pollution events have put forward higher requirements on the natural resources' carrying capacity of cities [40]. Effective management of resources, ensuring resource security, and improving the ability to deal with environmental pollution are important requirements of a resilient city [41–43]. Infrastructure is the basis for social development and the improvement of people's quality of life, as well as the basic requirement of resilient cities [44,45]. Energy conservation and emission reduction in buildings and transportation have a profound impact on the sustainable use and development of energy [46,47], which may directly affect urban economic development. Technological innovation enhances the dynamic nature of urban carrying functions, plays an important role in economic growth, improves resource utilization efficiency and renews urban facilities [48], which is also a key means for cities to cope with external disturbances.

Although the resilience framework is a hot area of urban resilience research, the depth needs to be further deepened. The study areas are mainly concentrated in the United States and Europe, and few studies have compared the key elements of attentions for developing resilient cities in Asian cities. Therefore, this paper synthesized the existing multi- and one-dimensional frameworks and added the general overlooked issues of energy, water, material & waste, green building & green transportation, and innovation to form the preliminary elements of attentions for enhancing urban resilience. An interview with the planners and researchers in the field of urban planning was conducted in January 2015 to validate the preliminary indicators by deleting irrelevant indicators or adding missing important indicators. A total of nine categories, which comprise energy, water, material & waste, environmental planning, green building & green transportation, community, economy, governance and innovation, with thirty-five indicators were derived, as shown in Table 3. The relationship between the various indicators is not a simple addition, rather, it is interrelated and mutually supportive.

Table 2. Comparison of themes in resilient city frameworks.

Framework	Themes					
	Resilience Planning	**Environment**	**Climate/Water/Energy Society**	**Disaster Risk Management**	**Governance**	**Economy**
City Resilience Framework	♦	♦	♦		♦	♦
Disaster Resilience of Place (DROP)	♦	♦	♦	♦	♦	♦
Baseline Resilience Indicators for Communities (BRIC)		♦	♦		♦	♦
Resilient City Planning Framework (RCPF)	♦	♦	♦	♦	♦	
CoBRA	♦	♦	♦	♦	♦	

Source: The themes are collated from the respective frameworks themselves. Specific indicators can be found in the corresponding reference listed in Table 1.

Table 3. The preliminary elements of attentions for enhancing urban resilience.

Category	No.	Element	References
Energy	EN1	Energy Efficiency for Infrastructure & Public Amenities	[49]
	EN2	On-site Energy Generation	[50]
	EN3	Energy Management Plan & System	[41]
	EN4	Site Planning & Building Orientation	[51]
Water	WA1	Water Strategy	[39]
	WA2	Stormwater Management	[42]
	WA3	Alternative Water Source	[52]
	WA4	Water Efficient Landscape	[42]
	WA5	Water Efficient Fittings for Infrastructure & Public Amenities	[53]
Material & waste	MW1	Waste Management and Segregation	[40]
	MW2	Resource Management	[43]
	MW3	Low Impact Materials and Sustainable Products for Infrastructure & Public Amenities	[43]
	MW4	Sustainable Construction for Infrastructure & Public Amenities	[54]

Table 3. *Cont.*

Category	No.	Element	References
Environmental planning	EP1	Flood Risk Assessment & Management	[55]
	EP2	Adapting to Climate Change	[1]
	EP3	Noise Pollution	[56]
	EP4	Site Selection	[51]
	EP5	Environmental Management System	[40]
	EP6	Self-sufficiency & Accessibility Within District	[57]
	EP7	Conservation & Integration of Existing Structure	[58]
	EP8	Green & Blue Spaces Within District	[59]
	EP9	Future Provision & Connections	[60]
	EP10	Land Use	[61,62]
Green building & green transportation	GBT1	Green Buildings Within District	[44]
	GBT2	Green Urban Design Guidelines	[45]
	GBT3	Green Transport Within District	[46]
	GBT4	Public Transport Facilities	[47]
Community	CO1	Stakeholder Engagement, Feedback & Evaluation	[63]
	CO2	Public Awareness & Education	[64]
	CO3	Green Lease	[65]
	CO4	Inclusive Design	[45]
Economy	EC1	Economic Impact	[50]
Governance	GO1	Community Management of Facilities	[66]
	GO2	Design Review	[67]
Innovation	I1	Green Features & Innovations	[48]

3. Research Method

3.1. Study Area

This paper uses three typical Asian cities as study areas: Singapore, Hong Kong and Hangzhou. Table 4 shows a general comparison of the three cities.

Table 4. A general comparison of the three Asian cities.

Study Area	Area (sq km)	Total Population	Population Density (Per sq km)	Regional GDP (Trillion US$)	Characteristic
Singapore	724.4	5,685,800	7848.98	0.34	Coastal city, developed city, high population density, shortage of resources
Hong Kong	1106.66	7,481,800	6844.20	0.35	Coastal city, high population density, high economic level
Hangzhou	16,850	11,936,000	708.37	0.23	Coastal city, urbanization, digitalization, historical city

Source: The corresponding government's public information in 2020.

Singapore is an island city in Southeast Asia, and its urban construction has always been hailed as a role model. As an urban developed country with a land area of only 724.4 km^2, a population of 5.68 million and a regional GDP of USD 0.34 trillion (2020 data), three urgent challenges to Singapore's national governance were observed: labor shortage, insufficient water supply and lack of land area. Statistics in 2017 show that the population density of Singapore is the second highest in the world [68]. At the same time, the problem of population aging and declining fertility rates is becoming worse, and the labor force gap is expanding, which is affecting the development of the country's overall economy. Moreover, population growth directly leads to insufficient land area and doubts about water supply [69]. Therefore, the Singaporean government plans to increase the land area by expanding land reclamation. In addition, the newly reclaimed land will also help in collecting and storing rainwater, alleviating the shortage of water resources in Singapore. In terms of systems and planning, The Singapore Sustainable Blueprint 2015 aims to extend the 2030 targets laid out by the first blueprint. In 2019, the Urban Redevelopment Authority (URA) of Singapore released the "Singapore Master Plan (2019)", which takes building a sustainable and resilient city as one of the directions for urban development. In conjunction with relevant documents issued by other departments, Singapore has formed a spatial planning system guided by the concept of resilience.

Hong Kong, which is located on the southeast coast of China, is one of the world's leading financial centers. Hong Kong has a small spatial scale (1106.66 km^2 in area) and dense population distribution (6844 people/km^2) [70]. Against the backdrop of climate change and rising sea levels, Hong Kong's sustainable development faces greater challenges. First, Hong Kong was recognized as the city with the highest risk of natural disasters (e.g., tropical cyclones) in Asia in the inaugural Sustainable Cities Index [71], while the average annual loss of multiple disasters in Hong Kong is around USD 1138.64 million. Second, Hong Kong faces water security challenges, including floods [72] and severe water shortages [73]. Over-consumption has become a prominent problem in Hong Kong. Hong Kong has one of the highest daily consumption of drinking water per capita in the world [73]. Third, population growth, economic development and shortage of land supply have made housing a major challenge that affects the resilience of Hong Kong [74]. With the accelerated aging of the population, the elderly living alone has also become a topic that needs attention [75]. Therefore, the government has formulated a series of policies and initiatives to promote the resilience of Hong Kong actively. In 2019, the Hong Kong Planning Department released "Hong Kong 2030+", which focuses on reconciling the contradiction between high-density environment and future urban upgrading. The vision is to make Hong Kong a livable, competitive, and sustainable city. The Environment Bureau has published various plans, which include "Energy Saving Plan for Hong Kong's Built Environment 2015–2025+" and "Hong Kong Blueprint for Sustainable Use of Resources 2013–2022".

Hangzhou is the capital city of Zhejiang Province, located in the Yangtze River Delta region. By 2020, the total area of Hangzhou was 16,850 km^2 with a resident population of 11.936 million in 2020, and the city's GDP is 1.61 trillion RMB, accounting for 24.87% of Zhejiang province's GDP, and the urbanization rate had reached 83.29% [76]. As a typical coastal city in eastern China, Hangzhou has a complex and diverse terrain and a subtropical monsoon climate. In the context of global climate change, Hangzhou's rapid urbanization is dominated by population growth, industrialization and land use, thus bringing a series of economic, environmental and social security issues, such as land use restructuring [77], underground space development [78], heat island [79], flood disasters [80], air pollution [81], and affordable housing provision [82]. These problems have seriously affected the resilience of the city and are unconducive to the sustainable development of the city. Moreover, as a city with a long history, Hangzhou needs to balance the relationship between economic development and the protection of historical legacies in the process of urban construction [83]. In order to achieve high-quality development, in 2020, Hangzhou issued the "Proposal of the Hangzhou on Formulating the Fourteenth Five-Year Plan for National Economic and Social Development and the Long-term Goals for 2035", thus emphasizing the importance of enhancing urban resilience. As the birthplace of the City Brain and the leader of the digital economy, Hangzhou devotes itself to digitalization reform. In 2021, Hangzhou formulated the "14th Five-Year Plan for Comprehensive Disaster Prevention and Mitigation in Hangzhou", which aims to build Hangzhou into a demonstration city for integrated intelligence and safe development and to improve the city's disaster monitoring and early warning, risk prevention, public services and emergency response ability.

Thus, investigating the key elements of attentions for enhancing urban resilience in Singapore, Hong Kong and Hangzhou can provide general lessons for risk governance, disaster and emergency management, and urban sustainable development under climate change in Asian cities. Three reasons exist for selecting these three cities as study areas. First, the three cities are developed cities, and their flow of people, materials, capital, technology and information is highly concentrated, but they all face uncertainties and challenges brought by issues related to climate change, urbanization and globalization. Second, although Singapore, Hong Kong and Hangzhou all attached great importance to the construction of resilient cities, due to their unique geographical locations, urbanization development stages and governance strategies, cities need to focus on various priorities in the process of resilience development. For example, in high-density cities such as Hong Kong and Singapore, the number of residents in one building may be equal to several administrative units in low-density cities [84]. Singapore is an independently developed city-state, while Hong Kong and Hangzhou are administrative regions in China. The differences in institutions may lead to differences in urban governance capabilities. Therefore, each situation requires a different approach and ability to deal with emergencies. Third, the three cities not only represent the most cutting-edge urban development models in Asia, but they also have different priorities in the process of building resilient cities due to various cultural and developmental environments. Hong Kong is an example of the localization of international urban planning due to its historical and geographical relationship. Singapore is the epitome of Asia's creative frontier city. Hangzhou is a representative city of the Chinese mainland's digitalization and urbanization. Therefore, the comparison of the resilience of these three cities can provide a meaningful reference for the construction of resilient cities.

3.2. Research Process

In order to realize the research objective, this study took a series of research steps. The first is to conduct a questionnaire survey (Appendix A) to collect data to assess the significance level of the preliminary elements of attentions for enhancing urban resilience in Singapore, Hong Kong and Hangzhou, respectively. The second is to conduct statistical analysis to identify the key elements of attentions for enhancing urban resilience in the three cities. The third is to compare and discuss the similarities and differences in key elements of attentions for enhancing urban resilience in the three cities. The specific research process is introduced as follows.

Based on the preliminary elements of attentions for enhancing urban resilience identified from the literature review, which is summarized in Section 2, this study made a questionnaire to collect data assessing the significance level of the preliminary elements. The questionnaire had three parts: a brief introduction to the survey, background information of the interviewees and an invitation to assess the significance level of the preliminary elements. The significance level was assessed between 1 and 5, with 1 having the least significance and 5 with the highest significance. The same questionnaire was used in the survey of the three cities. The English version was used in Singapore and Hong Kong, while the Chinese version was used in Hangzhou in consideration of the dominant language in the three cities. Efforts have been spent to minimize information losses during the translation. The target respondents of the questionnaire survey were planners and researchers in the field of urban planning because professional knowledge is required in the survey. A random survey was used by sending an email to or interviewing the planners and researchers on the contact list of the authors. Owing to the limited access to the professional group, a snowball technique was used to increase the response rate by requesting the respondents to send the questionnaire survey to their friends or colleagues qualified to fill the survey [60]. The survey was stopped when no new information can be obtained through snowball techniques.

The questionnaire survey in Singapore was conducted from January to April 2015. Sixty questionnaires were sent to potential respondents through a webpage link in an email. A total of 34 effective responses were received for a response rate of 56.67%. The questionnaire survey in Hong Kong was conducted between January and March 2016. Eighty questionnaires were sent to potential respondents via a webpage link in an email or conducted by interview. A total of 32 effective responses were received for a response rate of 40.00%. The questionnaire survey in Hangzhou was conducted between March and May 2016. A total of 106 questionnaires were sent to potential respondents through a webpage link in an email or conducted by interview. A total of 41 effective responses were received for a response rate of 38.68%. The statistics of the background information of the respondents in the three cities are shown in Table 5. To validate the findings, a follow-up round of interviews was also conducted in August and September 2020.

Table 5. Statistics of background information of the respondents in Singapore, Hong Kong and Hangzhou.

		Singapore (*n* = 34)	**Hong Kong (*n* = 33)**	**Hangzhou (*n* = 41)**
Year of work experiences	Mean value	4.5	3.7	4.1
Type of institution	Governmental departments (%)	32.35	15.15	19.51
	Research institutions (%)		45.45	31.71
	Industry (%)	67.65	39.40	48.78

The average significance level of the preliminary elements of attentions for enhancing urban resilience in Singapore, Hong Kong and Hangzhou was calculated using the effective questionnaires collected. Statistics of mean and standard derivation were performed. The indicator with an average significance value above 4 was identified as a key element of attentions for enhancing urban resilience in corresponding cities. These key elements were further compared to find the similarities and differences in the three cities. Section 4 presents the specific results of this study.

4. Results

Results can be found in Table 6, which shows 14 elements whose average significance level is above 4 for Singapore, 13 elements for Hong Kong, and 14 elements for Hangzhou. For Singapore, the EP3 (*Noise Pollution*) is ranked as the lowest significance, while that for Hong Kong is EP1 (*Flood Risk Assessment & Management*) and for Hangzhou, it is EN2 (*On-site Energy Generation*).

Figure 1 demonstrates the differences in the significance level of each category for elements of attentions for enhancing urban resilience. *Innovation* is the highest priority for Singapore and Hangzhou, while *Material & Waste* is the highest priority for Hong Kong. This difference is echoed by socio-economic conditions. Singapore and Hangzhou placed a much higher priority on innovations for urban development and management through their various governmental policies. Hangzhou is recently considered as a digital city, which takes innovative technologies, e.g., cloud computing and artificial intelligence, to advance urban governance and solve the serious problems of traffic jams. On the other side, Hong Kong is facing increasing problems related to the limited land for waste landfills; therefore, relevant elements in the *Material & Waste* category are prioritized. In addition, Singapore takes the highest priority in the categories of *Green Building & Green Transportation*, *Community* and *Innovation* among the three cities. Hong Kong takes the leading role in the categories of *Energy*, *Water*, *Material & Waste*, *Environmental Planning* and *Economy* among the three cities. Hangzhou takes the leading role only in the category of *Governance* among the three cities.

Figure 2 demonstrates the significance level of each element of attentions for enhancing urban resilience in the three cities. This research defines the elements with an average significantly higher than 4 as key elements of attentions for enhancing urban resilience in the case city. Among the 14 significant elements for Singapore, WA1 (*Water Strategy*), MW2 (*Resource Management*), GBT4 (*Public Transport Facilities*), and CO1 (*Stakeholder Engagement, Feedback, & Evaluation*) are the elements of the three highest significance. MW1 (*Waste Management and Segregation*), EP10 (*Land Use*) and GBT3 (*Green Transport within District*) are the elements ranked with the three lowest significance. Among the 13 significant elements for Hong Kong, MW2 (*Resource Management*), MW1 (*Waste Management and Segregation*), and CO2 (*Public Awareness & Education*) are the elements of the three highest significance. MW4 (*Sustainable Construction for Infrastructure & Public Amenities*), GBT2 (*Green Urban Design Guidelines*), and I1 (*Green Features & Innovations*) are the elements ranked with the three lowest significance. Among the 14 significant elements for Hangzhou, EP2 (*Adapting to Climate Change*), WA1 (*Water Strategy*) and EN3 (*Energy Management Plan & System*) are the elements with the three highest levels of significance. EP7 (*Conservation & Integration of Existing Structure*), EP10 (*Land Use*), WA5 (*Water Efficient Fittings for Infrastructure & Public Amenities*), EP8 (*Green & Blue Spaces within District*) and GBT2 (*Green Urban Design Guidelines*) are the elements with the two lowest levels of significance.

Table 6. The average significance level of preliminary indicators in Singapore, Hong Kong and Hangzhou.

Element	Singapore (n = 34)		Hong Kong (n = 33)		Hangzhou (n = 41)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Energy Efficiency for Infrastructure & Public Amenities	**4.18**	0.67	**4.21**	0.65	**4.07**	0.69
On-site Energy Generation	3.71	0.76	3.48	1.25	3.27	0.92
Energy Management Plan & System	3.50	0.66	**4.06**	0.66	**4.10**	0.77
Site Planning & Building Orientation	3.18	0.97	**4.09**	0.72	3.80	0.71
Water Strategy	**4.32**	0.81	**4.09**	0.72	**4.12**	0.84
Stormwater Management	3.47	0.61	3.64	1.03	3.56	0.81
Alternative Water Source	3.06	0.69	3.64	1.08	3.56	0.95
Water Efficient Landscape	3.38	0.55	3.82	0.77	3.66	0.66
Water Efficient Fittings for Infrastructure & Public Amenities	3.74	0.71	3.94	0.83	**4.02**	0.79
Waste Management and Segregation	**4.00**	0.74	**4.30**	0.73	3.95	0.74
Resource Management	**4.24**	0.65	**4.39**	0.66	**4.07**	0.69
Low Impact Materials and Sustainable Products for Infrastructure & Public Amenities	3.53	0.56	3.94	0.9	3.54	0.81
Sustainable Construction for Infrastructure & Public Amenities	**4.09**	0.45	**4.03**	0.64	3.90	0.7
Flood Risk Assessment & Management	3.59	0.61	3.45	0.87	3.41	0.84
Adapting to Climate Change	**4.06**	0.69	**4.09**	0.91	**4.17**	0.89
Noise Pollution	2.79	0.41	3.91	0.84	3.39	0.97
Site Selection	3.74	0.51	3.76	0.87	3.63	0.8
Environmental Management System	3.91	0.62	**4.06**	0.7	**4.05**	0.59
Self-sufficiency & Accessibility Within District	**4.15**	0.61	3.94	0.79	3.93	0.75
Conservation & Integration of Existing Structure	3.38	0.6	3.67	0.85	**4.00**	0.74
Green & Blue Spaces Within District	**4.18**	0.52	**4.09**	0.58	**4.02**	0.61
Future Provision & Connections	3.74	0.62	3.88	0.7	3.73	0.67
Land Use	**4.00**	0.65	3.91	0.8	**4.00**	0.77
Green Buildings Within District	3.97	0.58	3.88	0.78	3.68	0.76
Green Urban Design Guidelines	3.94	0.65	**4.03**	0.68	**4.02**	0.72
Green Transport Within District	**4.00**	0.7	3.91	0.8	3.78	0.79
Public Transport Facilities	**4.21**	0.48	3.97	0.77	3.88	0.71
Stakeholder Engagement, Feedback & Evaluation	**4.21**	0.73	3.76	0.9	3.85	0.99
Public Awareness & Education	3.85	0.66	**4.24**	0.79	**4.05**	0.8
Green Lease	**4.09**	0.62	3.64	0.82	3.85	0.88
Inclusive Design	3.68	0.77	3.67	0.74	3.73	0.87
Economic Impact	3.12	0.69	3.70	0.92	3.51	0.81
Community Management of Facilities	3.65	0.65	3.91	0.77	3.85	0.73
Design Review	3.74	0.62	3.76	0.83	**4.07**	0.72
Green Features & Innovations	**4.15**	0.74	**4.03**	0.68	**4.05**	0.74

Note: the average value above 4 indicates key elements of attentions of the case city.

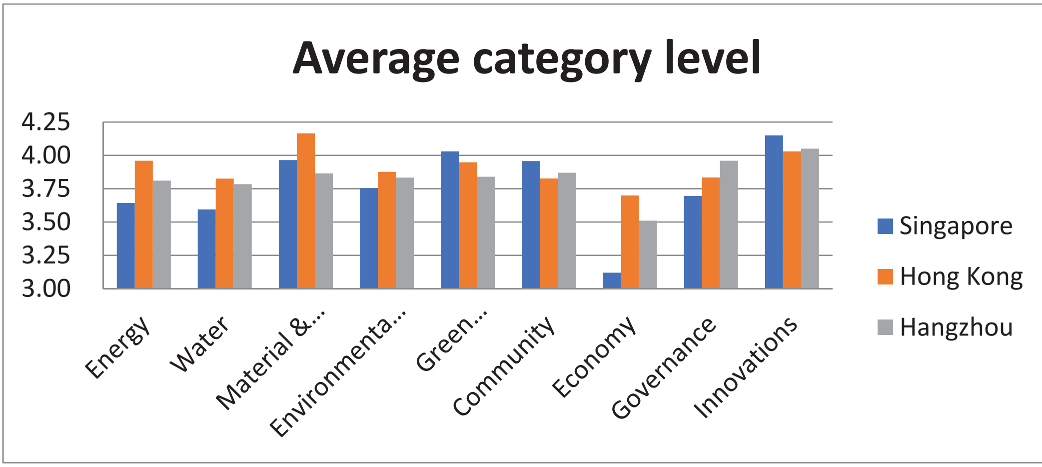

Figure 1. Importance of each category of elements of attentions for enhancing urban resilience in the three cities.

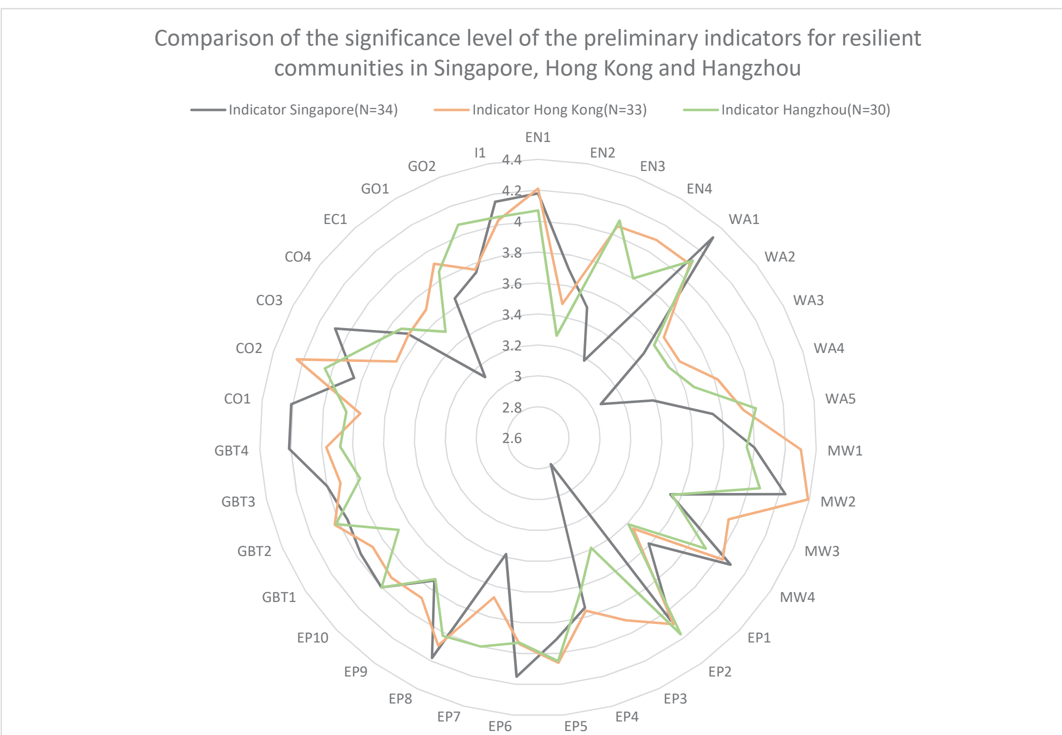

Figure 2. Comparison of the significance level of the preliminary elements of attentions for enhancing urban resilience in Singapore, Hong Kong and Hangzhou.

5. Discussions

The three cities have different key elements of attentions for enhancing urban resilience (see Figure 2). Although the elements EN1 (*Energy Efficiency for Infrastructure & Public Amenities*), WA1 (*Water Strategy*), MW2 (*Resource Management*), EP2 (*Adapting to Climate Change*), EP8 (*Green & Blue Spaces within District*), and I1 (*Green Features & Innovations*) have varying average significance, they are the common elements for all three cities. EN3 (*Energy Management Plan & System*), EP6 (*Self-sufficiency & Accessibility within District*), GBT3 (*Green Transport within District*), GBT4 (*Public Transport Facilities*), CO1 (*Stakeholder Engagement, Feedback, & Evaluation*), and CO3 (*Green Lease*) are the six significant elements emphasized by Singapore. By contrast, EN4 (*Site Planning & Building Orientation*) is the single significant element emphasized by Hong Kong, while WA5 (*Water Efficient Fittings for Infrastructure & Public Amenities*), EP7 (*Conservation & Integration of Existing Structure*), and GO2 (*Design Review*) are the three significant elements that Hangzhou emphasized. The following section will thoroughly discuss the identified key elements of attentions for enhancing urban resilience in the three cities.

In terms of *Energy*, *Energy Efficiency for Infrastructure & Public Amenities* is the common key element in the three cities. Previous studies determined that improving the energy efficiency of infrastructure and public amenities is useful for enhancing the ability of cities to cope with external disturbances, e.g., climate change and supply shortage. Energy efficiency is a huge concern of the three cities, which cannot produce sufficient energy by themselves. For example, Hangzhou proposed to replace existing buses in urban areas with new energy vehicles in the 2020 government work report (A breakdown of key responsibilities in the 2020 government work report). Singapore proposed integrated planning and sound governance to ensure secure, competitive and sustainable energy supply (Energising Singapore: Balancing Liveability and Growth). *Energy Management Plan & System* is the common element for Hong Kong and Hangzhou. An improved energy management plan and systems can bring higher energy efficiency in the building operation and management stage. This result reflects that Hong Kong and Hangzhou still have much room to improve the performance of their energy management plans. Hong Kong also emphasizes *Site Planning & Building Orientation* in the *Energy* category. In a high-density city such as Hong Kong, the site planning and relevant building orientation affect whether natural resources, e.g., wind and light, may be sufficiently utilized, which further affects energy consumption in the construction and operation and management stage. Hong Kong's building practices are regularly updated to fulfill international standards. For example, steel structures in Hong Kong are designed to be resilient to disasters. Therefore, Hong Kong should also pay due attention to optimizing site planning and building orientation to save energy.

With respect to the *Water* category, *Water Strategy* is the common key element in this category among the three cities. Singapore and Hong Kong are troubled by sufficient water for use because of their geographical constraints. Hangzhou is worried about the quality of water and formulates policies to cope with sewage water, flood and urban waterlogging, as well as further ensuring the water supply and saving water. Therefore, *Water Strategy*, or ensuring sufficient quality water, is important for the three cities. A series of measures were adopted to promote the water strategy. For example, Hangzhou implemented projects to ensure sufficient water resources (Hangzhou Disaster Prevention and Mitigation Action Plan). Hong Kong formulated Desalination-A Critical Element of Water Solution for the 21st Century. Singapore proposed to create a robust system to manage the impact of rising sea levels and changing weather with multi-functional water storage projects. Hangzhou also stresses the importance of *Water Efficient Fittings for Infrastructure & Public Amenities*, because its utilization efficiency of water for infrastructure and public amenities is still quite low compared to other cities. Hangzhou proposed to promote the construction of zero-direct sewage discharge areas and speed up the construction of flood control and drainage projects, such as the Bapu Pumping Station (A breakdown of key responsibilities in the 2020 government work report).

With regard to the category of *Material & Waste*, *Resource Management* is the common key element among the three cities. Waste resource management affects the material used and waste generated during the construction stage. All three cities are concerned with improving the management of their resources to achieve more sustainability and resilience. Better waste resource management enhances resourcefulness, redundancy and efficiency of the urban system, which can improve urban resilience. For example, Hong Kong proposed the “Hong Kong Blueprint for Sustainable Use of Resources 2013–2022” and “A Clean Air Plan for Hong Kong”. *Waste Management and Segregation* and *Sustainable Construction for Infrastructure & Public Amenities* are two common key elements for Singapore and Hong Kong. Efficient waste management can reduce the generation or increase the reuse of construction waste, which helps achieve sustainability. The *Sustainable Construction for Infrastructure & Public Amenities* is useful to provide critical support for resilient cities. For example, the Hong Kong government ensures that the infrastructural environment is assessed and made disaster-resilient to a great extent [30]. Singapore proposed a new future city initiative which focused on advanced building methods, resilient infrastructure, new spaces and sustainable cities.

In terms of *Environmental Planning*, *Adapting to Climate Change* and *Green & Blue Spaces within District* are two common key elements in this category among the three cities. Hangzhou, which held the G20 meeting in 2016, actively promoted the “Paris Agreement” as soon as possible, to enhance the priority position of environmental sustainability in the structure and expedite the green financial development. China is promoting the implementation of the 2030 Sustainable Development Agenda program, and Hangzhou actively responds to the policy and strives to move forward. *Environmental Management System* is the common key element for Hong Kong and Hangzhou. This element emphasizes an improved environmental management to achieve sustainability and resilience. *Land Use* is the common key element for Singapore and Hangzhou. Unlike the high-density utilization in Hong Kong, Singapore and Hangzhou still have room to improve their land use, to realize sustainability and resilience. *Self-sufficiency & Accessibility within District* is the distinctive key element for Singapore, a concern that is a natural response to the limited resources within the city. *Conservation & Integration of Existing Structures* is the distinctive key element for Hangzhou, which has many existing structures built throughout its long history. Therefore, the conservation and integration of existing structures are important to realize cultural sustainability and to better utilize existing resources. The conservation measures can further enhance the social cohesion with a common memory, improve social capital and further increase urban resilience.

Concerning the category of *Green Building & Green Transportation*, no common key element is found in the three cities. *Green Urban Design Guidelines* is the common key element for Hong Kong and Hangzhou. This result indicates a current lack of such guidelines. The respective governments should explore such issues and develop appropriate guidelines according to the local conditions. *Green Transport within District* and *Public Transport Facilities* are distinctive key elements for Singapore because of the dispersed distribution of housing in the city and the huge demand for transportation. Singapore made the “Land Transport Master Plan” and promoted a transit-oriented approach to development and planning, which aims to make public transport the preferred mode of transit, through improved connectivity and better services.

In the *Community* category, *Public Awareness & Education* is the common key element for Hong Kong and Hangzhou, thus reflecting the lack of direct guidelines to initiate resilient cities in these cities. Public education should be conducted to promote the public’s awareness of resilient cities. For example, Hangzhou proposed to build a platform for urban safety publicity and education and promote the construction of a multi-functional base integrating urban disaster reduction and prevention, building fire safety, road traffic safety, occupational safety and health, and other real scene experiences, as well as practical operations to avoid disasters (Three-Year Action Plan of Hangzhou City to Create a National Demonstration City for Security Development (2018–2020)). *Stakeholder Engagement*, *Feedback, & Evaluation* and *Green Lease* are distinctive key elements for Singapore. These concerns reflected the awareness of the importance of stakeholder management and the green lease in Singapore.

The element of *Economic Impact* is not identified as a key element of attentions for enhancing urban resilience for the three cities. This meant that the economic issues are not that important compared with other indicators for the interviewees. The alternative interpretation is that the three cities have a sufficient budget to consider more than the economy in promoting resilient cities. In addition, *Design Review* is the distinctive key element in the *Governance* category in Hangzhou, a result indicating the comparatively low design quality and high concern for government departments.

6. Conclusions

6.1. Research Significance

Enhancing urban resilience is critical for cities to withstand the rapidly changing world and potential disasters. This study compares the key elements of attentions for enhancing urban resilience among Singapore, Hong Kong and Hangzhou. The findings demonstrated that the three cities have varying elements of attentions in enhancing urban resilience despite many similarities. Singapore has taken the highest priority in the categories of *Green Building & Green Transportation*, *Community* and *Innovation* among the three cities. Hong Kong has taken the leading role in the categories of *Energy*, *Water*, *Material & Waste*, and *Environmental Planning* among the three cities. Hangzhou has taken the leading role only in the category of *Governance* among the three cities.

The findings demonstrated the similarity and difference between elements of attentions among the three cities, which are deeply rooted in the economic development and governance backgrounds. Therefore, we should be cautious when using a general framework or specific model derived from one case to conduct a comparative analysis of urban resilience. The localization of developing and measuring urban resilience is necessary while learning from international cases. Common key elements of attentions reminded the government to learn from one another to find more useful measures to enhance urban resilience. Due attention should be paid to various elements of attentions generated based on the local conditions of each city. This research also provides a reference for other international comparisons.

6.2. Limitations and Future Study

Several limitations were observed in this paper. First, the findings were derived from data collected in 2015 and 2016. Although the comparison and uncovered reasons are worthwhile, progress has been made in the past five years around the world. Updated analysis and a comparison in the time series can be conducted to further deepen the understanding. In addition, the framework and elements of attentions for enhancing urban resilience should also be updated with socio-economic development and a deepened understanding of urban resilience. For example, COVID-19 provides a chance, and also new requirements, to comprehend urban resilience. Second, the sample size for analyzing the experts' opinions was limited. Therefore, the derived results may be more indicative than representative. It can provide certain references or implications when considering enhancing urban resilience in the case cities. Yet, it should be cautious to generalize the findings, which may not be suitable for this study. Future studies can consider increasing the sample size with support from some official channels when making plans for resilient cities. Third, this study investigated the elements of attentions for enhancing urban resilience with a top-down approach with an expert centric approach in the survey. The views of residents can be indirectly reflected by the planners and governmental officers, who are assumed to include public opinions before making planning or policies. Yet, the bottom-up approach to enhancing urban resilience is also important, which means that the direct views of the residents should be considered in such a condition. Future studies can be conducted to compare the differences in elements of attentions between the top-down and bottom-up approaches. Fourth, the key elements of attentions were identified based on the comprehension of interviewees, which is partially subjective. As more and more cities formulate strategies for enhancing urban resilience, comparisons based on these official documents is an alternative and objective approach to identify the similarities and differences of elements of attentions. Last, the comparison is conducted only among three Asian cities. Future studies can be conducted to compare the key elements of attentions for enhancing urban resilience among cities with significantly different cultural and governance backgrounds. The comparison of large samples of different cities is also beneficial for explaining why different cities pay similar and various attentions when enhancing urban resilience.

Author Contributions: Conceptualization, M.C., Y.L. and Y.Z.; formal analysis, M.C., Y.L., Y.P., T.C. and Y.Z.; investigation, Y.L., Y.P. and T.C.; methodology, M.C. and Y.P.; software, Y.P.; validation, M.C., Y.L. and T.C.; writing—original draft, M.C., Y.L., Y.P. and Y.Z.; writing—review and editing, M.C., Y.L., Y.P. and T.C. All authors have read and agreed to the published version of the manuscript.

Funding: The work described in this paper was jointly supported by the National Natural Science Foundation of China (52078374), the Shanghai Municipal Science and Technology Commission (19DZ1202803), the Urban Emergency Management Research Innovation Team of Zhejiang University of Finance and Economics, and the Innovation Research Team of Urban Governance and Public Policy of Zhejiang Province.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would also thank the students for the efforts placed in collecting and compiling survey data for the initial analysis.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Questionnaire Survey Sample

Dear Sir/Madam,

We are a joint research group to investigate the key elements of attentions for enhancing urban resilience in Singapore, Hong Kong and Hangzhou. The research group promotes the development of resilient cities in facing challenges like climate change. This study aims to find the significant elements of attention that should be paid to in developing such cities. All data would be kept confidential and just used for research. Please answer the following questions according to your work experience.

Thank you again for your kind support.

Best wishes

1 The Joint Research Group of Resilient Cities
   (1) General Information of Respondent
   (2) Company type:
       (A) Governmental departments; (B) Research institutions; (C) Industry
   (3) Years of relevant work experience:
2 Significance level of the preliminary elements of attentions for enhancing urban resilience

Please rate the significance level of the following elements of attentions for enhancing urban resilience between 1 and 5 with 1 as the least significant, while 5 as the most significant.

Category	No.	Element	Meaning	Significance Level
Energy	EN1	Energy Efficiency for Infrastructure & Public Amenities	Energy modeling or calculation to include energy demand and operating carbon emissions for infrastructure and public amenities	
	EN2	On-site Energy Generation	Introduction of on-site generation of energy for self-sufficiency in common areas	
	EN3	Energy Management Plan & System	To design and incorporate energy monitoring and/or control system to facilitate energy consumption monitoring and management for public facilities	
	EN4	Site Planning & Building Orientation	To minimize heat gain/loss by use of passive solar strategies to reduce the energy demand	
Water	WA1	Water Strategy	To develop water management plan to minimize water demand through efficiency and appropriate supply-side options	
	WA2	Stormwater Management	Introduction of treatment of stormwater run-off before discharge to public drains and to reduce frequency of flooding in community	
	WA3	Alternative Water Source	To introduce possible alternative water sources for non-potable usage to reduce use of potable water	
	WA4	Water Efficient Landscape	To reduce water demand by introducing drought resistant plants in landscape design	
	WA5	Water Efficient Fittings for Infrastructure & Public Amenities	Introduction of use of water efficient fittings	
Material & waste	MW1	Waste Management and Segregation	To increase recycling and have proper disposal of waste and provide waste management infrastructures	
	MW2	Resource Management	To promote resource efficiency by reducing waste during construction and throughout lifecycle of development	
	MW3	Low Impact Materials and Sustainable Products for Infrastructure & Public Amenities	To encourage use of environmentally friendly products	
	MW4	Sustainable Construction for Infrastructure & Public Amenities	To encourage recycling and adoption of designs, practices and materials that are environmentally friendly and sustainable in the construction of infrastructure and public amenities	

Category	No.	Element	Meaning	Significance Level
Environmental planning	EP1	Flood Risk Assessment & Management	To demonstrate that development is appropriately flood resilient and resistant	
	EP2	Adapting to Climate Change	Climate change adaptation plans made in accordance to current best practice and planning policy	
	EP3	Noise Pollution	To mitigate impacts of noise, which includes mitigation of existing sources of noise, reducing potential noise from future sources, and protecting potential noise-sensitive areas	
	EP4	Site Selection	To avoid use of greenfield sites and take proper remediation measures carried out on contaminated land to restore land for use	
	EP5	Environmental Management System	To introduce planning, design and management integration to adopt an environmentally friendly management system and practices during development	
	EP6	Self-sufficiency & Accessibility Within District	To ensure sufficient range of facilities provided in the community to meet the needs and to increase accessibility to key facilities for all the people	
	EP7	Conservation & Integration of Existing Structure	Conservation, preservation or restoration of historic remains, buildings, or natural spaces or views	
	EP8	Green & Blue Spaces Within District	To provide adequate green and blue spaces for the city	
	EP9	Future Provision & Connections	To encourage plans for future adaptability and flexibility of urban development	
	EP10	Land Use	To maintain sufficient land for use and improve ecological biodiversity	
Green building & green transportation	GBT1	Green Buildings Within District	To introduce adoption of green building practices in building design, construction and retrofitting	
	GBT2	Green Urban Design Guidelines	To ensure key green features are carried out throughout all levels of urban development	
	GBT3	Green Transport Within District	To introduce green transportation in the city	
	GBT4	Public Transport Facilities	To conduct traffic modeling for the city to assess and make improvement to existing transportation facilities	
	CO1	Stakeholder Engagement, Feedback & Evaluation	To conduct residents' feedback survey or engage in public consultation exercise to gather feedback to enhance quality of living environment in common areas	

Category	No.	Element	Meaning	Significance Level
Community	CO2	Public Awareness & Education	To introduce sustainable lifestyle and integration within the community through outreach of education program to increase public awareness on urban resilience	
	CO3	Green Lease	To encourage green lease as an alternative to regular economic rental models	
	CO4	Inclusive Design	To ensure inclusive urban design by encouraging construction of built environment that optimizes accessibility for all residents	
Economy	EC1	Economic Impact	To ensure community contributes to local area by enhancing, diversifying or adding employment opportunities and/or skills training	
Governance	GO1	Community Management of Facilities	To support communities in active involvement in developing, managing and/or owning selected facilities	
	GO2	Design Review	To ensure masterplan's design supports a vibrant, healthy and functional and inclusive city	
Innovation	I1	Green Features & Innovations	To support any innovation within design, planning and construction of the city through recognition of sustainability and resilience related benefits	

3 Please add any elements of attentions and their significance level that you think is important for enhancing urban resilience.

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Commentary

Thinking Critically through Key Issues in Improving the Effectiveness of Waterlogging Prevention and Control System in China's Historic Districts

Shuai Si [1,2], Junqi Li [1,2,*], Yuzhen Wang [3] and Lian Liu [4]

1 Key Laboratory of Urban Stormwater System and Water Environment, Ministry of Education, Beijing University of Civil Engineering and Architecture, Beijing 100044, China; sishuai@bucea.edu.cn
2 Beijing Energy Conservation & Sustainable Urban and Rural Development Provincial and Ministry Co-Construction Collaboration Innovation Center, Beijing 100044, China
3 No.1 Sewer Maintenance Branch Company of Beijing Drainage Group, Beijing 100034, China; wyz@bdc.cn
4 Beijing Waterworks Group Co., Ltd., Beijing 100031, China; linger-ll@foxmail.com
* Correspondence: lijunqi@bucea.edu.cn

Abstract: Solving the problem of waterlogging is of great significance to the protection of historic districts and urban renewal. To solve the problem of waterlogging, it is necessary to comprehensively consider technical aspects such as the "Major-Minor-Micro" drainage system and the connection of urban/watershed flood control systems. At the same time, attention should be paid to the role of management in the entire system. However, there are a series of problems in the current waterlogging prevention and control system in China's historic districts. The effectiveness improvement plan of the waterlogging prevention and control system is not sufficiently targeted. The various subsystems in the waterlogging prevention and control system play a role in poor coordination. The waterlogging prevention and control system does not work closely with the flood control system. Different management departments have weak coordination in the prevention and control of waterlogging. Aiming at the problems in the waterlogging prevention and control system in historic districts, this paper proposed a series of countermeasures. The waterlogging prevention and control system in historic districts should make full use of the current advanced concepts and practical experience of stormwater management. In order to enhance the role of the waterlogging prevention and control system in historic districts, specific issues should be analyzed in detail. The waterlogging prevention and control system in historic districts needs to be divided into different levels. The waterlogging prevention and control system should be aligned with historic attributes and be highly pertinent. The waterlogging prevention and control system should be closely coordinated with the larger-scale flood control system. At the same time, the intelligent management platform should be used to increase the supervision of the whole process of waterlogging in historic districts.

Keywords: historic districts; waterlogging prevention and control system; urban renewal; rainwater management

Citation: Si, S.; Li, J.; Wang, Y.; Liu, L. Thinking Critically through Key Issues in Improving the Effectiveness of Waterlogging Prevention and Control System in China's Historic Districts. *Sustainability* **2022**, *14*, 2913. https://doi.org/10.3390/su14052913

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 9 January 2022
Accepted: 28 February 2022
Published: 2 March 2022

1. Introduction

The waterlogging prevention and control system is an important part of historic districts and plays an important role in historic districts and architectural heritage protection, urban renewal, environmental improvement, and improvement of residents' quality of life. Chinese scholars have carried out some research on the waterlogging prevention and control system in historic districts. The Beijing Municipal Planning Commission carried out systematic research on the municipal planning technology of 25 historic and cultural preservation areas such as Beijing Nanchizi, and proposed plans and construction methods for the planning and transformation of municipal facilities such as water supply, heating, gas, and drainage under special conditions in the historic districts [1]. Che W. systematically sorted out the main storm flood issues involved in the protection of Beijing's old city, analyzed the role and significance of storm flood control in the protection of the old city, and proposed that the modern urban storm flood control and utilization concept and technical system should be integrated into the old city protection [2]. Liu Y. analyzed the causes of waterlogging in the central city of Beijing, and proposed that the control and utilization of rainwater sources should be strengthened and the construction of urban flood storage and detention areas should be strengthened to strengthen urban flood control and comprehensive utilization of rainwater [3]. Based on the dual characteristics of both protection and development needs in historic districts, Li X. proposed technical principles and specific measures for the comprehensive planning of directly-buried municipal pipelines adapted to narrow streets in historic districts, and studied planning, design, and construction methods [4]. Li J. analyzed the problems, difficulties, ideas, and technical approaches in the construction of sponge cities in built-up areas, and proposed reasonable selection of infiltration, retention, and storage-related facilities, and a combination of decentralized and concentrated measures to solve the rainwater problem [5,6].

At present, there is some research on the occurrence mechanism of urban waterlogging prevention and control, process simulation, response management, and system construction [7]. However, the problem of urban waterlogging has not been solved well, and the problem of road water accumulation and waterlogging still exists, especially in historic districts, where the problem of waterlogging is more prominent [8]. The current research on the drainage system of historic districts has not systematically analyzed the internal connections and key issues between the various links and systems involved in waterlogging. In this paper, we analyzed the key problems of waterlogging in historic districts, examined the status quo of drainage systems in historic districts, and proposed specific countermeasures to improve the efficiency of waterlogging prevention and control systems in the context of protection and renewal of historic districts from the perspective of system efficiency improvement.

2. Dimension of Waterlogging Prevention and Control System

System effectiveness emphasizes system thinking, and needs to coordinate closely with all units, departments, links, and subsystems to achieve certain goals in coordination. In order to improve the waterlogging prevention and control system in historic districts, we must focus on the technical and management dimensions. Regarding the technical dimension, the waterlogging prevention and control system in the historic districts involves a "Major-Minor-Micro" drainage system, a combined overflow system, and also needs to be connected to the urban/watershed flood control system. Regarding the management dimension, the waterlogging prevention and control system in the historic districts covers multiple departments, professions, and links.

2.1. Technical Dimension of Waterlogging Prevention and Control System in Historic Districts

The waterlogging prevention and control system is a systematic project covering the whole process of rainwater production/convergence, regulation and storage, utilization, and discharge, including three subsystems: source control system (Micro-drainage system), minor drainage system, and major drainage system [9]. Three subsystems correspond to intercepting different rainfall events: the micro drainage system controls the rainfall event up to 6 months, the micro drainage system controls the peak runoff for 2 to 5 years, and the major drainage system controls the peak runoff for 10 to 100 years [10]. For historic districts, the micro-drainage system mainly corresponds to the permeable ground and courtyard green space in the courtyard, the minor-drainage system mainly refers to the gray infrastructure such as pipes and ditches in the street, and the major-drainage system mainly corresponds to the river and lake system in the larger area, road discharge channels/undesigned channels, and urban rainwater multifunctional storage space [11–13]. The flow direction of drainage in historic districts and the response relationship between the "Major-Minor-Micro" subsystems are shown in Figure 1.

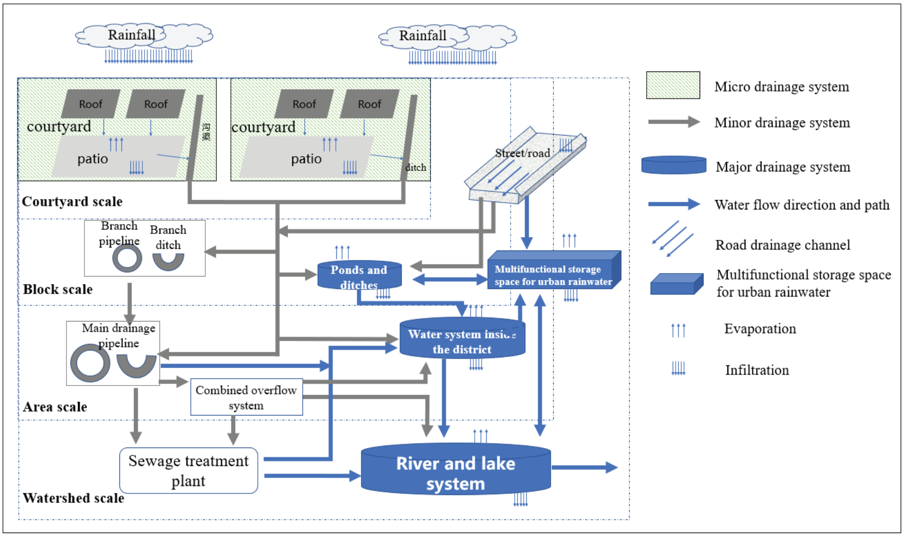

Figure 1. A schematic diagram of the "major-minor-micro" waterlogging prevention and control system in historic districts.

The waterlogging prevention and control system also needs to cooperate with the flood control system. People are accustomed to living in the location of water sources, so historic districts are often adjacent to rivers and lakes, and the increase in rainfall in the rainy season is prone to flooding. Therefore, to improve the drainage efficiency of historic sites, attention should also be paid to larger-scale flood control systems. China's design codes require that the comprehensive flood control and disaster mitigation capabilities of the central urban area meet the flood control standards of super-large cities that occur once in 100–200 years. The recurrence period of waterlogging prevention and control in megacities is once in 50 to 100 years. The waterlogging prevention and control system and the flood control system are closely linked and jointly affect the water environment and water safety of the city.

2.2. Management Dimension of Waterlogging Prevention and Control System in Historic Districts

The prevention and control of waterlogging in historic districts is a systematic project, which cannot be completely solved only from the engineering and technical aspects. From the perspective of government management departments, it involves cultural relic protection, planning, urban construction, environmental protection, urban management, development and reform, gardening, and emergency management. From the perspective of the disciplines covered, architectural heritage protection, architecture, planning, municipal administration, roads, and environment are all closely related. From the perspective of involving intermediate processes, it is inseparable from the links of surveying and mapping, design, planning, construction, supervision, and operation and maintenance. The solution to the waterlogging problem is inseparable from efficient management. The smooth implementation of project construction, the close integration of various industry norms and standards, and even the effective play of the role of individual structures require the cooperation of multiple departments and multiple disciplines. Scientific technical means can theoretically solve the problem of waterlogging, but the ultimate solution is inseparable from effective management [14]. The solution to the prevention and control of waterlogging is a comprehensive manifestation of the level of urban management, and it is a comprehensive indicator that highlights the level of social governance and the quality of the social environment.

3. Problems in the Improvement of the Effectiveness of the Waterlogging Prevention and Control System in Historic Districts

At present, with the development of China's economy and society, the problem of waterlogging in historic districts is more prominent. In terms of water cycle, the greening rate in historic districts is generally low, the impervious surface area is large, and the natural circulation path of water is destroyed. In terms of facilities, the pipeline network/pipeline facilities are outdated, the standard is low, the renovation space is limited, and the update and maintenance are not in place [15]. In terms of the water system, the historic water system in the urban area disappeared, and the rivers and lakes were artificially separated, which caused the water discharge path to be unsmooth. In terms of management, various departments or intermediate processes are divided and cannot be well integrated. At present, some studies have carried out many program studies on some specific issues or specific projects, but these studies or programs do not consider the special attributes of historic districts protection and the core elements of improving the effectiveness of the waterlogging prevention and control system. There are generally a series of problems. They are manifested in the following four aspects.

3.1. Lack of Pertinence in Planning and Design

For historic districts, whether it is the selection of municipal pipelines or road layouts, planning, design, and construction have been carried out in accordance with general urban construction standards for many years, and there is a lack of special policies that coordinate with the protection goals of historic districts [16]. In recent years, this situation has improved, but the problem is still unresolved. Regarding the protection and renewal of historic districts and the prevention and control of waterlogging, China has successively issued a number of measures and standards for the central and local governments. For example, the "Urban Purple Line Management Measures" promulgated by the Ministry of Housing and Urban-Rural Development of China require that historic and cultural districts be renovated and updated, and the improvement and construction of infrastructure and public facilities should be strengthened on the premise of improving the living environment [17]. Beijing local standard "Sponge City Construction Design Standards" requires that historic and cultural districts should not be set up with runoff rainwater control indicators, should be based on the premise of protecting cultural relics and historic features, and should mainly solve the problems of local water accumulation, misconnection of pipelines, and runoff pollution [18]. On the whole, for the infrastructure construction and waterlogging problems of historic districts, the relevant regulations or standards only provide a guiding opinion, and there are no clear regulations on how to implement it. This leads to different understandings of different professionals. Judging from the current overall research, the relevant norms or standards only put forward a guiding opinion for the infrastructure construction and waterlogging problems of China's historic districts.

In the practice of improving the efficiency of the drainage system in historic districts, a "one size fits all" situation is likely to occur due to the lack of targeted methods and measures. On the one hand, the protection and renewal only pursue the protection of the style and features of the historic districts, the drainage system is not renewed in place, and the problem of waterlogging and stagnant water cannot be effectively solved. On the other hand, with the improvement of China's economic level, drainage standards have also been continuously improved. The development process of rainfall frequency based on the design of rainwater pipes reflects the continuous improvement of the design standards of urban drainage systems in China, as shown in Table 1. At the same time, some cities, especially the old urban areas and even historic districts, hope to solve the problem of waterlogging and accumulation of water by continuously improving the design standards of the pipe network and increasing the diameter of the drainage pipe network, which often increase investment [19]. At the same time, this approach has brought some damage to the historic districts and affected the normal lives of residents, but the waterlogging problem has not been effectively alleviated.

Table 1. Evolution and Development Process of Design Rainfall Frequency of Drainage Pipes and Canals in China.

Year	Related Design Codes and Standards	Specific Requirements
1953–1957	Urban planning adopts the Soviet model	Mainly rely on the design and construction experience of the designer, 0.33–1 year
1963	Code for design of urban wastewater engineering (JG11-63)	Calculate the amount of rainwater with the design overflow period, and then design the rainwater pipeline according to the settlement result [20], 0.33–1 year
1974	Code for design of outdoor wastewater engineering (TJ14-74)	0.33–2 years
1987	Code for design of outdoor wastewater engineering (TJ14-87)	0.5–3 years
2006	Code for design of outdoor wastewater engineering (GB50014-2006) [1]	general areas: 0.5–3 years; important areas: 3–5 years
2011		Cancel the lower limit of 0.5 years; general areas: 1–3 years; Important area: 3–5 years
2014		Small and medium cities: 2–3 years; large cities: 2–5 years
2016		Same as the regulations in 2014, while the standard regulations should adopt the upper limit

[1] The standards were revised in 2006, 2011, 2014, and 2016.

3.2. The Sub-Systems of the Waterlogging Prevention and Control System Are Not Closely Coordinated

Due to the historic nature and special protection of historic districts, some studies often hope to solve the problem of waterlogging at one time through gray facilities [21,22]. Some specific projects and research results focus on contemporary advanced stormwater management concepts, and one-sided pursuit of low-impact development and other source control facilities to completely solve the problem of waterlogging. These views and practices have caused the “Major-Minor-Micro” drainage system to be artificially split, resulting in insufficient integrity and systemicity of the drainage project, and various subsystems cannot be integrated to play a synergistic effect.

Historic districts are subject to relevant restrictions such as architectural heritage protection, and the development and renovation space is very limited, but the drainage system can play a synergistic effect with surrounding districts. However, in the current protection and renewal of historic districts, the protection and renewal work are often carried out on the local area of the districts. Various facilities and structures cannot be integrated and function well. In addition, there are regulation and storage facilities distributed in different places that cannot perform as needed. If it is purely for the protection of architectural heritage, it is feasible to only consider the waterlogging prevention and control system in the historic districts, but the drainage system is a systematic project and does not exist in isolation, and the surrounding neighborhoods must be considered. In particular, the overall role of the drainage system of historic districts under the same drainage districts or catchment districts should be considered.

3.3. The Waterlogging Prevention and Control System Does Not Closely Cooperate with the Flood Control System

Waterlogging is mainly to control the whole process of rainfall production and confluence at the urban scale, while flood control is managed on a larger scale of the river basin [23]. In China, the planning and implementation of the waterlogging prevention and control system and the flood control system belong to different management departments. In general, waterlogging is mostly local power and managed by the local government, while flood control is mostly the central power, which belongs to the Ministry of Water Resources. Due to the difference in understanding and the different subject backgrounds involved, in the actual management and operation process, the relevant personnel often consider the problem from the perspective of their own understanding, and there are differences in the selection of facilities and calculation methods [24]. All of the above have led to poor coordination between the role of the city's river flood control system and the waterlogging prevention and control system [25]. Coupled with the factors of architectural heritage protection, the waterlogging prevention and control system is not smoothly connected with the flood control system and with the architectural heritage protection system.

In fact, internal waterlogging and external floods are closely related, and the two are internal and external causes of each other. The causes of internal waterlogging and external floods are different. Waterlogging is due to excessive rainwater that cannot be discharged in time, especially in historic districts, which generally have a high degree of development and insufficient capacity to absorb runoff and rainwater. In addition, inadequate standards for infrastructure such as pipe networks, low-lying terrain, and heavy rainfall have made the waterlogging problem more prominent. Floods are caused by the rapid rise of rivers, lakes, and reservoirs caused by precipitation and overflowing or breaking of dams [26]. Internal waterlogging is closely related to external floods: internal waterlogging can cause external floods, and external floods can also cause internal waterlogging. In general, heavy rainfall will cause waterlogging in cities and towns, the excess water will be discharged into rivers, and the accumulation will become floods. The occurrence of floods will also increase the risk of waterlogging in downstream towns. Therefore, only starting from the waterlogging system in the historic districts cannot completely solve the waterlogging problem, and we must also pay attention to the larger-scale flood control system. The waterlogging prevention and control system and the urban flood control system work together to truly solve the waterlogging problem.

3.4. Inadequate Coordination between Government Departments and between Different Professions

The prevention and control of waterlogging in historic districts involves multiple departments, multiple disciplines, and multiple intermediate links, including architectural heritage protection, planning, construction, municipal administration, and management. In general, special plans will be prepared for the protection and renewal of historic districts, including specific planning content such as architectural heritage protection, water conservancy, municipal administration, and the environment, while the detailed regulatory and constructional detailed regulations will clarify the specific content of control. The government departments involved in the protection and renewal of historic districts and the planning content involved are shown in Figure 2. For this kind of systematic project of waterlogging prevention and control, all departments need to work together, and various plans and constructions should be closely connected.

In the traditional Chinese government management model, the functions of various departments are based on professional division of labor coupled with the lack of effective communication mechanisms, which are prone to fragmentation; however, in some cases, there are overlapping jurisdictions [27]. For example, the management of rivers and water systems in historic districts is related to local administrative divisions, which may belong to different departments such as urban construction, water affairs, and urban management, and the boundaries of the matters in charge of each department are sometimes unclear, especially the limits of the management area. It is easy for all departments to ignore the situation within the border area. At the same time, the points of attention of various management departments are also deviated. The architectural heritage protection department pays more attention to the protection of historic buildings and the preservation of styles and features, and less to the feasibility and operability of some infrastructure deployment. Pipe network planning and design departments often work in accordance with specifications and design standard documents and focus more on theoretical effects, paying little attention to subsequent actual operations and effect inspections. The construction unit pays more attention to the reduction of construction costs, and does not pay enough attention to the later operation and maintenance management. The lack of effective work connection among various business departments, proneness to prevarication, and other phenomena when problems arise restrict the improvement of the overall system efficiency.

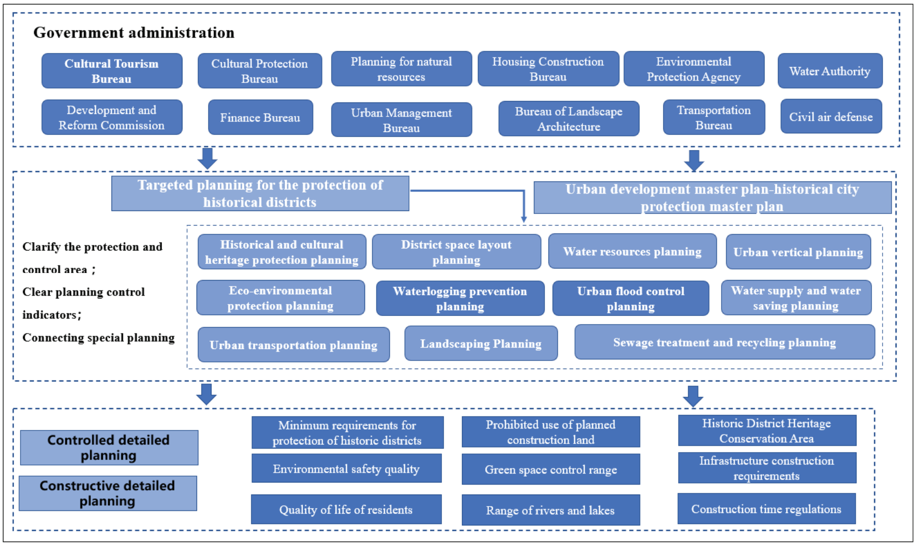

Figure 2. Drainage and Waterlogging Prevention Management and Planning Framework for China's Historic Districts.

4. Specific Countermeasures to Improve the Effectiveness of Waterlogging Prevention and Control Systems in Historic Districts

4.1. Relevance and Adaptability

The improvement of the efficiency of the drainage system in the historic districts should meet the needs of both the protection of architectural heritage and the improvement of the quality of life of residents. However, this work still has a long way to go. For example, in a historic district in Beijing, around 2014, only 68% of residents still used sewers for drainage, while the remaining 32% of households' domestic sewage was directly discharged into the street, putting pressure on street drainage and the environment [28]. Due to the special attributes of historic districts, it is necessary to adopt pertinent and applicable transformation and update technologies according to the attributes and characteristics of historic districts [29]. We should further sort out and standardize the national norms, methods, and strategies for pipeline design in historic districts based on existing conditions [30] and strengthen the diagnosis of existing pipeline network facilities based on technologies such as multi-level analysis and evaluation of collaborative diagnosis [31]. We should use model simulation and vertical optimization to improve the drainage efficiency of old alleys in collaboration with pipe trenches and road drainage [32]. We should also comprehensively consider the narrow streets and lanes space and the needs of residents, and further refine the pipeline laying sequence, arrangement method, pipe size, horizontal and vertical spacing technical methods in historic districts [33].

The current sponge city construction provides a new direction for waterlogging prevention and environmental improvement in historic districts. The construction of sponge cities clarified the division and value of annual runoff volume control in mainland China, and proposed the construction of sponge cities in accordance with local conditions [34]. The problems of waterlogging and water environment pollution exist objectively in historic districts. Therefore, it is very necessary to carry out rainwater source control for the protection of historic districts in different levels, plots, and precision. The goal of prevention and control of water safety and waterlogging in historic districts should be determined. At the same time, the rate of total annual runoff control in historic districts should be determined [35]. For courtyards in historic districts, different indicators can be set according to the protection levels of national laws and regulations. As shown in Table 2, the requirements for courtyard protection and renewal should be clarified, and the extent to which sponge cities in historic districts can be renewed should be clarified. For the streets in the historic districts, we can refer to the current advanced green street design concepts [36], and on the basis of preserving the street style remains and architectural heritage protection, we can set up design guides and sample atlases according to local conditions.

Table 2. Renewal requirements for protection of courtyards in historic districts.

Types of Courtyards in Historic Districts	The Extent of Sponge City Construction Can Be Carried Out	Specific Requirements for the Protection and Renewal
Key cultural relics protected courtyard	Low degree of renewability	Strictly protected, within the scope of relevant national laws and regulations
Historic courtyard	Low degree of renewability	According to the specifications and document requirements, evaluate the value of the courtyard heritage in detail, and carry out protection and renewal according to the construction age and current situation of the courtyard
General courtyard	Medium degree of renewability	According to the overall layout and style of the historic districts, take appropriate measures for reconstruction
Newly built courtyard	High degree of renewability	It is in harmony with the overall layout and style of the districts. The total amount of runoff control target can be set reasonably according to the courtyard conditions
Other types of courtyards	Take refined evaluation and improvement measures	Clarify the ownership and current conditions of the property rights of the internal units of the courtyard. Carry out courtyard protection in a refined manner according to the investigation and evaluation situation

The waterlogging prevention and control system in historic districts should highlight "multi-level" and "adaptability". "Multi-level" means to take different technical and management measures to prevent and control waterlogging according to the different protection requirements of the historic district. "Adaptability" means that the special attributes of heritage protection of historic districts need to be fully considered when carrying out waterlogging prevention and control work. Combined with the construction of sponge cities, a reasonable runoff volume control rate must be clarified. Through a systematic and refined approach, specific and adaptive measures are determined. In turn, the rainwater discharge path will be unblocked, with multi-channel stagnant storage and multi-channel transfer. Eventually, the unity of protection and renewal of historic districts, prevention of waterlogging, and improvement of the living environment of residents will be achieved.

4.2. Connection of Waterlogging Prevention and Control System and Flood Control System

For the prevention and control of waterlogging in historic districts, it is necessary to comprehensively consider the requirements of historic building heritage protection, landscape design, landscaping, and other aspects, and connect the drainage and waterlogging prevention in the urban area with the flood prevention system in the river basin.

First of all, attention should be paid to the convergence of standards. The content of urban drainage standards, waterlogging prevention standards, and flood control standards and the conditions of convergence between them should be analyzed to clarify the relationship between waterlogging and external flooding. Combining design water level analysis and flood volume calculation results, the boundary conditions and implementation requirements of flood control systems in historic districts should be clarified, and supporting evidence for the connection of urban flood control and river basin flood control systems provided [37]. Secondly, we should strengthen the connection of vertical design. Combined with water conservancy calculations, the layout and elevation of flood control facilities such as dykes and dams under the flood control plan should be determined [38]. Through model simulation and scientific calculations, various elevations and vertical designs of waterlogging prevention and control system facilities should be determined, and a waterlogging drainage mode of "regulation- storage, self-draining, and drainage" constructed so as to achieve multifunctional coordination and connection of flood control and drainage. Although existing simulation tools cannot directly simulate external floods and waterlogging, one-dimensional and two-dimensional mathematical models can be combined to study the response relationship between external floods and waterlogging [39]. Third, the application connection of storage and drainage facilities should be strengthened. Through comparative analysis of typical experiences and practical cases of urban drainage deep tunnel construction [40], the planning and design of drainage deep tunnel planning and construction methods and models suitable for historic districts should be explored, and a complete flood control and drainage system should be linked [41]. Deep tunnels and large-scale storage facilities can adjust the peak rainfall flow and total runoff to prevent waterlogging in urban areas. Research on the role of historic water systems in flood control and drainage, landscape effects, microclimate improvement, environmental enhancement, and historic and cultural inheritance should be intensified, and ways to achieve the convergence of flood control and drainage systems from the perspective of historic water system restoration explored [42,43]. Fourth, we should strengthen the connection of various subsystems. The layout of emission reduction facilities should be reasonably set up and optimized at the source, the drainage system and some gray infrastructure should be updated, lakes and water systems should be rationally used, and the positive effects of water system connectivity on flood control and drainage should be explored [44]. Engineering facilities and non-engineering facilities should be coordinated and cooperate with dams, reservoirs, and flood storage facilities to give full play to the overall effectiveness of the flood control and drainage system.

In the process of urbanization development, cities in developed countries and regions such as the United States, Germany, the United Kingdom, Japan, Australia, Singapore and Hong Kong have suffered from waterlogging problems [45]. Developed countries and regions have a clear concept of "Waterlogging Disaster or Local Flooding" in the drainage system [46]. Drainage and flood control in the United States is clearly composed of two parts: Urban Flooding and Watershed Flooding, whose responsibilities are the Local Government and the Federal Government respectively. The United States has paid enough attention to the connection of standards and technologies between waterlogging and external floods [47]. The international development experience of developed countries in the prevention and control of urban floods shows that attention should be paid to the connection between internal and external floods, including standards, management, and technical strategies.

4.3. Intelligent Management Platform for Waterlogging Prevention and Control in Historic Districts

At present, the construction of smart cities has brought new ideas and new methods to the protection and renewal of historic districts and the construction of waterlogging prevention and control systems [48]. The protection and renewal of historic districts can rely on the advantages of current informatization and comprehensively use online monitoring, geographic information system (GIS), digital models, AR technology, and advanced technologies of 5G Internet of Things. An intelligent management platform for waterlogging prevention and control in historic districts that integrates architectural heritage protection and waterlogging prevention and control should be built.

The intelligent management of waterlogging prevention and control in historic districts should include content related to architectural heritage protection (distribution of architectural heritage protection objects, important monitoring points, key monitoring indicators) and basic information of waterlogging prevention facilities (distribution of facilities, topography of catchment area, underlying surface type, elevation data). The relevant information of the objects of architectural heritage protection and the dynamic information records and data updates of the operation status of the waterlogging prevention and control system facilities can be displayed dynamically. As shown in Figure 3, the smart platform should also contain multiple databases to enable entry and upload of drawings for review, on-site inspection related materials and rectification opinions, and rectification responses of construction and maintenance management units. The intelligent management platform should also realize the real-time reporting, query, and management functions of monitoring data and manual monitoring data, and timely operate and maintain facilities and carry out inspections. It is particularly important to emphasize that the installation of various types of sensors must undergo corresponding professional assessments in advance to avoid damage to the architectural heritage. At the same time, it should also realize the informatization of emergency management plans within urban watersheds or drainage districts, with early warning and real-time information release functions.

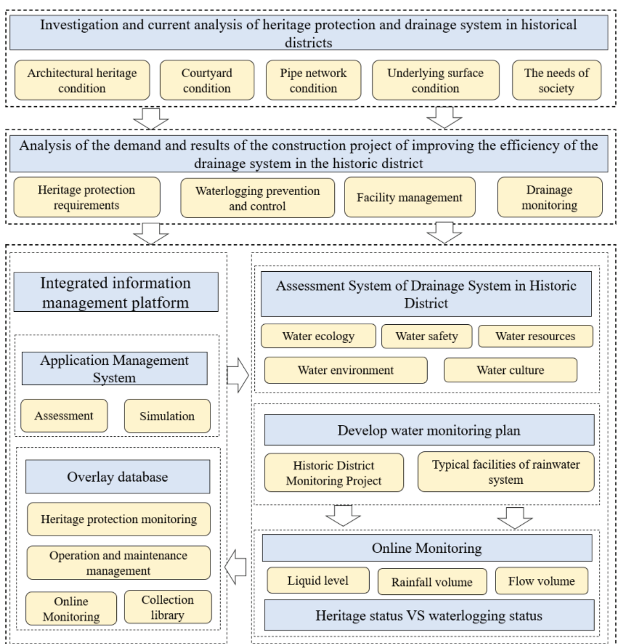

Figure 3. Intelligent management platform for waterlogging prevention and control system in historic districts.

The establishment of an intelligent management platform provides support for comprehensively grasping first-hand information and carrying out precise decision-making. At the same time, intelligent management can improve the speed of information transmission and the efficiency of resource allocation, which is of great significance to the cross-regional and cross-departmental protection and renewal of historic districts and the prevention and control of waterlogging.

4.4. Strengthen Management Coordination and Improve Governance Effectiveness

The solution to the problem of waterlogging in historic districts is a comprehensive manifestation of urban management capabilities. In order to improve the effectiveness of the waterlogging prevention and control system in historic districts, improvements should be made in the following aspects. First, we should optimize the organization and work process. Functional departments or work items with similar business segments or work attributes should be reorganized and integrated. We should abandon the fragmentation of urban waterlogging control, combine the holistic governance theory to clarify the waterlogging control path in the historic districts, and form a coordinated and diversified governance body. Second, we should build a consultation mechanism and create a good communication platform. Government management departments should play an organizing and coordinating role, social experts, institutions, groups, etc. should master the technology, and the people should live in it. Therefore, in the process of preservation and renewal of historic districts, the opinions of various professional experts and the people should be widely listened to, and conservative or radical practices and ideas should be eliminated. Residents living in historic districts should be given certain opportunities to express their opinions because they are more familiar with the living environment. They clearly know which locations are prone to waterlogging and which locations are more harmful. At the same time, they can play the role of supervising maintenance, and we can rely on them to report timely when the drainage facilities are damaged. They can help the management department with timely maintenance management. Third, we should strengthen process control and supervision. The protection and renewal of historic districts is a multi-departmental, multi-professional, and interdisciplinary work. The prevention and control of waterlogging in historic districts involves many links, which means that more responsibilities and interest demands are involved. Therefore, the construction of waterlogging prevention and control system in historic districts must pay attention to process management and control. We should clarify the requirements and indicators of each link, and attach importance to process acceptance and process supervision.

For the waterlogging prevention and control system, the construction time sequence and target requirements of each protection and renewal project must be clear, as shown in Figure 4. In order to better coordinate the various departments of the government, a special comprehensive management department for the protection of historic districts can be established to be responsible for the protection and renewal of historic districts. The main work of this agency covers management, supervision, coordination, approval, service, assessment, and acceptance. For the construction of the waterlogging prevention and control system in the historic districts, under the unified dispatch and coordination of the comprehensive management department, the corresponding business departments of the cultural relics/cultural tourism, planning, housing construction, development and reform, and other government departments can carry out the design and review of the waterlogging prevention and control plan, protection planning permission, and acceptance. In contrast to construction goals such as architectural heritage protection and waterlogging prevention plans, the core indicators and construction requirements are clarified, and at the same time, the supervision and verification of various links before, during, and after the event are strengthened. Unclear responsibilities or unclear authority can be solved by the comprehensive management department of historic districts protection through coordination with all parties to solve the shortcomings of poor information communication and improve the overall governance effectiveness.

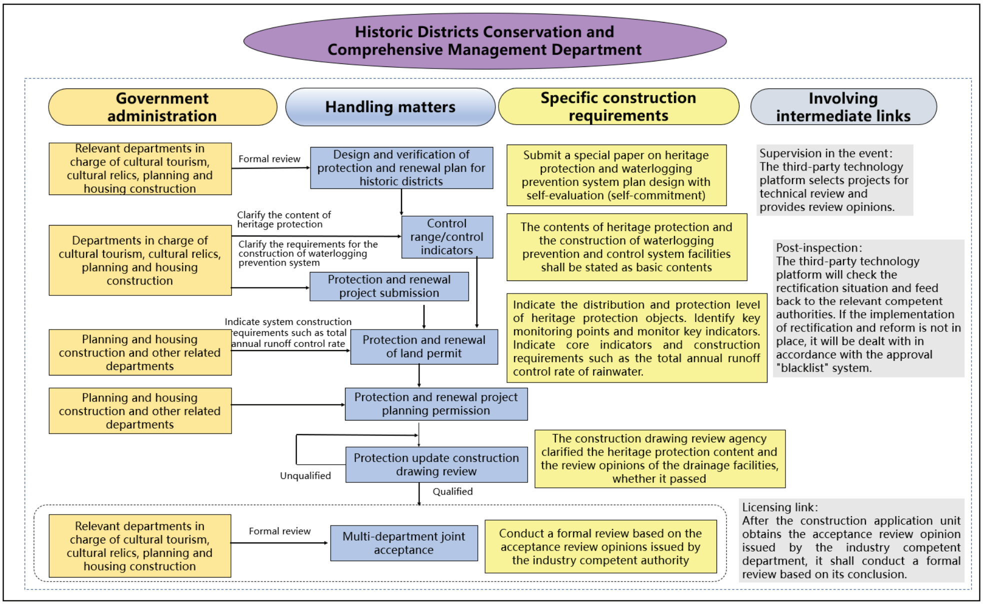

Figure 4. Departments and links involved in the construction of waterlogging prevention and control system projects in historic districts.

5. Conclusions

The waterlogging problem in historic districts is a systemic problem. We should coordinate the technical aspects of waterlogging prevention and control systems such as the "Major-Minor-Micro" drainage system and the joint flood control system. At the same time, it is necessary to clarify the problems existing in the management of the waterlogging prevention and control system, and improve the effectiveness of the waterlogging prevention and control system in the historic districts from the perspective of the entire system.

(1) The improvement of the effectiveness of the waterlogging prevention and control system in historic districts should coordinate the protection of architectural heritage and the improvement of the quality of life of residents. From the perspectives of courtyards and streets in historic districts, the control of rainwater sources is carried out hierarchically, by plots, and accurately.

(2) Regarding the connection between the waterlogging prevention and control system and the flood control system, consideration should be given to standards, vertical design, storage and drainage facility applications, and subsystems. At the same time, comprehensive consideration should be given to the protection of historic building heritage, landscape design, and landscaping related professional requirements to achieve the scope of towns. The drainage and waterlogging prevention and flood prevention in the river basin are coordinated and unified.

(3) In order to achieve accurate monitoring and decision-making for the protection and renewal of historic districts and the prevention and control of waterlogging in cross-regional, cross-professional, and other circumstances, a joint prevention and control intelligent management platform for waterlogging prevention and control in historic districts should be built, which includes content related to architectural heritage protection and waterlogging prevention facilities. This information platform improves the speed of information transmission and the efficiency of resource allocation.

(4) In order to coordinate with multiple departments to improve in the protection and renewal of historic districts and the prevention and control of waterlogging, the orga-

nization and work process should be optimized. We should establish a consultation and consultation mechanism, create a good communication platform, strengthen process control and supervision, implement process acceptance and control, and improve the comprehensive management ability of waterlogging prevention and control in historic districts.

Author Contributions: Methodology: J.L. and S.S.; literature review: S.S. and L.L.; drawing and modifying diagrams: S.S. and Y.W.; validation: L.L. and Y.W.; writing—original draft preparation; S.S. and J.L.; writing—review and editing: J.L. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by ECERC and was funded by the key project of Beijing Municipal Natural Science Foundation, China, grant number (8191001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors do not have any commercial or associative interests that represent conflicts of interest in connection with the submitted work.

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Barriers to Offsite Construction Adoption: A Quantitative Study among Housing Associations in England

Andrew Agapiou

Department of Architecture, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow G1 1XJ, UK; andrew.agapiou@strath.ac.uk

Abstract: Housing associations (HAs) play a pivotal role in the delivery of affordable homes and, therefore, offsite construction could be beneficial in alleviating the crisis. Existing literature has focused on the perceptions of the housing sector at large towards offsite construction (OSC), particularly private housebuilders. This research addresses this gap in the literature. This paper explores the perceived barriers of using OSC through a survey of the largest HAs in England [n = 69], and how these compare with the perceptions within the wider housing sector. The evidence from this research indicates cost-related barriers are perceived to be the most significant barriers to OSC use for HAs, followed by the capacity of suppliers and end-user preferences for traditional construction. The perceived barriers of those with experience are aligned with the OSC literature, whilst the responses of those without direct experience suggested heightened concerns towards the key barriers. A conceptualised feedback model is proposed to monitor, capture knowledge and share best practice as HAs commit to accelerating project delivery through strategic partnerships with offsite manufacturing firms, local authorities at a local/regional level, that leverage the high-value, high-impact transformation of the housebuilding sector in tangible terms of efficiency, cost, and material savings.

Keywords: barriers; housing associations; offsite construction; perceptions

Citation: Agapiou, A. Barriers to Offsite Construction Adoption: A Quantitative Study among Housing Associations in England. *Buildings* **2022**, *12*, 283. https://doi.org/10.3390/buildings12030283

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 20 January 2022
Accepted: 28 February 2022
Published: 2 March 2022

1. Introduction

Since the housing crisis of 2008, the delays in housing starts and completions has resulted in a widespread housing shortfall in the UK that has challenged policymakers and developers to re-evaluate their position on modern methods, acceleration techniques, and technological opportunities [1]. Whilst traditional construction continues to serve as the primary mode of new housing fulfilment, recent evidence suggests that in order to meet the future needs of UK households and fulfil a more diversified spectrum of housing solutions, modern methods, and offsite techniques are of critical importance [2,3].

Alternative methods to traditional construction are increasingly being explored as a way to address the housing crisis in England. This is demonstrated by the recent parliamentary inquiry into MMC and Homes England's Strategic Plan in which developers receiving funding for developments of over 50 units must incorporate some form of MMC [4,5]. In England, up to 340,000 houses are needed per year to meet housing demand [6], however, only 164,390 new homes were completed in the England during 2018 [7]. Of these, approximately 17% were completed by HAs and less than 2% by local authorities, showing HAs is crucial in the delivery of affordable housing [8]. With 145,000 affordable properties required in England per year [6], based on recent performance, HA development will be critical to achieve the required output.

As a central agency responsible for providing adequate and quality housing to residents throughout a given region, UK housing associations (HAs) are defined as 'not-for-profit social landlords that provide homes and support for around 6 million people all around England' [9]. With pressure to accelerate the rate of delivery for such social housing solutions that are affordable and high-quality, the viability of offsite manufacturing is a pragmatic consideration that must be weighed, assessed, and considered for meeting future needs. Whilst a growing body of literature has critically explored the advantages and potential limitations of prefabricated, modular, and offsite construction practices, the lack of consensus and dependency upon traditional methods of construction have led to conceptual and ideological gaps that are continuing to threaten the long-term viability of this modern solution.

The extant research has largely focused on the experiences of the housing sector at large towards offsite construction, particularly private housebuilders. Currently, there is a dearth of research into the potential for adopting offsite solutions within HA developments, notwithstanding the 2017 report published by the University of the West of England which assessed the evidence for the take-up of prefabrication in the social housing sector in England [9]. For HAs, organizations that are confronted with a need to accelerate the rate of construction and mitigate the longstanding reputational threats of low-quality, low-efficiency housing, the practical opportunities of offsite housing are significant.

There is a growing interest in OSC from HAs, demonstrated by investment in their own manufacturing facilities [10,11] and research projects, such as Gateshead Innovation Village (Home Group 2019). Of the top 50 biggest developing HAs, 23 expect to complete homes using MMC in 2019/20, an increase from 16 in 2018/19 [12,13]. Despite this, OSC uptake nationally for HAs is low. If uptake is to increase, the perceptions of HAs towards OSC need to be understood, including the perceived barriers to OSC adoption. Currently, there is no literature focusing on these perceptions; a gap that this research begins to address.

Therefore, the aim of this research is to explore the perceived barriers within housing associations towards the use of OSC and how these compare with the perceptions within the wider housing sector. The objectives of the study are three-fold: (i) to critically review perceived barriers for OSC in the housing sector; (ii) to identify perceived barriers among HAs in using OSC methods and how these compare with the perceptions of the wider housing sector; and (iii) to explore whether experience in OSC methods affects perception of OSC usage.

2. Housing Associations and Offsite Housing

Despite an increasingly robust history in UK housing deliveries, offsite construction is often confronted with industry resistance, particularly in public housing sectors where government officials are challenged to justify value for money. Rowley et al. [14], for example, have observed that the delivery of affordable social housing by government agencies is threatened by a variety of concerns, including changing housing prices, economic conditions, demand-side variables (e.g., employment, wage growth, investment yields) and supply-side variables (e.g., land supply, construction efficiency, labour costs, planning regulations). The resultant bullwhip effect in housing supply, a phenomenon initially observed by Wheaton [15] in relation to private sector housing fulfilment, results in an over-under supply model that, whilst progressing towards natural equilibrium, is at risk for cyclical changes and delays. Therefore, MacAskill et al. [16] argue that where the primary 'goal of affordable housing is to achieve equilibrium', thereby eliminating the need for a waiting list or stricter qualifications, gap mitigation strategies (e.g., housing transfer, expedited construction methods) are needed to overcome systemic gaps in the housing supply. Central to the primary economic advantages of offsite housing identified by the NAO [17] is the volumetric housing benefits that provide housing associations with distinct advantages, including earlier rent recovery, a shorter borrowing period, less project delays, and less on-site inspections. Forecasting upwards of 80% fewer project defects and upwards of 80% compression of the time of delivery, the findings presented by Miles and Whitehouse [18] also confirmed a direct benefit to the housebuilder and a significant, broader social impact due to the accelerated delivery of high-quality, often affordable housing solutions. As developers weigh the functional and systemic advantages of offsite construction, Barton et al. [19] confirm that higher quality, higher efficiency prefabrication will not only reduce the operational costs and emissions of the property over time, but will prescribe a future structural standard that dramatically improves the broader standard of practice in the construction industry.

2.1. Literature Review

A cursory review of the offsite construction literature reveals a dearth of academic research into the perceptions of HAs specifically towards OSC. Only Kempton and Syms [20,21] have explored this, focusing on the perceived impact on maintenance and asset management. To address the first objective, the literature focusing on perceptions towards OSC within the housing sector was identified and reviewed. Literature was obtained through searches on online databases, including Google Scholar, ARCOM, Science Direct and Ingenta Connect. Terms, such as "offsite construction", "off-site manufacture", "prefabrication", "modern methods of construction" were used in conjunction with "housing association", "housing" and "residential". For brevity, only UK based or UK concerned literature was included for detailed examination. The literature search was expanded through snowballing; reviewing the citations and reference list of each paper and further literature in which the original paper has been cited [22]. The literature predominantly consisted of journal articles, conference papers, and industry generated reports. Abstracts and executive summaries were read to ascertain whether the literature contained research into perceptions. Those that did were thoroughly examined to establish the perceived barriers to OSC use, in order to address the first research objective.

The literature contained a larger range of perceived barriers within the wider housing industry, with 24 themes identified. Figure 1 illustrates that the results were multimodal with four barrier themes, each featured in 53% of the literature reviewed: industry perceptions, customer perceptions, skills requirements, and cost.

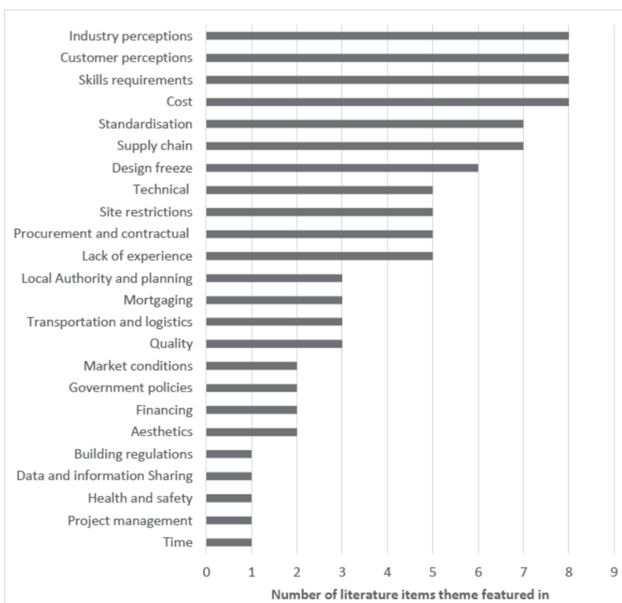

Figure 1. The number of pieces of literature on each barrier theme is featured within the literature.

The section below discusses the level of importance attributed to these four key barrier themes, with comparisons made between their significance within the wider OSC housebuilding literature and studies related to housing association perceptions. A critique of the wider body of knowledge is also provided, highlighting both methodological gaps and weaknesses within the OSC housebuilding literature, and how this may limit the scope of direct comparison with the research findings. The theoretical gap is then defined as the basis for further consideration and exploration.

2.1.1. Industry Perceptions

The attitudes of the housing building industry towards OSC are a frequently occurring barrier; however, it is not considered to be highly significant, ranking sixth out of seven most important barriers to the use of prefabrication [23]. In Pan et al. [24,25], "Attitudinal barriers due to historic failures" was selected by 11% of participants as being one of the three most significant barriers to the use of offsite-MMC. This is supported by [20,21,26], who identify that previous negative experience with non-traditional construction methods has fueled tarnished perceptions and negative attitudes towards OSC. The perceived risk of adopting new processes and systems was a highly ranked constraint in [27], selected by 24% of participants. In Pan et al. [24,25], "Reluctance to innovation" was selected by 11% of participants as being one of the three most significant barriers to using modern methods of construction. Conversely, "Want to modernise" was presented as a driver for investing in MMC in [28] and selected by 39% as a driver. However, [28] reveal that the majority of housebuilders and HAs considered themselves "Followers" or "Late adopters" to MMC. Only 3% of HA participants consider their organisation to be "Market leaders" [29].

2.1.2. Customer Perceptions and Attitudes

Public attitude is also considered an important barrier to prefabrication uptake by housebuilders [23], supported by [27], where it ranks as the joint fourth biggest constraint. "Buyer reactions" is also the third most selected main barrier to modular construction [29]. This is supported by [20,21,29], who identify that previous negative experience with non-traditional construction methods has fuelled tarnished perceptions and negative attitudes towards offsite construction methods. However, "Culture resistance-poor public perception" is a lowly ranked barrier in [30], jointly ranked 17th in significance out of 20 perceived barriers. "No demand for prefabrication" is the lowest-ranked barrier affecting prefabrication uptake in [31].

2.1.3. Skills Requirements

The need to address skills shortage is frequently cited as a significant perceived barrier to the wider take-up of OSC. For example, 87% of participants in [31] considered this to be a significant barrier, making it the second highest selected barrier. It was also considered significant by participants in [29], where it was the fourth most selected main barrier to modular construction.

Dave et al. [27] highlighted the perceived concerns over the lack of training and experience of builders, contractors, developers, and designers, including architects and engineers. However, skills requirements are not a significant perceived barrier according to [28], in which only 6% of participants considered it to be a barrier to MMC uptake by developers. This is supported by [24,25], in which only 11% of participants selected "Skills shortage" within the top three barriers to offsite-MMC, and [23] where it is considered the least important out of the seven presented barriers for prefabrication.

2.1.4. Cost

Cost features function equally as a driver and barrier within the OSC literature. The two most important barriers from the [23] housebuilders survey were "More expensive than masonry" and "High upfront capital cost". These two barriers are supported in [31], where they are considered significant constraints by 64% and 71% of participants, respectively. Cost-related barriers were also the two most frequently selected within the top three barriers in [24,25]: "Higher capital cost" was selected by 68% of respondents, and "Difficult to achieve economies of scale" was selected by 43% of respondents. "Extra expenses" was the most frequently selected barrier affecting prefabrication in [30]. Increased capital cost is shown as the main barrier to the use of modular construction for both housebuilders and Has in [29].

2.2. Critical Appraisal of OSC Housebuilding Literature

The use of questionnaire surveys which characterise much of the extant literature discussed is a valuable method to help understand the barriers to OSC as perceived by the UK housebuilding industry. To further understand how these barriers are operationalised in the public sector and to explore how they might be overcome, it is necessary to ascertain the views of Has and compare these with perceptions seen in the wider housing building sector. There is a need to exercise caution when considering such a comparative exercise, as there is limited information on methodology, responses received, the format of questions and the weightings given to responses.

For example, very limited information is provided by [20,26,29] about how suitable samples were decided and survey participants or interviewees selected. In contrast, [28,29] provided greater detail on how participants were selected through purposive sampling to ensure views from across the organisation were represented and to ensure participants had the appropriate level of knowledge. The information provided on samples, or lack of, must be referred to when determining whether results are representative of a population. The sample size is also a limitation for all research in which a questionnaire was the primary data collection method [23–25,27,32,33]. In addition to differences in research aims and targeted participants, the specific type of non-traditional construction being researched in the literature varies between MMC, OSM, OSC, prefabrication and modular. This should also be considered when comparing results. All the identified research has been conducted at the higher level of classification of the construction method. Research into perceptions of lower-level classifications, such as volumetric, panelised systems and pre-assembled sub-components should be conducted to evaluate the differences between the perceived barriers for each of these methods.

2.3. The Theoretical Gap

After a thorough literature review on the perceived barriers to adopting offsite construction, the authors identified the theoretical gaps in this topic. While the most frequently cited perceived key barriers to the adoption of OSC within the literature were related to industry and customer perceptions, cost, and skill requirements, the review also showed a lack of research into HA perceptions towards OSC, with only NHBC Foundation (2016) providing some results for HA participants independently of private housebuilders. In summary, the differences in results seen in NHBC Foundation (2016), between HAs and private housebuilders, indicates that perceptions are not consistent between the two populations.

3. Research Methodology

To achieve the research objective, firstly a review of the literature on the topic was conducted and related articles were reviewed. In order to achieve the second and third objectives, a quantitative survey was used to explore the perceptions of housing associations towards the barriers to OSC usage in England. Questionnaires are suited to the exploratory nature of this research [34] and have been commonly deployed within OSC research to establish perceptions (e.g., [21,24,25,28]).

An online platform, Smart Survey, was used to distribute the questionnaire survey, due to the time advantage of automated data collection, cost, and environmental benefits compared with a postal survey [35].

The 24 barrier themes identified from the literature review were thematically coded. These were used to develop questions for primary data collection and analysis of questionnaire results, allowing for additional categories to be added and refined in response to the data collected [36]. The literature also provided secondary source data which has been used for triangulation during the analysis of the primary data. Further research, using different primary data collection methods, such as interviews, were also considered to improve the process of triangulation.

3.1. Questionnaire Design

The survey tool was developed with the aim of investigating the perceived barriers of using OSC through a survey of the largest HAs in England and how these compare with the perceptions within the wider housing sector. The questionnaire survey included four sections:

Section 1: General information about the respondent and the extent to which they have had direct experience of different types of OSC systems on UK housebuilding developments.

Section 2: In the second part of the questionnaire, five-point Likert scale questions were initiated to measure HA professionals' perceptions towards the 24 barrier themes listed in Figure 1.

Section 3: In the third part of the questionnaire, HA professionals were asked to select the three most significant barriers militating against the adoption of OSC methods on UK housebuilding developments from 24 options listed in Figure 1.

Section 4: in the fourth part of the questionnaire, HA professionals were asked to select the types of OSC systems most beneficial for housing association development projects, ranging from panelised, volumetric, hybrid, through to modularised systems.

On reflection, these questions did not allow participants who felt they could not give an answer to bypass this question, which may have introduced bias by requiring the participant to make only three selections [36]. Additionally, responses only show the three most selected barriers from the options given; participants may consider other reasons to be the key barriers [36]. To address this, an "Other" option was provided to allow additional reasons.

3.2. Sample Design

It is beyond the scope of this research to use a census study; therefore, two sample sets of HAs were established to focus the study.

It was decided to target HAs who are most likely to have experience in OSC, mirroring the approaches of [23–26]. To target experienced developing HAs, organisations featured in the 'Inside Housing Top 50 Biggest Builders 2019' were used as a non-random purposive sample [12,36].

HAs identified through the literature review as experienced or having previously shown interest in OSC, formed the second sample; a number of which are not present in the Top 50. It is understood that results from these samples cannot be inferred into all HAs, as these samples contain HAs most established in development or OSC usage. Consequently, the perceptions of these organisations may differ from HAs with limited experience in these remits; an area requiring future research. To establish target participants, employees of the organisations in the sample sets were identified through online searches. Organisational websites, news articles, and LinkedIn were used to identify job roles and valid email addresses for 180 HA employees. Those with senior or managerial positions within development, construction, technology, design, innovation, commercial, property services, sustainability, and project management were targeted. Additionally, network contacts were used to identify employees of HAs within the two sample populations. It is acknowledged that there is an inherent bias in the process of identifying recipients for the questionnaire.

Assumptions had to be made regarding job titles and listed experience for LinkedIn profiles to determine whether the employee should be a targeted recipient, such as whether a project manager was involved in construction project management. The online search was heavily dependent on the detail of information each organisation publicly shares. Where information was available on employees and job roles, this was often provided for a whole team. Therefore, some HAs in the sample sets had multiple targeted participants where such information was available, the highest being twelve, whereas some only had two. A larger number of targeted employees were also identified for some HAs through network connections. Consequently, some organisations had a greater opportunity to be represented than others and this bias may be reflected in the results. To alleviate the risk of this bias impacting results, demographic information was collected to understand the types of participants who completed the questionnaire, such as the operating regions of the organisation.

3.3. Survey Response Rate

In total, 69 responses were received, representing a response rate of 38% based on the 180 targeted participants. A response rate around this figure is reasonable in comparison with similar surveys conducted by [24,25,31], which set a benchmark response rate between 31% and 36% [34].

3.4. Triangulation of Results

The original intention was to explore views of HA through both a quantitative and qualitative approach. It was anticipated that semi-structured interviews with senior managers from the larger HA developers in the UK would provide a source for triangulation for the questionnaire results. Due to unforeseen circumstances, it became difficult to secure interviews in the required time frame. Therefore, interviews were not included in this research, with a greater focus given to the questionnaire. Interviews would have been beneficial in providing depth to the questionnaire results and obtaining more intricate detail, overcoming criticism of using a questionnaire in isolation [30]. To mitigate this weakness, comment boxes were used throughout the questionnaire to collect optional further detail from participants, as recommended by [37]. This was beneficial, as 27 comments were received, adding additional value to the responses. It would have not been suitable to consider interview findings as representative of typical HA attitudes, but they would have helped with the triangulation of the questionnaire results to examine the accuracy of the datasets [34]. Consequently, questionnaire results have been triangulated with the existing literature only. This is a limitation of this study and future research should conduct interviews with HA professionals to add depth to and verify the questionnaire results. However, as seven sources directly address the ranking of perceived barriers to OSC, triangulation between the primary data collected and the extent OSC literature is suitable.

3.5. Survey Results and Findings

The forgoing section presents the results from the questionnaire survey of housing association perceptions of the barriers towards adopting offsite construction.

3.6. The Demographics of the Survey Respondents

The demographic information was collected to allow understanding of the type of participants who responded and determine whether these are representative of the targeted sample that the questionnaire was sent to. Demographic information on location and experience in OSC were selected as appropriate to use for results analysis due to the size of the subsets of these populations.

As seen in Figure 2 the South East and West Midlands were the most represented regions that respondents work in. The Northern regions (Yorkshire and the Humber, North East, and North West) and South West were significantly under-represented. To determine how representative the results are for the sampled population, the operating regions of the targeted sample and the respondents were compared. As shown in Figure 3, the percentage of respondents whose organisations operate in the South East, East Midlands, West Midlands, and East is much greater than the percentage of the targeted sample HAs who operate in these regions. This shows bias may have been introduced due to a higher chance of a direct contact of the researcher completing the questionnaire and forwarding to their own network than those whose details were established from online searches [37].

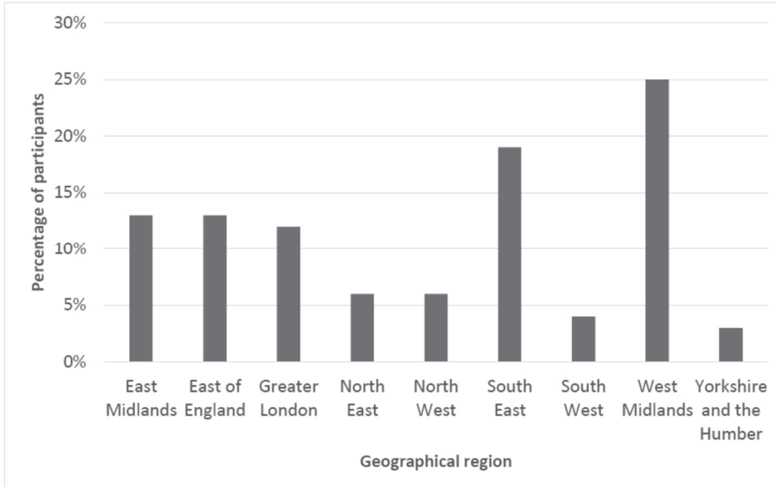

Figure 2. The distribution of geographical regions worked in by respondents.

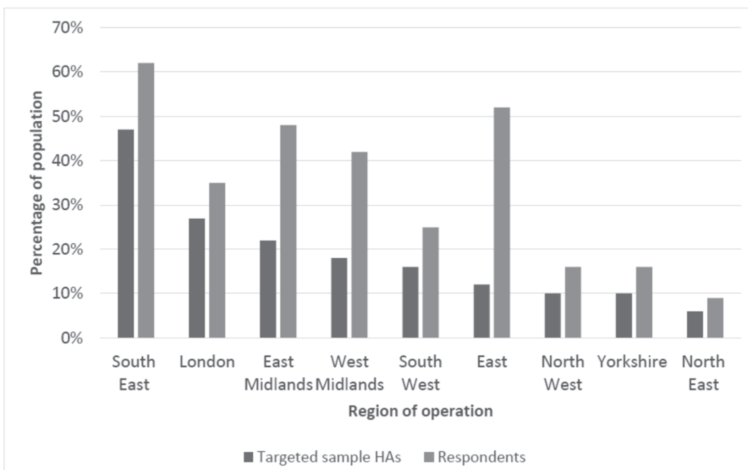

Figure 3. Comparison of the distribution of operational regions of the targeted sample, and those who responded.

3.7. Experience in Offsite Construction Methods

Demographic information on whether a participant has direct experience in OSC methods is applied during data analysis to explore whether perceptions towards OSC are influenced by direct experience, fulfilling research objective 4. A majority, 77%, of respondents have direct experience in at least one OSC method. Seven participants have experience in all five OSC methods presented. The methods experienced are shown in Figure 4.

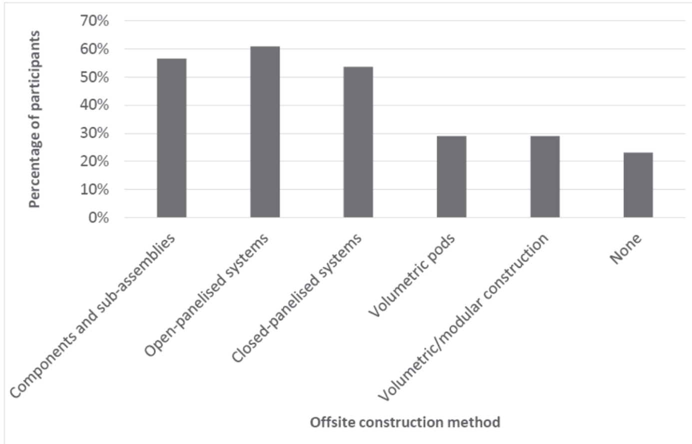

Figure 4. Distribution of experience in given types of the offsite construction method. (Direct experience was stated as "You have been directly involved in a project where the following offsite construction methods were considered or used").

3.8. Perceived Barriers to Offsite Construction

The findings from the questionnaire survey indicated the inability to achieve economies of scale and increased project costs were the two most selected barriers (both 35%), closely followed by increased capital cost (33%), the capacity of suppliers (32%) and end-user preference for traditional construction methods (30%). The results correspond with the perceptions seen in the literature. The most selected cost-related barriers support the results of [31] in which cost was considered the third highest important decision factor to OSC use. In [24–26], an increased capital cost was considered the main barrier by private housebuilders and housing associations, respectively. Difficulty in achieving economies of scale was also the second most selected barrier in [24,25]. The fourth and fifth most selected barriers also align with [29], in which the capacity of suppliers was the second most selected barrier, and customer preference for traditional construction was the third. Equivalent barriers were not presented in [24,25].

3.9. The Impact of Experience on Perceptions towards Barriers

The responses from the population with experience are more in keeping with the results of [24–26] than the population without direct experience. The inability to achieve economies of scale" is the second most selected perceived barrier by both populations, however, there is a noticeable difference between the two for most perceived barriers towards OSC usage, as shown in Figure 5.

Figure 6 indicates that the perception of those with experience aligns with the findings within the extant OSC literature. In [24,25], only 7% of housebuilder participants considered it the third most significant barrier and in [38], although it was the fourth highest perceived concern, it was only the ninth most selected top barrier out of 15. Similarly, "Transportation limitations", the seventh most selected barrier for those without experience (11%) and 12th for those with (19%), has the second largest divergence in perceived barriers.

Again, those with experience agree with [24–26] in which transportation and logistics are considered significant drivers by only 7% and 9% of participants, respectively. These both show that those without experience may have inflated concerns towards these barriers. Without further quantitative research into the reality of these barriers, it is not possible to ascertain whether these perceptions are justified. Increased project costs are the most selected barrier for those with experience, however, it only ranked sixth for those without experience. Although there is not an equivalent barrier presented in [24–26], increased costs compared with traditional methods was the highest-ranked barrier by housebuilders in [23,31]. This suggests that those without experience are not aware of the full extent of implications on cost when using OSC for a project. The capacity of suppliers/manufacturers is the most selected barrier for those without experience and the fourth for those with experience. In [29], this is also highly ranked by HAs; the second most selected top-three barriers. In [24,25], conversely, only 11% of private housebuilders perceived this to be in the top three most significant barriers, placing it eighth out of 17 barriers. This difference between the literature may be attributed to two causes: HAs face greater difficulties in securing a supplier due to supplier capacity, or that capacity has become a greater barrier over the last decade.

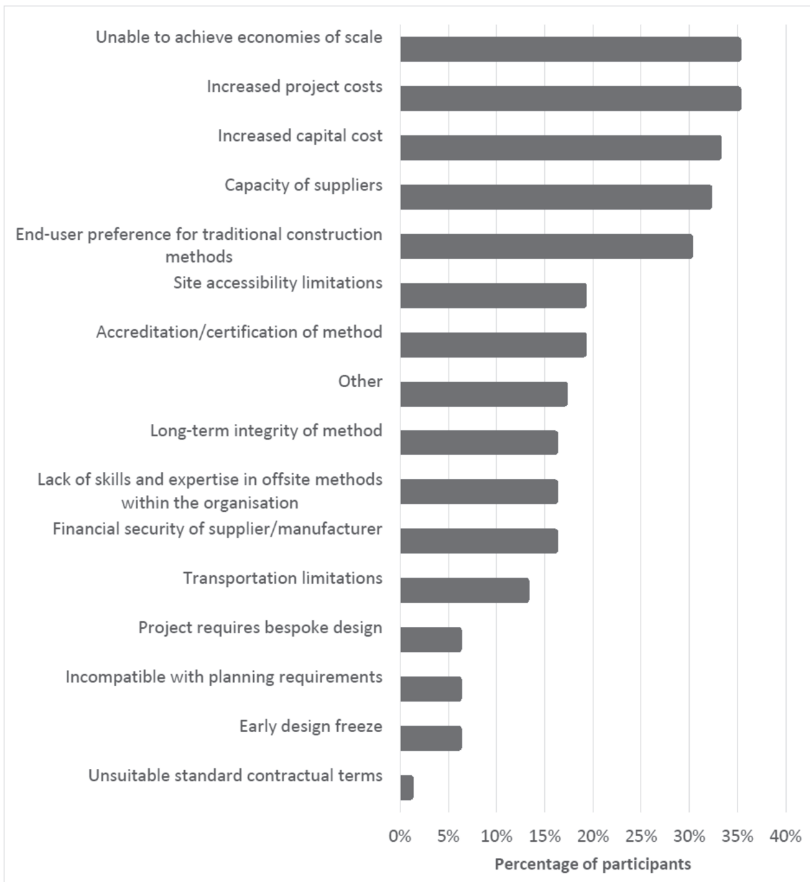

Figure 5. The three most significant barriers to using OSC methods on a project.

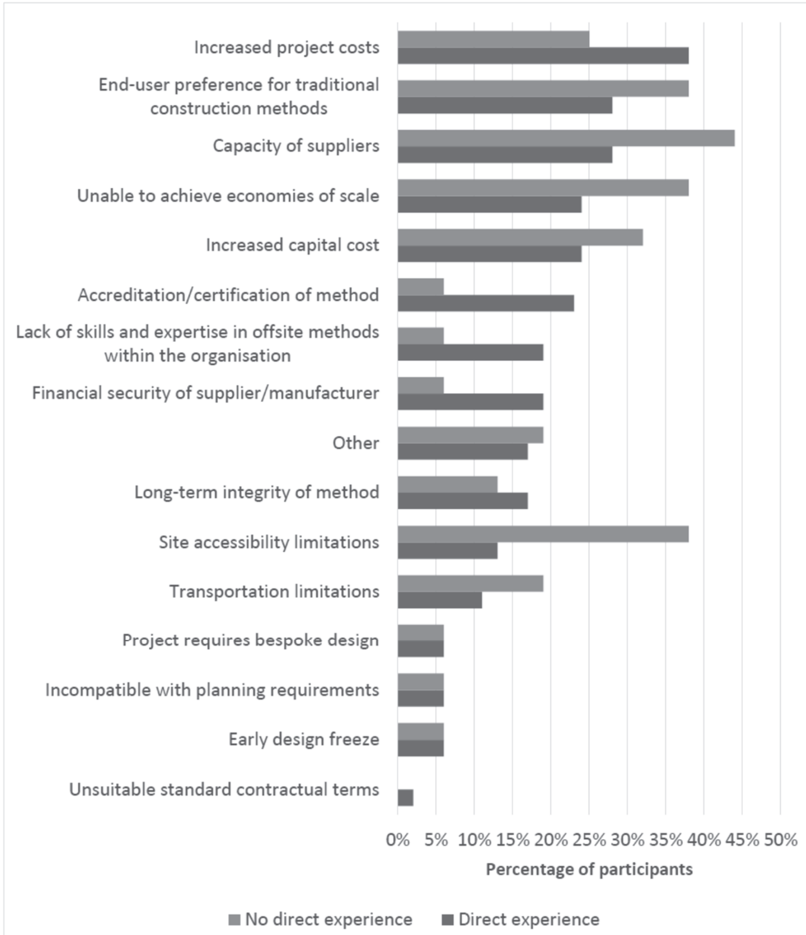

Figure 6. A comparison of the frequency at which respondents considered a barrier to be a top-three biggest barrier between those with direct experience in OSC methods and those without.

4. Discussion

The quantitative survey results reveal cost-related barriers to be the most perceived significant barriers to OSC usage for HAs, followed by the capacity of suppliers and end-user preferences for traditional construction. These results correspond with the literature which presented the perceptions of the wider housing sector. The results also revealed noticeable differences in the perceived barriers between those with experience and those without. The perceived barriers of those with experience are aligned with the OSC literature, whilst the responses of those without direct experience suggest inflated concerns towards barriers. The survey comment box also allowed respondents to elaborate on and share additional insight into the perception of the key barrier to adopting OSC, and how the barriers themselves could potentially be addressed. These comments provided nuance and richness to quantitative survey responses and helps to probe the respondents' views on the most influential barriers affecting the adoption of OSC in housebuilding. Overall, 27 comments were received. Of these, 8 comments directly addressed the comparisons between OSC and traditional methods of construction and 19 comments covered perceptions of the most significant barriers to the wider adoption of OSC in the UK housebuilding sector.

The analysis of free-text comments revealed a clustering of views around the costs associated with the introduction of OSC methods, the industry's reluctance to innovate, the risk-averse nature of the housebuilding sector, customer perceptions, and the role of local authorities in facilitating the transition from traditional on-site construction to offsite construction methods.

4.1. The Comparison between OSC and Traditional On-Site Methods

Many of the respondents felt that OSC could be cheaper if done at scale. One HA developer observed that 'there is no difference between offsite and traditional, other than the time savings, without the economies of scale'. Consequently, without securing economies of scale, OSC appears more expensive than traditional construction, and risk-averse housebuilders are unwilling to engage because their existing delivery models generate healthy profits. Although several survey respondents saw significant benefits in OSC in the longer term, there was concern at being the 'one to stick their neck out' and 'taking all the risk'. Without committed investment into developing offsite capabilities, including factories and digital transformation, the capacity of the OSC supply is constrained. Yet without increased volume, the individual unit costs are uncompetitive compared to traditional methods and are thus unattractive to developers and homebuyers. Whilst there is clearly a need and demand for more homes, the various other barriers we have discussed influences market confidence and acts as a hindrance to committed investment.

4.2. The Significant Barriers to the Wider Adoption of OSC in the UK Housebuilding Sector

The reluctance of the housebuilding industry to modernise has been cited by others [38], and our participants from the housing association sector, perhaps surprisingly, agreed. They felt that housebuilders are 'historically averse to taking innovative' steps and are heavily committed to existing supply chains, relying on 'archaic' construction processes which they feel are 'tried and tested'. Therefore, they are 'very much wedded to brick and block' and 'getting them to change is incredibly difficult'. This hostility to change is associated with risk management, particularly as current business models already provide significant profits, and private housebuilders are cautious of trying to 'fix something that isn't broken'. The housebuilders' own reluctance to innovate was seen as a greater influence on OSC uptake than that of social perceptions, with the industry using traditional consumer preferences as an excuse for a lack of investment. The author in [38] and others have warned that modernisation may become essential, particularly in terms of the labour market and the risks of Brexit.

Regarding the different processes of design, the housebuilding associations representatives suggested that there should be more collaboration between the different parties involved. Such collaboration could enable greater diffusion of knowledge around OSC.

HA developers were keen to be involved in decision-making earlier in the planning process, to involve the supply chain and develop plans and proposals around the capabilities available. Most participants emphasised the need to address end-users. Participants from the HA development sector suggested the use of digital tools, which not only provide opportunities to share information but also to visualise final outputs, challenging historical perceptions of poor design quality. All of these options are technically feasible, however, the main limiting factor at present is a lack of an opportunity space to bring together the various parties and promote OSC housing to end-users.

There was a remarkable consensus between the various participants about the possible options for overcoming the barriers discussed above. HA developers argued that local authorities should be doing more by engaging in more direct building and procurement of OSC homes. They felt this tied into the fact that 'There is obviously a lot of pressure on local authorities to deliver housing growth', and that 'there is enough housing need in almost every local authority in England for them to have their own factory' to build OSC houses. Whereby traditional housing favours design-build solutions, offsite construction offers the unique opportunity to actively plan, diversify, and integrate modern technologies and structural innovations into a regional design platform [39]. Relying upon advanced and technological skill sets that are steeped in innovation and adaptive design, modern manufactured homes will be developed by skilled workers with advanced degrees, clear visions, and adaptive structural solutions [39]. Whilst the justification for the adoption of new offsite methods is likely to be predicated on a variety of influences and performance measures, the emergent platform of high-performing case histories and successful integration outcomes is offering a justified frame of industry knowledge for both reference and integration. Accordingly, to demonstrate the evolving proposition of modular, prefabricated, and offsite construction technologies in the UK, it is important to weigh the evidence from empirical evidence and ongoing case studies that reflect the systemic, structural, and developmental opportunities and challenges encountered during recent years.

4.3. Strategic Partnerships to Increase the Prevalence of OSC in HA Developments

Whilst much of this and prior research in this field seems to propose that housing association expectations and demands (or end-user preferences) are a leading cause of resistance to prefabrication, another conclusion can be drawn from the juxtaposition of recent housing association cases and industry innovation: the traditional construction industry is perpetuating the barriers to change. Ultimately, this transition is about formative, functional, and skills-based hurdles which much of the traditional industry is likely to resist. The loss of revenue due to offsite construction, for example, will have severe consequences for traditional home builders. Site-specific trades related to framing, structural supports, and utilities (e.g., electrical, plumbing) will no longer play a central role in the delivery of each individual home. Instead, a paradigm shift from multi-tiered to project-specific contracting will evolve as residential builders rely increasingly heavily upon specialised labour and strategic partnerships with offsite firms. From local partnerships with HAs to manufacturing innovations and bespoke facility development, these skills transition away from one-off residential development to integrative, modular solutions that can be adapted to systematically improve the process of residential construction.

As HAs are not looking at offsite construction as a one home solution and are targeting larger-scale developments, strategic partnerships with offsite professionals, such as those exemplified by, for example, the Home Group, LoCal, and Swan, have the potential to significantly improve the overall cost basis of the structural delivery process, eliminating many of the intermediary costs and waste streams that permeate the traditional construction industry. There is a recognition that local authorities could influence the market if sites could be aggregated to create a scalable pipeline, but this would require support in terms of coordination and incentives to encourage local authorities to limit the market to specific technologies. Predicated upon a foundation of what Hopkin et al. [40] characterise as organisational learning, the transition amongst housing associations away from traditional methods and towards modern construction methods and offsite solutions are increasingly dependent upon justified, purposeful, and experiential integration of new capabilities. Networking effects, for example, encourage housing associations to transfer tacit knowledge across structural boundaries, encouraging behavioural modifications on the basis of direct expertise or emergent innovations [40].

From delivering affordable housing to under-developed or growing areas to rehabilitating existing sites and brownfield spaces, the accelerated rate of structural delivery, high-quality housing, and sustainable residential solutions have the potential to fundamentally alter the nature and focus of housing association strategies. In a multi-case study report on various responses to the volumetric housing crisis in the UK, [39] reveal that critical hurdles, such as regulatory and political ambiguity, stakeholder resistance, and technological gaps have continued to delay the widespread adoption of offsite solutions. However, when coupled with other triggers and enabling events, there are several pathways to improved offsite construction that will translate the examples presented by LoCal and Swan into market-leading examples for an industry that continues to be confronted by unresolved delays and systemic challenges.

BIM and Digitization: Under the Construction 2025 strategy, government commitments of 50% faster construction delivery, 33% lower costs, and 50% lower emissions require a fundamental revision to existing standards of practice in the traditional construction industry [40]. BIM and smarter construction design solutions prioritise real-time tracking, site-system management modelling, and component-based construction practices that not only justify offsite solutions but compel traditional firms to explore new ways of conducting business and executing their residential deliveries [41].

Building Performance and Sustainability Goals: Underscoring the commitment to more efficient construction, the UK government has also committed to new standards by 2025, whereby new residential construction must attain a 31% decrease in carbon emissions from 2021 [42] (Whilst long-term goals challenge firms to develop strategies for reducing emissions by at least 75% [42]), the short-term considerations for new home construction mandate an immediate change in design and system performance. Performative improvements via offsite construction will allow HAs to not only improve the efficiency of their properties but improve the quality of life (e.g., cost reduction, high-quality residences) for their social applicants, dispelling many lagging stereotypes about social housing and affordable inefficiencies.

Skills, Contracting, and Collaboration: Whereby traditional housing favours design-build solutions, offsite construction offers the unique opportunity to actively plan, diversify, and integrate modern technologies and structural innovations into a regional design platform [40]. Relying upon advanced, technological skill sets that are steeped in innovation and adaptive design, modern manufactured homes will be developed by skilled workers with advanced degrees, clear visions, and adaptive structural solutions [40].

From local partnerships with HAs to manufacturing innovations and bespoke facility development, these skills transition away from one-off residential development to integrative and modular solutions that can be adapted to systematically improve the process of residential construction.

Speed of Delivery, Systems, and Vision: The case study evidence has confirmed that the rate of project delivery can be accelerated as HAs partner with offsite manufacturing companies to develop solutions that leverage the advantages of modular, prefabricated solutions. From schedule planning for installation to component pre-installation and quality inspections, the responsibilities that once required in-depth on-site scheduling and intensive trades negotiation can now be accomplished in a one-stop facility without requiring multiple streams of coordination and planning [43].

Whereas contractor profit margins were once based upon the gap between trades and contracted rates, offsite solutions increase the cost-material transparency, establishing a new standard of oversight and expense mitigation that can be used to improve the overall cost-performance of offsite initiatives [44]. As HAs are not looking at offsite construction as a one home solution and are targeting larger-scale developments, strategic partnerships with offsite professionals, such as those exemplified by LoCal and Swan, have the potential to significantly improve the overall cost basis of the structural delivery process, eliminating many of the intermediary costs and waste streams that permeate the traditional construction industry.

Figure 7 presents an initial proposal for a more strategic housing association approach to OSC projects.

Through this positive feedback loop, it is suggested that by aggregating demand between housing associations, OSC demonstration projects could be built at sufficient scale to allow cost savings, which would then be monitored, with lessons learned and good practice fed back. Such demonstration projects could gradually increase in scale to meet more of an area's needs and to stimulate further investment in manufacturing capacity. Further, if housing needs could be aggregated, perhaps at the city-region or county level, housing associations could work together with offsite firms, local authorities, and other public sectors to deliver more housing through offsite construction and other technologies.

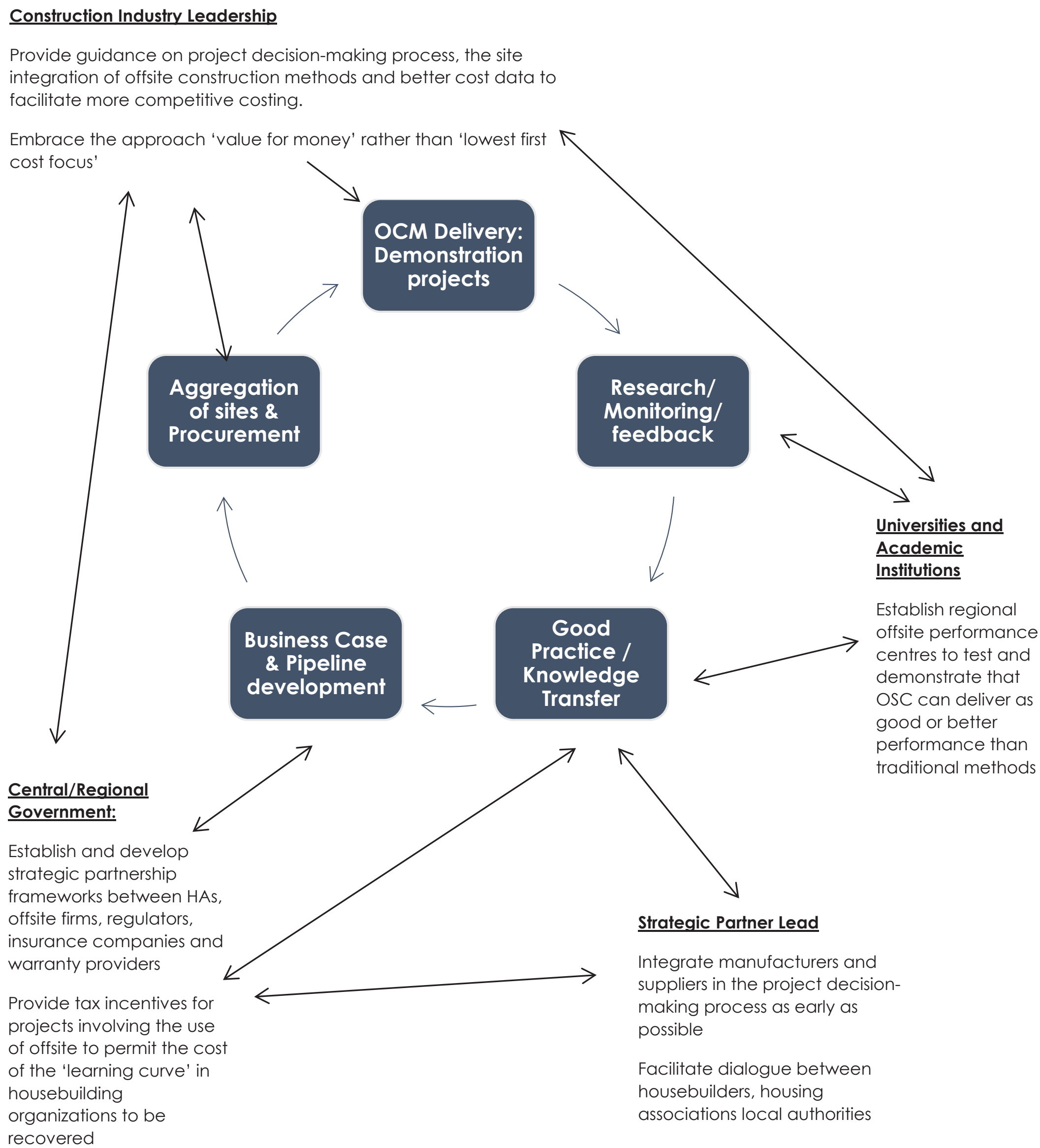

Figure 7. Conceptualized feedback loop for strategic approach for wider adoption of OSC in the HA sector.

This could lead to an OSC sector that becomes more vibrant, robust, thus increasing the resilience of the HA housing sector. In the shorter term, it will allow HAs to build more and higher quality homes that are more energy efficient—providing benefits to their residents and society as a whole.

5. Conclusions

This paper has explored HAs' views on the barriers towards the adoption of OSC, how these compare with the perceptions within the wider housing sector, and whether experience in offsite construction methods affects perception towards offsite construction usage. The evidence from this research indicates cost-related barriers are perceived to be the most significant barriers to OSC use for HAs, followed by the capacity of suppliers and end-user preferences for traditional construction. The study was nevertheless limited to the larger HA developers and to HAs with experience of OSC. Consequently, it is not suitable to consider results as representative of all the views of HAs in England, as the perceptions of the sample may differ from HAs with limited experience in relation to OSC. This is an aspect that could be explored through a larger scale, representative study of HAs across England.

To explore whether experience in OSC methods affects perception towards OSC, survey results were analysed based on two subsets: participants with direct experience and those without. The results revealed some noticeable differences between the perceived barriers of the two sample populations. Further, the population with experience were seen to hold stronger opinions. Neither population held perceptions consistently in keeping with the OSC literature. The perceived barriers of those with experience were more aligned with the wider housing sector. Although based on limited sample sizes, this initial exploration indicates that experience does impact perceptions.

The paper proposes that the conceptualised feedback model is proposed to monitor, capture knowledge and share best practices as HAs commit to accelerating project delivery through strategic partnerships with offsite manufacturing firms, local authorities at a local/regional level that leverage the high-value, high-impact transformation of the housebuilding sector in tangible terms of efficiency, cost, and material savings. It is through a coordinated commitment to a unified pursuit of offsite housing throughout a given region or network of housing associations that will ultimately transition this sector from a one-off, bespoke solution approach to one that will support value-added targets of evolving projects.

Funding: This research was funded by the Royal Insituttion of Chartered Surveys Research Trust Project 517: Procurement and contract strategies for offsite manufacturing within UK housebuilding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the University of Strathclyde.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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Site Selection of Co-Working Spaces under the Influence of Multiple Factors: A Case Study in Hangzhou, China

Weiwu Wang [1,2,*], Jingyi Liang [1] and Jie Niu [1]

[1] Institute of Urban and Rural Planning Theories & Technologies, Zhejiang University, Hangzhou 310058, China; liangjingyi0721@zju.edu.cn (J.L.); niujie1010@zju.edu.cn (J.N.)
[2] Center for Balance Architecture, Zhejiang University, Hangzhou 310058, China
* Correspondence: weiwuwang@zju.edu.cn

Abstract: Co-working spaces (CWSs) have gradually become a new form of spatial economic activity in large cities in China. This not only innovates the traditional office model, but also helps to realize the efficient utilization of office buildings and the sustainable development of office spaces. Taking Hangzhou as a case study, this paper uses big data analysis technologies including Python and ArcGIS to reveal the distribution characteristics of CWSs. From the perspectives of traffic accessibility, business atmosphere, innovation environment, living convenience, and rental cost, we innovatively constructed an indicator system of factors affecting site selection of CWSs. We then conducted an empirical study to reveal the influence mechanism behind different factors. Our conclusions are as follows: (1) CWSs in Hangzhou generally present a multi-center distribution pattern; (2) based on the different degrees of dependence of the target customer groups on resources such as commerce, capital, and information, the factor that has the most significant impact on the site of CWSs is the regional innovation environment, and its weight is 0.3941. The order of importance of other influencing factors is the convenience of life (0.3147), business atmosphere (0.1352), and traffic conditions (0.1171). The cost of rent has the most negligible impact on site selection, and its weight is only 0.0195. We hope that the research can be used to provide a scientific basis for the rational planning and development guidance of CWSs.

Keywords: co-working spaces; sharing economy; site selection; distribution characteristics; entropy method; innovation environment; sustainable development

Citation: Wang, W.; Liang, J.; Niu, J. Site Selection of Co-Working Spaces under the Influence of Multiple Factors: A Case Study in Hangzhou, China. *Sustainability* **2022**, *14*, 2676. https://doi.org/10.3390/su14052676

Academic Editor: Pierfrancesco De Paola

Received: 17 January 2022
Accepted: 22 February 2022
Published: 25 February 2022

1. Introduction

With the development of technologies such as the mobile internet, the internet of things, and big data, the sharing economy, as a new collaborative economy that maximizes value, has gradually replaced the old and closed capital model. Its development has not effectively integrated the market's idle resources, improving the overall utilization of resources, dramatically reducing transaction costs, and fostering new economic forms and consumption concepts, covering areas involving transportation, urban housing, tourism, leisure, and green energy [1–7]. At the same time, the development of the sharing economy and the knowledge-based economy has also significantly changed people's lifestyles and work styles, leading to a continuous increase in the proportion of decentralized, mobile, and independent laborers [8]. In this context, as a new office model that uses shared office space to reduce rental costs and improve space resource utilization, the co-working space (CWS) caters to many small and medium-sized enterprises with its low price, flexible lease period, and intense community atmosphere. With the help of capital, the co-working industry has gradually developed a wave of rapid expansion around the world, and many international enterprises such as WeWork, Regus, and Hub have been born [9]. Major operators integrate vacant office resources on the market through leasing, by leasing out to multiple companies in a subleasing model of "breaking up the whole into parts" after a renovation, while providing a series of diversified value-added services.

The concept of CWS was first proposed by BradNeuberg in 2005. In this space, users not only share the office environment and facilities but also share some information resources, which naturally produces a cooperative relationship [10]. Specifically, CWS is a common area composed of people sharing the same office space, with workers of different occupations. It provides professional facilities and a social communication place, aiming to promote interpersonal relationships and cooperation within the space [11,12]. CWS is also a new type of workplace characterized by an open-space working-environment between the home office and traditional office, which reflects a living atmosphere, spirit, and lifestyle [13,14]. CWS is regarded as an emerging social innovation within the collaborative economy. It provides users with a low-cost office space and an information exchange platform, which helps achieve the sustainable use of office resources. Furthermore, it also plays a crucial role in supporting social and professional interaction and promoting urban innovation and intellectual development [15–17].

Current research of CWSs has mainly concentrated on economic management and space design. In terms of business operation, Capdevila [18] believes that traditional industrial clusters are being replaced by innovative networks composed of networked micro-enterprises, and that CWSs happen to provide the necessary intermediaries and physical platforms for such network activities. Zhang et al. [19] used the business model canvas and found that CWSs advocate community development in the growth strategy. Liang [20] constructed an indicator system for rent influencing factors, proposing that the rent of CWSs is positively correlated with office building facilities, the number of surrounding banks, and regional centrality. In terms of interior space design, Soegoto and Hafandi [21] started with anthropometry and ergonomics, believing that the good design of a CWS is closely related to an increase in its users productivity. Ondia et al. [22] have shown that the barriers and field elements in CWSs have a significant impact on the four working modes of coworking, cooperation, socialization, and learning. Nagarathinam et al. [23] proposed that a CWSs design needs to address users with potentially widely varying thermal comfort preferences. As the design concepts of humanization, intelligence, and environmental protection continue to rise, it also provides new ideas for the development and design of interior furniture in CWSs [24–26].

Location refers to the space of human economic activities, and the development of location theory is closely related to actual economic development. Thunnen's agricultural location theory held that due to the difference in the distance between the land and the urban market, the diverse agricultural costs will have different effects on land rent [27]. Location selection is an economic behavior, and the subjects of location selection make choices under imperfect competition and imperfect information [28]. Weber [29] believes that cost is the basic factor affecting the site selection of industrial enterprises, a factor that is composed of transportation costs and labor costs. Hamilton et al. [30] emphasized how the site selection of enterprises depends on the interaction of organizational management objectives. Some scholars have also pointed out that the main factor affecting the site selection of high-tech enterprises is the regional milieux innovation, while the location choice of manufacturing small and medium enterprises is influenced by a combination of location-specific, personal, and community factors [28,31].

As a new form of spatial economic activity in large cities, the location of CWS can often reflect its commercial preferences. And the distribution characteristics of CWSs have received attention in the literature. Salinger [32] studied the spatial location of CWSs, finding they have prominent cluster distribution characteristics, and most of them are located in urban centers. Mariotti et al. [33] took Milan as an example to explore the distribution characteristics of CWS, as well as their impact on the urban area, and believe that their site model is similar to the service industry in urban areas. Wu et al. [34] studied the geographical distribution pattern of CWSs in Shanghai and found that CWSs are mainly concentrated on the west side of the Huangpu River in the inner ring area. Dianovita and Khoirunurrofik [35] found that the distribution pattern of Jakarta's CWSs is clustered, with the densest sites in the central areas of offices, trade, and services. At the same time, it has been shown that there is a strong relationship between the site of CWSs that consumers frequently visit and the choice of transportation type. However, there are currently few quantitative studies on the multiple factors affecting the location of CWSs.

In this paper, we analyze the geographic distribution of CWSs and the multiple factors that influence the location of CWSs. This will help us to further understand the spatial distribution pattern of the new type of office space and guide the scientific site selection and planning layout of CWSs in urban cities. First, we expound the development of the co-working industry in China and analyze the distribution characteristics of CWSs in Hangzhou as a typical case. Then, we innovatively construct an indicator system of influencing factors from five aspects, including traffic conditions, the convenience of life, regional business atmosphere, regional innovation environment, and rental cost. Finally, we conduct an empirical analysis of CWSs in Hangzhou, and reveal the influence mechanism of different factors on the site selection. As a frontier city for the development of CWSs in China, the conclusions drawn from Hangzhou are also universal across the country. This study is expected to contribute to urban planning by providing a valuable reference for development of the co-working industry.

2. Development of CWSs in China and Related Policy Support

The first CWS in China appeared in 2007 and is located on Yongjia Road, Shanghai. Its purpose is to provide meeting and office space for entrepreneurs in design and art [36]. Based on multiple reasons, such as the rising tide of entrepreneurship, the diversification of demand for new office space, and the transformation of office product forms, the domestic co-working industry entered a period of rapid development in 2015 [37]. Hundreds of companies represented by Kr Space, Ucommune, Mydreamplus, and Nashwork were established in just a few years. CWSs are mainly concentrated in first-tier cities such as Beijing, Shanghai, Guangzhou, and Shenzhen, occupying nearly 80% of the domestic co-working office market share. Furthermore, CWSs have gradually expanded to new first-tier cities such as Chengdu, Changsha, Hangzhou, and Nanjing in recent years.

According to the report on China's co-working market by iiMedia Research Group [38], it can be found that from 2016 to 2019 China's co-working industry was in a stage of rapid development, with an average annual growth rate of over 100%. In 2020, due to the impact of COVID-19, the growth rate of the market dropped significantly. The entire industry has undergone a profound reshuffle, gradually shifting from large-scale expansion to a stage of delicate operation, and the trend of differentiation between brands is apparent. At the end of 2020, the total operating area of CWSs nationwide exceeded 30 million square meters, and the industry market scale reached 136.82 billion yuan. The industry market scale will continue to grow in the next few years, and it is expected to exceed 200 billion yuan by 2022. China is gradually evolving into one of the largest markets in the world. At the same time, according to the relevant data of the Chinese Academy of Social Sciences, the number of newly registered market entities nationwide in 2020 is 27.354 million, an increase of 12.8% over last year. Various industries have entered a period of full recovery after the epidemic [39]. The emergence of numerous new companies has brought about large-scale office demand, which provides the necessary objective conditions for the development of CWSs.

The development of CWSs in China has greatly benefited from the domestic entrepreneurial wave of "mass entrepreneurship and innovation." In September 2015, the State Council issued guidance on accelerating the construction of an innovation support platform [40], in which several key tasks around crowd creation were proposed, encouraging the public and the capital market to provide the platform, financial services, etc. As a particular innovation space, the CWS has developed by leaps and bounds after the policy was promulgated [10]. In addition, one of the most important reasons why the CWS can attract a large number of small and medium-sized enterprises is that it provides value-added services such as industrial and commercial registration. As early as March 2014, the State Council issued a reform plan related to the registered capital registration system [41], in which the minimum registered capital limit for many types of companies was removed. Furthermore, a reform of the registration system for residences (business premises) has been implemented, allowing "one license for multiple sites" and "multiple licenses at one site." The reform of this system has greatly lowered the company's entry barriers and promoted the growth of the number of start-up teams. Furthermore, it has also allowed the CWS to be registered as a residence for multiple companies, something which has become a favorable condition for attracting many micro-enterprises and individual entrepreneurs to settle in.

On the whole, the support from top-level policies has dramatically stimulated the entrepreneurial enthusiasm of the crowd, thereby driving the rapid expansion of the CWS market. At the same time, local governments at all levels have successively introduced a series of preferential tax policies and fiscal subsidy policies, which, to a large extent, have helped the growth of CWSs and their settled enterprises. Taking Hangzhou as an example, the "Outline of the Thirteenth Five-Year Plan for National Economic and Social Development of Hangzhou" proposed to promote Hangzhou and to build an internationally influential internet entrepreneurship and innovation center [42], leading to a large upgrade of the facilities for innovation and entrepreneurship. Specific measures can be divided into the following three categories: the first is the implementation of various recruitment plans to attract high-level talent to settle in Hangzhou with generous material rewards; the second is to focus on the cultivation of innovative companies, with the government granting funds for project subsidies, rent subsidies, and patent sales subsidies to start-ups that settle in crowd-creation spaces, technology business incubators and other technology platforms; the third is strengthening the building economy and increasing the enthusiasm of CWSs in the spatial layout of such buildings by offering rental discounts to companies that settle in key buildings, and implementing a mechanism to link building owners' incentives and financial contributions.

3. Research Method and Data

3.1. Research Area

As one of the cities with the most developed private economies in China, Hangzhou has become a focal city for co-working operators to expand their business. In the past three years, with the rapid rise of the internet economy, the number of enterprises in Hangzhou has maintained rapid growth, with a total of 274,100 new small and micro enterprises. The resulting large-scale office demand provides opportunities for the development of CWSs. The co-working market in Hangzhou has been showing explosive growth, with the supply of CWSs exceeding 300,000 square meters. Overseas co-working enterprises represented by Regus and Servcorp entered Hangzhou earlier and seized market opportunities, while domestic enterprises represented by Kr Space have also accelerated their deployment in Hangzhou after a new round of financing. In addition, a group of local co-working brands in Hangzhou, represented by Will Space, have also emerged on the market.

The research area covers eight administrative districts of Hangzhou, including Shangcheng District, Gongshu District, Xihu District, Binjiang District, Xiaoshan District, Yuhang District, Linping District, and Qiantang District (Figure 1). These administrative districts make up the main urban area of Hangzhou. During acquisition of the data all CWSs were found to be distributed in these eight regions.

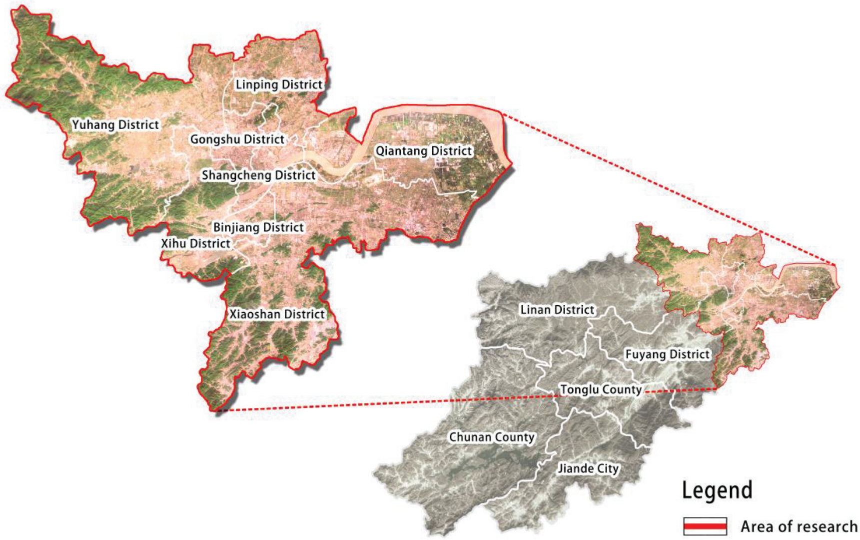

Figure 1. Map of Hangzhou and the research area.

3.2. Research Method

3.2.1. Data Collection

There are three ways to collect data. One is the compilation of publicly available information on the internet. The information of CWSs in this study comes from various office rental websites, such as the "51 banban" website (https://hz.51banban.com/gongwei/ (accessed on 1 December 2021)). As of December 2021, there are 301 CWSs within the research area. The second is to crawl point of interest (POI) data. Second the POI data involved in this research, such as transportation facilities, business facilities, life service facilities, and innovative space facilities are crawled based on the Baidu map open platform using Python. The third method is to crawl web page data, with house-price data in this study obtained through the use of a collector named "Octoparse" that can crawl second-hand housing price information on the "Fang Tianxia" website (https://www1.fang.com/ (accessed on 1 December 2021)). The above data have been screened, deduplicated, inspected, verified, and corrected.

3.2.2. Data Analysis

In Section 4, we use the kernel density analysis tool of ArcGIS to carry out a continuity simulation calculation for the density distribution of the data points of CWSs, which visually reflects the overall aggregation situation in the geographical space. It can be used to study the distribution characteristics of CWSs in Hangzhou.

In Section 5, three data analysis methods are used. One is to use the buffer tool of ArcGIS to establish a circular buffer area centered on the data points of CWSs and filter the number of transportation facilities and living service facilities located nearby, this is used to analyze the traffic conditions and living convenience of CWSs. The second is to use the grid tool of ArcGIS to divide the 1 km $\times$ 1 km grid of the research area, the density of business facilities and innovative facilities within the unit grid is then calculated to analyze the regional business atmosphere and innovation environment. The third method is to use the buffer tool of ArcGIS to filter out the surrounding communities and calculate the average second-hand housing prices of these communities, to analyze the land price cost of CWSs.

3.2.3. Indicator Weight Calculation

In Section 5, we use the entropy weight method to calculate the weights of the influencing factors of Hangzhou CWSs' site selection. The entropy weight method determines the weight of each indicator according to the amount of useful information provided by the observation value of each index, and then establishes a multi-index evaluation model based on entropy, so as to obtain a more objective evaluation result. The research on the entropy weight method is relatively mature. It has been widely used in the site analysis of hotels, banks, passenger stations, logistics centers, etc. [43–48], and its feasibility is verified by examples. In the study of factors influencing the site selection of CWSs, it is assumed that there are n indicators and m evaluation objects to form the original data matrix:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

In the formula, $i = 1, 2, 3, \ldots, m$; $j = 1, 2, 3, \ldots, n$; x_{ij} is the corresponding value of the i-th evaluation object under the j-th indicator.

Standardize the data of each indicator, assuming that the value of the standardized data of each indicator is:

$$Y_{11}, Y_{12}, Y_{13}, \ldots\ldots, Y_{mn}$$

So,

$$Y_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)}$$

Calculate the characteristic proportion of the i-th evaluation indicator under the j-th indicator:

$$P_{ij} = \frac{W_{ij}}{\sum_{i=1}^{m} W_{ij}}, \sum_{i=1}^{m} W_{ij} > 0$$

If $P_{ij} = 0$, define $\lim\limits_{P_{ij} \to 0} P_{ij} ln P_{ij} = 0$. Calculate the information entropy of the j-th indicator:

$$E_j = -\mathrm{k} \sum_{i=1}^{m} P_{ij} \cdot ln P_{ij}$$

In the formula, k is the coefficient of entropy, usually k = 1/lnm, and the weight of indicator corresponding to each influencing factor can be further obtained by the following formula:

$$Z_j = \frac{1 - E_j}{\sum_1^n 1 - E_j}$$

4. Distribution Characteristics of CWSs in Hangzhou

According to quantitative statistics (Table 1), most CWSs are located in the relatively mature downtown area of Hangzhou. Among these, Gongshu District has the largest number of CWSs, followed by Binjiang District, Xihu District, and Shangcheng District, with more than 50 spaces. Yuhang District, Xiaoshan District, and Qiantang District in the periphery have few, while Linping District has the least number of spots, and the difference is noticeable. In comparison, the Gongshu District, Shangcheng District, and other central urban areas, based on the advantages of the complete transportation network, rich service facilities, convenient life, and incentive systems formed by long-term development experience, have attracted more CWSs to settle in. However, along with the comprehensive development of new urban areas, the capital, enterprises, and human resources of Yuhang District, Xiaoshan District, and other peripheral urban areas have gradually accumulated. This also drives more and more co-working enterprises to choose sites in these areas.

Table 1. Statistics on the number of CWSs in Hangzhou.

Administrative District	Number of CWSs	Percentage
Shangcheng District	51	16.89%
Gongshu District	63	20.86%
Xihu District	58	19.21%
Binjiang District	61	20.53%
Xiaoshan District	21	6.95%
Yuhang District	23	7.62%
Linping District	6	1.99%
Qiantang District	18	5.96%
Total	301	100%

We used the kernel density analysis tool in ArcGIS software to analyze the acquired geographic data points of CWSs and "natural discontinuities" to classify and identify them based on the inherent natural grouping in the data, allowing us to maximize the difference between the various types [49]. The analysis result is shown in Figure 2. The redder the color, the higher the concentration of CWSs. Overall, the distribution of CWSs in Hangzhou presents a multi-center pattern. Among them, the three core business districts of Wulin CBD, Huanglong CBD, Qianjiang New Town CBD, and Binjiang High-tech Zone are the areas with the highest concentration of CWSs. Sub-level agglomeration centers have appeared in Qianjiang Century City CBD, Future Sci-Tech City CBD, Xiasha Higher Education Park, and other areas. The supply of high-quality office buildings in these areas is relatively sufficient, and there are a large number of business offices, hotel apartments, conventions, and cultural and entertainment facilities, which not only provide high-quality building space but also create an overall atmosphere of strong entrepreneurial vitality, something that is convenient for the development of modern business offices [50]. In addition, there is also a tiny fraction of CWSs distributed in featured towns, schools, and communities.

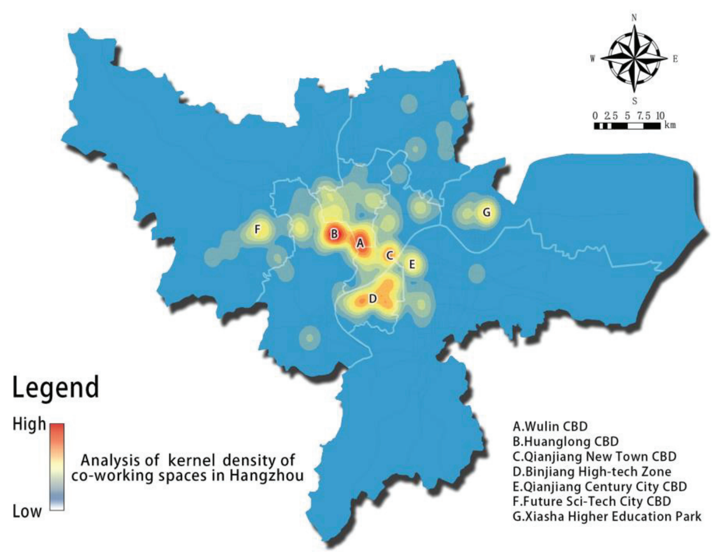

Figure 2. Analysis of kernel density of CWSs in Hangzhou.

5. Analysis of Factors Affecting the Site Selection of CWSs

5.1. Influencing Factors and Indicator Selection

Through the above analysis of the distribution characteristics of CWSs in Hangzhou, we found that most CWSs are located in the old urban areas of Hangzhou, which have denser transportation networks and public transportation stations, as well as a large number of living service facilities. The agglomeration centers of CWSs are also geographically consistent with the major business districts in Hangzhou, which have a strong business atmosphere. In combination with other scholars' research, we also found that the location of office space is closely related to transportation convenience and rent [34,51]. Moreover, CWS is a form of commercial service that meets the needs of users as much as possible. According to a report on China's co-working market by iiMedia Research Group [38], it can be found that, among the users of CWSs, people engaged in the internet, finance, cultural and creative industries accounted for a relatively high proportion. These industries often also put forward higher requirements for business cooperation and innovation activities in the region. Therefore, we determined the factors affecting the site selection of CWSs into five aspects, including traffic conditions, the convenience of life, regional business atmosphere, regional innovation, and rental cost.

5.1.1. Traffic Conditions

Urban road traffic has vital flexibility and convenience, and the layout of the urban road system has a robust guiding role in the direction of urban development. The road transportation network is the key to gathering various production factors such as people flow, financial resources, and information. It has also become an important consideration factor affecting the site selection of CWSs because the efficient and convenient road network can reduce business travel time and increase the occupancy rate of office space. At the same time, the public transportation system represented by subway and bus has the characteristics of large capacity, safety and punctuality, low prices, and green environmental protection, which can effectively break the geographical area restrictions and have a profound impact on the land use structure, the distribution of residences, and real estate development along the subway and bus lines [52–54]. Zhen et al. [55] empirically analyzed how rail transit interchange stations have a positive guiding role in the location of office spaces, and found that, as the coverage range of interchange stations expands, the number of high-level office clusters covered by them also gradually increases. Therefore, the indicators selected in this study in terms of traffic conditions mainly include main urban roads and public transportation (subway and bus).

5.1.2. The Convenience of Life

The convenience of life is the fundamental aspiration of urban people. With the current blurring of the boundaries between work and life, the convenience of life service facilities has also become an essential factor in the choice of office space for office workers, which in turn affects the site of CWSs. In terms of the selection of indicators for the convenience of life, Ying et al. [56] chose catering, education, medical care, culture, leisure, and entertainment facilities to evaluate of the convenience of residents in the main urban area of Wuhan. Zhang et al. [57] found in the analysis of Beijing urban office space satisfaction that the spatial distribution characteristics of the fulfillment of the office crowd are closely related to the spatial distribution of commercial supporting facilities. Based on this, combined with the features of the user population of CWSs, the indicators selected in this study for the convenience of life mainly include catering facilities, recreational facilities, and medical facilities.

5.1.3. Regional Business Atmosphere

The urban business district is a product of the developed city economy, and it is also the concentrated area of the city's high-end productive service industry, with a strong business atmosphere. In particular, there are a large number of high-quality business office buildings in the area, making it an excellent choice for the location of CWSs. Start-up entrepreneurs can take advantage of low-cost CWSs' rental fees, enjoy perfect office facilities and high-quality meeting spaces in the urban business district, thereby enhancing their enthusiasm for office work, and even contributing to successful business negotiations with partners. At the same time, users of the CWSs can also participate in frequent training, salons and other activities held in the business district, so as to learn professional business knowledge and expand their social circles. As a result, more and more CWSs sprout in business centers. Therefore, an intense business office atmosphere has also become the site preference of CWSs. This study selects the number of business office buildings within a specific range as an indicator to measure the regional business atmosphere.

5.1.4. Regional Innovation Environment

From the perspective of a static environment, the regional innovation environment represents the physical environment that carries the transportation, public services, information network and other infrastructure required for innovation activities. Moreover, the innovation environment is also a dynamic development process. It is a relatively stable cooperation and communication system that is formed based on the long-term formal or informal relationships between innovation entities [58]. Due to its entrepreneurial incubation function, the CWS can almost be regarded as a new type of innovative cyberspace node that allows different participants to collect, link, and share information. The innovation environment affects the innovation activities of CWSs to different degrees. In the study of regional innovation environments, Zhao et al. [59] analyzed Hangzhou's innovation system at the two levels of innovative enterprises and innovation parks. Innovative enterprises cover industries such as internet, technology, e-commerce, and cultural creativity, while innovation parks are physical carriers of industrial space gathering, including high-tech zones and creative blocks. To a certain extent, the number of innovative enterprises represents the scale of innovation activities and can also reflect the vitality of the innovation environment in the region. Innovation parks, on the other hand, represent the physical environment that carries innovation activities. Therefore, this study selects the density of innovative enterprises and innovation parks within a specific range as indicators to measure the innovation environment of the area where the CWS is located.

5.1.5. Rental Cost

The operating costs of CWSs mainly include property rent, decoration costs, and water, electricity, and labor costs in operation. At this stage, most co-working operators adopt the business model of "low-cost overall leasing in, and high-priced leasing after segmentation." The most direct income comes from the leasing difference earned as a "second landlord." Therefore, property rent has become a key factor affecting the site of CWSs. Due to the privacy of property rent, we cannot obtain this data through public information or questionnaires, so this study uses land price as a measure. The land price is essentially the capitalized land rent, which forms the basis of the property rent [60]. The urban bid rent model established by Alonso shows that different land use properties form different bid rent curves, among which commercial and office land are most sensitive to changes in land prices [61]. Moreover, since the land price in China is usually set for a certain district of the city, it cannot accurately represent the land price of CWSs. A large number of domestic empirical studies have shown that there is a positive correlation between land prices and housing prices [62–65]. Therefore, this study uses the average housing prices within 1 km of CWSs as a substitute.

In summary, on the basis of theoretical research and combined with existing research results, we initially selected five types of influencing factors and ten specific evaluation indicators and formulated statistical radii according to the service radius standards of different facilities, so as to establish an indicator system of factors affecting the site selection of CWSs (Table 2).

Table 2. Indicator system of factors affecting site selection of CWSs.

Influencing Factor	Evaluation Indicator	Statistical Method	Radius (m)	Evaluation Unit	Indicator Description
Traffic conditions (A1)	Main roads of city (B1)	1/0	500	1/0	The accessibility of urban road traffic
	Subway station (B2)	quantity	1000	/	The convenience of the subway
	Bus stop (B3)	quantity	500	/	The convenience of the bus
The convenience of life (A2)	Catering facilities (B4)	quantity	500	/	The convenience of catering facilities
	Recreational facilities (B5)	quantity	500	/	The convenience of recreational facilities
	Medical facilities (B6)	quantity	1000	/	The convenience of medical facilities
Regional business atmosphere (A3)	Business office building (B7)	density	1000	/km^2	The convergence of the business industry in the region
Regional innovation environment (A4)	Innovative enterprise (B8)	density	1000	/km^2	The concentration of innovative enterprises in the region
	Innovation park (B9)	density	1000	/km^2	The concentration of innovation parks in the region
Rental cost (A5)	Property rent (B10)	land price	1000	yuan/m^2	Land price (replaced by average housing prices) affects rental cost

5.2. An Empirical Study on Site Selection of CWSs in Hangzhou

5.2.1. Analysis of Each Influencing Factor

Based on the indicator system of factors affecting CWSs' site selection as mentioned above, a comprehensive evaluation of the site of 301 CWSs in Hangzhou was carried out using ArcGIS software. This can be inferred by calculation:

(1) By analyzing the traffic conditions of CWSs in Hangzhou, it is found that 94.02% of CWSs in the research area are located within 500 m of the city's main roads (Figure 3a); 87.71% of CWSs are located within 1000 m of the subway station, and the number of subway stations around CWSs is 1.8 on average (Figure 3b); 98.67% of CWSs are located within 500 m of the bus stop, and the number of bus stops around CWSs is 6.3 on average (Figure 3c). It can be concluded that CWSs in Hangzhou generally have high accessibility of urban road traffic, and the public transportation around them is also very convenient.

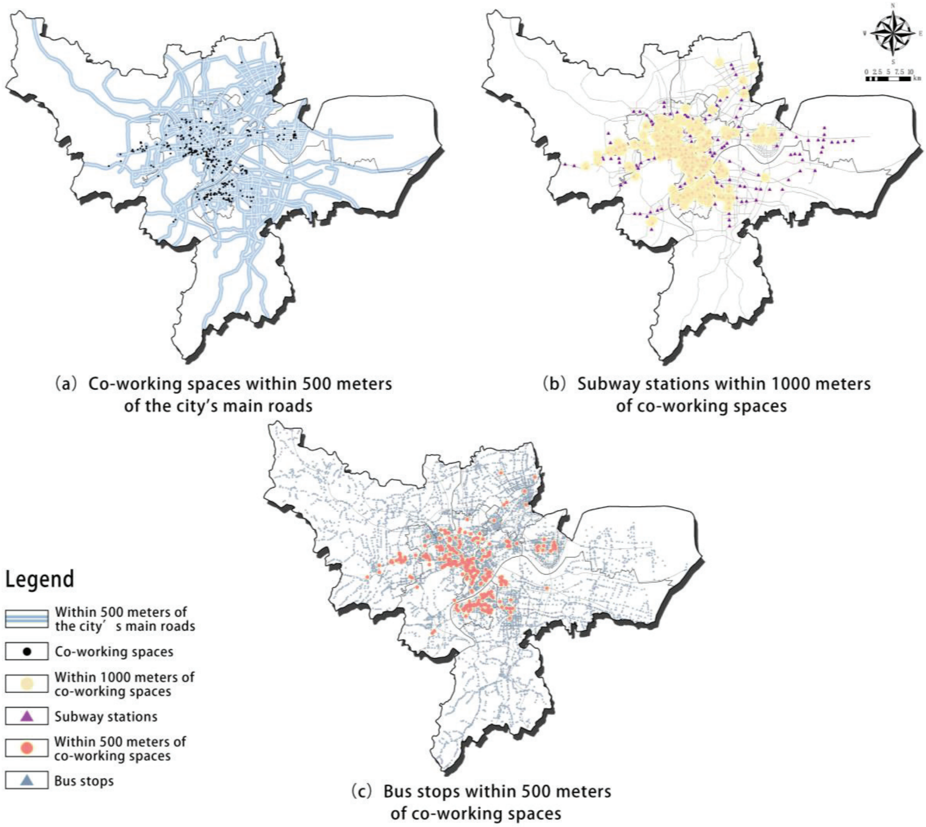

Figure 3. Analysis of the traffic conditions of CWSs in Hangzhou. (**a**) CWSs within 500 m of the city's main roads, (**b**) Subway stations within 1000 m of CWSs, (**c**) Bus stops within 500 m of CWSs.

(2) We analyzed the convenience of life of CWSs in Hangzhou and found that there are an average of 152 catering facilities (Figure 4a) and 22 recreational facilities (Figure 4b) within 500 m of CWSs; there are an average of 26 medical facilities within 1000 m of CWSs (Figure 4c). These facilities are rich in variety, covering catering, entertainment, leisure, culture, sports, medical care, etc., and so can meet the basic life needs of office workers.

(3) We analyzed the regional business atmosphere of CWSs in Hangzhou by calculating the density of business office buildings within a specific range (Figure 5) and found that most CWSs are located in areas with dense business office buildings. Within 1 km^2 of CWSs, the average density of business office buildings is 14/km^2, and the highest density is 52/km^2. It can be seen that the business facilities near CWSs are highly clustered, and the business atmosphere is relatively strong.

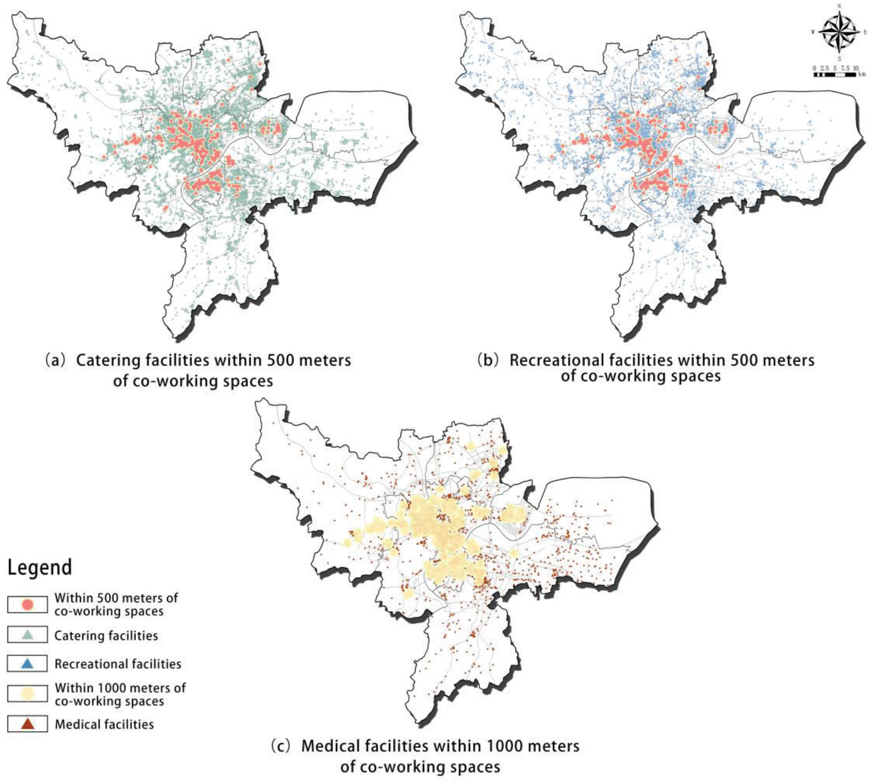

Figure 4. Analysis of the convenience of life of CWSs in Hangzhou. (**a**) Catering facilities within 500 m of CWSs, (**b**) Recreational facilities within 500 m of CWSs, (**c**) Medical facilities within 1000 m of CWSs.

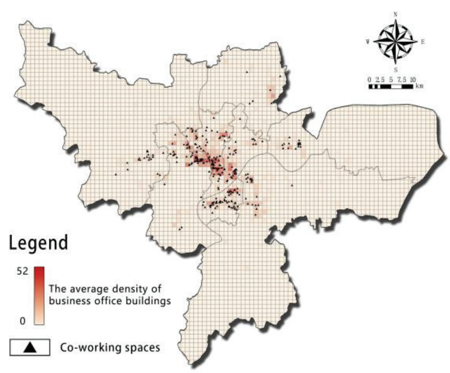

Figure 5. Analysis of the regional business atmosphere of CWSs in Hangzhou.

(4) Based on two evaluation indicators (innovative enterprise density and innovation park density), we analyzed the regional innovation environment of CWSs in Hangzhou. We found that within 1 km^2 of CWSs, the average density of innovative enterprises is 29/km^2, and the highest density can reach 288/km^2 (Figure 6a); the average density of innovation parks is 1.2/km^2, and the highest density can reach 8/km^2 (Figure 6b). It can be concluded

that the area where a CWS is located forms a strong innovation agglomeration effect and a powerful innovation atmosphere.

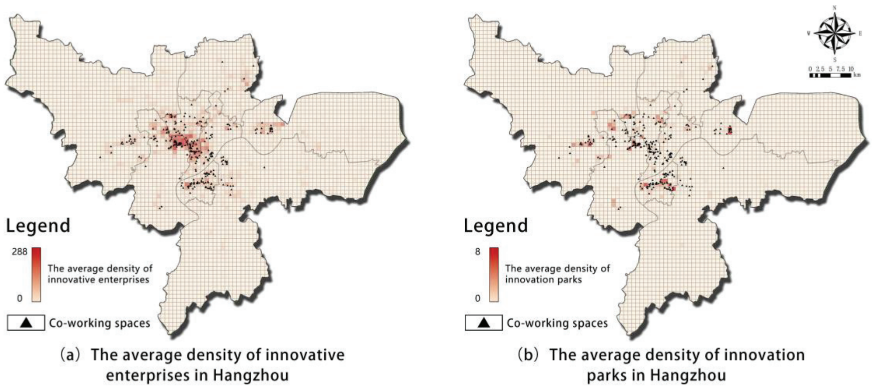

Figure 6. Analysis of the regional innovation environment of CWSs in Hangzhou. (**a**) The average density of innovative enterprises in Hangzhou, (**b**) The average density of innovation parks in Hangzhou.

(5) We infer the level of the rental cost of CWSs by analyzing the surrounding housing prices (Figure 7). It can be seen that the housing prices in the area where CWSs are located are at a relatively high level. Within 1000 m of CWSs, the average price of second-hand housing in the community is as high as 44,437 yuan/m^2. To some extent, this can reflect the preference of CWSs to be located in areas with high land prices and high rental costs.

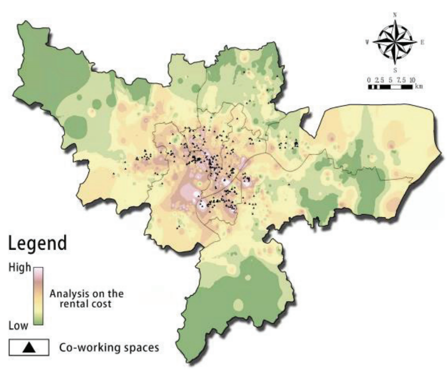

Figure 7. Analysis of the rental cost of CWSs in Hangzhou.

5.2.2. Weight Calculation of Each Influencing Factor

Based on the statistical results of 301 CWSs, a multi-indicator evaluation model based on entropy was established, and the weights of different influencing factors in the site selection of CWSs in Hangzhou were calculated (Table 3). Among the five influencing factors, the regional innovation environment factor has the most prominent weigh at 0.3941, this is followed by the convenience of life, regional business atmosphere, and traffic conditions, with weights of 0.3147, 0.1352, and 0.1171, respectively. The least influential factor is rental cost, which is only 0.0389. Among the ten specific evaluation indicators, the indicator "Density of innovative enterprises within 1 km × 1 km" has the highest weight at 0.2466; the indicator "Whether it is within 500 m of the city's main roads" has the lowest weight, only 0.0195.

Table 3. Weights of different factors influencing the site selection of CWSs in Hangzhou.

Influencing Factor	Evaluation Indicator	Weight
Traffic Conditions (A1) (0.1171)	Main roads of city (B1)	0.0195
	Subway station (B2)	0.0596
	Bus stop (B3)	0.0380
The convenience of life (A2) (0.3147)	Catering facilities (B4)	0.0904
	Recreational facilities (B5)	0.0808
	Medical facilities (B6)	0.1435
Regional business atmosphere (A3) (0.1352)	Business office building (B7)	0.1352
Regional innovation environment (A4) (0.3941)	Innovative enterprise (B8)	0.2466
	Innovation park (B9)	0.1475
Rental cost (A5) (0.0389)	Property rent (B10)	0.0389

6. Discussion and Suggestions

When a co-working company begins to expand its business in a certain city, its executives will choose the location of CWSs. We attempt to explore the factors that influence the site selection by analyzing the distribution characteristics of existing CWSs. From the above research results, we find that the effects of several influencing factors on site selection are significantly different, and the reasons for these differences are discussed below.

The factor of regional innovation environment plays a vital role in the site selection of CWSs in Hangzhou, which intuitively reflects the high degree of dependence of the CWS on innovative elements. This relationship is closely related to the innovative characteristics of the CWS itself, because, to a certain extent, it can be regarded as an incubator for innovative enterprises and innovative talents. Therefore, based on the self-development of the CWS and the growth of its users, major co-working brand operators will prefer to choose sites in an urban area with an intense atmosphere of innovation and entrepreneurship. As one of the most prosperous and developed cities in China's internet industry, Hangzhou has significant advantages in terms of innovation conditions, which further magnifies the impact of the innovation environment on site selection.

The convenience of life has a high degree of influence on the site selection, which is inseparable from the user population of spaces. Since the CWS was initially established to serve individual workers and micro-enterprises, the age structure of the user population is often mainly young people. Most of them are still in the early stage of entrepreneurship, so there is a more robust demand for catering, leisure, entertainment, and other service facilities, making this factor particularly important.

The regional business atmosphere and traffic conditions have relatively little impact on the site selection. In terms of regional business atmosphere, office buildings in the core business districts of cities are often concentrated, and the business atmosphere is intense. However, the vacancy rate of buildings in these areas is relatively low, which causes difficulties for co-working operators to lease large-scale office space. In addition, some industrial parks, universities, and residential communities can also provide the space conditions required for co-working. Therefore, business office buildings are not the only resident of CWSs, and the influence of the regional business atmosphere factor is not strong. In terms of traffic conditions, compared to main roads of the city, public transportation based on subway and bus has a more significant impact on the site selection. This is mainly due to the dense public transportation network in the main urban area of Hangzhou where commuting by public transportation is the first choice for CWSs' users.

Rental cost is the most minor factor affecting the site selection, something which can be attributed to the diversified profitability of CWSs. Although the most direct income of CWSs comes from the lease price difference, many co-working enterprises have explored new value-added derivative services after years of development, these include brand franchises, membership services, equity investment, and financial training. These diversified value-added service revenues help break through the original profitability bottleneck. Therefore, rental cost is no longer a key factor affecting the site selection of CWSs.

Through this research, we think the following suggestions can be considered in the site selection of CWSs: (1) Before selecting a site, it is necessary to evaluate the dependence of target users on business, capital, information and other resources. Co-working operators need to grasp the guidance of regional policies, so as to create more investment and development opportunities for start-ups. (2) Urban CBD is the preferred choice for the site selection of CWSs. It not only has a good economic effect on office buildings and can continuously attract talents and businesses, but also has multiple public transportation facilities and living service facilities in the area, which can well meet the needs of employees' commuting and daily life. (3) Nowadays, a number of second and third tier cities have formed several powerful technological innovation clusters while showing great economic vitality. If CWSs are located in these clusters which, by including places such as internet industrial parks and higher education parks, have a strong atmosphere of innovation, it will help to form a benign interaction between the CWSs' users and surrounding high-tech enterprises, thereby accelerating the transformation of technological achievements. (4) With the blurring of the boundaries between work, life, and entertainment, the site of CWSs should also consider their integration with co-living spaces and commercial spaces, relying on the vibrant atmosphere of youth apartments, hotels, shopping centers, and other areas to attract and exploit potential users. On this basis, CSW operators can adopt a diversified profit model to further integrate land, corporate, and community resources, thereby expanding the industrial chain.

7. Conclusions

To some extent, the original intention of the CWS was to innovate and supplement the traditional office leasing model and help promote the inventory and transformation of office buildings. More and more practices have also shown that, as a new form of spatial economic activity, CWS has played an essential role in the development of the regional economy and the revival of urban space. In the new round of urban district renewal, CWS can rely on its comprehensive professional office services to quickly focus on social capital and attract talents. It not only realizes the sustainable use of resources, but also generates diversified needs, thereby continuously improving the economic benefits of surrounding areas.

Based on previous research, we innovatively proposed an indicator system for the influencing factors of CWSs' site selection and conducted an empirical analysis. This study takes CWSs in Hangzhou as the research object and explores their distribution characteristics and influencing factors. The results show that CWSs in Hangzhou generally present a multi-center distribution pattern, gradually spreading from the central urban area to the peripheral regions. Based on the development positioning and customer needs of different types of CWSs, the site is also affected by various indicators. The most crucial factor is the regional innovation environment, followed by the convenience of life, regional business atmosphere, and traffic conditions, while rental cost has the most negligible impact on site selection.

In addition, this study has certain limitations. First, this study only explores the factors affecting the site selection of CWSs in Hangzhou, and the selected sample size is limited, with particular geographical characteristics. It is necessary to expand the scope of research further and conduct comparative verification of the site selection system for CWSs in different cities. Secondly, since the CWS industry has not yet formed a complete development system in China, this study only combines the relevant research literature and the distribution characteristics of CWSs in the selection of influencing factors. The completeness of the weight needs to be further verified. Therefore, the perspectives of experts, CWSs' founders and users should be introduced through questionnaires and interviews in future research, so that more scientific indicators and variables underlying influencing factors can be selected. Furthermore, due to the limited availability of data, this study did not evaluate the success of CWSs' site selection. Therefore, performance reports or occupancy rates for individual sites can be introduced in micro-scale studies to indicate that the site selection is successful.

Author Contributions: Conceptualization, W.W. and J.L.; methodology, W.W.; data collection, J.N.; data analysis, J.L.; validation, W.W. and J.N.; model, J.L. and J.N.; writing—original draft preparation, J.L., J.N. and W.W. W.W. are responsible for future questions from readers as the corresponding author. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The National Natural Science Foundation of China, grant number 51578482.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data are not publicly available due to privacy. The data presented in this paper are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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Determinants of the Economic and Financial Feasibility of Real Estate Development Projects: A Comparative Analysis between Public and Private Development Projects in South Korea

Heecheoul Shim and Jaehwan Kim *

Department of Real Estate Studies, Kongju National University, Yesan-gun 32439, Korea; sim@kongju.ac.kr
* Correspondence: jaehwan@kongju.ac.kr; Tel.: +82-41-330-1402

Abstract: We analyse the factors involved in the selection of a development site to secure the economic feasibility and profitability of a public development real estate project through a comparative analysis with private development projects. Logistic regression was used as the analysis method. In the case of public development projects, whether or not the investment screening passed was used as a dependent variable, and in the case of private development projects, the successful bid rate was used as a dependent variable. Independent variables were selected based on prior research on variables suitable for the purpose and situation of the project. The results show that the greater the total development costs of a public development project and the greater the size of a private development project, the greater the rate of approval and bidding success. For public projects, the rate of approval decreases when there are several subways, train stations, and supermarkets; however, this is not the case for private projects, owing to differences in development methods and project purposes. From a public standpoint, the balanced regional development, revitalisation of old city centres, and implementation of social overhead capital projects in neighbourhoods lacking infrastructure have a strong influence. From a private sector perspective, the mobile/resident population, modification in extra demand, and feasibility analysis have a strong influence. In sum, if the private sector avoids large-scale supermarket projects, they can be conducted as public development projects to enhance residents' quality of life and revitalise the regional economy. Researchers should examine what could be benchmarked in the private sector in the operational stage and explore ways to maximise profitability and reduce financial burden.

Keywords: public development project; private development project; investment appraisal; location suitability; project feasibility analysis

Citation: Shim, H.; Kim, J. Determinants of the Economic and Financial Feasibility of Real Estate Development Projects: A Comparative Analysis between Public and Private Development Projects in South Korea. *Sustainability* **2022**, *14*, 2135. https://doi.org/10.3390/su14042135

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 28 December 2021
Accepted: 8 February 2022
Published: 13 February 2022

1. Introduction

1.1. Background and Purpose

Studies have been conducted on real estate development projects concerning the similarities and differences between public and private development projects by country and time of development. If there are no significant differences between these two types of projects, it would be difficult to identify a reason for dividing them according to the project type [1]. For a private development project, to maximise financial return, the project is implemented by establishing detailed and specific strategies at the operation stage, along with identifying indicators for the selection of the development site. For public development projects, the development entities primarily focus on areas associated with total project cost, in which most resources are invested; however, there are also in-depth analyses on the adequacy of development project site selection and the operating expenses arising in the operational stage [2]. In fact, the feasibility assessment—a procedure necessary to initiate a public development project in South Korea—has different impact ranges in demand and benefits, depending on the project site and the economic feasibility analysis stage; it also includes the total project cost and operating expenses over 30 years [3,4]. This process indicates that the total project cost at the construction stage is not the only major project determinant. Additionally, since most of the financial resources for a public development project are covered by tax income, there is a pressing need to consider the rate of return, which is similar to the perspective of the private sector in terms of project site selection and operation. This is because, in the case of a development project for a public facility that is continuously in deficit in the operating stage, when analysed over 30 years (i.e., the length of time used for calculation in the economic feasibility analysis), the results will show a negative impact on the local government's fiscal soundness. In fact, 21 public real estate development projects in South Korea have had an annual operating deficit of over KRW 5 billion [5].

For some public development projects that involve public interest and cannot be developed by the private sector, operational deficits may be inevitable. However, there are many other cases of public development projects where this is not the case. Therefore, by not considering the profitability aspect of the project—such as the geographic and environmental conditions of the development site and the operational plans, even when income generation is possible—the overall fiscal soundness of the country can deteriorate, and the project can run in a neglectful manner [6]. Pushing for indiscriminate development without considering competing and similar facilities for public development projects may lead to intrusion into the private sector and concerns about duplicate investment in a facility. Consequently, this approach only results in the unnecessary division of the facility within the region without an increase in total demand while incurring additional costs. Therefore, in selecting a development site for a public development project, it is necessary to implement a project based on the understanding of the competing facilities or the surrounding environment, which are considered for private development projects [7]. Specifically, for large-scale public development projects, there is an unavoidable increase in costs in proportion to the scale of the project. That is, the larger the total project costs are, the more important it is to investigate the status of the environment and establish a development plan for project site selection.

Therefore, it is important to understand the determinants for the selection of a development site and the differences from private development projects to ensure the validity of project site selection [8]. The feasibility study and Central Investment Appraisal, which are preliminary administrative procedures for large-scale public development projects, present only the analysis results and appraisal for the planned project, rarely considering the adequacy of a location as a development site [7].

In this study, an analysis model is constructed as follows. A comparative analysis is performed between the public and private development projects, and the implications of the findings are presented. First, among the administrative procedures for public development projects in South Korea, we analyse those that have been requested to undergo the Central Investment Appraisal for large-scale projects over five years. Among these projects, those that were recommended for additional review for location suitability and consideration of environmental factors, such as similar and competing facilities, are judged to be projects closely matching our purpose. We investigate environmental factors and conditions and identify the factors that affect success in the Central Investment Appraisal.

Second, among the indicators that determine the business feasibility of a private development project, environmental factors around the development project site are substituted and the development site selection method is explored, as well as the measures for ensuring higher profitability and economic feasibility. By comparing the results with those for a private development project, we revise and supplement the research on the determinants of successful bidding for insolvent project financing (PF) projects conducted by Shim and Kim [9] to determine the characteristics of project sites for the business sites that underwent the bidding process in the private sector. To this end, as in the analysis method for public development projects, we derive the determinants for successful bidding in private development projects by considering the environmental factors related to location suitability.

Third, based on the results of the two analyses, we conduct a comparative analysis of public and private development projects and present measures to improve economic feasibility and profitability and their implications by using development project site selection—an area that has received little attention in relation to public development projects.

1.2. Scope

Through the comparative analysis of public and private development projects, the common points and differences between the two types of development projects are analysed in terms of project site selection with the scope of improving operating balance and increasing demand, which have been largely overlooked in the public sector; thus, the measures to ensure the economic feasibility and financial feasibility of public development projects are explored. In particular, since the public and private sectors have different objectives and business development methods, it is important to achieve a balance. We provide basic data for the effective operation of public facilities and to improve the Central Investment Appraisal system. First, among the public development projects, undergoing a Central Investment Appraisal from 2016 to 2019 was a preliminary procedure for large-scale projects in South Korea. Among these, 117 projects [10] were recommended for additional review in terms of location suitability and consideration of environmental factors, such as similar facilities and competing facilities. We investigate environmental factors and conditions, such as basic infrastructure development and environmental factors within a 5-km radius [11], as well as competing facilities. We identify the factors that lead to Central Investment Appraisal success and discuss their implications. For a private development project, the main factors related to the environmental aspects around the project site, along with the indicators that determine the business feasibility of a project before implementation, are examined. We thus identify the determinants for the site selection of private development projects, the selection methods for the development site that need to be considered in public development projects, and the measures that increase profitability and economic feasibility. By comparing private and public development projects, we revise and supplement the research on the determinants of successful bidding for insolvent PF projects conducted in a previous study [9], and among the 484 sites of insolvent PF projects, we analyse the 32 business sites [12] determined by the Korea Asset Management Corporation (KAMCO) that underwent a bidding process in the private sector. Specifically, we derive the factors that lead to successful bidding for private development projects, considering environmental factors within a 5-km radius (Table 1).

Table 1. Model.

Project Type	Description
Public development project	• We identify and classify the 117 project sites that have been notified of the appraisal results in relation to the location suitability among those that underwent Central Investment Appraisal from 2016 to 2019. • We identify the environmental factors related to project characteristics and site selection based on previous studies. • We conduct regression analysis based on the approval status of the investment appraisal. • We identify factors that affect the approval of the investment appraisal and derive implications and conclusions.
Private development project	• Among the 484 sites of insolvent PF projects, the 32 project sites determined by the Korea Asset Management Corporation restored for normalisation that underwent bidding in the private sector are identified and organised. • The factors related to project site selection are similar to those for public development projects in previous studies. • We conduct regression analyses based on the bidding success status of the project site. • We identify the factors that affect the bidding success and derive implications and conclusions.
Comparative analysis	• Through a comparative analysis of the analysis results for each project type, common points and differences, as well as the implications for economic feasibility and financial profitability are derived.

2. Theoretical Background

2.1. The Economic and Financial Feasibility of a Development Project

An economic feasibility analysis was conducted to maximise the total utility by the efficient allocation of limited resources, with nationwide considerations rather than from the viewpoints of individual businesses. The social benefits received by beneficiaries and social costs were estimated to evaluate social investment efficiency. The target projects for economic feasibility analysis are public facilities, called social infrastructure, including social overhead capital such as roads, railroads, airports, ports, water resources, water supply and sewage, and tourism facilities, which are development projects in the public sector [3]. Regarding the methods of evaluating economic feasibility, decisions are made based on comprehensive considerations, including the benefit/cost (B/C) ratio, the net present value (NPV), and the internal rate of return (IRR). The B/C ratio, which is mainly used as an indicator of economic feasibility in South Korea, is the ratio of the discounted amount of total benefits to total costs; if this value is greater than or equal to 1, it is considered that economic feasibility has been achieved.

The B/C ratio can be derived using the following equation:

$$\text{B/C Ratio} = \sum\nolimits_{t=1}^{n} \frac{B_t}{(1+r)^t} / \sum\nolimits_{t=1}^{n} \frac{C_t}{(1+r)^t},$$

where B_t is the social benefit at time t, C_t is the cost at time t, r is the social discount rate, and n is the analysis period or the duration of the facility project. That is, a benefit–cost analysis is conducted by measuring and comparing the difference between the social benefits from using the applicable facility by an individual user with the number of users and costs (i.e., the total expenses required for the construction and maintenance of the applicable facility). At this time, social costs can be divided into initial project costs and operational maintenance costs. Project costs include not only construction and land acquisition costs but also opportunity costs, considering the loss of benefits that could have been enjoyed if the best alternative was selected. In South Korea, the social discount rate of the economic feasibility analysis is applied at a uniform rate of 4.5% in all cases, and the analysis was performed considering the operating costs over 30 years [5].

A financial feasibility analysis is also called a business feasibility analysis or profitability analysis. It is conducted by an individual business that aims to maximise the assets owned by an individual project development entity. That is, the business entity conducts the development project under its own responsibility to create wealth and charges the price for service provision to users in the form of tolls, entrance fees, and usage fees for a set period, thereby seeking certain profits or returns; profitability is analysed using financial feasibility analysis [3]. The targets for financial feasibility analysis are all the economic activities that generate direct profits among social overhead capital, public facilities, and the private sector, such as individuals or corporations, investing for profit. Financial feasibility is evaluated based on the profitability index (PI), NPV, IRR, and payback period. PI, which is mainly used as an indicator for financial feasibility analysis in South Korea, is a value obtained by dividing the present value of the incoming cash flow by the business by the present value of the outgoing cash flow; if the value is greater than 1, the business is considered financially feasible. The PI can be derived using the following equation:

$$\text{PI} = \sum_{t=1}^{n} \frac{B_t}{(1+r)^t} / \sum_{t=1}^{n} \frac{C_t}{(1+r)^t},$$

where B_t is the incoming cash flow at time t; C_t is the outgoing cash flow at time t; r is the financial discount rate; and n is the analysis period, which is measured as the duration of the facility business. In financial feasibility analyses in South Korea, the present value is calculated by discounting cash flows at a real discount rate of 4.5%, while PI, NPV, and IRR are calculated based on the present value obtained. However, over the analysis period, quantification is somewhat difficult because the values vary depending on the type of business or operating period [5]. In summary, an economic feasibility analysis is performed to determine the impact on the public and national economy by measuring the social NPV. That is, income and losses are calculated based on social benefits and social costs, while taxes such as the value-added tax are excluded. Therefore, even revenues that are not actually generated are estimated through shadow prices. In contrast, a financial feasibility analysis measures the NPV of the business entity, and the entity for the analysis is the actor that directly conducts the business or investment. Additionally, only real cash flows are estimated, and various taxes, such as corporate and property tax, are included in the analysis. Furthermore, the analysis is conducted based on the market price rather than the shadow price [13]. The two analyses are summarised in Table 2.

Table 2. Comparison between the economic and financial feasibility analyses.

Characteristic	Economic Feasibility Analysis	Financial Feasibility Analysis
Purpose	Measurements of social net present value	Net present value measurements of the business entity
Subject of analysis	Public or national economy	Business entity or the investor
Rules for including income and loss	Social benefits/costs	Incoming/outgoing cash flow
Positive (+) variables	Economic benefits of the facility user	Revenue of the business entity
Negative (−) variables	Initial investment and operating maintenance cost	Initial investment, operating maintenance cost, and corporate tax
Evaluation of income and loss	Shadow price	Market price
Distributive equality	Extensive use of weights or conditions	Not considered

2.2. Literature Review

To date, few studies have directly conducted comparative analyses on the site selection of public and private development projects [14] because the purposes and directions of project implementations differ for each project type. In the case of public development projects in South Korea, project site selection tends to be determined by political standards or by the one-sided judgement of administrative authorities [15]. Consequently, the comparison mainly entails the extensive administration performed in terms of organisational management in the operational stage, while the developments of these two types of projects have been rarely compared [1,16]. However, studies have been conducted from the development project perspective for each project entity and on sprawling development, redundant investment, the direction of the urban development project, operational style, and organisational management. These studies can be largely classified into two categories.

First, research has been conducted on location suitability and environmental factors, such as the presence of competing facilities and duplicate investment for public and private development projects. Site selection analysis has been applied based on the principle of efficient utilisation of limited land, and ecological site selection analysis is regarded as a scientific approach [14]. Among them, a previous study that investigated urban growth and analysed sprawling development for newly developed areas using indicators such as employment potential, distance from roads, distance from a highway entrance, distance from educational facilities, and flood risk is representative. It analysed the suitability of the development level by simultaneously considering the various aspects of land use, such as connectivity, dispersion, density, scattering, and utilisation [17]. Another study measured the development level based on the land use plan in terms of density, continuity, concentration, compressibility, centrality, nuclear, diversity, and proximity in relation to environmental factors and suggested preventing duplicate investment in development [18]. A similar study used four indicators: the population who migrated from urban areas to the suburbs, the population growth rate relative to the increased rate of land development area, the time lost due to traffic congestion, and the area lost to open spaces [19]. Based on location theory, extant research has also assessed the level of sprawling development related to location by using spatial information indicators such as the distance to an existing development site, distance to roads, distance to city centre, and floor area ratio [20]. One of the representative studies is the analysis of employment potential, using distance from the road, the entrance to the highway, and the risk of flooding as indicators [21]. Moreover, another study demonstrated that accessibility indicators are higher for private development compared to public development based on the psychological space of residents and movement patterns according to distance for residential development under both public and private development projects [14]. A similar study suggested indicators for residential density, residential areas, mix level of jobs and services, suction power of activity centres and downtown areas, and accessibility to road networks [22,23]. It also conducted a comparative analysis based on the distance from main roads, distance from public transportation, development density, and job–housing balance, thus identifying the development status of South Korea and arguing the necessity for the development projects that reflect the actual changes in society. Another study reported on the necessity of considering detailed development of evaluation standards related to site selection in a development project, regardless of whether the project entity is the public or private sector, thus emphasising the impact on the potential of success of a project [24].

Second, in the operating stage—that is, after the completion of the development project—prior studies mainly discussed administration in terms of organisational management. Public development projects face operational difficulties compared to private development projects in the operating stage, owing to their limitation in the continuous generation of profits [25]. A prior study proposed that for a project site where demand is derived by the coexistence of private and public sectors, the harmonisation of sustainable operation and management serves as a measure that determines project success [26]. Accordingly, there is a trend to improve operational balance through symbiotic relationships between the two sectors in terms of operations [27]. Most studies mainly reflect the level of spatial segmentation based on the level of infrastructure development as a standard indicator. Many focus on the operating stage rather than on the adequacy of the project site, and the discussion centres around the workers involved in the project and the project operation entity. Additionally, few studies have performed a direct comparative analysis between the two sectors. Therefore, in this study, in the stage prior to the implementation of real estate development projects, project site selection is comparatively analysed between the public and private development projects using quantitative data, and measures for public development projects to ensure economic feasibility and create profitability are explored. To derive variables for sprawling development, issues of redundant investment, and approaches with spatial indicators, all of which are related to site selection, the research themes in previous studies on the environmental factors of the development project were used. To ensure analysis objectivity, we considered a 5-km radius [11], which is a close distance for the consumer in transportation geography, and the derived variables were specified considering actual circumstances. Therefore, this study proposes improvement measures to ensure balanced local financing and the prevention of duplicate investments through optimal location selection for public development projects. The findings can thus support the successful implementation of projects through the selection of suitable project sites and their ramifications, such as deriving necessary projects in the region and assigning priority projects. Moreover, the results are expected to be utilised as the basic data for the implementation and validation of future development projects in countries that do not have an investment appraisal system in place for public development projects.

3. Comparative Analysis of Public and Private Development Projects

For the comparative analysis between public and private development projects, the variables were selected based on previous studies. Since each project entity has a different purpose and direction for its development project, it was not possible to unify these aspects; however, data were processed to maintain consistency between variables for the comparative analysis. The process variable selection is described below.

3.1. Variables

As a result of the literature review, for developing a model for the comparative analysis of public and private development projects, the accessibility of the project site, distance, size, and development density were identified as major determinants. The variables also reflect the circumstances specific to South Korea, where the distance within a 5-km radius [11] from the project site and the number of facilities within this range were added as additional factors. This is because the most decisive factor in the site selection of each project entity is the demand of users for the facility after actual development. Therefore, the psychological distance is set according to the sphere of influence to ensure the validity of the comparative analysis. In sum, the variables used in previous studies were organised to accommodate our purpose (Table 3) [9,11,17–20,28,29].

Table 3. Variable selection.

Study	Variables							
	Size	Road Accessibility	Access to Public Transportation	Distance to the City Centre	Floor Area Ratio or Building-to-Land Ratio	Development Density	Convenience Facilities	Educational Facilities
Shim et al. (2018)	○	○	○	○	○	○	○	○
Poelmans et al. (2009)		○	○					
Galster et al. (2000)	○	○	○	○		○	○	○
Jiang et al. (2007)		○	○	○	○	○	○	○
Shin et al. (2015)	○	○	○	○		○	○	○
Angel et al. (2007)						○	○	○

Concerning project size, the public development projects were analysed based on the Central Investment Appraisal, a preliminary procedure for large-scale projects; thus, the size of a project was added as a variable. Moreover, because the size is, to some extent, linked to the gross floor area or building-to-land ratio, these factors were also selected as variables for the public and private sectors, respectively. For public development projects, it is common practice to develop projects on public land; in the case of private development projects, a similar variable, which is the rate of project site purchase, was selected. For accessibility to roads and public transportation, the range was limited to subways and train stations within a 5-km radius, considering the nature of most projects located in the Seoul metropolitan area. In addition, regarding the development level around the project site, which is closely related to the development density, this variable was divided into cultural/convenience facilities and educational facilities. These variables are detailed in Tables 4 and 5.

Table 4. Variables for public development projects.

Variable		Description	Unit
Dependent variables	Approval status	Approval status for the Central Investment Appraisal; 0 for an approved project and 1 for a failed project	Dummy
Subfactors of independent variables			
Project characteristics	Total project cost	Total project cost required for the public development project	100 million won
	Project period	Period required for the project duration	Months
Building characteristics	Gross floor area	Gross floor area of the building	m^2
Public transportation	Adjacent subways/train stations	Number of subway stations within a 5-km radius	No.
Culture/convenience facilities	Adjacent large-scale supermarkets	Number of large-scale supermarkets within a 5-km radius	No.
	Adjacent cultural facilities	Cultural facilities within a 5-km radius	No.
Educational facilities	Elementary, middle, or high schools or colleges within a 5-km radius	Distance to the elementary, middle, or high schools or colleges adjacent to the project site	km

Table 5. Variables for private development projects.

Variables		Description	Unit
Dependent variables	Bidding success status	Status of the bidding success of the project site; 1 for bidding success and 0 for bidding failure	Dummy
Subfactors of independent variables			
Building characteristics	Building-to-land ratio	Building-to-land ratio	%
	Size	Number of households in the building	No.
Project progress	Rate of project site purchase	Rate of project site purchase	%
	Project suspension period	Period of the project suspension	Months
Public transportation	Subways within a 5-km radius	Number of subway stations within a 5-km radius	No.
Culture/convenience facilities	Adjacent cinema complex	Distance to the cinema complex most adjacent to the building	km
	Adjacent large-scale supermarkets	Distance to the large-scale supermarket most adjacent to the building	km
	Large-scale supermarkets within a 5-km radius	Number of large-scale supermarkets within a 5-km radius	No.
Educational facilities	Elementary, middle, or high schools or colleges within a 5-km radius	Number of elementary, middle, or high schools or colleges within a 5-km radius	No.

3.2. Analysis of Public Development Projects

For the construction of analysis models of public development projects, analysis was performed for the projects [10] that were recommended for additional review in terms of location suitability and environmental factors, such as similar and competing facilities. The data used for the analysis were for 117 projects from 2016 to 2019, and environmental factors and conditions such as the development of basic infrastructure, including environmental factors within a 5-km radius [10] were identified, as well as competing facilities to determine which factors affected Central Investment Appraisal approval. As a result of conducting descriptive statistical analysis prior to the empirical analysis, 81 (68.6%) projects were approved in the Central Investment Appraisal, and

36 (31.4%) failed to obtain approval. The total project cost was KRW 29.7 billion on average, and the mean gross floor area was 9876.18 m^2, which indicate that most projects were large-scale ones. For public transportation facilities, there were 68 project sites (58.1%) with subways and train stations within a radius of 5 km, mainly distributed in Seoul and its metropolitan area, which is believed to have contributed to the Central Investment Appraisal approval. In addition, 68 project sites (58.1%) were for large-scale supermarkets and culture/convenience facilities, and 103 (88.0%) project sites were for cultural facilities, thereby indicating that most cultural facilities are located within a 5-km radius. Elementary, middle, or high schools or colleges were located within 0.99 km from the project site on average, and the distance to the farthest facility was 3.86 km, which shows that the proximity to educational facilities was high (Table 6).

Table 6. Descriptive statistics.

Variable	N	Min.	Max.	Mean	Std. Dev.
Approval status	117	0	1	0.31	0.46
Total project cost	117	73	1240	297.15	220.52
Project period	117	0	156	40.82	26.97
Gross floor area	117	1000	65,000	9876.18	11,828
Adjacent subways/train stations	117	0	55	8.52	14.25
Adjacent large-scale supermarkets	117	0	16	2.74	4.01
Adjacent cultural facilities	117	0	255	28.82	52.58
Elementary, middle, or high schools or colleges within a 5-km radius	117	0	3.86	0.99	0.88

In the analysis, the -2-log likelihood value was 27.944. In terms of the assessment of goodness-of-fit of the model, *Cox* and *Snell's* R^2 and Nagelkerke's R^2, both with the same utility for the model fit decisions, accounted for 33.8% and 58.4% of the total variance, respectively. Additionally, the model fit was verified by the Hesmer–Lemeshow test: Pearson's chi-square statistic was 15.316 (p = 0.053), thereby indicating that the fit of the model was significant. The analysis showed that the significant variables were the total project cost (Exp(β) = 1.003), adjacent subways/train stations (Exp(β) = 0.929), and adjacent large-scale supermarkets (Exp(β) = 1.153). In summary, for large-scale projects with a large total project cost, the rate of Central Investment Appraisal approval was high and decreased with increasing numbers of subways/train stations in the adjacent area. Furthermore, the approval rate increased with the increasing number of large-scale supermarkets in adjacent areas (Table 7).

Table 7. Analysis results.

Category		B	S.E.	Wald	DoF	*p*	Exp(β)
Step 1	Total project cost	0.003	0.001	8.647	1	0.003	1.003
	Project period	0.013	0.081	0.025	1	0.876	1.013
	Gross floor area	0.000	0.000	1.761	1	0.184	1.000
	Adjacent subways/train stations	−0.074	0.035	4.384	1	0.036	0.929
	Adjacent large-scale supermarkets	0.143	0.067	4.472	1	0.034	1.153
	Adjacent cultural facilities	0.009	0.007	1.573	1	0.210	1.009
	Elementary, middle, or high schools or colleges within a 5-km radius	0.180	0.167	1.162	1	0.281	1.197
	Constant term	−1.617	0.425	14.491	1	<0.001	0.198

3.3. Results

Here, to identify the factors for project site selection for private development projects, 32 insolvent PF business sites that underwent the bidding process in the private sector and had their construction suspended were investigated (Table 8) [20]. Of the 32 sites, 15 succeeded in bidding in the private sector, and 17 failed to bid. The model was further developed based on the bidding success statuses of the projects, and the location suitability factors were analysed according to the surrounding environment for the simultaneous analysis of internal and external factors. Additionally, to ensure consistency with public development projects, facilities within a 5-km radius were considered. As a result of conducting descriptive statistical analysis prior to the empirical analysis, 15 sites (46.8%) succeeded in bidding, and 17 (53.2%) failed. The ratio of the holding bonds of the project site (amount of holding bonds/amount of total bonds) was 78.1% on average, and the project site purchase rate was 91.3% on average, which indicate that the land purchase rate at the project site was relatively easy. In the case of public transportation facilities, 17 project sites (53.1%) had subways within a 5-km radius and were primarily distributed in Seoul and its metropolitan area, which is believed to have contributed to the bidding success. Furthermore, in the case of cultural and convenience facilities, cinema complexes were located within 2.47 km, on average, from the project site, and the distance to the farthest cinema complex was 14.68 km, thereby indicating that the facilities were distributed within 15-km or 20 min by car.

Table 8. Basic statistics.

Variable	N	Min.	Max.	Mean	Std. Dev.
Bidding success status	32	0	1	0.469	0.502
Building-to-land ratio	32	0.13	0.66	0.262	0.153
Size	32	38	2059	528.688	463.937
Rate of project site purchase	32	0.53	1	0.913	0.143
Project suspension period	32	4	111	53.200	21.017
Subways within a 5-km radius	32	0	54	6.750	11.670
Adjacent cinema complex	32	0.27	14.68	2.741	3.456
Adjacent large-scale supermarkets	32	0.22	11.63	2.684	3.180
Elementary, middle, or high schools or colleges within a 5-km radius	32	8	161	64.313	42.106

In the analysis model of this study, the -2-log likelihood value was 71.616. Concerning the assessment of goodness-of-fit of the model, *Cox* and *Snell's* R^2 and Nagelkerke's R^2 accounted for 47.1% and 62.9% of the total variance, respectively. In addition, the fit of the model was verified by the Hesmer–Lemeshow test. Consequently, the Pearson's chi-square statistic was 8.945 (p = 0.347), thereby indicating that the fit of the model was significant.

The significant variables were the building-to-land ratio (Exp(β) = 0.004); size (Exp(β) = 1.002); subways within a 5-km radius (Exp(β) = 1.267); adjacent large-scale supermarkets (Exp(β) = 0.308); and elementary, middle, or high schools or colleges within a 5-km radius (Exp(β) = 0.968) (Table 9). In summary, when the building-to-land ratio is high, the bidding success rate decreases, and as the size of the project increases, the bidding success rate also increases. The higher the number of subway stations located within a 5-km radius, the better the connection to adjacent areas and, therefore, the higher the rate of bidding success. Additionally, the larger the size of the project, the higher the rate of bidding success, and the lower the rate of bidding success for adjacent large-scale supermarkets, elementary, middle, or high schools and colleges within a 5-km radius.

Table 9. Analysis results.

	Category	B	S.E.	Wald	DoF	p	Exp(β)
Step 1	Building-to-land ratio	−5.616	2.665	4.441	1	0.035	0.004
	Size	0.002	0.001	4.778	1	0.029	1.002
	Project suspension period	−0.023	0.015	2.266	1	0.132	0.978
	Subways within a 5-km radius	0.237	0.088	7.166	1	0.007	1.267
	Adjacent cinema complex	−0.439	0.317	1.922	1	0.166	0.645
	Adjacent large-scale supermarkets	−1.176	0.363	10.481	1	0.001	0.308
	Elementary, middle, or high schools or colleges within a 5-km radius	−0.032	0.016	3.955	1	0.047	0.968
	Constant term	5.166	1.663	9.647	1	0.002	175.137

4. Implications of the Comparative Analysis

To ensure the economic feasibility and profitability of public development projects, the analysis used similar variables for the two project types to identify the factors considered in the implementation of private development projects. To this end, a model was constructed for each project entity, and the analysis was performed accordingly. Significant variables in the rate of approval for public development projects and the rate of bidding success for private development projects are outlined in Table 10.

Table 10. Comparative analysis results.

Public Development Project		Private Development Project	
Variable	**Analysis Results**	**Variable**	**Analysis Results**
Total project cost	The higher the value, the higher the rate of approval	Building-to-land ratio	The higher the value, the lower the rate of bidding success
Adjacent subways/train stations	The higher the value, the lower the rate of approval	Size	The higher the value, the higher the rate of bidding success
		Subways within a 5-km radius	The higher the value, the higher the rate of bidding success
Adjacent large-scale supermarkets	The higher the value, the higher the rate of approval	Adjacent large-scale supermarkets	The higher the value, the lower the rate of bidding success
		Elementary, middle, or high schools or colleges within a 5-km radius	The higher the value, the lower the rate of bidding success

First, when increasing the total cost of a public development project and the size of a private development project, the rates of approval and of bidding success also increased. Considering that total project cost increases with project size because of the nature of real estate development projects, it would be reasonable to consider these two items as similar. That is, both public and private development projects increase their expectations of success through the principle of economies of scale. In the analysis results, subways/train stations and large-scale supermarkets are important factors to consider. These two variables had opposite results for public and private development projects. For public development projects, the rate of approval decreased with the increasing number of subways and train stations adjacent to the project site; however, for private development projects, the rate of bidding success increased. The opposite results are interpreted as differences in the project development method and the purpose of project implementation. For a public development project, it is common practice to develop on a previously secured public land rather than purchase private land. However, most of the areas adjacent to subways and train stations are located on private land. Therefore, to prevent negative effects such as civil complaints and project delays that occur in the process of purchasing private land, the development of public land is necessary. Owing to the specific circumstances of South Korea, most development projects receive additional points in the appraisal process to secure governmental funding when the project site is public land, which has been considered in the interpretation of the results. Additionally, since most areas adjacent to subways and train stations tend to have basic infrastructure already in place, the development of the underprivileged area is more important when considering the project in terms of public interest and balanced regional development. In contrast, for private development projects, financial profitability is prioritised over economic feasibility. Therefore, the demand derived from areas adjacent to subways and train stations is predicted to be high, and development projects are mainly conducted in these areas. The rate of approval increased with the number of large-scale supermarkets in the public sector, while in the case of the private sector, the rate of bidding success decreased. This finding is thought to be the result of concerns over the increasing percentage of supply, rather than additional demand owing to excessive development around the project site and over the unsold estate due to an increase in sale price. For public development projects, unlike in the case of subways/train stations, the rate of approval increases when there are many large-scale supermarkets adjacent to the project site. Therefore, for investment appraisal approval, measures to consider competing facilities without interfering with the private sector should be explored.

5. Conclusions

This study analysed the factors that should be considered when selecting a development project site through a comparative analysis between private and public development projects to ensure the economic feasibility and profitability of public development projects among real estate development projects. Most public development projects focus on total project cost before the start of construction, in which most resources are invested, and there has been less interest in the adequacy of project site selection and operating expenses arising in the operational stage. In this context, the main environmental factors considered in public and private development projects were examined, and through direct comparative analysis, their characteristics, similarities, and differences were identified and the implications of the findings presented.

For public development projects, among the projects requested to undergo Central Investment Appraisal from 2016 to 2019, which is a preliminary procedure for large-scale projects in South Korea, 117 projects were recommended for additional review on location suitability and environmental factors such as similar and competing facilities to avoid duplicate investment. For private development projects, among the 484 sites of insolvent PF projects, project characteristics were investigated for the 32 business sites [12] determined by KAMCO, which were normalised and underwent bidding in the private sector. To this end, a model was constructed to select variables applicable to each project entity based on a previous study. In the variable selection process, for both types of development projects, the sphere of influence within a radius of 5-km was set to consider environmental factors and select the final variables. The results showed that for large total project costs and large-scale projects, both the public and private sectors showed positive responses to project development. This finding is similar to the trend in which various types of facilities are accommodated in a single building or for mixed-use projects for public social overhead capital (SOC) or private development projects. That is, through economies of scale, operating costs and rental fees can be saved by integrating facilities, with diverse types of facilities being enjoyed in a single building. Furthermore, in preparation for the post-COVID-19 period, this result also reflects a change in design development, in which the radius of action is increased with the expansion of public spaces. These results indicate that both the public and private sectors consider that increases in total project cost and size augment the possibility of success for a development project. In the analysis results, subways/train stations and large-scale supermarkets are important factors to consider. For public development projects, the more adjacent subways/train stations are available, the lower the approval rate is. This aspect is true because station areas are usually equipped with basic infrastructure, and it is thus not reasonable to input additional public resources in such areas. In addition, these results reflect the recent trend of promoting development projects in areas with weak infrastructure as part of the balanced regional development and revitalisation of old city centres in South Korea. Another point to consider is that most areas around subways/train stations are private land rather than public. Therefore, to prevent negative effects such as civil complaints and project delays occurring in the process of purchasing private land, the public sector is thought to prefer developments on public land.

In contrast, for the private sector, the bidding success rate increased. This difference is interpreted as the expectation for additional demand derived from the accumulation of migrant and resident populations around the station area. This result deserves attention for public development projects as well. Regarding the construction of facilities, in all cases, the number of facilities is not the only relevant one, but also the fact that the areas are equipped with basic infrastructure that can provide adequate services in proportion to the population in the area. Therefore, for project areas such as sports, culture, and tourism, which can generate income for the public sector, demand should be estimated by considering the competing or duplicate facilities adjacent to the station area while not interfering with the private sector. If there are cases where the public requires the use of a facility, but it cannot be used because of inadequate SOC and infrastructure, this facility is provided by the public sector to improve the quality of life and enhance residential welfare. The rate of approval increased when there for many adjacent large-scale supermarkets, whereas the rate of bidding success decreased in the private sector. In the private sector, it is the result of concerns over the increasing percentage of supply rather than the additional demand owing to excessive development around the project site and unsold estate owing to an increase in sale price. In the public sector, unlike for subways/train stations, the rate of approval increased when there were many large-scale supermarkets adjacent to the project site. This result indicates a difference in approaches between the public and private sectors, in that for project areas with a strong public interest, it is difficult to consider whether it is wrong to conduct a development project in an area. This perspective is because if the private sector currently tends to avoid development projects adjacent to large-scale supermarkets, it is possible that it conducts the development project to improve the quality of life for local residents and revitalise the local economy in terms of public interest. Nevertheless, as described above, the public sector should make efforts to reduce the financial burden by seeking ways to obtain the most profits in the operating stage. Additionally, it is possible that there is an area with private development adjacent to a large-scale supermarket already in operation. For the future approval of investment appraisal, preparation is needed in advance to prevent duplicate investment without intruding in private sector projects already in operation.

The significance of this study lies in the following: (1) it examines the key factors for the selection of project sites for public and private development projects in the presence of competing and redundant facilities to avoid duplicate investment issues, and (2) it explores methods to increase the economic feasibility and profitability of public development projects through a direct comparative analysis with private development projects. However, because the purpose and direction of each development project are inconsistent, the same variables could not be applied to both project types. In addition, although the variables were selected using an objective estimation method, it is possible that they may vary depending on the perspectives adopted by public and private development projects. Finally, the results and the actual evaluation of experts may be different, and the inability to consider experts' evaluation is another limitation of this study. If enough data are published in the future, useful results can be derived from multiple perspectives through systematic improvement and supplementation of internal and external factors of development projects.

Author Contributions: H.S. conceived, designed, analysed, and wrote this paper. J.K. advised on this research, from concept to writing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by a research grant from the Kongju National University in 2021.

Conflicts of Interest: The authors declare no conflict of interest.

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Nationwide Evaluation of Urban Energy System Resilience in China Using a Comprehensive Index Method

Ziyi Wang [1], Zengqiao Chen [2], Cuiping Ma [1], Ronald Wennersten [1] and Qie Sun [3,*]

[1] Institute of Thermal Science and Technology, Shandong University, Jinan 250061, China; ziyiw@kth.se (Z.W.); macp@sdu.edu.cn (C.M.); rw@kth.se (R.W.)
[2] School of Energy and Power Engineering, Shandong University, Jinan 250061, China; czq@sdu.edu.cn
[3] Institute for Advanced Technology, Shandong University, Jinan 250061, China
* Correspondence: qie@sdu.edu.cn; Tel.: +86-(0)531-8839-2009-308

Abstract: The carbon peak and carbon neutrality goals for China signify a critical time of energy transition in which energy resilience is a vital issue. Therefore, a comprehensive evaluation of urban energy system resilience (UESR) is important for establishing a theoretical foundation. To this end, in this paper, 309 Chinese cities were evaluated using a comprehensive UESR assessment framework composed of 113 indices that measured vulnerability and capabilities of resistance and restoration. The results showed that China's UESR is distributed unevenly and that cities in the eastern region generally have higher resilience than those in other regions. The minimum and maximum UESR results corresponded to Tibet and Shandong, respectively, at the provincial level and Rikaze and Weifang, respectively, at the city level. Regression analysis showed a positive correlation among UESR, carbon dioxide emissions, and GDP.

Keywords: urban energy system resilience; comprehensive index method; resilience evaluation

Citation: Wang, Z.; Chen, Z.; Ma, C.; Wennersten, R.; Sun, Q. Nationwide Evaluation of Urban Energy System Resilience in China Using a Comprehensive Index Method. *Sustainability* **2022**, *14*, 2077. https://doi.org/10.3390/su14042077

Academic Editor: Francesco Tajani

Received: 20 December 2021
Accepted: 7 February 2022
Published: 11 February 2022

1. Introduction

On 22 September 2020, President Xi Jinping announced that China would adopt more forceful policies and measures to reach the peak of carbon dioxide emissions by 2030 and to achieve carbon neutrality by 2060; these goals are referred to as the 3060 targets [1]. Energy structure transformation is key to achieving the 3060 targets. The main approaches include reducing the proportion and total amount of fossil fuel consumption, developing renewable energy, reforming the power system, and developing clean and green industries. These approaches assist in building resilient energy systems, as energy system resilience refers to the ability to maintain the essential functions and services of the energy system, ensure stable energy supply and demand with controllable fluctuations, and quickly adapt to new conditions when disruption occurs. Therefore, the 3060 targets, which involve all aspects of energy production, transmission, distribution, consumption, and storage, provide an important opportunity to enhance energy system resilience.

Cities are the macroscopic consumption unit of national energy systems and are responsible for 70% of global greenhouse gas emissions; thus, they should play an important role in this energy transition [2]. When cities meet various urban energy demands related to citizens' daily lives and provide other infrastructures with enabling functions, a plethora of threats with natural, technical, or human causes might jeopardize the security of their energy systems, leading people to realize that urban energy system resilience (UESR) is becoming increasingly important in the process of urban development [3–5].

Billions of dollars in resilience investment are being mobilized globally, creating demand for a rigorous and decision-oriented resilience measurement [6]. However, the evaluation of UESR has not received much attention or research despite its importance. On the one hand, current research on the evaluation of urban resilience has mainly addressed disturbances due to climate change and natural disasters on cities [7,8], while

UESR has been rarely studied. As a means of evaluation, the comprehensive index method has been applied to evaluate resilience at the community [6–9], region [10], city [11–13], and country [14,15] levels. For example, resilient city research for China has proposed a set of indicators such as networks and transportation [9,10]. However, the energy sector is usually not considered the major focus of urban resilience [9–13]. On the other hand, though energy system resilience has been defined by many researchers [14–20], and the quantification thereof is an important branch of energy system resilience research, there is still no consensus on a suitable and comparable evaluation methodology, and the mainstream quantitative methods have limitations of broad applicability and comparability for various cities. Apart from comprehensive index methods, [21] divided the evaluation methods into two categories: quantitative and qualitative. The quantitative methods are mainly time-dependent matric methods and consider resilience to be capacities of resistance, absorption, and restoration [22–24]. The metrics assess the system performance, which is ad hoc, i.e., system- or event-specific and backed by historical data [25–28]. The complexity and computability of the models and the requirement for historical data limit the broad applicability and comparability of these methods, especially across hundreds of cities. Besides, very few such qualitative methods have been applied to study at the city level. Though a dynamic energy balance-based model has been proposed to measure UESR, this methodology also requires input data and cannot sufficiently providing resilience enhancement strategies at the regional and national levels [29]. Qualitative methods have been less studied; these mainly include checklists and questionnaires [30], the matrix scoring system [31], and the analytic hierarchy process [32]. Case studies to verify feasibility are few as well. In summary, a broadly applicable and comparable quantitative method for evaluating energy system resilience of various cities has not hitherto existed.

To fill this knowledge gap, in this paper, a comprehensive index method is proposed to semi-quantitatively evaluate baseline UESR, which involves the capacities of resistance and restoration combined with vulnerability assessment. To do so, the system boundary of the urban energy system was clarified and UESR was defined; based on the definition, the capacities of resistance and restoration were qualitatively evaluated by three dimensions, namely the multifarious capabilities of the energy system within a city (CE), the interdependencies between other basic city subsystems and the energy system (CI), and the comprehensive vulnerabilities of cities and energy (CV); and these three dimensions were quantitively evaluated by 113 indices, which were selected through a relatively thorough literature review under a set of selection principles. The applicability and comparability of the comprehensive index method are demonstrated through case studies of 309 cities in China.

2. Materials and Methods

The resilience discussion herein is proposed to be constrained to high-impact rare events (HR events), also called black swan events [4,33]. The system boundary is constrained on the city level, which represents an adequate unit for policy implementation and is convenient for the overall management of practical events in terms of China's existing realities.

2.1. Characterization of Urban Energy System (UES)

The system boundary for an UES can be clarified, as in the working paper of the cross-center UKERC Energy 2050 project [17]. The energy resources, energy carriers, energy technologies, energy infrastructures (physical and virtual), and surrounding supporting facilities in a city are collectively referred to as the UES. Energy resources include fuels, such as coal, charcoal, gasoline, diesel, natural gas, biogas, uranium, and hydrogen, and natural energy sources, such as hydropower, geothermal power, solar power, and wind power. Energy carriers work in terms of electricity, heat, and cold in addition to fuels. Energy technologies are related to centralized power plants, distributed energy systems, and (micro)grids. Supporting facilities incorporate monitoring and protection devices, electric energy storage supporting equipment, etc. Generally, the UES can also be traced through the energy flow through production, transmission, distribution, conversion, consumption, and storage within a city's physical boundaries, while part of production, i.e., exploration, exploitation, transportation, and processing, usually occurs outside the UES.

2.2. Definition of UESR

In accordance with the essence of the definitions, UESR can be defined as the ability of a UES to resist HR events' impacts, so as to maintain essential functions and services and ensure energy supply and demand within controllable fluctuations, and to quickly restore full energy production. With higher UESR, a UES has a greater capacity to handle foreseeable and/or unforeseeable impacts. From the time dimension, UESR requires the UES to reduce the probability of risk occurrence through measures of risk mitigation in the pre-event stage; diminish the direct and indirect impacts and shorten the duration when an HR event occurs; and withstand various sequential impacts, accommodate and recover from degradation, adapt to new conditions, and learn lessons for future mitigation strategies in the post event stage. In short, for UESs, resilience signifies the capacities of resistance and restoration.

When an HR event occurs, higher resistance helps the UES suffer less performance decline, and higher restoration helps the UES undergo quicker adaptation to new conditions, as shown in Figure 1. The height of the blue-shaded triangle is negatively related to resistance capacity, representing the decrease in system performance. The base of the blue-shaded triangle is negatively related to restoration capacity, representing the restoration of the system performance. As the reverse of the blue-shaded area depicts the simplified resilience level, resilience can be determined as follows:

$$Resilience = Resistance \times Restoration \tag{1}$$

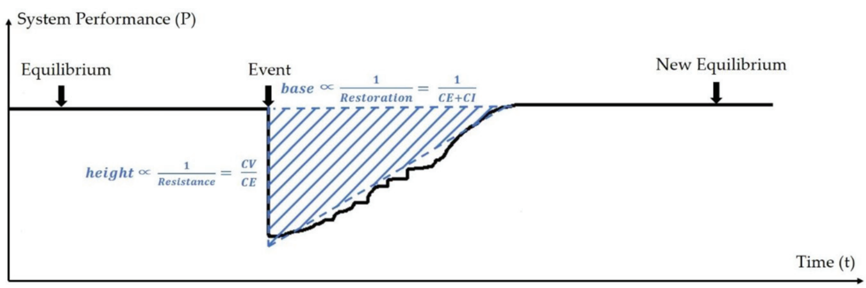

Figure 1. Time-based system performance in an HR event.

To evaluate the capacities of resistance and restoration, three dimensions are proposed: CE, CI, and CV. CE refers to the comprehensive quality of UESs, including robustness, diversity, flexibility, and availability: (1) robustness refers to the condition of hardware and its ability to resist external impacts to reduce the physical influence of disasters and prevent widespread grid outages and energy supply failures. Hardware refers to grid lines, transformers, energy practitioners, and power generation capacity in this framework. Energy reserves of various fuels play an important role in energy feedstock cutoff. Technological and financial feasibilities should also be considered, e.g., improving energy supply stability and enriching the fuel stock. (2) Diversity consists of energy generation and consumption as well as enterprise productive capacity. To evaluate energy diversity, the Shannon–Weaver index is applied, since it is widely preferred for variety and balance [34]. The Shannon–Weaver index is defined as [35,36]:

$$D = -\sum_{i} p_i ln(p_i) \tag{2}$$

where p_i represents the share of energy source i in the mix of energy generation/consumption for an energy system. The higher the value of D is, the more diverse a system is evaluated to be. (3) Flexibility is based primarily on the view of the UES as a complex and flexible integrated system that includes organizational, technical, and administrative factors. The system should have the ability to take precautions, study disaster prediction, and obtain the latest information before an event so that rational planning and allocation can be performed in advance in terms of equipment, technology, organization, personnel, resources, and capital. This quality enables the system to flexibly adapt to new internal and external conditions and find a new stable state when an HR event is about to end or after a long period of time following the event. Thus, many aspects at the system-management level are inspected. Evaluation of practice includes demonstration projects, energy savings, and equipment decommission. (4) Availability refers to the ability to adjust the system based on resource availability and financial feasibility. Resource exploitation and processing are considered for coal, petroleum, and other fuels. Financial feasibility is evaluated in terms of the fixed and current assets of energy industries.

CI involves basic city subsystems that closely interact with the energy system. The interdependencies between critical infrastructures should be taken into consideration since a powerful countermeasure of energy sector that does not explore potential synergies between other pertinent sectors may exacerbate the vulnerability or reduce the overall UESR [37–39]. Thus, CI refers to the capability of a city to cope with hazardous events, including interdependencies between UESs and other societal sectors, such as water, transportation, ecology, emergency services, medical services, and information and telecommunications [40,41]. Water systems are critical in an emergency, and they interact with energy systems via water flow, sewage discharge, cooling water, and circulating water. The transportation system is powered mainly by gasoline, diesel, natural gas and electricity; moreover, the accessibility of the transportation system plays a key role in emergency situations. Ecological systems can provide effective buffering, such as vegetation management and green open space [42]. Emergency services, medical services, and information and telecommunications are high priorities for energy supply and are essential for urban system restoration [43,44].

CV refers to the number of objects with regard to the basic urban conditions in the city and the energy infrastructures in the energy system, that could possibly be affected by hazard [45–47]. City vulnerability takes demographic, economic, and architectural factors into consideration. Energy vulnerability is associated mainly with pipeline and gas stations of various fuels. District heat and electricity consumption have direct impacts on urban residents' daily lives when HR events occur.

According to the above, the greater the CE or CI, the faster the system performance is restored; the greater the CE or the smaller the CV, the less the system performance decreases. The evaluation of resilience, i.e., the UES's capacities of resistance and restoration, is converted into the evaluation of CE, CI, and CV as shown in Figure 1 [48].

2.3. Index Selection

Comprehensive index methods have become a standard approach to simplifying governmental and organizational policy making, decision making, performance appraisal, and progress tracking at all levels [48]. This study proposes a comprehensive index method, providing each dimension with a series of indices for evaluation. In the early stage of developing the comprehensive index framework, a large number of proposed indices by other researchers and database were collected based on a literature review and data research. The index selection procedure is depicted in Figure 2. To organize a consistent UESR framework, indices must first suit the scope of UES. To this end, hundreds of primary indices were obtained. These primary indices were then classified according to the meaning and category into three dimensions: CE, CI, and CV. Each index was described in accordance with the referred literature as closely as possible. Following that, a set of selection principles was examined to evaluate the index's systematism, unicity, feasibility, objectivity, and representation. To describe the overall dimension, the index set should systematically reflect every subsystem and be neither too detailed nor too general [49]. Unicity means that repeated indices should be removed. Feasibility refers to the availability of data from reliable sources with no obvious errors and the operability of quantitative methods and statistical approaches. To be objective, indices should conform to objective facts and not be interfered with subjective values. Representation means that limited indices should describe a dimension as comprehensively as possible. Indices that met the five selection principles were retained, and those that did not meet any principle were deleted. Detailed primary index selection records are shown in Tables A1–A3 (Appendix A). The deletion of each index was related to its original meaning as it underwent the index selection process. There were two main reasons for deleting indices. Unicity is part of the reason, as most scholars generally attach great importance to output of renewable energy, application of distributed energy system, energy sources, energy diversity, etc. Feasibility was the main reason, because some indices were difficult to quantify, some were not suitable for too many measurement objects because the quantization process was too tedious or the quantization workload was large, and some did not apply to China's actual situation. Therefore, 113 indices were finally retained for the UESR assessment index framework, as shown in Figure 3.

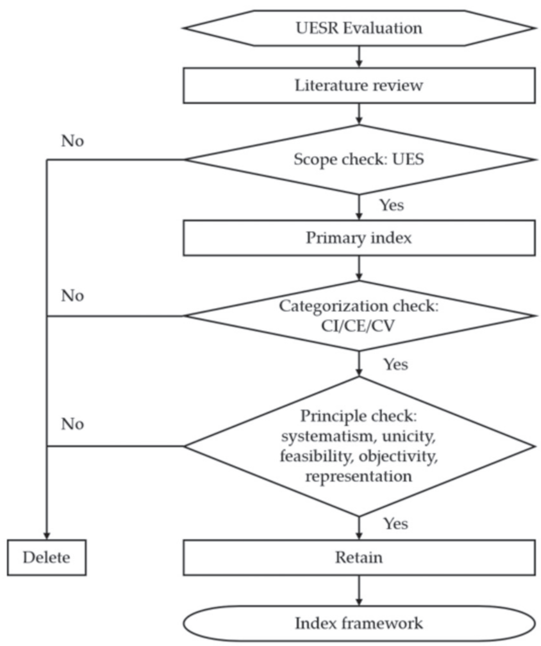

Figure 2. Index selection procedure for UESR evaluation.

The selected 113 indices are quantitatively measured and equally weighted, and they can be assigned differently to satisfy various assessment purposes through a dialogue process between decision makers and stakeholders.

2.4. Normalization of the Indices and Calculation of UESR

Indicators were divided into positive and negative indicators according to their supporting or inhibiting effects on resilience [50]. The higher the negative indicators, the lower the corresponding criteria and resilience, such as the share of imported electricity, daily water consumption per capita, and railway access index. All other indicators are positive. Min–max normalization is used to process the original data as follows.

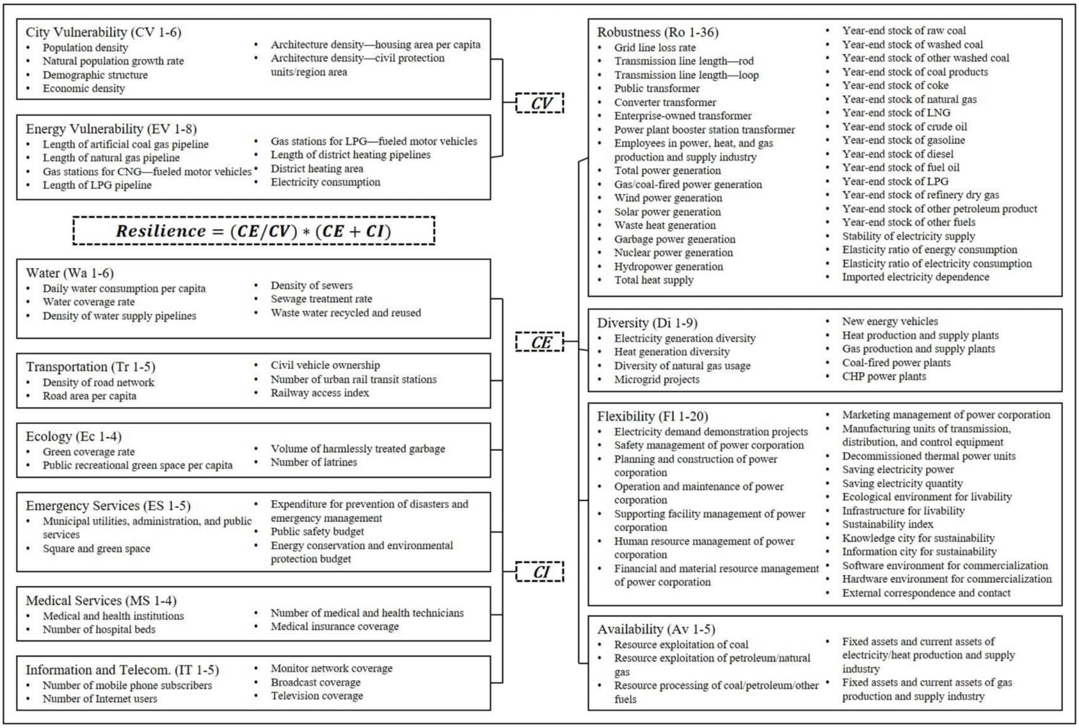

Figure 3. Assessment index for resilience of urban energy systems.

For positive indicators:

$$y_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \quad (3)$$

For negative indicators:

$$y_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \quad (4)$$

where x_{ij}, y_{ij} represent the original and normalized data, respectively; $max(x_{ij})$ is the maximum value of this indicator; and $min(x_{ij})$ is the minimum value of this indicator;

$$CI = \sum_{i=1}^{n} I_i \times \omega_i \quad (5)$$

$$CE = \sum_{i=1}^{n} E_i \times \omega_i \quad (6)$$

where I_i and E_i represent the normalized value of index i for CI and CE, respectively, and ω_i represents the weight of index i. According to the universal risk evaluation model, CV is determined as follows [47]:

$$V^2 = \sum_{i=1}^{n} V_i \times \omega_i \quad (7)$$

where V_i represents the normalized value of index i for city vulnerability or energy vulnerability. Then, resilience is determined as:

$$Resilience = \frac{(\sum_{i=1}^{n} E_i \times \omega_i) \times (\sum_{i=1}^{n} I_i \times \omega_i + \sum_{i=1}^{n} E_i \times \omega_i)}{(\sum_{i=1}^{n} V_i \times \omega_i)^{\frac{1}{2}}} \tag{8}$$

Based on data survey, statistics, and analysis, the UESR of a city can be obtained by substituting these 113 parameters into Equation (8).

3. Results

The energy resilience of 309 Chinese cities is shown in Figure 4. The entire country was divided into four regions according to the National Bureau of Statistics of China [51], namely, the western region (107 cities), the central region (81 cities), the eastern region (87 cities), and the northeastern region (34 cities). Several cities were more resilient than the surrounding areas. There were four types for different reasons. First, provincial capital cities generally had better political resources, management levels, and economic development advantages compared with their surrounding cities and thus had stronger comprehensive city strength and better performance in CI and CE. This applied to Changchun of Jilin, Harbin of Heilongjiang, Taiyuan of Shanxi, Kunming of Yunnan, and Fuzhou of Fujian. Second, Zhangjiakou of Hebei is close to the capital, Beijing, and serves as an important satellite city. It is located in the coal transport corridor, has abundant wind energy resources, has developed a number of microgrid projects, and has few energy-consuming industries, all of which made it a relatively energy-resilient city. Third, Zhuhai of Guangdong has relatively small population density, industrial density, and economic size in Guangdong province, resulting in low CV. As CE and CI were not significantly different, Zhuhai's resilience value was higher. Fourth, Shenzhen of Guangdong was more resilient within the province because of its better performance in energy diversity, microgrid projects, and development of nuclear power.

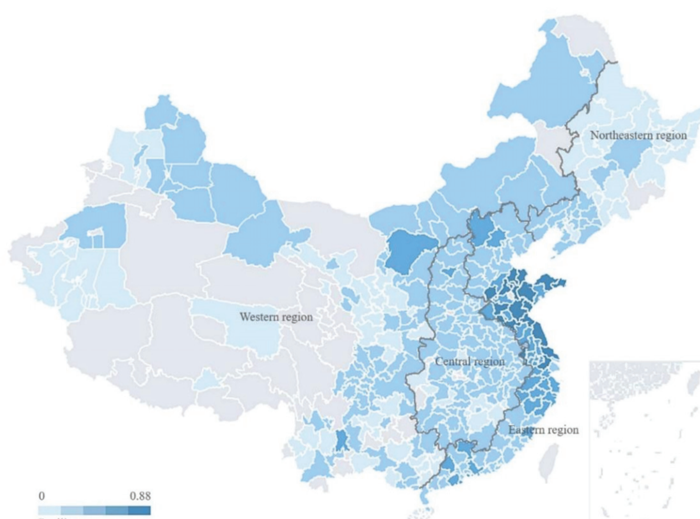

Figure 4. Resilience of urban energy systems for 309 Chinese cities. (Note: The gray areas were not included in the assessment because of lack of data.).

3.1. Regional Level

In general, a majority of the 309 cities, especially those in the northeastern and western regions, had relatively low energy resilience. In contrast, UESR in the eastern region was generally higher. The average resilience (R) result of the eastern region was more than twice that of the northeastern and western regions. The resilience variance (S^2) of the eastern region was nearly an order of magnitude higher than that of the other three regions. The most evenly distributed cities were located in the central region. The differences in CV among the four regions were not significant in terms of average, maximum, minimum, or variance, with the eastern region only slightly higher than the other three regions. From the perspective of CE, there were no obvious distribution characteristics. The eastern region had the highest average. The central region had the lowest variance. The situations of the western and northeastern regions were similar. The highest CI average occurred in the eastern region as well. The statistics of the evaluation results are shown in Table 1. The detailed data and evaluation results can be seen in Tables S1–S4 of the Supplementary Materials.

Table 1. Statistics of the evaluation results.

Region	Resilience	S^2	CV	CE	CI
Nationwide	0.32	0.022	0.36	0.20	0.36
Western	0.24	0.0053	0.35	0.16	0.34
Central	0.28	0.0028	0.35	0.18	0.36
Eastern	0.50	0.022	0.38	0.28	0.40
Northeastern	0.22	0.0035	0.37	0.16	0.33

3.2. Provincial Level

Among the evaluated 27 provinces/autonomous regions:

- The highest average resilience occurred in Shandong (0.69), and the lowest, in Tibet (0.039). The distribution of resilience development was most balanced in Qinghai, with the lowest variance (0.000050) and the smallest range (0.020), and least balanced in Yunnan, with the second-highest variance (0.0046) and the largest range (0.26).
- The highest average CV occurred in Shandong (0.40), and the lowest, in Guizhou (0.32). The distribution of CV was most balanced in Tibet, with the lowest variance (0.000098) and the smallest range (0.028), and least balanced in Guangdong, with the highest variance (0.0046) and the largest range (0.24).
- The highest average CE occurred in Shandong (0.36), and the lowest, in Tibet (0.049). The distribution of CE was most balanced in Qinghai, with the lowest variance (0.000057) and the smallest range (0.018), and least balanced in Ningxia, with the highest variance (0.0019) and the second-largest range (0.12).
- The highest average CI occurred in Jiangsu (0.41), and the lowest, in Tibet (0.26). The distribution of CI was most balanced in Hainan, with the lowest variance (0.000045) and the smallest range (0.016), and least balanced in Guangdong, with the highest variance (0.0038) and the largest range (0.25).

3.3. City Level

- Among the 309 cities, 107 (35%) had higher energy resilience than the national average, while 202 (65%) had lower energy resilience than the national average.
- The four municipalities, Tianjin, Shanghai, Chongqing, and Beijing, ranked 88th, 84th, 71st, and 48th in resilience, respectively. All municipalities were above the average level, not only for resilience but for CV, CE and CI. Beijing ranked first in CI and CV.
- The minimum, median, and maximum resilience results corresponded to Rikaze, Yingkou, and Weifang, respectively. Detailed comparisons of these three cities are shown in Figures 5 and 6. The numbered acronyms on the left in Figure 6 correspond to the indices in Figure 3. The levels of the three cities' CV varied little. Rikaze had an obvious advantage in energy vulnerability, but its city vulnerability was due mainly to a large number of civil protection units in the city, such as historic sites,

temples, and repositories of ancient books, pictographs, and other cultural relics. Its city competitiveness (index FI 13-20), including the city's external connectivity, software and hardware environment, knowledge and information development level, and infrastructure construction, was in a disadvantageous position as well. These data were obtained from the Yearbook of China's Cities sponsored by the Sustainable City Committee of the China Research Society of Urban Development. According to the editor, the evaluation indices mainly reflected the competitiveness of cities in transforming from quantitative growth to qualitative sustainable development. To improve the resilience of Rikaze, this sustainable competitiveness should be comprehensively considered. Additionally, the reliability of the power supply can be improved, and the line loss rate of power enterprises can be reduced. Electricity conservation could be further advocated and executed, and new energy vehicles and enhanced transportation accessibility could be promoted. In terms of energy diversity, the use of natural gas and heat supply also lagged. However, this is related to the local climate and residents' habits and customs, which are difficult to change in the short term and require long-term adjustment and planning.

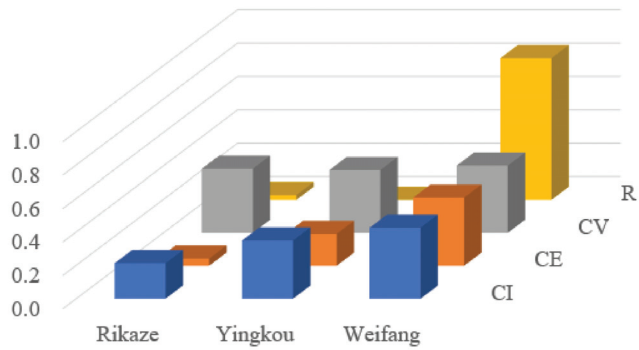

Figure 5. Comparison of the three cities' R/CV/CE/CI results.

- For Yingkou, the main means of improving resilience would include promoting and practicing electricity conservation; improving the management of State Grid Liaoning Power Co., Ltd., among the major power grid companies in the country; and improving the diversity of power generation. With the current Huaneng Yingkou Thermal Power plant as the dominant plant, the city could develop microgrid projects, distributed energy systems, etc., to develop capacity other than thermal power generation.
- As the comparison of financial feasibility was based on provincial data, Weifang's advantages in both the fixed assets and current assets of the energy industry benefit from Shandong's advantages among provinces, as do the decommissioning of thermal power units and the achievement of energy savings. In addition, according to the China Electric Power Industry Annual Development Report, State Grid Shandong Power Co., Ltd., has relatively better comprehensive management on the supply side in its industry, so cities in Shandong also scored high on this series of indices. This implies that financial and managerial resilience can be improved at the provincial level.

3.4. Regression Analysis

Since the resilience of UESs is a critical issue in the current energy transition toward the 3060 targets, it is interesting to understand the relation among a city's energy system resilience, carbon dioxide emissions (megaton) and GDP (10^{10} RMB).

By the weighted least squares method (weight = $1/\text{resid}^2$), the following binary nonlinear regression equation is obtained, and the model fits the evaluation results well.

Figure 6. Comparison of cities with minimum/median/maximum resilience results.

$$RESILIENCE_i = -0.049111 + 0.177735CO2E_i^{0.204} + 0.045861\ln GDP_i + e_i \quad (9)$$

$$t = (705.8698^{***})\ (749.1603^{***})\ (484.5519^{***})$$

$$R\_squared = 0.9999,\ n = 309$$

where *** means at 1% significant level. The empirical results showed a positive correlation between resilience and carbon dioxide emissions, suggesting that there should be a balance among loss of resilience, reduction in carbon dioxide emissions, and increase in GDP. For an example, in Yingkou, a reduction in carbon dioxide emissions of one million tons would sacrifice resilience by 0.0073 and drop the city 12 places in the ranking, and an increase in GDP of 22,949.87 million RMB would enhance resilience to maintain the original position. Therefore, in the process of achieving the 3060 targets, to ensure the safety and sustainability of a city and allow its resilience to fluctuate within reasonable limits, how to appropriately allocate the carbon dioxide emission reduction quota to each city is critical. Based on the evaluation framework of this study, the options for both reducing emissions and enhancing resilience vary from city to city. Generally, feasible alternatives include advancing the financial feasibility of the energy sector, promoting, and practicing energy conservation, and improving the management of power enterprises.

4. Conclusions

With the ambitious 3060 targets, China is looking forward to an unprecedented energy transition. As a core part of energy transition and sustainability, resilience must be given serious attention, especially when extreme events have occurred more frequently in recent years.

To this end, this paper implemented a nationwide comprehensive assessment of the resilience of UESs in China. The results showed that the current capabilities of Chinese UESs to handle exogenous extreme events are very uneven, and that cities in the eastern region generally have higher resilience than those in other regions. The minimum, median, and maximum UESR results corresponded to Rikaze, Yingkou, and Weifang, respectively. Regression analysis of 309 cities' resilience evaluation results showed a positive correlation among UESR, carbon dioxide emissions, and GDP. When the details of this evaluation are combined and the differences lucubrated at the urban/provincial levels, each city should develop a tailored plan to reduce carbon emissions, ensure reasonable changes in UESR, and flexibly utilize economic instruments.

The aim of this study was to establish a benchmark to understand the complicated correlations and challenges of energy transition. The findings of this study may assist municipal and provincial decision makers with unique insights for enhancing overall UESR. Moreover, continual assessments of the UESR of these cities in future years could offer policy makers much more valuable information on energy transition and urban development.

The proposed indicators mainly suit China's current reality, and different, specific indices should be adopted when the assessments are applied to cities in other countries. The results do not contain value or other judgments.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14042077/s1, Table S1: Resilience evaluation results of 309 Chinese cities, Table S2: CI data and results of 309 Chinese cities, Table S3: CE data and results of 309 Chinese cities, Table S4: CV data and results of 309 Chinese cities.

Author Contributions: Conceptualization, Z.W. and R.W.; methodology, Z.W. and Q.S.; software, Z.W.; validation, Z.W., C.M. and Q.S.; investigation, Z.W. and Z.C.; resources, Q.S.; data curation, Z.W. and Z.C.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W.; supervision, R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sources included scholarly publications, trade organization publications, research reports produced by governmental departments and educational organizations, and, when possible, direct contact with experts in related fields. In detail, the CI data sources included governmental yearbooks and bulletins at the city/provincial/country levels, the academic research results of transportation accessibility in [40], and the China Urban Construction Statistical Yearbook. The CE data sources included governmental yearbooks and bulletins at the city/provincial/country levels; the business inquiry platform www.tianyancha.com (accessed on 22 May 2021); the official website of the Ministry of Industry and Information Technology of the People's Republic of China, https://www.miit.gov.cn/ (accessed on 1 February 2022); the official website of the National Development and Reform Commission of the People's Republic of China, https://www.ndrc.gov.cn/ (accessed on 1 February 2022); and the China Urban Construction Statistical Yearbook, China Electric Power Yearbook, China Electric Power Statistical Yearbook, State Grid Yearbook, China Electric

Power Industry Annual Development Report, China Automobile Industry Yearbook, China Industrial Statistical Yearbook, Yearbook of China's Cities, and China Basic Unit Statistical Yearbook. The CV data sources included the China Urban Construction Statistical Yearbook and the China Economic and Social Big Data Research Platform, https://data.cnki.net/NewHome/index (accessed on 1 February 2022).

Acknowledgments: This work was supported by the Shandong University Seed Fund Program for International Research Cooperation.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Aggregated index selection for CE (note: ✓ indicates compliance with the selection principle and ✗ indicates noncompliance; selection principles: systematism (S), unicity (U), feasibility (F), objectivity (O), and representation (R)).

No.	Primary Index	Ref.	S	U	F	O	R	Result
1	Energy feedstock	[52]	✓	✓	✗	✓	✓	Deleted
2	Energy not supplied	[53]	✓	✓	✗	✗	✓	Deleted
3	Energy storage	[54]	✓	✓	✓	✓	✓	Retained
4	Hydrophobic coating on equipment	[55]	✗	✓	✗	✓	✗	Deleted
5	Key replacement equipment stockpile	[55]	✗	✓	✗	✓	✗	Deleted
6	Redundant power lines	[55]	✓	✓	✗	✓	✗	Deleted
7	Reinforced concrete versus wooden distribution poles	[55]	✗	✓	✗	✗	✓	Deleted
8	Siting infrastructure	[55]	✗	✓	✗	✓	✗	Deleted
9	Underground, overhead, undersea distribution/cable lines	[56,57]	✓	✓	✗	✓	✓	Deleted
10	Unique encrypted passwords for utility "smart" distribution	[55]	✗	✓	✗	✗	✗	Deleted
11	Workers employed	[52,55,58]	✓	✓	✓	✓	✓	Retained
12	Communication/control systems/control centers	[59]	✗	✓	✗	✓	✓	Deleted
13	Electrical protection and metering	[59]	✗	✓	✗	✓	✗	Deleted
14	Equipment positioning	[55]	✗	✓	✗	✗	✗	Deleted
15	Flow paths, line flow limits	[60]	✗	✓	✗	✓	✗	Deleted
16	Gen/load bus distribution	[60]	✗	✓	✗	✓	✗	Deleted
17	Reserve/spare capacity	[57,61,62]	✓	✓	✓	✓	✓	Retained
18	Substations (switchyards)—overhead lines and underground cables are interconnected	[59]	✗	✓	✗	✓	✗	Deleted
19	Ancillary service	[54]	✗	✓	✗	✗	✓	Deleted
20	Function-altered hazard rate of component after certain maintenance	[63]	✗	✓	✗	✓	✓	Deleted
21	Net ability—measures the aptitude of the grid in transmitting power from generation to load buses efficiently	[60]	✓	✓	✗	✓	✓	Deleted
22	Path redundancy—assesses the available redundancy in terms of paths in transmitting power from generation to a load bus based on entropy	[60]	✓	✓	✗	✗	✓	Deleted
23	Viability of investments	[52]	✗	✓	✗	✗	✓	Deleted
24	Coefficient of variation of the frequency index of sags	[64]	✗	✓	✗	✓	✓	Deleted
25	Bulk electric system reliability performance indices	[65]	✓	✓	✓	✓	✓	Retained
26	Derated power—rated power multiplied by the reliability of the plant	[66]	✗	✓	✗	✓	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
27	Energy efficiency/intensity	[62,67–70]	✓	✓	✓	✓	✓	Retained
28	Failure rate	[63]	✗	✓	✓	✓	✗	Deleted
29	Resilience index—parameter that quantifies the potential probability of malfunction of the system	[71]	✓	✓	✓	✓	✓	Retained
30	Resilience index—derived from robustness, resourcefulness, and recovery; ranges from 0 (low resilience) to 100 (high resilience)	[30,72,73]	✓	✓	✓	✓	✓	Retained
31	Survivability—evaluates the aptitude of the network to assure the possibility of matching generation and demand in case of failures or attacks	[60]	✓	✓	✗	✗	✓	Deleted
32	System average interruption duration/frequency index	[74]	✗	✓	✗	✓	✓	Deleted
33	Load loss damage index—damage caused by fire to the electrical system	[75]	✗	✓	✗	✓	✗	Deleted
34	Transmission lines available	[76]	✓	✓	✓	✓	✓	Retained
35	Functional zones—generation, transmission, and distribution	[52]	✓	✓	✓	✓	✓	Retained
36	Operator training	[55]	✗	✓	✗	✗	✓	Deleted
37	Mutual assistant agreements	[55]	✓	✓	✗	✗	✓	Deleted
38	Transformers—connecting parts of the network operating at different voltages	[59]	✓	✓	✓	✓	✓	Retained
39	Tree-trimming metrics	[55,57]	✓	✓	✗	✗	✓	Deleted
40	Adequacy—the ability of the system to supply customer requirements under normal operating conditions	[52]	✓	✓	✓	✓	✗	Deleted
41	Congestion control	[77]	✗	✓	✗	✓	✓	Deleted
42	Customer average interruption duration index—sustained outage metric; measures average duration of sustained outage per customer	[74]	✗	✓	✗	✓	✓	Deleted
43	Economy—achieving the best profits by adjusting the power system operation mode to minimize line losses, making full use of equipment, ensuring the security of the power system, and meeting utility users' demand	[68]	✓	✓	✗	✗	✓	Deleted
44	Fairness—consists of the fulfillment rate of contracts and standard deviation indexes	[68]	✗	✓	✗	✗	✗	Deleted
45	Interrupted energy assessment rate	[65]	✗	✓	✗	✓	✓	Deleted
46	Security—the dynamic response of the system to unexpected interruptions; relates to the system's ability to endure them	[52]	✓	✓	✗	✗	✓	Deleted
47	Transmission losses	[56]	✓	✓	✓	✓	✓	Retained
48	Cost of interruption—social, commercial, industrial, etc.	[56]	✓	✓	✗	✗	✓	Deleted
49	Impact factor on the population—share of the population affected by the power loss	[78]	✓	✗	✗	✓	✓	Deleted
50	Long-distance transmission costs	[56]	✓	✗	✓	✓	✓	Deleted
51	Noise	[56]	✗	✓	✗	✗	✓	Deleted
52	Performance-based regulation reward/penalty structure	[65]	✗	✓	✗	✗	✓	Deleted
53	Price of electricity	[56]	✓	✓	✓	✓	✓	Retained

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
54	Value of lost load—value of unserved energy; customers' value of the opportunity cost of outages or benefits forgone through interruptions in electricity supply	[61]	✓	✓	✗	✗	✓	Deleted
55	Fuel nodes with the most links are the most interconnected and serve as hubs	[79]	✓	✓	✗	✓	✗	Deleted
56	Flow between nodes takes place on links (roads, electric power transmission lines, water mains, etc.)	[79–81]	✗	✓	✗	✗	✓	Deleted
57	Elements of the energy network that can receive fuels from storage facilities, pipeline interconnections, or production areas	[79,81]	✓	✓	✓	✓	✓	Retained
58	Primary energy supply—includes the systems and processes used to supply a primary energy resource to its point of conversion into the final energy product of interest	[52]	✓	✓	✓	✓	✓	Retained
59	Storage facilities/nodes, intermediate storage	[80,81]	✓	✓	✓	✓	✓	Retained
60	Emergency procedures/emergency shutdown system	[82]	✓	✓	✗	✗	✓	Deleted
61	Response to equipment outages—degree to which the system is able to continue to reliably operate in the event of equipment downtime	[52]	✗	✓	✗	✗	✓	Deleted
62	Adaptive capacity—degree to which the system is capable of self-organization for recovery of system performance levels	[83]	✓	✓	✗	✗	✓	Deleted
63	Ability of the system to provide sufficient throughput to supply final demand	[52]	✓	✓	✓	✓	✓	Retained
64	Information security—the degree to which information assets in the system are secure against threats	[52]	✓	✓	✓	✓	✓	Retained
65	Physical security—the degree towhich physical assets in the systemare secure against threats	[52]	✓	✓	✗	✗	✓	Deleted
66	Absorptive capacity—degree to which a system can automatically absorb the impacts of perturbations and minimize consequences with little effort	[83]	✓	✓	✗	✗	✓	Deleted
67	Connectivity loss—the average reduction in the ability of sinks to receive flow from sources	[78]	✓	✗	✓	✓	✓	Deleted
68	Energy processing and conversion—relates to production of the final energy product	[52]	✓	✓	✓	✓	✓	Retained
69	Flexibility—the degree to which the system can adapt to changing conditions	[52]	✓	✓	✗	✗	✓	Deleted
70	History—the degree to which the system has been prone to disruption in the past	[52]	✓	✓	✓	✓	✓	Retained

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
71	Intermittency—the degree to which the system lacks constant levels of productivity	[52]	✗	✓	✗	✗	✗	Deleted
72	Network resiliency—measured by its ability to keep supplying and distributing fuels in spite of damage to pipelines, import terminals, storage, and other sources	[79]	✓	✓	✗	✗	✓	Deleted
73	Response to demand fluctuations—the extent to which the system is able to adapt to changes in the quantity of energy demanded or location of demand	[52]	✓	✓	✓	✓	✓	Retained
74	Systemic impact—impact that a disruption has on system productivity; measured by evaluating the difference between a targeted system performance level and the actual system performance	[80,83]	✓	✓	✗	✗	✗	Deleted
75	Impacts on interdependent systems—the degree to which a disruption in the system might feasibly cause damage to interdependent systems	[52]	✓	✓	✗	✗	✓	Deleted
76	Optimal resilience costs—resilience costs for a system when the optimal recovery strategy (minimizing the combined system impact and total recovery effort costs) is employed	[83]	✗	✓	✗	✗	✓	Deleted
77	Recovery-dependent resilience costs—resilience costs of a system under a particular recovery strategy	[83]	✗	✓	✗	✗	✓	Deleted
78	Diversity of import fuels	[67]	✗	✓	✗	✓	✓	Deleted
79	Natural gas strategic reserve	[84]	✓	✓	✓	✓	✓	Retained
80	Import levels—the degree to which primary energy supply relies on resources originating outside of the system	[17,52,62,81,85–92]	✓	✓	✓	✓	✓	Retained
81	Industrial aspects—vulnerability indicator	[85]	✓	✓	✗	✗	✓	Deleted
82	Vulnerability—proportional to the reliance on imported gas from countries in geopolitical conflict	[85]	✗	✓	✗	✓	✓	Deleted
83	Ability to expand facilities—the degree to which the system can be easily and cost-effectively expanded	[52]	✓	✓	✗	✗	✓	Deleted
84	Pipeline capacity used	[79]	✓	✓	✗	✓	✓	Deleted
85	Resiliency—ability to supply gas to customers willing to pay the clearing price, even in the face of supply constraints	[84]	✗	✓	✗	✗	✓	Deleted
86	Restorative capacity—ability of a system to be repaired easily; these repairs are considered to be dynamic	[83]	✓	✓	✗	✗	✓	Deleted
87	Total recovery effort— efficiency with which a system recovers from a disruption, measured by analyzing the amount of resources expended during the recovery process	[83]	✓	✓	✗	✗	✓	Deleted
88	Sector coordination—the degree to which coordination between stakeholders within the sector results in an effective exchange of information, alerting stakeholders of emerging threats and mitigation strategies	[52]	✓	✓	✓	✓	✓	Retained

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
89	Price/price volatility	[52,84]	✓	✓	✓	✓	✓	Retained
90	Intelligent institutional leadership with heightened sensitivity and/or preparedness for rapid and pervasive changes	[93]	✗	✓	✗	✗	✓	Deleted
91	Diversity of electricity generation	[16,17,31,34,62, 86–91,94–108]	✓	✓	✓	✓	✓	Retained
92	Diversity of imports of embodied electricity	[34]	✗	✓	✗	✓	✓	Deleted
93	Diversity of electricity consumption	[34]	✓	✓	✓	✓	✓	Retained
94	Renewable energy electricity, mainly wind and solar power	[109–111]	✓	✓	✓	✓	✓	Retained
95	Share of buildings with low thermal insulation in the total building stock	[112]	✓	✓	✗	✗	✓	Deleted
96	Share of renewables in total heating energy	[112]	✓	✓	✗	✓	✓	Deleted
97	Share of fossil fuels in total energy consumption	[112]	✓	✗	✓	✓	✓	Deleted
98	Share of electricity produced by renewables in total electricity consumption	[8,112]	✓	✗	✓	✓	✓	Deleted
99	Nonrenewable fuel used in generation	[62]	✓	✗	✓	✓	✓	Deleted
100	Generation efficiency	[62]	✓	✗	✓	✓	✓	Deleted
101	Distribution efficiency—transmission and distribution losses and the amount of electricity consumed by energy industry	[62]	✓	✗	✗	✓	✓	Deleted
102	Carbon intensity of generation	[17,49,62,87,91, 98,113]	✓	✗	✗	✓	✗	Deleted
103	Redundant power for use	[62]	✓	✓	✓	✓	✓	Retained
104	Existence and monitoring of officially approved electrification plan	[114]	✗	✓	✗	✗	✗	Deleted
105	Framework for grid electrification	[114]	✗	✓	✗	✗	✓	Deleted
106	Framework for minigrids	[114]	✗	✓	✗	✗	✓	Deleted
107	Framework for standalone systems	[114]	✓	✓	✗	✗	✓	Deleted
108	Consumer affordability of electricity	[110,114]	✓	✓	✗	✗	✓	Deleted
109	Utility transparency and monitoring	[114]	✗	✓	✗	✗	✗	Deleted
110	Utility creditworthiness	[114]	✗	✓	✗	✗	✗	Deleted
111	Information provided to consumers about electricity usage	[114]	✓	✓	✗	✗	✓	Deleted
112	Financing mechanisms for energy efficiency	[114]	✓	✓	✗	✗	✓	Deleted
113	Energy efficiency entities	[114]	✗	✓	✗	✗	✓	Deleted
114	Incentives from electricity rate structures	[114]	✗	✓	✗	✗	✓	Deleted
115	Incentives and mandates: large consumers/public sector/utilities	[114]	✗	✓	✗	✗	✓	Deleted
116	Minimum energy efficiency performance standards	[114]	✓	✓	✗	✗	✓	Deleted
117	Energy labeling systems	[114]	✓	✓	✗	✗	✓	Deleted
118	Building energy codes	[114]	✓	✓	✗	✗	✓	Deleted
119	Carbon pricing and monitoring	[95,114–117]	✓	✓	✗	✗	✓	Deleted
120	Legal framework for renewable energy	[114]	✓	✓	✗	✗	✓	Deleted
121	Planning for renewable energy expansion	[114]	✓	✗	✗	✗	✓	Deleted
122	Incentives and regulatory support for renewable energy	[114]	✓	✓	✗	✗	✓	Deleted
123	Attributes of financial and regulatory incentives for renewable energy	[114]	✓	✓	✗	✗	✓	Deleted
124	Network connection and pricing	[114]	✓	✗	✗	✗	✓	Deleted
125	Counterparty risk of renewable energy	[114]	✗	✓	✗	✗	✗	Deleted
126	Maximized availability of operational power supply	[118]	✗	✓	✗	✗	✓	Deleted
127	Replacement inventories of equipment and supplies	[110,118]	✓	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
128	Maximized provision target power supply level of restoration	[118]	✓	✓	✗	✗	✓	Deleted
129	Largest single source of supply	[17]	✓	✓	✓	✓	✗	Deleted
130	Energy portfolios—price volatility	[17]	✓	✗	✓	✓	✓	Deleted
131	Statistical probability of supply interruption in network industries (gas and electricity)	[17]	✗	✓	✗	✓	✓	Deleted
132	Expected number of annual hours in which energy is unserved	[17]	✓	✓	✗	✗	✓	Deleted
133	Value/level of unserved energy	[17]	✓	✓	✓	✓	✓	Retained
134	Energy storage capacity and/or stocks by fuel and market	[17]	✓	✗	✓	✓	✓	Deleted
135	Redundancy in network architecture	[17]	✗	✓	✗	✗	✓	Deleted
136	Expected probability of interruption for long-term planning and design	[119]	✗	✓	✓	✗	✓	Deleted
137	Expected energy not served per interruption	[119]	✗	✓	✓	✗	✓	Deleted
138	Expected outage duration per interruption for short-term operational planning	[119]	✗	✓	✓	✗	✓	Deleted
139	Expected energy loss	[24]	✗	✗	✓	✗	✓	Deleted
140	Collapse ratio	[24]	✗	✓	✓	✓	✗	Deleted
141	Recovery ratio	[24,110]	✗	✓	✓	✓	✗	Deleted
142	Energy cost stability	[120]	✓	✗	✓	✓	✓	Deleted
143	Stability of energy generation	[120]	✓	✓	✗	✗	✓	Deleted
144	Peak load response	[120]	✗	✓	✓	✓	✓	Deleted
145	Market concentration on supply	[120]	✗	✓	✗	✗	✓	Deleted
146	CO_2eq emissions	[120]	✗	✗	✓	✓	✓	Deleted
147	Fuel use	[120]	✓	✗	✓	✓	✓	Deleted
148	Employment	[120]	✓	✗	✓	✓	✓	Deleted
149	Levelized costs (incl. capital, operational/maintenance, fuel costs)	[120]	✓	✓	✗	✓	✓	Deleted
150	Technological maturity	[120]	✓	✓	✗	✗	✓	Deleted
151	Technological innovation ability	[120]	✓	✓	✗	✗	✓	Deleted
152	Energy demand and consumption	[8,121]	✓	✗	✓	✓	✓	Deleted
153	Flexibility of grid	[8,121]	✗	✓	✗	✗	✓	Deleted
154	Urban energy supply systems for increasing shares of renewable energy	[121,122]	✓	✗	✓	✓	✓	Deleted
155	Reduced end-use energy demand	[111,121,122]	✓	✓	✓	✓	✓	Retained
156	Energy monitoring	[8,121]	✗	✓	✗	✗	✗	Deleted
157	Reduced reliance on energy	[16,62,123–125]	✓	✗	✓	✓	✓	Deleted
158	Energy source diversity	[16,62,111,123, 125–127]	✓	✗	✓	✓	✓	Deleted
159	Energy storage capabilities	[124–126]	✓	✗	✓	✓	✓	Deleted
160	Redundancy of critical capabilities	[62,126,128,129]	✓	✓	✗	✗	✓	Deleted
161	Preventative maintenance on energy systems	[110,126,129]	✗	✓	✗	✗	✓	Deleted
162	Sensors, controls, and communication links to support awareness and response	[125,126,129]	✓	✓	✗	✗	✗	Deleted
163	Protective measures against external attack	[123,126,128]	✓	✓	✗	✗	✓	Deleted
164	Design margin to accommodate range of conditions	[124,126,129–131]	✗	✓	✗	✗	✓	Deleted
165	Limited performance degradation under changing conditions	[16,124,126,129, 130]	✓	✓	✗	✗	✓	Deleted
166	Operational system protection, e.g., pressure relief, circuit breakers	[126,129]	✓	✓	✗	✗	✓	Deleted
167	Installed/ready redundant components	[16,31,49,90,126, 128,129,132–135]	✓	✓	✗	✓	✓	Deleted
168	Ability to isolate damaged systems/components (automatic/manual)	[62,126,129]	✓	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
169	Capability for independent local/subnetwork operation	[126,128]	✓	✓	✗	✗	✓	Deleted
170	System flexibility for reconfiguration and/or temporary system installation	[16,125,126,128, 130]	✓	✓	✗	✗	✓	Deleted
171	Capability to monitor and control portions of system	[124,126,129]	✓	✓	✗	✗	✓	Deleted
172	Fuel flexibility	[16,31,62,99,128, 130,136,137]	✓	✗	✓	✗	✓	Deleted
173	Capability to reroute energy from available sources	[16,126,128–130]	✓	✓	✗	✗	✗	Deleted
174	Investigate and repair malfunctioning controls or sensors	[129]	✗	✓	✗	✗	✓	Deleted
175	Energy network flexibility to reestablish service by priority	[16,126,129]	✓	✓	✗	✗	✓	Deleted
176	Backup communication lighting, power systems for repair/recovery operations	[126,129]	✓	✓	✗	✓	✓	Deleted
177	Flexible network architecture to facilitate modernization and new energy sources	[16,126,128,130]	✓	✓	✗	✗	✓	Deleted
178	Sensors and data collection and visualization capabilities to support system performance trending	[62,126,128,129]	✓	✓	✗	✗	✓	Deleted
179	Ability to use new/alternative energy sources	[16,125,130]	✓	✓	✗	✗	✓	Deleted
180	Updating system configuration/functionality based on lessons learned	[16,126,128–130]	✓	✓	✗	✗	✓	Deleted
181	Phasing out obsolete or damaged assets and introducing new assets	[123,126,128–130,133,138,139]	✓	✓	✗	✗	✓	Deleted
182	Integrating new interface standards and operating system upgrades	[126,128,129]	✓	✗	✗	✗	✓	Deleted
183	Updating response equipment/supplies based on lessons learned	[128]	✓	✓	✗	✗	✓	Deleted
184	Capabilities and services prioritized based on criticality or performance requirements	[124]	✓	✓	✗	✗	✓	Deleted
185	Internal and external system dependencies identified	[124,125,140]	✗	✓	✗	✗	✗	Deleted
186	Design, control, operational, and maintenance data archived and protected	[124,129]	✓	✓	✗	✓	✓	Deleted
187	Vendor information available	[124]	✗	✓	✗	✓	✗	Deleted
188	Control systems operational and protected with antivirus and other safeguards	[124,126,129]	✓	✓	✗	✗	✓	Deleted
189	Operating environment forecasts captured in planning scenarios	[123,124,126,129]	✓	✓	✗	✗	✗	Deleted
190	Response/recovery plans established and distributed	[124,126,129]	✓	✓	✗	✗	✗	Deleted
191	Environmental condition forecast and event warnings broadcast	[62,125,129]	✓	✓	✗	✗	✓	Deleted
192	System status, trends, and margins available to operators, managers, and customers	[62,110,125,126, 128,129]	✓	✓	✗	✗	✓	Deleted
193	Critical system data monitored; anomalies alarmed	[62,126,128,129]	✓	✗	✗	✗	✓	Deleted
194	Operational/troubleshooting/response procedures available	[126,129]	✓	✓	✗	✗	✓	Deleted
195	Status/trend limits trigger safeguards and isolate components to stop cascade effect	[62,125,126]	✓	✓	✗	✗	✓	Deleted
196	Status/response/mitigation information transmitted effectively and efficiently to stakeholders/decision makers	[124]	✓	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
197	Information and communications coordinated throughout supply chain	[126]	✓	✗	✗	✗	✓	Deleted
198	Information available to authorities and crews regarding customer/community needs/status	[128,129]	✓	✓	✗	✗	✓	Deleted
199	Recovery progress tracked, synthesized, and available to decision makers and stakeholder	[128,129]	✓	✓	✗	✗	✓	Deleted
200	Design, repair parts, and substitution information available to recovery teams	[126]	✓	✓	✗	✗	✓	Deleted
201	Location, availability, and ownership of energy, hardware, and services for restoration teams	[126]	✓	✓	✗	✗	✓	Deleted
202	Resource needs, sources, and authorities available to decision makers	[128]	✓	✗	✗	✗	✓	Deleted
203	Information regarding centralized facilities and distribution of essential supplies and services available to community	[128]	✓	✗	✗	✗	✓	Deleted
204	Coordinating information and communications among recovery organizations	[128]	✓	✓	✗	✗	✓	Deleted
205	Initiating event, incident point of entry, and associated vulnerabilities and impacts identified	[123,125,126,128,129]	✓	✓	✗	✗	✓	Deleted
206	Event data and operating environment forecasts utilized to anticipate future conditions/events	[125,126,128,129]	✓	✓	✗	✗	✓	Deleted
207	Updated information about energy resources, alternatives, and emergent technologies available to managers and stakeholders	[16,125,128,129]	✓	✗	✗	✗	✓	Deleted
208	Design/operation/maintenance information updated consistently with system modifications	[16,126,129]	✓	✓	✗	✗	✓	Deleted
209	Consumer/stakeholder awareness of energy alternatives, cost/benefits, and implementation requirements	[16,124,125]	✓	✓	✗	✗	✓	Deleted
210	Community impacts, priorities, interdependencies updated to capture lessons learned	[124,128,129]	✓	✓	✗	✗	✗	Deleted
211	Response plans updated with lessons learned	[125,126,128,129]	✓	✓	✗	✗	✓	Deleted
212	Understood performance trade-offs of organizational goals	[123,125]	✗	✓	✗	✗	✗	Deleted
213	Broad-based operational and maintenance training	[126,129]	✗	✓	✗	✗	✓	Deleted
214	Periodic operator, management, and community drills	[126,128,129]	✗	✓	✗	✗	✓	Deleted
215	Developed individual expertise in energy impacts, techniques, and alternatives (energy-informed culture)	[124]	✓	✓	✗	✓	✓	Deleted
216	Awareness of and focusing of effort on identified critical assets and services	[124,126,128]	✗	✓	✗	✗	✗	Deleted
217	Decision-making protocol or aid to determine proper course of action	[125,126,128]	✗	✓	✗	✗	✓	Deleted
218	Operators and managers utilizing critical thinking and maintain proactive posture to recognized and arrest events	[125,126]	✓	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
219	Community response to mitigate impact, e.g., demand curtailment	[124,126,128]	✓	✓	✗	✓	✓	Deleted
220	Utilizing data and decision-making aids to quickly select recovery options	[128]	✓	✓	✗	✗	✓	Deleted
221	Recovery crew managing incremental recovery with available equipment	[126]	✓	✓	✗	✗	✓	Deleted
222	Community members utilizing available resources and improvised to meet local needs	[16,124,125,128]	✗	✓	✗	✗	✓	Deleted
223	Community members managing constrained energy resources responsibly and consistent with public guidance	[16,124,128]	✗	✓	✗	✗	✓	Deleted
224	Documentation and review of management response and decision-making processes	[125,126,128]	✗	✓	✗	✗	✗	Deleted
225	Periodic revisitation of organizational risk tolerance and mission priorities, adjusting as necessary	[124,125]	✗	✓	✗	✗	✓	Deleted
226	Integration of lessons learned and best practices from internal and external sources	[125,126,128,129]	✓	✓	✗	✗	✓	Deleted
227	Customers and stakeholders taking action to implement more resilient energy solutions	[16,124–126,129]	✓	✗	✗	✗	✓	Deleted
228	Identification of stakeholders (internal and external)	[126,128]	✗	✓	✗	✗	✓	Deleted
229	Use of scenario-based war gaming to develop understanding of system dependencies and interactions	[125,126,128,131]	✓	✓	✗	✗	✓	Deleted
230	Robust risk analysis and decision support capabilities to facilitate response	[123–126,128,129]	✓	✗	✗	✗	✓	Deleted
231	Decreased overall reliance on energy or specific sources of energy	[123,124]	✓	✓	✗	✓	✓	Deleted
232	Priorities and policies established for event response	[123–126,128,129]	✗	✓	✗	✗	✓	Deleted
233	Priorities and operating limits mitigating disruption to energy needs for key community functions	[123,126,128]	✗	✓	✗	✗	✓	Deleted
234	Predefined protective actions limiting external influences in physical, information domains	[124–126]	✗	✓	✗	✗	✓	Deleted
235	Agile operational management enabling rapid and effective response under changing conditions	[125,126]	✓	✓	✗	✗	✓	Deleted
236	Individuals and organizations implementing response plans	[124–126,128]	✗	✗	✗	✗	✓	Deleted
237	Individuals and organizations taking action in response to observations and/or direction from authorities	[124,128]	✗	✓	✗	✗	✓	Deleted
238	Recovery organizations and communities following contingency recovery plans	[124,125,128]	✓	✓	✗	✗	✓	Deleted
239	Community stakeholders participating in establishment of energy priorities and coordination of restoration actions	[124,126,128]	✓	✓	✗	✗	✓	Deleted
240	Shelters and other centralized services increasing efficiency and control of scarce energy resources to meet critical needs	[126]	✗	✗	✗	✗	✗	Deleted
241	Public/private entities coordinating to deliver aid to affected parties	[128]	✗	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
242	Proactive neighborhood assistance, volunteerism, and compliance with energy response manager direction	[128]	✗	✓	✗	✗	✓	Deleted
243	Reallocation of human resources to better address adverse events	[128]	✓	✓	✗	✗	✓	Deleted
244	Local governments and stakeholders staying informed about threats, changing environment, and protective methods and technologies	[123–126,128,129]	✓	✓	✗	✗	✓	Deleted
245	Local governments and stakeholders collaborating to develop, prioritize, and implement energy portfolio improvement	[16,123–126,128,129]	✓	✓	✗	✗	✓	Deleted
246	Incentives for customers and stakeholders to implement more resilient energy solutions	[16,62,123–126,128,129]	✓	✓	✗	✗	✓	Deleted
247	Energy-informed culture leading to collective decisions and investments which continually improve energy effectiveness	[16,62,126,128]	✗	✓	✗	✗	✓	Deleted
248	Accurate estimation of weather location and severity	[57]	✓	✗	✗	✗	✓	Deleted
249	Energy consciousness of the public and consumption behavior/demand-side management	[8,31,57,69,70,94,99,101,104,113,133,139,141–154]	✓	✓	✓	✓	✓	Retained
250	Fast topology reconfiguration	[57]	✓	✓	✗	✗	✓	Deleted
251	Automated protection and control actions: load and generation rejection, system separation, etc.	[57]	✓	✓	✗	✗	✓	Deleted
252	Monitoring—development of situation awareness, advanced visualization and information systems	[57]	✓	✗	✗	✗	✓	Deleted
253	Ensured communications functionality	[57]	✓	✗	✗	✗	✓	Deleted
254	Microgrids	[57,155,156]	✓	✓	✓	✓	✓	Retained
255	Advanced control and protection schemes	[57,110]	✓	✗	✗	✗	✓	Deleted
256	Disaster assessment and priority setting	[57]	✓	✗	✗	✗	✓	Deleted
257	Risk assessment and management for evaluating and preparing for the risk introduced by such events	[57,122]	✓	✗	✗	✗	✓	Deleted
258	Black-start capabilities installed	[57]	✓	✓	✗	✗	✓	Deleted
259	Repair crew member mobilization	[57]	✓	✓	✗	✗	✓	Deleted
260	Installation of DER or other onsite generation units	[57]	✓	✓	✗	✓	✓	Deleted
261	Coordination with adjacent networks, and repair crews	[57]	✓	✓	✗	✗	✓	Deleted
262	Upgrading poles and structures with stronger, more robust materials	[57]	✗	✗	✗	✗	✓	Deleted
263	Elevating substations and relocating facilities to areas less prone to flooding	[57]	✗	✓	✗	✗	✓	Deleted
264	Redundant transmission routes via additional transmission facilities	[57]	✓	✓	✗	✗	✓	Deleted
265	Available energy sources/generation methods	[110]	✓	✗	✓	✓	✓	Deleted
266	Number of service connections able to handle entire load	[110]	✗	✓	✗	✗	✓	Deleted
267	Damage assessment methods	[110]	✓	✓	✗	✗	✓	Deleted
268	Scenario/contingency planning	[110]	✓	✓	✗	✗	✓	Deleted
269	Local availability of tools/expertise to address damage	[110]	✗	✓	✗	✗	✓	Deleted
270	Load shedding and load factor	[110]	✓	✓	✗	✗	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
271	Estimated lifespan of generation plant	[110]	✓	✓	✗	✓	✓	Deleted
272	Fortification and robustness (physical security)	[62,89,96,98,143, 157–159]	✓	✗	✓	✓	✓	Deleted
273	Operational system protection, e.g., system relief, circuit breakers	[31]	✓	✗	✗	✗	✓	Deleted
274	Diversification of energy supply—fuel mix, multisourcing, type of generation	[16,17,31,62,86–91,94–108]	✓	✗	✓	✓	✓	Deleted
275	Spatially distributed generation (and critical facilities)	[31,95,96,99,109,138, 139,141,160–163]	✓	✗	✗	✗	✓	Deleted
276	Energy production near point of use (colocation of supply and demand)	[96,164,165]	✓	✓	✗	✗	✓	Deleted
277	On-site energy production (photovoltaics, micro-combined heat and power, trigeneration, thermal panels, small wind turbines mounted at the corners of the roof)	[16,70,99,102,147–150,158,159,161, 166–175]	✓	✗	✗	✓	✓	Deleted
278	Solar absorption cooling	[176,177]	✗	✓	✗	✓	✓	Deleted
279	Large wind turbines located outside the built-up area	[162,178,179]	✗	✓	✗	✓	✓	Deleted
280	Large solar thermal collectors	[149,178]	✗	✓	✗	✓	✓	Deleted
281	Smart microgrids fed by microturbines and solar panels (photovoltaics, building integrated photovoltaics) and storage facilities	[62,104,109,136,138, 141,142,144,151,152, 158,180–183]	✗	✓	✗	✓	✓	Deleted
282	Building-integrated photovoltaic/thermal for recovery of heat loss form photovoltaics and building integrated photovoltaics	[180]	✗	✓	✗	✓	✓	Deleted
283	Ground source heat pumps	[149,150,178,184,185]	✗	✓	✗	✓	✓	Deleted
284	Waste heat or biomass-fueled combined heat and power plants	[138,178,186]	✓	✓	✓	✓	✓	Retained
285	Biofuel energy (food waste, second generation cellulosic biofuels, third generation using algae, etc.)	[139,182,184,187–190]	✓	✓	✓	✓	✓	Retained
286	Biomass supply chain, wood pellet systems	[101,139]	✗	✓	✗	✓	✓	Deleted
287	Interdependency and interconnection of infrastructures and their networks	[95,96,99,115,159, 160,165,191]	✓	✓	✓	✓	✓	Retained
288	Regular maintenance	[31,33,88,96]	✓	✓	✗	✓	✓	Deleted
289	Generation, transmission, and distribution efficiency (leakages, etc.)	[62,86,87,98,192]	✓	✗	✓	✓	✓	Deleted
290	Age of the fleet (feeder lines, etc.)	[62,193]	✗	✓	✗	✓	✓	Deleted
291	Type of feeder lines (overhead/underground cables; looped/interconnected or radial configuration)	[49,95,146,158,159, 193,194]	✗	✓	✗	✓	✓	Deleted
292	Natural gas distribution: continuous (grid) vs. discontinuous (propane tanks)	[195]	✗	✓	✗	✓	✓	Deleted
293	Alternative and safer energy sources for critical infrastructure such as parking gates, traffic lights, subway, etc.	[96,191]	✓	✓	✗	✓	✓	Deleted
294	Intelligent ICT infrastructure and cybersecurity thereof for maintaining grid operation	[31,33,49,96,133,158, 191,196,197]	✓	✓	✗	✓	✓	Deleted
295	Flexible network architecture	[31]	✗	✓	✗	✗	✓	Deleted
296	Number of configuration of nodes and links in the transmission and distribution grid	[17,22,198]	✓	✓	✓	✓	✓	Retained
297	Backup energy sources and stocks of energy	[17,33,96]	✓	✗	✓	✓	✓	Deleted
298	Energy storage facilities involving electro-chemical batteries, flow batteries, hydrogen, etc.	[16,49,70,86,90,109, 138,144,146,199]	✗	✓	✗	✓	✓	Deleted
299	Distributed storage	[95,158]	✓	✗	✗	✓	✓	Deleted

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
300	Connectivity of generation and storage infrastructure	[88,89,200]	✗	✓	✗	✗	✓	Deleted
301	Backup data of the utility infrastructure (information networks, data sharing, etc.)	[31,157]	✗	✓	✗	✗	✓	Deleted
302	Spare capacity and reserve margins—resources, transmission lines, etc.	[31,49,62,98,100,191, 201,202]	✓	✗	✗	✗	✓	Deleted
303	Vehicle-to-grid and vehicle-to-community selling of surplus power	[70,150,203]	✗	✓	✗	✗	✓	Deleted
304	Parks and open space, bioswales, etc. (attention to regular trimming of trees)	[193,204–218]	✓	✗	✓	✓	✓	Deleted
305	Indigenous (native) vs. invasive plants	[138,208]	✗	✓	✗	✓	✗	Deleted
306	Deciduous trees for cold climate	[168]	✗	✓	✗	✓	✗	Deleted
307	Xeriscape for hot and arid climates	[207,219]	✗	✓	✗	✓	✗	Deleted
308	Urban agriculture (vacant lands, marginal lands, etc.)	[220]	✗	✓	✗	✗	✗	Deleted
309	Green area ration	[213]	✓	✗	✓	✓	✓	Deleted
310	Green wall (vegetative covering, green façade)	[213,221–223]	✗	✓	✗	✗	✗	Deleted
311	Green roof (living roof)	[138,206,215,219, 224–227]	✗	✓	✗	✗	✗	Deleted
312	Rainwater harvesting, decentralized water harvesting systems	[137,147,204,228]	✗	✓	✗	✗	✗	Deleted
313	Water conservation	[147,219]	✗	✓	✗	✗	✗	Deleted
314	Heat recovery and energy generation from sewage	[204,229]	✗	✓	✗	✓	✓	Deleted
315	Separation of used water into grey and black flows	[219]	✗	✓	✗	✓	✗	Deleted
316	Removing and recovering ammonium and phosphate from wastewater	[219]	✗	✓	✗	✓	✗	Deleted
317	Waterscape as a natural heat sink	[209,215,230]	✗	✓	✗	✗	✗	Deleted
318	Roof ponds	[99,122,136,231]	✗	✓	✗	✗	✗	Deleted
319	Redesign and refurbishment (retrofit)	[113,115,139,148, 149,151,164,207,219, 232–235]	✗	✓	✗	✗	✗	Deleted
320	Glazing	[113,115,139,148, 149,151,164,207,219, 232–235]	✗	✓	✗	✗	✗	Deleted
321	Net zero- and net positive-energy buildings	[148,163,235,236]	✓	✓	✗	✗	✓	Deleted
322	Insulation and dynamic insulation of buildings	[104,109,139,141, 147–149,152,153, 159,168,176,214,219, 233,235,237–239]	✗	✓	✗	✗	✓	Deleted
323	Cut-off air conditioning waste heat discharge	[223]	✗	✓	✗	✗	✗	Deleted
324	Net zero-energy neighborhoods	[148]	✗	✓	✗	✗	✓	Deleted
325	Pooling of the built environment (shared walls)	[148,217]	✗	✓	✗	✗	✓	Deleted
326	District energy systems—using low-temperature heat from renewable sources and industrial waste heat	[87,137,138,151,184]	✓	✓	✗	✗	✓	Deleted
327	Infrastructure for active transportation modes	[136,138,164,168, 196,220,240–244]	✗	✓	✗	✗	✗	Deleted
328	Modal split	[87,241]	✗	✓	✗	✗	✗	Deleted
329	Size of cars	[196]	✗	✓	✗	✗	✗	Deleted
330	Fuel efficiency of cars	[115,196,243]	✗	✓	✗	✗	✗	Deleted
331	Supporting promotion of hybrid vehicles and installing electric vehicle plug-ins in locations where multiple use can be achieved	[31,70,99,136–138]	✓	✓	✓	✓	✓	Retained

Table A1. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
332	Enhancing energy efficiency through innovation and technology (building, industry, transportation)	[31,62,69,94,96,99,117,143,144,147,150,164,165,180,184,186,228,237,241,243,245]	✓	✓	✗	✗	✓	Deleted
333	Energy conservation	[139]	✓	✗	✓	✓	✓	Deleted
334	Energy self sufficiency	[91,99,160]	✗	✓	✓	✓	✗	Deleted
335	Energy cycling	[70,142]	✗	✓	✗	✗	✓	Deleted
336	Waste management and waste incineration	[86,108,147,184]	✓	✗	✓	✓	✓	Deleted
337	Environmental and socioeconomic impacts of energy system	[86,98,99,108]	✗	✓	✗	✗	✓	Deleted
338	Reducing energy footprint of water production, treatment, and distribution	[95,116,138,192,228,229,246,247]	✗	✓	✗	✗	✓	Deleted
339	Provision of less energy-intensive rainwater harvesting systems in buildings	[228]	✗	✓	✗	✗	✓	Deleted
340	Water and energy resource coupling	[109]	✗	✓	✗	✗	✓	Deleted
341	Reducing energy footprint of wastewater collection, treatment, and discharge	[138]	✗	✓	✗	✗	✓	Deleted
342	Reducing water footprint of energy production and transmission	[95,116,192,246,247]	✓	✓	✗	✗	✓	Deleted
343	Improving the efficiency of energy production by enhancing water quality	[187]	✓	✓	✗	✗	✓	Deleted
344	Understanding the water intensity of fuels used for electricity generation	[247]	✗	✓	✗	✗	✓	Deleted
345	Less water-intensive technologies for cooling purposes in thermoelectric plants	[95,192,246]	✗	✓	✗	✗	✓	Deleted
346	Use of natural gas for steamed turbines and combined cycle plants	[192,246]	✓	✓	✗	✗	✓	Deleted
347	Use of wet cooling towers instead of once-through cooling	[246]	✓	✓	✗	✗	✓	Deleted
348	Knowing groundwater implications of energy (technologies, extraction, etc.)	[86,187,229]	✗	✓	✗	✗	✓	Deleted
349	Scenario-based energy planning and risk management	[31,133,229]	✗	✗	✗	✗	✓	Deleted
350	Risk communication and energy response of urban governance	[96]	✗	✗	✗	✗	✓	Deleted
351	Community involvement in and/or ownership of renewable energy generation	[96]	✓	✓	✗	✗	✓	Deleted
352	Institutional coordination on water, food, health, and energy nexus	[116]	✓	✓	✗	✗	✓	Deleted
353	Reliance on nuclear energy	[31,154]	✓	✓	✓	✓	✓	Retained
354	Regular publication of energy planning documents and statistics	[99]	✗	✓	✗	✗	✓	Deleted
355	Market competitiveness and investment risk of decentralized renewable energy	[99,139,150,239]	✗	✓	✗	✗	✓	Deleted
356	Requirement for suppliers to source a proportion of electricity from renewables	[239]	✗	✓	✗	✗	✓	Deleted
357	Legal and regulatory frameworks to encourage technological development and transition towards energy resilience	[161,180,248]	✗	✓	✗	✗	✓	Deleted
358	Measures against electricity theft	[249]	✗	✓	✗	✗	✓	Deleted
359	Attracting private sector's investment in low-carbon development	[95,115–117]	✗	✓	✗	✗	✓	Deleted
360	Financial and nonfinancial mechanisms and incentives for promoting green products and renewable energy technologies and enhancing affordability	[95,115–117]	✗	✓	✗	✗	✓	Deleted

Table A2. Aggregated index selection for CI.

No.	Primary Index	Ref.	S	U	F	O	R	Result
1	Train transportation	[250]	✓	✓	✓	✓	✓	Retained
2	Emergency organization and infrastructure in place and critical functions identified	[44,118]	✓	✓	✗	✗	✓	Deleted
3	Waste and disposal	[41,120,122]	✓	✓	✓	✓	✓	Retained
4	Land use requirement	[120]	✗	✓	✗	✗	✓	Deleted
5	Level of public resistance/opposition	[120]	✗	✓	✗	✗	✗	Deleted
6	Market size—domestic/potential export	[120]	✓	✓	✗	✗	✓	Deleted
7	Permeable pavement and bioswales	[121]	✓	✓	✗	✗	✓	Deleted
8	Urban tree canopy	[121]	✗	✓	✗	✗	✗	Deleted
9	Water demand and consumption	[8,121,122,251,252]	✓	✓	✓	✓	✓	Retained
10	Water-efficient landscaping	[8,41,121]	✗	✓	✗	✗	✗	Deleted
11	Protection of water-sensitive lands	[121]	✓	✓	✓	✗	✗	Deleted
13	Water quality and quantity monitoring	[121,252]	✗	✓	✓	✓	✗	Deleted
14	High-efficiency irrigation	[8,121]	✗	✓	✓	✓	✗	Deleted
15	High-frequency schedule for public transportation	[41,42,121]	✗	✓	✓	✗	✗	Deleted
16	Principle arterial miles per square mile	[121]	✗	✓	✓	✗	✗	Deleted
17	Vehicle ownership	[8,10,121,251,253]	✓	✓	✓	✓	✓	Retained
18	Parks	[8,121]	✗	✓	✓	✓	✗	Deleted
19	Forest conservation	[8,121]	✗	✓	✓	✗	✗	Deleted
20	Waste management	[8,121]	✓	✗	✓	✓	✓	Deleted
21	Provision of open space for shelter	[8,121,122]	✓	✓	✓	✓	✓	Retained
22	Percentage of vacant rental units	[121]	✗	✓	✗	✓	✗	Deleted
23	Number of hotels/motels per square mile	[8,121]	✗	✓	✓	✓	✗	Deleted
24	Evacuation route	[8,121]	✗	✓	✓	✗	✗	Deleted
25	Building insulation, layout, and orientation	[121]	✗	✓	✗	✓	✗	Deleted
26	Reducing air infiltration and thermal bridging	[121]	✗	✓	✗	✓	✓	Deleted
27	Natural ventilation	[121]	✗	✓	✗	✗	✗	Deleted
28	Preservation of housing	[121]	✗	✓	✗	✗	✗	Deleted
29	Building codes	[121]	✗	✓	✓	✓	✗	Deleted
30	Housing age	[121]	✗	✓	✓	✓	✗	Deleted
31	Generating and making use of information	[121]	✓	✓	✗	✗	✓	Deleted
32	Geospatial information and communication technology	[121]	✓	✓	✗	✗	✓	Deleted
33	Volunteered geographic information	[121]	✗	✓	✗	✗	✓	Deleted
34	Visualization technologies	[121]	✗	✓	✗	✗	✓	Deleted
35	Alerts and emergency notification systems	[121]	✓	✓	✗	✗	✓	Deleted
36	Embracing e-commerce	[121]	✗	✓	✗	✗	✓	Deleted
37	Biodiversity	[8,121]	✗	✓	✗	✗	✓	Deleted
38	Restoration of hydrologic flows	[8,121]	✗	✓	✗	✗	✓	Deleted
39	Conservation of ecologically vulnerable areas	[121,254]	✗	✓	✗	✗	✓	Deleted
40	Proximity of different habitats	[121]	✗	✓	✗	✗	✓	Deleted
41	Erosion rates	[121]	✓	✓	✗	✗	✓	Deleted
42	Urban green commons	[121,122]	✓	✓	✓	✓	✓	Retained
43	Culture of cooperation	[121]	✗	✓	✗	✗	✗	Deleted
44	Balance demographic distribution	[121]	✗	✗	✓	✓	✓	Deleted
45	Aging population	[121]	✗	✓	✗	✗	✓	Deleted
46	Responsive health systems	[121]	✓	✓	✓	✓	✓	Retained
47	Health coverage and access	[8,121,253]	✓	✓	✓	✓	✓	Retained
48	Road density	[10,45,251]	✓	✓	✓	✓	✓	Retained
49	Distribution of fire stations	[45]	✓	✓	✗	✓	✓	Deleted
50	Distribution of police stations	[45]	✓	✓	✗	✓	✓	Deleted

Table A2. *Cont.*

No.	Primary Index	Ref.	S	U	F	O	R	Result
51	Distribution of civil air defense facilities	[45]	✓	✓	✗	✓	✓	Deleted
52	Distribution of emergency shelters	[45]	✓	✓	✗	✓	✓	Deleted
53	Land types	[45]	✗	✓	✗	✗	✗	Deleted
54	College students	[251]	✗	✓	✓	✓	✓	Deleted
55	Hospital distribution	[10,45]	✓	✓	✓	✓	✓	Retained
56	Medical rescue capability	[10,45,251]	✓	✓	✓	✓	✓	Retained
57	Ecological restoration capacity—green coverage ratio	[10,45,251]	✓	✓	✓	✓	✓	Retained
58	Social security	[45]	✓	✓	✓	✓	✓	Retained
59	Gas supply pipeline	[10]	✓	✓	✓	✓	✓	Retained
60	Drainage pipeline	[10,41]	✓	✓	✓	✓	✓	Retained
61	Internet users	[10,251]	✓	✓	✓	✓	✓	Retained
62	Mobile phone users	[41,251,253]	✓	✓	✓	✓	✓	Retained
63	Medical insurance coverage	[251,253]	✓	✓	✓	✓	✓	Retained
64	Unemployment insurance coverage	[251]	✗	✓	✓	✓	✗	Deleted

Table A3. Aggregated index selection for CV.

No.	Primary Index	Ref.	S	U	F	O	R	Result
1	Human health impact—the degree to which a disruption in the system might feasibly harm the health of employees or the public	[52]	✓	✓	✓	✓	✓	Retained
2	Electricity consumption per capita	[112]	✓	✓	✓	✓	✓	Retained
3	Climate resilience	[120]	✗	✓	✗	✗	✓	Deleted
4	Noise pollution	[120]	✗	✓	✗	✓	✓	Deleted
5	Aesthetic/functional impact	[120]	✗	✓	✗	✗	✓	Deleted
6	Mortality and morbidity due to air pollution	[120]	✗	✓	✗	✗	✓	Deleted
7	Accident fatalities	[120]	✗	✓	✓	✓	✓	Deleted
8	Ecosystem damages due to acidification and eutrophication caused by pollution from electricity production	[120]	✗	✓	✗	✗	✓	Deleted
9	Seismic risk	[45]	✗	✓	✓	✓	✓	Deleted
10	Flood risk	[45,122]	✗	✓	✓	✓	✓	Deleted
11	Meteorological hazard	[45]	✗	✓	✓	✓	✓	Deleted
12	Geological hazard risk	[45]	✗	✓	✓	✓	✓	Deleted
13	Hazard of industrial disaster	[45]	✗	✓	✗	✗	✓	Deleted
14	Population density	[45,251]	✓	✓	✓	✓	✓	Retained
15	Demographic structure	[45,251, 253]	✓	✓	✓	✓	✓	Retained
16	Demographic change	[45,251]	✓	✓	✓	✓	✓	Retained
17	Distribution of important buildings	[45]	✓	✓	✓	✓	✓	Retained
18	GDP per capita	[10,45,251]	✓	✓	✓	✓	✓	Retained
19	Affected elements and components	[110]	✗	✓	✓	✓	✓	Deleted
20	Number of households affected	[110]	✗	✓	✓	✓	✓	Deleted

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Multitemporal Total Coliforms and *Escherichia coli* Analysis in the Middle Bogotá River Basin, 2007–2019

Mario Fernando Castro Fernández [1,*], Ileana Romea Cárdenas Manosalva [2], Ramón Fernando Colmenares Quintero [1], Carlos Enrique Montenegro Marín [2], Yeffer Edilberto Diaz Cuesta [2], Daniela Escobar Mahecha [2] and Paula Andrea Pérez Vásquez [2]

[1] School of Engineering, Universidad Cooperativa de Colombia, Bogota 111311, Colombia; ramon.colmenaresq@campusucc.edu.co

[2] School of Environment and Natural Resources, Universidad Distrital Francisco José de Caldas, Bogota 111311, Colombia; ircardenasm@udistrital.edu.co (I.R.C.M.); cemontenegrom@udistrital.edu.co (C.E.M.M.); yediazc@correo.udistrital.edu.co (Y.E.D.C.); descobarm@correo.udistrital.edu.co (D.E.M.); paperezv@correo.udistrital.edu.co (P.A.P.V.)

* Correspondence: mario.castrof@campusucc.edu.co; Tel.: +57-3183777072

Abstract: Currently, one of the main environmental problems that need to be addressed is the pollution inflicted upon different ecosystems by anthropic activities. One example of this problem can be seen in the Bogotá River, a major river in the Cundinamarca department of Columbia and the main water source supplying the Bogotá savannah, which reaches the Colombian capital city. The Bogotá River is highly affected by effluents and wastewater of domestic and industrial origin, among others. These pollutants are generated and accumulated throughout the entire basin, without ever receiving any type of treatment. The pollution levels to which the Bogotá River is subjected can be determined with the calculation of environmental indices, including microbiological contamination indicators such as total coliforms (TC) and fecal coliforms, which include *Escherichia coli*, *Enterobacter*, *Klebsiella*, *Serratia*, *Edwardsiella*, and *Citrobacter* bacteria, living as independent saprophytes. This paper assesses the quality of the water in the Bogotá River, using microbiological indicators and data provided by the Regional Autonomous Corporation (CAR) of Cundinamarca to assess water samples, extracted based on the climatic bimodality exhibited in the basin in dry and wet seasons. The scope of this study was limited to the 35 monitoring Regional Autonomous Corporation of Cundinamarca (CAR) stations located throughout the middle basin. For these purposes, a multitemporal analysis of the TC and *Escherichia coli* variables was conducted for the 2007–2019 period, which evidenced the contamination levels in this section of the water body. In broad terms, the current state of the middle section of the Bogotá River basin is unacceptable, due to the different activities occurring within its riparian buffer zone, such as uncontrolled domestic, industrial, and/or commercial wastewater discharges. To optimize water treatability, the continuous improvement of existing treatment plants is expected, as well as the implementation of new sustainable treatment alternatives aimed at improving water quality.

Keywords: total coliforms; fecal coliforms; *Escherichia coli*; Bogotá River; wastewater; water quality; microorganisms

Citation: Castro Fernández, M.F.; Cárdenas Manosalva, I.R.; Colmenares Quintero, R.F.; Montenegro Marín, C.E.; Diaz Cuesta, Y.E.; Escobar Mahecha, D.; Pérez Vásquez, P.A. Multitemporal Total Coliforms and *Escherichia coli* Analysis in the Middle Bogotá River Basin, 2007–2019. *Sustainability* **2022**, *14*, 1769. https://doi.org/10.3390/su14031769

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio, Felicia Di Liddo and Agostina Chiavola

Received: 23 August 2021
Accepted: 10 January 2022
Published: 3 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Over 2,000,000,000,000 people live in countries experiencing high water stress, and 4,000,000,000,000 people worldwide experience severe water scarcity for at least one month of the year. The environmental impact of this shortage will continue to increase, as water demand grows and the effects of climate change intensify [1]. Within this context, it is evident that some rivers exhibit high concentrations of organic matter and nutrients, high pollution levels caused by heavy metals, and high levels of contamination. Hence, continuous inspection and improvement are required to prevent major negative effects in these rivers [2]. The 2030 Agenda for Sustainable Development is committed to "leaving no one behind", seeking universal and equitable access to drinking water, thus fostering socio-economic development and achieving the full realization of human rights across the globe [3].

Its vast hydrographic wealth ranks Colombia among the top 10 countries in the world in terms of water availability. Its water supply is 59 L/s/km^2, which equates to six times the world average and three times the Latin American average. In addition, the country reports an annual rainfall of 3000 mm, exceeding the global average by three times and approximately twice the South American average [4]. However, according to the World Health Organization (WHO), 1,500,000 young children (under the age of 5) die every year due to the lack of safe water and sanitation, which is a common issue in developing countries such as Colombia [5].

Moreover, if Colombia is to remain a water power, the national government must be committed to defending the country's water resources. It must also enforce the local regulations issued by Colombia's Ministry of Environment, Housing and Territorial Development [6]. It is important that for the proper management of domestic and industrial wastewater treatment plants (WWTPs), investments are made to ensure that they run at optimal operating conditions throughout the national territory [7].

Colombia reports significant progress in the management of conventional and hazardous solid waste against other Latin American countries. However, this is not completely feasible because there are still opportunities for improvement regarding the final disposal of solid waste in rural areas and municipalities, which still face issues due to the inappropriate disposal of solid waste, a situation fueled by poor landfill infrastructure and poor coverage of basic sanitation services [8]. Solid-waste mismanagement has caused cracks in landfills around the country, leading to landslides and leachate leakage, in addition to biogas accumulations that can generate atmospheric pollution [9]. This issue directly or indirectly affects the quality of water resources, since the subsoil and groundwater may become contaminated. Furthermore, poor garbage collection service coverage contributes to degrading not only the environment but also human health [8].

Total and fecal coliforms are Gram-negative bacteria, with aerobic and facultative growth capacity, that are commonly found in plants, soil and animals, as well as in humans [10]. The presence of coliforms in water bodies clearly indicates contamination by sewage discharges or decaying matter and especially by organic waste. Fecal contamination constitutes the main sanitary risk for water bodies since, given these conditions, this water will contain pathogenic microorganisms that can cause diseases threatening human health [11]. In fact, the presence of enteropathogenic microorganisms represents a high risk to public health [12].

Waterborne diseases are related to the presence of these fecal bacteria in both sewage and drinking water, which generate high morbidity and mortality rates, mainly in children [13]. Acute diarrheal disease is characterized by frequent discharges of feces with abnormal consistency. Approximately 85% of diarrhea-related deaths involve children under one year of age. The pathogens associated with diarrhea are: viruses, such as rotaviruses, which usually infect 10–50% of all humans; protozoa, such as *Cryptosporidium* sp., *Giardia lamblia*, and *Entamoeba histolytica*, which report a lower frequency of 1–8%; and bacteria, such as *Shigella* sp. (8–30%), enterotoxigenic *E. coli*, and enteropathogenic *E. coli*, which usually affects 5–40% of the population [14]. As mentioned above, *E. coli* is one of the direct causes of diarrheal diseases. Therefore, sanitary controls aimed at mitigating microbiological risks are extremely important and represent a critical measure for the population. Environmental management in watersheds should necessitate a social responsibility approach, with the participation and commitment of different stakeholders at the governmental and national levels [15].

The Magdalena river basin has an area of 257,400 km^2, occupying 22.5% of the Colombian territory, with a length of 1612 km [16]. This basin supplies water to 80% of the country's population and supports ~85% of the national GDP [17]. However, due to its high level of contamination, the Magdalena River represents a health risk for a large part of the population in the center of the country who consume drinking water from this river [18]. The Magdalena riverbed experiences greater microbiological contamination by total coliforms (TC) and *Escherichia coli* during the dry season than during the rainy season because, during the rainy season, its flow increases due to rainfall, thus generating a dilution in the concentration of microorganisms [17]. Given that its major tributary is the Bogotá River, which flows directly into this body of water, serious social, economic, political, and environmental problems are observed [19].

In fact, one of the 17 goals proposed in the UN's Sustainable Development Goals for 2030 refers to adequate sanitation to ensure a clean watershed. In 2017, Colombia ranked 16th among 179 countries in the world, with a volume of 50,000 m^3 of water per inhabitant per year. With respect to this total volume, the Bogotá River provides ~300 m^3 of water per inhabitant per year [20]. The Bogotá river basin has been named as the most polluted water body in Colombia, as a result of sewage discharges from more than 7.4 million people residing in the area [21], and its waters flow into the Magdalena River, a major national river system [18].

The high concentrations of total and fecal coliforms in the middle reaches of the Bogotá River basin during the dry season are largely due to human and industrial settlements. There is also a relationship between the effects of climatic seasons and the pollution sources evaluated in this study [22]. In addition, discharges of untreated wastewater are the main source of contamination by these Enterobacteriaceae [23]. According to the 2014 Colombian Water Study, the Bogotá River reports an extremely high vulnerability index to water stress, which evidences the fragility of supply experienced by this water system during climatic phenomena, such as the El Niño event. Another critical variable to be evaluated is the water pressure reported by the different ecosystems and the amount of water that does not return to the basin. In fact, when analyzing the relationship between the green water footprint, which refers to the use and retention of water stored in the soil, and the blue water footprint, which refers to the retention of surface- and groundwater (rivers, lagoons, and aquifers) by anthropogenic activities, it becomes evident that water availability is seriously threatened by the large number of agricultural and livestock activities that are concentrated in the river subzones [24].

Historically, the Bogotá river basin has experienced significant uncertainty due to its pollution and sanitation, as well as water imbalances in its channel caused by inadequate land use and overexploitation. The different variables that influence anthropogenic modifications must be evaluated in order to preserve these ecosystems [25]. A better understanding of tipping points in lotic ecosystems will help to identify long-term impacts caused by human–ecosystem interactions and to establish adaptive and transformative management plans for large rivers [26]. Pollution caused by industrial and domestic wastewater in the municipalities of the Capital District is also fostered by nefarious and underperforming treatment plants [27]. The increasing development of urbanization has exceeded the normal balance, thus stimulating an increase in environmental services and goods, which is coupled with increased waste generation [28].

According to the 2018 Progress Report of the Colombian Water Study, the capital city of Bogotá accounts for most of the domestic pollutant load on water sources [29]. For this reason, multiple prevention and correction activities aimed at reducing pollution are being carried out, which directly benefits the city's localities, since the middle section of the Bogotá river basin is located in the urban area of the Colombian capital [20]. However, although the "El Salitre" WWTP has been in operation since 1999 [30], it has not been able to remove the expected load volume, as it cannot keep up with processing the required wastewater levels. This plant has the capacity to treat 4 m^3 of wastewater per second but receives 15 m^3 per second, generated by the ~3 million people living in Bogotá alone. Therefore, most of the wastewater is not adequately treated. In addition, the Bogotá River also receives multiple discharges as it passes through the city [20].

This work focuses on determining the spatiotemporal patterns of microbiological conditions reported between 2007 and 2019 by the 35 stations located along the middle basin of the Bogotá River.

2. Materials and Methods

2.1. Study Area

The Bogotá River runs through the Cundinamarca and Boyacá highlands, crossing the department of Cundinamarca from northeast to southeast. Its headwaters are at 3300 m above sea level (masl) in the Páramo de Guacheneque forest reserve, in the municipality of Villapinzón, and flow into the Magdalena River, in the municipality of Girardot, at 280 masl, covering an area of influence of ~589,143 ha [31]. The Bogotá River is divided into three basins—the high, middle, and low basins—passing through 47 municipalities of the department of Cundinamarca, which route represents an influence on just over 10 million people, who are mainly from the city of Bogotá [32].

The middle basin of the Bogotá River corresponds to the section located between the monitoring stations, as shown in Figure A1: Quebrada La Tenería (No. 68) and downstream Quebrada Honda (No. 67). This river basin receives discharges (either directly or indirectly) from the municipalities of Chía, Cota, Tenjo, Subachoque, El Rosal, Funza, Madrid, Mosquera, Bojacá, Facatativá, Soacha, Tena, San Antonio del Tequendama, and part of the discharges from Cajicá, but especially the discharges from the Capital District of Bogotá. Its main tributaries in this section are the discharges from the Frio, Chicú, Balsillas, Salitre, Fucha, Tunjuelo, Soacha rivers, and the La Cuy and Honda streams. The data of the stations in this study were provided by the Corporación Autónoma Regional de Cundinamarca (CAR).

2.2. Station Sampling Design

For the last 12 years, the Environmental Laboratory of the CAR has studied the middle basin of the Bogotá River, performing microbiological analysis in 35 monitoring stations, taking as a reference the highest values, these being the most representative of the study. The sampling frequency was in the two seasons of the year, taken as the high-water and low-water seasons, which indicate the rainy and dry periods. For the development of microbiological analysis, two periods were identified. They were given the numbers 01, which includes the months from January to June, and 02, which includes the months from July to December. This designation is added after specifying the year of sampling, for example, 2014-02. The numbering of each station corresponds to the identification provided in the data by the CAR; these numbers do not have a sequential order. The monitoring stations are described below: Quebrada La Tenería (No. 68), upstream of Chía (No. 14), Chía Municipal Discharge (No. 29), downstream of Chía (No. 3), Limnigrafica (LG) bridge (Pte). La Balsa station (No. 42), River Frio (No. 75), downstream River Frio (No. 10), Cota Municipal Discharge (No. 30), LG Pte. La Virgen station (No. 43), River Chicú (No. 74), Limnimetric (LM) Vuelta Grande (No. 58), Juan Amarillo Bypass (No. 22), El Salitre WWTP (No. 59), El Cortijo (No. 39), Jaboque discharge (No. 28), Engativá discharge (No. 27), Engativá downstream (No. 4), La Ramada (No. 53), LG Pte. Cundinamarca (No. 56), LM Hacienda San Francisco (No. 57), River Fucha (No. 76), downstream River Fucha (No. 11), Gibraltar pump (No. 24), LG La Isla (No. 54), Rio Tunjuelo (No. 70), downstream River Tunjuelo (No. 13), Rio Balsillas (No. 72), River Soacha (No. 79), Soacha cannel (No. 23), LG Las Huertas (No. 55), Mondoñedo bridge (No. 60), upstream Salto Tequendama (No. 18), San Antonio. Tequendama municipal discharge, Quebrada La Cuy (No. 31), Quebrada Honda (No. 67), and downstream Quebrada Honda (No. 9). Of the abovementioned stations, the ones closest to the urban area can be seen in Figure 1.

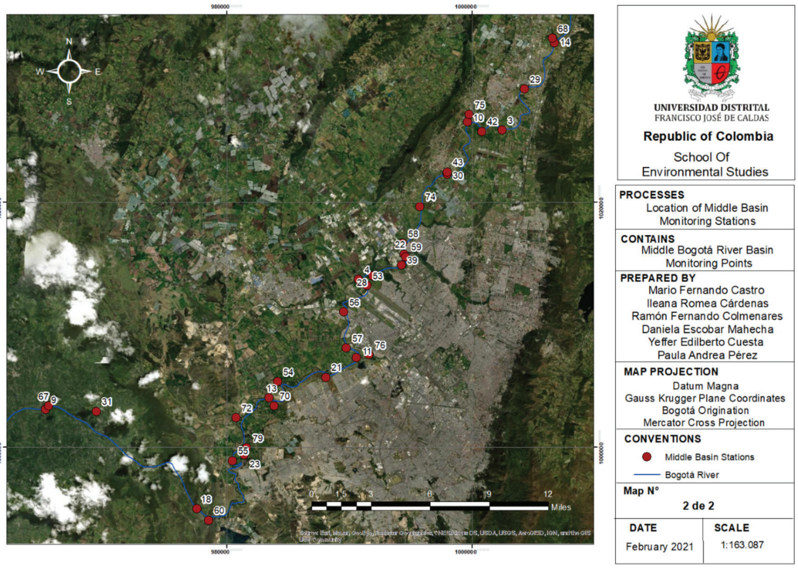

Figure 1. Location of Middle Basin Monitoring stations located with the identification number described above, Bogotá River approach. Source: prepared by the authors, 2021.

At a methodological level, coliforms were reported as per the Colilert method, which detects TC and *E. coli* using the defined substrate and a fluorescence technique. Then, spatial-temporal graphs were plotted for the TC and *E. coli* variables. The values reported were compared with the reference value of 2.0×10^4 MPN/100 mL for TC and 2.0×10^3 MPN/100 mL for *E. coli*, established by Executive Order 1594 in 1984.

The data collected for the middle Bogotá River basin were analyzed using a quantitative study that compared the results reported by the Regional Autonomous Corporation (CAR) in the 12 years from 2007-01 to 2019-02 at the 35 wastewater quality monitoring stations located along the waters of the middle river basin, taking the values established by Executive Order 1594 in 1984 as a reference. The results from the 35 stations or sampling points were organized sequentially according to each location within the middle basin, based on the coordinates provided by the Regional Autonomous Corporation (CAR), with each location being pinpointed using a geographic information system (ArcGis). Subsequently, the sets of values collected were cleaned using Excel and Origin Lab. Data analysis was performed using a descriptive statistical method to understand and analyze a given set of data [33], comparing the microbiological results of total coliforms and *Escherichia coli* over the 12-year period, in relation to the two seasons of the year, taking into account the maximum values of each season along the middle basin of the Bogota River (multitemporal analysis).

3. Results

After assessing the microbiological water-quality data collected from 35 stations during the 2007–2019 period for the middle Bogotá River basin, the following results were obtained.

For Station (No. 68) Quebrada La Tenería, the highest TC and *E. coli* levels were evidenced in 2014-02, with TC exceeding 2.4×10^8 MPN/100 mL and *E. coli* reaching 9.3×10^7 MPN/100 mL. The most recent report, for 2019-02, records 1.00×10^8 MPN/100 mL and 7.50×10^6 MPN/100 mL for TC and *E. coli*, respectively.

In the section that covers the municipality of Chía, three monitoring stations provided behavioral data. First, the upstream Chía station (No. 14) reported peak values for the first period of 2007, with a TC concentration of 2.40×10^7 MPN/100 mL and an *E. coli* concentration of 2.00×10^7 MPN/100 mL. A third maximum peak was reported in 2019-01, with 1.70×10^6 MPN/100 mL for TC and 8.20×10^5 MPN/100 mL for *E. coli*.

The Chía municipality discharge station (No. 29) reported a maximum concentration of 2.50×10^7 MPN/100 mL for TC and 1.70×10^6 MPN/100 mL for *E. coli* in the 2008-02 period. In addition, in 2014-02, these concentrations increased from the previous year to 1.60×10^7 MPN/100 mL for TC and 4.60×10^6 MPN/100 mL for *E. coli*. The third station is the downstream Chía station (No. 3), which reports concentrations of 6.50×10^7 MPN/100 mL for TC and 1.10×10^7 MPN/100 mL for *E. coli* in 2010-01, as may be observed in Figure 2, below.

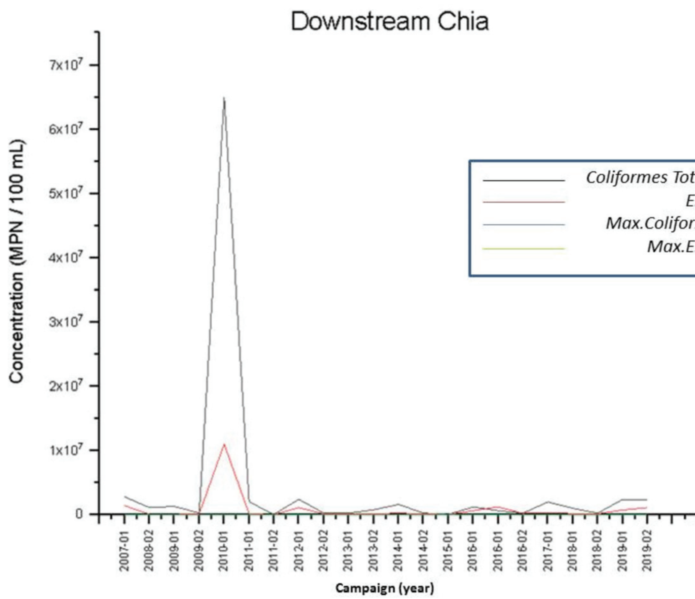

Figure 2. Downstream Chía concentration chart. Source: prepared by the authors, 2021.

The LG Puente la Balsa Station (No. 42) reported a significant increase in 2014-01, with TC values exceeding 2.40×10^6 MPN/100 mL and *E. coli* levels of 8.20×10^5 MPN/100 mL; in 2019-02, this station reported TC concentrations of 2.40×10^6 MPN/100 mL and *E. coli* concentrations of 2.90×10^5 MPN/100 mL.

At the next station, Rio Frio (No. 75), TC concentrations for 2011-01 were 5.80×10^7 MPN/100 mL, with *E. coli* levels of 9.60×10^6 MPN/100 mL. However, in 2019-02, TC concentrations decreased to 9.90×10^3 MPN/100 mL, as well as for *E. coli* concentrations, which showed a value of 100 MPN/100 mL.

Subsequently, at the downstream Rio Frio station (No. 10), concentrations remained high, as evidenced in 2010-01, when the station reported TC concentrations of 4.60×10^7 MPN/100 mL and *E. coli* concentrations of 1.80×10^7 MPN/100 mL; in 2016-02, TC values were observed of 1.70×10^7 MPN/100 mL, while the concentration of *E. coli* decreased (2.70×10^5 MPN/100 mL) (Figure 3).

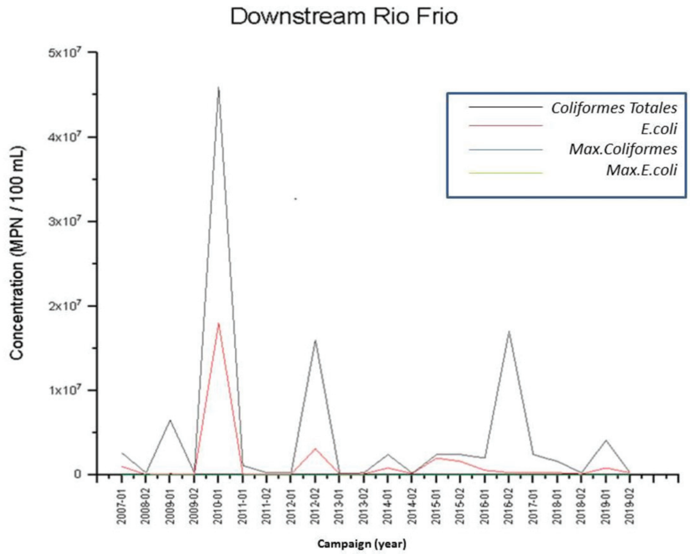

Figure 3. Downstream Rio Frio concentration chart. Source: prepared by the authors, 2021.

The Cota municipality station (No. 30) reported a large number of total coliforms and *E. coli*. Below, we list the main concentration peaks recorded throughout our 12-year assessment period: in 2010-01, concentrations were reported of 2.00×10^8 MPN/100 mL for TC and 5.30×10^7 MPN/100 mL for *E. coli* and, in 2019-02, TC concentrations were reported of 1.50×10^8 NMP/100 mL and *E. coli* concentrations of 3.40×10^7 MPN/100 mL.

The next monitoring point was the Puente La Virgen station (No. 43), where maximum concentrations were reported in 2007-01, with values of 9.80×10^6 MPN/100 mL for *E. coli* and 7.30×10^7 MPN/100 mL for TC. An overall decrease in coliforms was observed at this station for 2019-01; TC concentrations were 2.40×10^6 MPN/100 mL and *E. coli* concentrations were 5.00×10^5 MPN/100 mL (Figure 4).

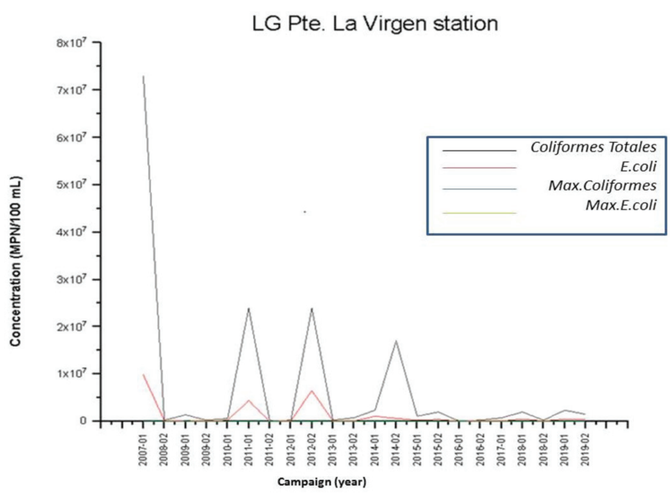

Figure 4. LG Puente La Virgen station concentration chart. Source: prepared by the authors, 2021.

The Rio Chicú station (No. 74) reported a 2007-01 TC concentration of 2.40×10^6 MPN/100 mL, and an *E. coli* concentration of 4.30×10^5 MPN/100 mL; in 2019-02, this station reported TC concentrations of 2.40×10^3 MPN/100 mL and *E. coli* concentrations of 3.10×10^2 MPN/100 mL. Here, the maximum concentrations reported by these stations significantly decreased for total coliforms and *E. coli*.

Subsequently, the data recorded at this point reveals higher concentrations than the LM Vuelta Grande station (No. 58). In 2014-02, these concentrations increased even more, as TC concentrations were reported at $>2.00 \times 10^7$ MPN/100 mL and *E. coli* concentrations were 2.00×10^7 MPN/100 mL, which denotes a lack of interest from the corporations in charge of improving water quality. However, in 2019-01, the maximum TC values ($>2.40 \times 10^6$ MPN/100 mL) and *E. coli* values (5.80×10^5 MPN/100 mL) decreased from the previous peak in 2014-02, but these values still exceeded the maximum permissible limits.

Subsequently, data from the Juan Amarillo Bypass station (No. 22) shows that for the season of 2008-02, the TC concentrations were 1.90×10^8 NMP/mL and *E. coli* was 1.20×10^7 NMP/mL; for 2014-02, these concentrations increased even more, since the TC concentrations were 2.00×10^8 NMP/mL and *E. coli* levels were 2.20×10^7 NMP/mL, which shows great disinterest on the part of the corporations in charge of improving the quality of the water.

Station No. 59, located at the discharge (channel) of the El Salitre Wastewater Treatment Plant reported high TC concentrations of 1.50×10^8 MPN/100 mL and *E. coli* concentrations of 1.30×10^7 MPN/100 mL for 2008-02. Although the plant has been in operation since 1999, high levels of contamination at 2.0×10^3 MPN/100 mL of TC were still being reported in 2008. In fact, 6 years later, in 2014-02, concentrations had increased significantly to 1.70×10^8 MPN/100 mL for TC and 2.20×10^7 MPN/100 mL for *E. coli*, as can be observed in Figure 5.

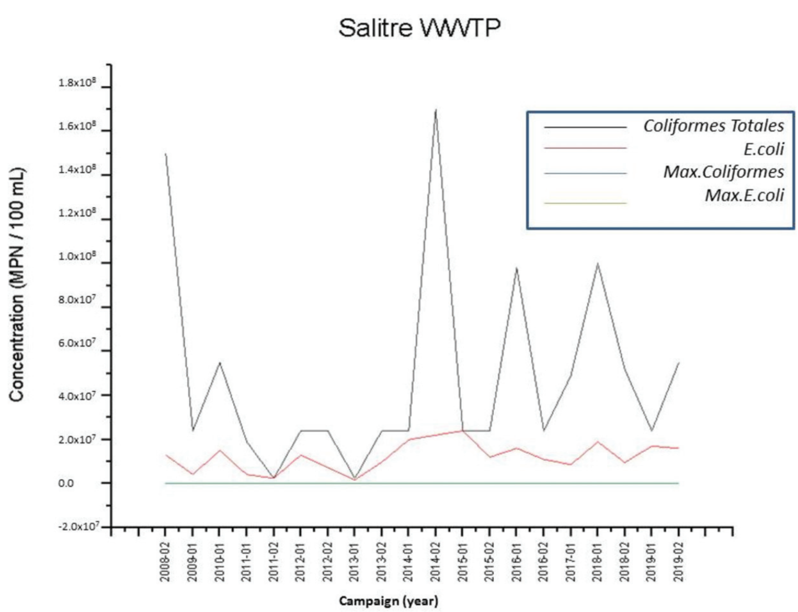

Figure 5. El Salitre WWTP concentration chart. Source: prepared by the authors, 2021.

Next in line is the monitoring station of El Cortijo (No. 39), located 500 m downstream of the El Salitre WWTP discharge point. In 2009-01, this station reported a TC concentration of 2.20×10^8 MPN/100 mL and *E. coli* concentrations of 1.20×10^7 MPN/100 mL. However, in 2016-02, this station reported TC concentrations of 1.70×10^8 MPN/100 mL and *E. coli* concentrations of 8.20 × 10^6 MPN/100 mL. These concentrations are extremely high compared to the concentrations reported by the Jaboque discharge station (No. 28), which are lower than the rest of the stations mentioned. For example, in 2011-01, TC concentrations only reached 4.70 × 10^3 MPN/100 mL and *E. coli* concentrations reached <1 × 10^2 MPN/100 mL, as shown in Figure 6. However, a peak was reported in 2015-01 with the presence of TC concentrations of 2.40 × 10^7 MPN/100 mL and *E. coli* concentrations of 9.8 × 10^4 MPN/100 mL.

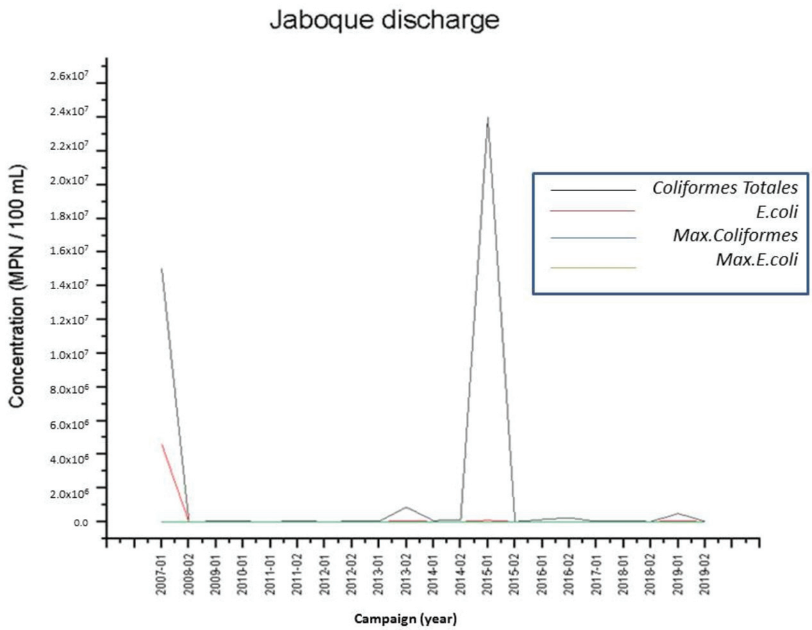

Figure 6. Jaboque discharge concentration chart. Source: prepared by the authors, 2021.

Upon entering the Engativá community, the water body is further affected, as is seen in the data reported by the Engativá discharge station (No. 27) for the year 2019-02, which shows that concentrations increased even more, reaching 2.00 × 10^8 MPN/100 mL for TC and 4.10 × 10^7 MPN/100 mL for *E. coli*.

The La Ramada station (No. 53) registered a decrease in the values reported by the downstream Engativá discharge station, given that the station reported TC concentrations of 1.4 × 10^7 MPN/100 mL and *E. coli* concentrations of 6.7 × 10^6 MPN/100 mL in 2010-01; no data records are available for more recent years. However, even so, high concentrations of these coliforms, which are pathogenic to humans, are evident.

The downstream Engativá station (No. 4) reported concentrations in 2016-02 for TC of 1.1 × 10^8 MPN/100 mL and 2.0 × 10^6 MPN/100 mL for *E. coli*, reaching a significant increase; to date, these results far exceed the permissible limits provided for in Decree 1594 from 1984 (Figure 7).

At this point, the Rio Fucha station (No. 76) reported TC concentrations of 4.5 × 10^8 MPN/100 mL and *E. coli* concentrations of 2.0 × 10^7 MPN/100 mL for the first half of 2009. Likewise, in subsequent years, these concentrations reached higher values. For example, in 2019-01, the station reported TC concentrations at 1.0 × 10^8 MPN/100 mL and a significant increase in *E. coli* concentrations at 5.5 × 10^7 MPN/100 mL, representing the maximum values of fecal coliforms reported, due to domestic, commercial, and industrial wastewater discharges [34].

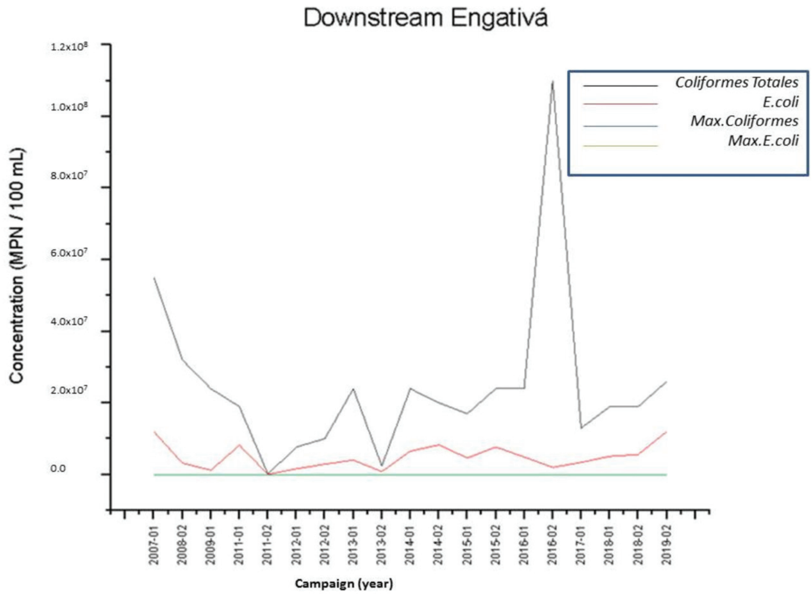

Figure 7. Downstream Engativá concentration chart. Source: prepared by the authors, 2021.

In 2009-01, the downstream Rio Fucha station (No. 11) reported TC concentrations of 1.5×10^8 MPN/100 mL and *E. coli* concentrations of 3.4×10^6 MPN/100 mL (Figure 8). The microbiological load was extremely high, showing that concentrations of TC and *E. coli* were maintained over the years.

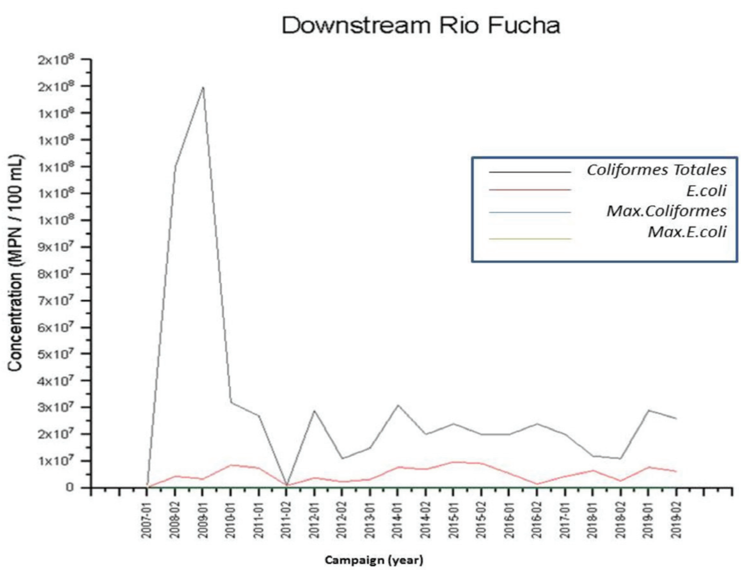

Figure 8. Downstream Rio Fucha concentration chart. Source: prepared by the authors, 2021.

In 2008-01, the Rio Tunjuelo station (No. 70) reported TC concentrations of 2.4×10^8 MPN/100 mL and *E. coli* concentrations of 1.1×10^7 MPN/100 mL.

The lower basin of the Tunjuelo River covers an area of 390 km^2 from the Cantarrana dam to the mouth of the Bogotá River [35]. In the downstream Rio Tunjuelo station (No. 13), in 2008-02, TC concentrations reached a maximum value of 1.7×10^8 MPN/100 mL and *E. coli* concentrations reached 1.2×10^7 MPN/100 mL, which indicates that there was a high contribution of wastewater and industrial waste throughout its course. In 2019-01, the same level of contamination was observed, with TC concentrations of 3.9×10^7 MPN/100 mL and *E. coli* concentrations of 8.6×10^6 MPN/100 mL. This station is affected by anthropic influences from the urban periphery (Figure 9).

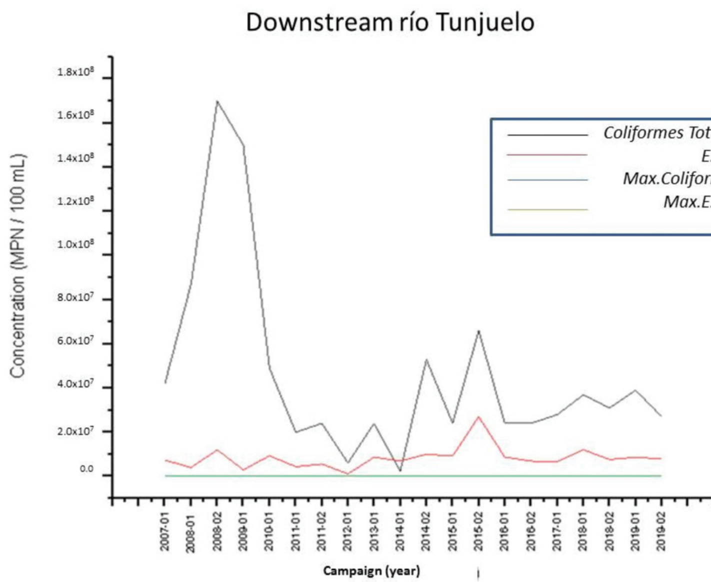

Figure 9. Downstream Rio Tunjuelo concentration chart. Source: prepared by the authors, 2021.

At the Rio Balsillas station (No. 72) in 2019-01, concentrations had decreased with respect to previous stations, yielding TC concentrations of 1.6×10^7 MPN/100 mL and *E. coli* values of 1.9×10^6 MPN/100 mL.

At the Rio Soacha station (No. 79), the 2009-01 microbiological results revealed that TC concentrations were at 1.6×10^8 MPN/100 mL and *E. coli* concentrations were at 1.1×10^7 MPN/100 mL. However, in 2019-02, TC concentrations had decreased to 9.2×10^7 MPN/100 mL but *E. coli* concentrations had increased to 2.6×10^7 MPN/100 mL.

At the Puente Variante Mondoñedo station (No. 60), the 2008-02 microbiological results revealed that TC concentrations were at 8.7×10^7 MPN/100 mL and *E. coli* concentrations were at 2.7×10^6 MPN/100 mL; for 2016-02, TC concentrations were 1.1×10^8 MPN/100 mL, and *E. coli* concentrations were 7.2×10^6 MPN/100 mL. At this point, the body of water had a very high level of biological oxygen demand (BOD), with a value of 320 mg BOD/L in 2012, which was directly related to the high TC and *E. coli* concentrations measured at this station.

At the station before reaching Tequendama Falls (the upstream Salto de Tequendama Station No. 18), a significant number of coliforms was recorded. In 2009-01, TC concentrations were at 2.4×10^8 MPN/100 mL and *E. coli* concentrations were at 1.5×10^5 MPN/100 mL (see Figure 10).

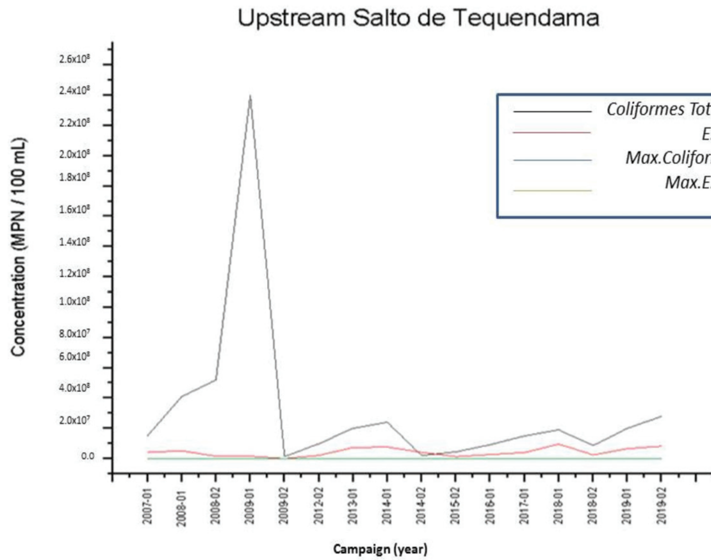

Figure 10. Upstream Salto de Tequendama concentration chart. Source: prepared by the authors, 2021.

At the Quebrada La Cuy station (No. 31), San Antonio Tequendama municipal discharge, an all-time-high percentage of coliforms was again recorded, In 2018-01, TC concentrations were at 1.6×10^8 MPN/100 mL and *E. coli* concentrations were at 2.0×10^7 MPN/100 mL (see Figure 11).

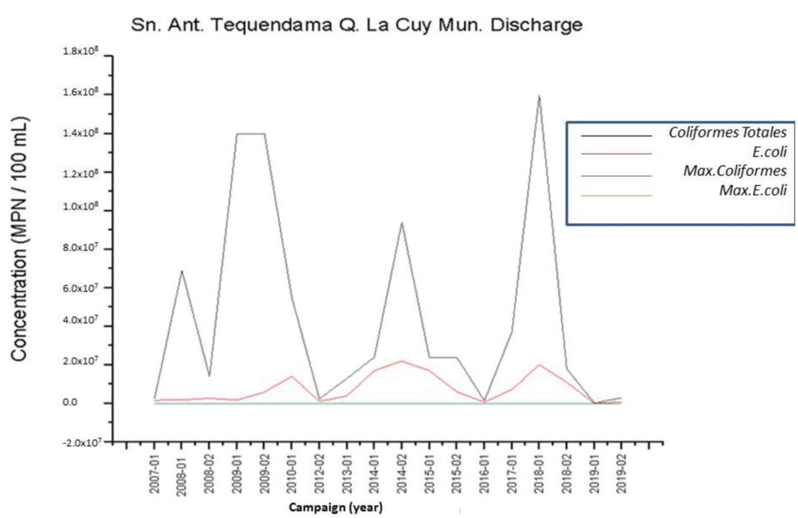

Figure 11. San Antonio Tequendama Quebrada, La Cuy Municipio. Discharge concentration chart. Source: prepared by the authors, 2021.

At the point when the Bogotá River reaches the Quebrada Honda station (No. 67) and these two water bodies merge, TC levels remain elevated and *E. coli* decreases. The concentrations recorded in 2019-02 of TC were 9.8×10^4 MPN/100 mL and those of *E. coli* were 8.4 × 10^2 MPN/100 mL. However, during the 12 years of study, it is evident that the highest peak was in 2007-01, with a total coliform value of 6.5 × 10^6 MPN/100 mL and *E. coli* value of 1.4 × 10^6 MPN/100 mL. Station Nos. 9, 21, 23, 54, 55, 56 and 57 also present maximum values of TC and *E. coli* in the different periods of the last 12 years; these data are shown in Table 1.

Table 1. Description of the 35 stations in the middle basin of the Bogotá River during the years 2007–2019, with their main characteristics, such as maximum values for TC and *E. coli*, the most representative of the study. Source: prepared by the authors, 2021.

POINTS ID	STATION NAME	COORDINATES		MUNICIPALITY	Year	TC	*E. coli*
		Latitude	Length			MPN/100 mL	MPN/100 mL
3	Downstream of Chía	4°49,806′ N	74°3330′ W	Chía	2010-01	65,000,000	11,000,000
4	Engativá Downstream	4°43,194′ N	74°9667′ W	Engativá	2016-02	110,000,000	2,000,000
9	Downstream Quebrada Honda	4°37,427′ N	74°23,469′ W	El socorro	2012-01	24,000,000	4,800,000
10	Downstream Rio Frío	4°50,167′ N	74°4852′ W	Zipaquirá	2010-01	46,000,000	18,000,000
					2016-02	17,000,000	270,000
11	Downstream Rio Fucha	4°39,732′ N	74°9757′ W	Bogotá	2009-01	150,000,000	3,400,000
13	Downstream Rio Tunjuelo	4°37,956′ N	74°13,608′ W	Bogotá	2008-02	170,000,000	12,000,000
					2019-01	39,000,000	8,600,000
14	Upstream of Chía	4°56,668′ N	74°1003′ W	Chía	2007-01	24,000,000	20,000,000
					2019-01	1,700,000	820,000
18	Upstream Salto Tequendama	4°33,049′ N	74°16,796′ W	Soacha	2009-01	240,000,000	150,000
21	Gibraltar Pump	4°38,865′ N	74°11,118′ W	Bogotá	2009-01	870,000,000	21,000,000
22	Juan Amarillo By Pass	4°44,303′ N	74°7655′ W	Bogotá	2008-02	190,000,000	12,000,000
					2014-02	200,000,000	22,000,000
23	Soacha cannel	4°35,467′ N	74°14,716′ W	Soacha	2019-01	<240,000,000	11,000,000
27	Engativa Discharge	4°43,303′ N	74°8952′ W	Engativá	2019-02	200,000,000	41,000,000
28	Jaboque Discharge	4°43,352′ N	74°9047′ W	Bogotá	2015-01	24,000,000	98,000
29	Chía Municipal Discharge	4°51,615′ N	74°2356′ W	Chía	2008-02	25,000,000	1,700,000
					2014-02	16,000,000	4,600,000
30	Cota Municipal Discharge	4°47,841′ N	74°5760′ W	Cota	2010-01	200,000,000	53,000,000
					2019-02	150,000,000	34,000,000
31	San Ant. Tequendama Municipal Discharge, Quebrada La Cuy	4°37,353′ N	74°21,237′ W	Soacha	2018-01	160,000,000	20,000,000
39	El Cortijo	4°43,817′ N	74°7781′ W	Bogotá	2009-01	220,000,000	12,000,000
					2016-02	170,000,000	8,200,000
42	LG Pte. La Balsa Station	4°49,744′ N	74°4226′ W	Cajica	2014-01	2,400,000	820,000
					2019-02	2,400,000	290,000
43	LG Pte. La Virgen Station	4°47,949′ N	74°5765′ W	Cota	2007-01	73,000,000	9,800,000
					2019-01	2,400,000	500,000
53	La Ramada	4°42, 915′ N	74°9305′ W	Funza	2010-01	14,000,000	6,700,000
54	LG La Isla	4°38,668′ N	74°13,249′ W	Tenjo	2009-01	92,000,000	3,300,000
55	LG Las Huertas	4°35,173′ N	74°15,228′ W	Bogotá	2016-02	87,000,000	5,000,000
56	LG Pte. Cundinamarca	4°41,748′ N	74°10,327′ W	Bogotá	2014-01	>24,000,000	6,900,000
57	LM Hacienda San Francisco	4°40,157′ N	74°10,204′ W	Normandia	2008-02	98,000,000	3,500,000

Table 1. *Cont.*

POINTS ID	STATION NAME	COORDINATES		MUNICIPALITY	Year	TC	*E. coli*
		Latitude	Length			MPN/100 mL	MPN/100 mL
58	LM Vuelta Grande	4°44,785′ N	74°7728′ W	Bogotá	2014-02	20,000,000	20,000,000
					2019-01	2,400,000	580,000
59	EL salitre WWTP	4°44,191′ N	74°7593′ W	Bogotá	2008-02	150,000,000	13,000,000
					2014-02	170,000,000	22,000,000
60	Mondoñedo bridge	4°32,546′ N	74°16,290′ W	Mosquera	2008-02	87,000,000	2,700,000
					2016-02	110,000,000	7,200,000
67	Quebrada Honda	4°37,584′ N	74°23,333′ W	El socorro	2007-01	6,500,000	1,400,000
					2019-02	98,000	840
68	Quebrada La Tenería	4°53,864′ N	74°1121′ W	Cajica	2014-02	240,000,000	240,000,000
					2019-02	100,000,000	7,500,000
70	Rio Tunjuelo	4°37,607′ N	74°13,397′ W	Bogotá	2008-01	240,000,000	11,000,000
72	Rio Balsillas	4°37,077′ N	74°15,078′ W	Mosquera	2019-01	16,000,000	1,900,000
74	Rio Chicú	4°46,415′ N	74°6971′ W	Tenjo	2007-01	2,400,000	430,000
					2019-02	2400	310
75	Rio Frío	4°50,501′ N	74°4799′ W	Zipaquirá	2011-01	58,000,000	9,600,000
					2019-02	9900	100
76	Rio Fucha	4°39,870′ N	74°9197′ W	Bogotá	2009-01	450,000,000	20,000,000
					2019-01	100,000,000,000	55,000,000
79	Rio Soacha	4°35,743′ N	74°14,595′ W	Soacha	2009-01	160,000,000	11,000,000
					2019-02	92,000,000	26,000,000

4. Discussion

The above results allow us to develop an analysis of the possible causes and triggers affecting the state of the basin. In the current investigation, most of the 35 stations located along the middle basin of the Bogotá River showed high levels of total coliforms and *E. coli*, exceeding the limits allowed and established at the national and international levels. For example, the WHO guidelines recommend that the amount of total and fecal coliforms should be 0 UFC (colony forming units)/100 mL for water supply sources [36]. Similarly, the results presented by the World Water Quality Monitoring Program show contamination by these pathogenic microorganisms affecting approximately one-third of the river sections in Asia, Africa, Asia and Latin America [37].

These results coincide with the study carried out by Ochoa-Herrera et al. (2020), who analyzed the water quality of 18 rivers located in Quito, the capital province of Pichincha, Ecuador, by means of microbiological parameters, where high levels of contamination by total coliforms and *Escherichia coli* are evidenced [38]. The maximum values of these enterobacteria, reported in the current study, in the different water bodies are shown in Table 1.

The initial station of the river system is Quebrada La Tenería No. 68, which reports a high degree of contamination from fecal coliforms since it receives a large part of the sewage waters from the municipality of Cajicá [39].

The municipality of Cajicá currently uses a combined sewer system, wherein only 48% of the wastewater and rainwater that collect are treated before being discharged into the river. Another important factor is that the Calahorra WWTP, which receives most of the municipal wastewater, can only treat ~50% of the wastewater received [40]; this has prompted strategies for extending the capacity of the plant. Likewise, hydraulic adaptation work has been conducted in the river, which may account for the lower values that have been reported recently.

Following this water along its trajectory through the municipality of Chía, the values remain above the provisions established in Executive Order 1594 of 1984 and Agreement 43 of 2006, which sought to establish measures for improving the quality of water in the

Bogotá River basin by 2020. This failure may be due to deficiencies in wastewater treatment, ultimately leading to direct discharges into water bodies. The municipality of Chía built a treatment plant in 1989, but the plant was not sufficient for the 68% population increase experienced since 2000, 78% of which corresponds to the urban population. Even when the treatment plan covers 83.6% of the sewer system [41], it only manages to properly treat 30–40% of the wastewater produced. In particular, due to the excessive increase in urban population, wastewater flow rates have also increased, exceeding by far the hydraulic capacity of the plant. Currently, a large part of the urban area is covered by the Chía I WWTP, which can only treat 2.36 m^3/s; this has caused a negative impact on the environment and the population at large [42].

In addition to the discharges from the WWTP into the Bogotá River, 11 domestic discharge points, five rainwater discharge points, and one industrial discharge point have also been identified [41]. To mitigate this issue, the municipal government built the Chía II treatment plant, seeking to treat 70% of the wastewater that reaches the Frio River, a body of water that is also deeply affected by municipal discharges and that flows into the Bogotá River. The Chía II plant began operation testing in February 2020 [43].

The next station at Puente de la Balsa (No. 42) is highly impacted by pollutants, since it receives significant discharges, including discharges from the Chía I WWTP. In addition, industrial and rural domestic discharges have been identified in this section, a situation worsened by the high number of water hyacinths found in this area of the river, which causes greater retention of suspended particles [44].

In the next section of the river system, the Rio Frio and downstream and Rio Frio stations No. 75 and No. 10, which were built to evaluate the behavior of the Frio River, an effluent of the Bogotá River, reported lower pollutant concentrations in some periods, especially for the first station. This is commonly caused by the dynamics between the hydraulic, morphological, and water quality characteristics of the water body [45], which, in the case of the Rio Frio, constitutes a fluvial and alluvial valley. For this reason, the area usually becomes flooded during the rainy season [46]. This process can help to dilute pollutants, as is supported by the fauna still present in the area. In addition, another influencing factor that may affect the first section of the river is that it flows through the municipality of Chía, where the river system does not receive significant urban discharges. Here, some of the wastewater produced in this municipality is treated by the Chía I WWTP, which mitigates its impact in this area. However, as evidenced by the data, low contamination concentrations are not constant. This may be because the river receives domestic and industrial discharges as it passes through the municipality of Cajicá and the entrance to Chía. Nevertheless, the downstream Rio Frio station (No. 10) exhibits an opposite dynamic, generated by the multiple discharges it receives. In fact, in 2018, 35 wastewater discharge points were identified—three were agricultural, 15 were rainwater, 15 were domestic water, and two were industrial [41]. The construction of the Chía II WWTP is supposed to mitigate this situation, but we will not know how efficient it is until the plant becomes operational.

The Frio River originates in the Páramo de Guerrero in the northeastern area of Zipaquirá and constitutes a structural axis for agricultural development and growth, since it flows through several irrigation districts and provides continuity to agricultural activities [47]. According to reports, this water source has not yet been considered as an alternative source of drinking water because it exhibits high concentrations of lead and heavy metals. In fact, the 2016 Quality Index issued by the Regional Autonomous Corporation (CAR) states that near the river mouth between the Frio and the Bogotá rivers, the water quality decreases by 20%, which is a level considered to be unpleasant for developing the ecosystem and aquatic life in said body of water [41]. Likewise, researchers have identified issues in the area, such as deforestation, eucalyptus trees, pasturelands, single-crop farming, e.g., potatoes and flowers, invasive acacia species, and inadequate canalization, which also trigger contamination through phytosanitary products, chemicals, and agricultural waste runoffs [47]. Although a significant decrease in pollutant concentrations is expected, the projections from the Chía development plan remain uncertain, due to the conurbation of the municipalities surrounding the city of Bogotá. Furthermore, to foster municipal urban development, the construction of 6–12-story buildings and an area of ~300 ha have been approved for urban expansion [48]. This will undoubtedly boost population growth and, in turn, increase wastewater generation, thus affecting the new plant's effectiveness.

As was observed at the station in the municipality of Cota, No. 30, in the first two years, large total coliform concentrations were reported. However, these concentrations somewhat decreased in 2012-01 and 2014-01, before increasing again and maintaining similar values. For fecal coliforms, such as *E. coli*, a significant increase in concentrations was observed. At this point, this behavior was related to different situations occurring in this municipality. Cota has an active Wastewater Treatment Plant (WWTP) located in Vereda El Rozo. The municipal sewer system covers 97.65% of its urban area and 68.56% of its rural area, using a combined system. However, there are still several natural drains and spillways (fences) in the rural areas [49]. Despite this sewer network coverage, wastewater treatment is still not optimal. For example, the El Rozo WWTP can only treat 13.96% of the wastewater produced in the area. In addition, this plant underwent an optimization process in 2016, during which time it remained nonoperational and did not treat any wastewater at all. However, even after these enhancements, it still has not been able to effectively meet the demand [50]. According to the Environmental Report issued by the municipality, 85.94% of the area discharges wastewater directly into the Bogotá River from the Pueblo Viejo discharge point. For this reason, the construction of a new WWTP has been planned. This new treatment plant was expected to start operations at the end of 2019. At the time of writing, no reports of its commissioning have yet been received. In addition, 73 discharge points have been identified, of which only 5 have been officially permitted [49]. One of the conflicts that also significantly impact water source contamination is the location of the municipality of Cota, which has been experiencing accelerated urban and industrial expansion. For example, this municipality hosts numerous industrial parks, such as Siberia [51]. Furthermore, their industrial discharges have not been characterized and, according to the latest analysis conducted in 2014, they constitute the largest pollutant load in the river due to the lack of a treatment system and the mixing that takes place within the sewer system, wherein domestic wastewater, industrial wastewater, and rainwater are mixed before being directly discharged into the Bogotá River [49]. According to Agreement 43 of 2006, this section of the river is expected to reach Class-IV quality parameters, which includes restricted agricultural and livestock use, especially considering that this section is used to supply irrigation and drainage to the La Ramada district. Still, according to a 2016 report, only 20% of this objective is being fulfilled [49].

Next in the watercourse, the Puente La Virgen station, No. 43, is located within the municipality of Cota. According to the study conducted, contamination at this point in the river is due to an invasion from the riparian buffer zone, which the municipal Territorial Organization Plan (POT) sets at 100 m for the Bogotá River. During this study period, both fillings and droughts were evident in areas surrounding the water body. In addition, this area has become a dumping ground for wastewater, garbage, and chemical waste from industrial establishments dedicated to grazing, farming, and some secondary sector industries [52]. This decrease may be due to the fact that the Regional Autonomous Corporation (CAR) has recently established a protection and conservation treatment area under the Central Savannah Association of Municipalities. Nevertheless, since this basin constantly suffers from moderate water stress, it still remains under conditions of contamination [53].

The performance of the Rio Chicú station, No. 74, is noteworthy, given that, in fact, this is one of the stations with the lowest concentrations. This may be due to the fact that the Chicú river is located in the municipality of Tabio, which has a wastewater treatment plant (WWTP) that reduces the sludge and microorganisms found in this body of water, thus complying with the maximum permissible values. In addition, since 2016, the municipal government managed the Tabio Territorial Organization Scheme before the relevant authorities, in accordance with the new Basin Organization and Management Plan (POMCA) guidelines for the Bogotá River [54].

In the case of the LM Vuelta Grande station No. 58, it continues to exceed the values allowed by the current regulations. According to an assessment conducted in 2015, the urban municipality of Tenjo has a wastewater treatment plant and uses two main purification processes: an anaerobic piston-flow reactor (RAP) and an oxidation pond. As these treatment units lack sufficient capacity to treat the total amount of wastewater generated throughout the year, all excess wastewater is left untreated and is discharged directly into the Bogotá River, where it eventually reaches the LM Vuelta Grande station No. 58. In addition, the oxidation pond presents some deformities caused by gases emanating from the decomposing organic matter due to poor maintenance, which reduces the hydraulic capacity of the pond [55].

In the case of the Juan Amarillo station No. 22, this receives its name from the eponymous wetlands; these wetlands work as a buffer pond and are used to prevent flooding of the Juan Amarillo River. The outlet or discharge from this river to the Bogotá River is located downstream. The increase in concentrations at the monitoring point is due to multiple erroneous connections making direct contributions to the wetlands, as well as to the amount of bovine and hog feces generated in the reserve [56]. This section of the river is afflicted by a lack of environmental awareness, illegal settlements and dwellings, fraudulent actions by people seeking to avoid paying utility bills, the growth and development of neighboring buildings, and total ignorance of the applicable environmental regulations [57].

Another station that shows unusual circumstances is the one located at the El Salitre WWTP, given the values recorded at the WWTP. Overall, these values are not justifiable as they should be in compliance with the regulations, since the effluent discharges are of water that is previously treated by the WWTP. Hence, this treatment plant is not playing its part properly. This may be due to the fact that the Bogotá urban drainage system (Salitre Channel–Salitre WWTP–Bogotá River) lacks a comprehensive scheme, which destabilizes the plant during contamination peaks. In addition, the Salitre channel exhibits low flow-rate speeds due to backwater and water storage effects, thus leading to the sedimentation of solids and organic matter. However, the structure and functionality of the plant are also inefficient, since it is not able to treat water received during the first few minutes of rainfall, which contains large pollutant loads from garbage and waste [58]. Currently, the El Salitre WWTP is being expanded and optimized to treat 7.0 m^3/s and prevent at least 450 t/month of garbage from reaching the Bogotá River. If this is successful, the pollution levels reported in previous years are expected to decrease [59].

The Cortijo station No. 39 was evaluated; it can be determined that here, the concentrations were caused by a number of cement industries operating in the area that use water to wash their aggregates and clean their equipment and plants. The waters are discharged completely untreated, or with low-quality treatment, into the Bogotá River, thus increasing the presence of sludge and, in turn, significantly increasing organic matter. Given the high load of organic matter transported by this tributary and the inefficient treatment of the El Salitre WWTP, the Rio Bogotá reach high levels of contamination [44].

The dynamics of the Jaboque station No. 28 show that concentrations did not undergo massive changes over time. This is because this station is located in the Jaboque wetlands, which are separated from the Bogotá River by dams to prevent river waters from flowing into the wetlands. This way, the wetlands discharge into the river but not the other way around, thus preventing the wetlands from functioning as buffer zones. In addition, at least 95% of the sewer wastewater was reduced due to the creation of the Capital District Wetlands Policy, as per Executive Order 624 of 2007 [60], wherein these wetlands were declared a wildlife sanctuary. For this reason, their contamination rates are minimal and fully comply with the corresponding regulations [61].

As it passes through the town of Engativá, the river system is faced with a problem; this section of the river flows through a community with no environmental awareness, in addition to the wastewater discharges from domestic, commercial, and industrial activities [27], coupled with inadequate solid waste management. Hence, a large part of this waste ends up on the Bogotá riverbed, causing the proliferation of disease vectors, offensive odors, and general deterioration around the area [62].

The community of Engativá has a significant hydrological system consisting of either the Salitre or Juan Amarillo river, in addition to three wetlands—Jaboque, Santa María, and Juan Amarillo. Near these buffer zones, there are hazardous areas that are prone to landslides and flooding, as well as to sewer, garbage, and excrement discharges produced by the surrounding population [63]. This improper management of liquid and solid waste (burning and agglomeration) produced by anthropic activities leads to favorable environments for the spread of pests, mosquitoes, rodents, bad odors, vector-borne diseases, and the continuous deterioration of the environment [62].

The population of the community of Engativá is ~797,000 inhabitants (11.6% of the total population of Bogotá), representing the third-largest region in terms of population. In addition, 20,579 Bogotá businesses operate in this area, representing 9% of all city businesses. The businesses operating in this community are mostly service-based (73%), industry (19%), and construction (5%) businesses [64].

In the case of the Ramada station, No. 53, this is an irrigation and management station for swamps and ponds within the Bogotá River basin program. Hence, this agricultural area is being contaminated with water from the Bogotá River, thus negatively impacting the environment due to the contamination levels reported in its middle basin [65]. Considering that Executive Order 1594 from 1984, which still remains in effect, establishes that the most probable number (MPN) should not exceed 5000 for total coliforms and 1000 MPN/100 mL for fecal coliforms when the water resource is used for irrigating fruits that are consumed unpeeled and for short-stemmed vegetables. The water quality is now expected to be in a better condition even when there are no records because, since 2019, the Regional Autonomous Corporation has been working on the recovery of the Bogotá River to prevent its degradation, especially in agricultural areas [66].

The Fucha River Basin, which originates in the El Delirio forest reserve in the Cruz Verde Páramo, flows into the Bogotá River, covering an area of 12,991 urban and 4545 rural ha, corresponding to the eastern hills of the city [34]. This basin includes the communities of San Cristóbal, Antonio Nariño, Los Mártires, and Rafael Uribe. This is the apparent reason for the maximum values of fecal coliforms obtained due to domestic, commercial, and industrial wastewater discharges. Many of these populations are illegal settlements, Strata 1 and 2, with a serious shortage of infrastructure and public spaces [67].

The Fucha River collects all the sewer wastewater from downtown Bogotá, and, from the industrial zone (Américas, Calle13), the wastewater from numerous slaughterhouses and the community of Fontibón is collected, comprising a total area of 16,390 ha that discharges directly into this river [34].

Due to the aforementioned issues, the Fucha River currently ranks as the second most polluted river basin in the city. The discharges from this river into the Bogotá River are calculated as being 65% industrial waste and 35% domestic waste. On a daily basis, the Fucha River discharges at least 590 t of solids and 274 t of biological waste into the Bogotá River, of which 107 t comes from dwellings and the rest comes from businesses and industries [34].

Our analysis confirmed the degradation of water quality for agricultural use. In fact, the concentrations of coliforms follow an exponential trend, which is related to the behavior of the Fucha River index [35]. However, the Territorial Organization Plan for the Fucha River comprises an ecological corridor that seeks to preserve natural channels within the city. However, this micro-basin has few green areas due to its high level of urbanization and industrialization, which fact has also brought about complex usage conflicts that have hindered the proper management and recovery of the river [68].

Continuing the analysis, the Tunjuelo River basin represents the largest of the three rivers flowing through the capital city. It originates in Los Tunjos Lake in the Sumapaz Páramo, at an altitude of ~3450 masl. The river basin is formed by three main channels—the

Mugroso, Chisacá, and Curubital rivers—with a length of 73 km. It is located in the southeastern part of the city of Bogotá and runs through the municipality of Soacha. The river basin covers an area of 41,534 ha, including the communities of Usme, Ciudad Bolívar, Kennedy, Tunjuelito, Rafael Uribe, San Cristóbal, Puente Aranda, Antonio Nariño, Bosa, and the municipality of Soacha [69]. The Tunjuelo River basin plays a critical role in supplying water to the southern areas of the city of Bogotá [70]. This basin is classified into the upper, middle, and lower basins, with the upper and middle areas being rural, while the lower basin is mostly urban. The upper basin is located between Lake Tunjos in the Sumapaz Páramo and the La Regadera dam. The middle basin extends from the La Regadera dam to the Cantarrana dam, very close to Quebrada Yomasa. The lower basin covers the area from the Cantarrana dam to the mouth of the Bogotá River. This area reports the greatest anthropic incidence, leading to higher contamination rates [69].

The Tunjuelo River faces various socio-environmental conflicts, such as the application of pesticides in crop areas, contamination by tanneries, mining activities, contamination due to its proximity to the Doña Juana sanitary landfills, agricultural activities in the conservation areas, danger due to hydraulic phenomena, land use issues, legal and illegal settlements, and extraction of construction materials, among others [70].

According to reports from the downstream Tunjuelo River station No. 13, the pollutant load at this point is mainly generated by the pollutants provided by the Tunjuelo River as it flows into the Bogotá River. A large percentage of the domestic, industrial, and commercial wastewater from the city's sewer system is discharged into the Tunjuelo River [71]. Alternatively, a large part of the leachate produced by the Doña Juana landfill eventually falls into the Tunjuelo River, a situation that worsens whenever the river flow decreases at times of drought and due to anthropic actions in the upper river basin. In addition, the pollution load carries mining wastewater and solid waste, which has turned this river into a complete sewer [72]. Although there is a leachate treatment system in the landfill, it can only treat 15 L per second, which falls short of the 25 L per second actually generated in 2017. This means that many pollutants that remain untreated or that are partially treated are discharged directly into the Tunjuelo River, which, starting from this point, runs through four other communities before flowing into the Bogotá River [73].

On the other hand, at the Balsillas River Station, No. 72, another contributor to the contamination of the Bogotá River basin is the Balsillas River sub-basin, which is part of its middle river basin. This body of water is a contributor of high-impact pollutants associated with the presence of coliforms. In addition, heavy metals are also an important factor because most of the activities developed in the area use raw materials with a high content of elements such as cadmium and lead in their production processes [74].

After this point, the municipality of Soacha is the main contributor of pollutants to this river. The municipality is located in the southern part of the Bogotá savannah, bordering the city of Bogotá to the west, at an altitude of 2600 masl. The municipal territory has a total area of 184.45 km^2, with an urban area of 19 km^2, a rural area of 165.45 km^2 and a population of approximately 535,000 inhabitants [75]. The Soacha River is highly polluted, as seen in the results from the Río Soacha station, No. 79, due to the presence of TC in its alluvial aquifers and fans. This is mainly due to biological and industrial factors and an average concentration of biodegradable organic matter that is outside the limits established by the regulations [76].

Next is the station of Puente Variante Mondoñedo Bridge, No. 60; in this area, the Bogotá river has already passed through several communities in the upper and middle basin, including the city of Bogotá DC and the municipality of Soacha, among others, receiving large amounts of domestic and industrial wastewater [77]. These values far exceed the water quality objectives established by the Regional Autonomous Corporation (CAR) for the year 2020 in Agreement 43 of 17 October 2006, "by which the water quality objectives for the Bogotá river basin to be achieved by the year 2020 are established", thus setting a maximum value of 7 mg BOD/L and a maximum permissible TC concentration value of 2.0×10^4 (MNP/100 mL) for this Class-II zone [78].

When evaluating the upstream Salto Tequendama station, No. 18, upon reaching the Tequendama Falls, due to the geomorphology of the area, which forms a natural 257-m-high waterfall [79], and the hydraulic characteristics of the water body at this point, the flow rate of the river increases, dragging garbage, colloidal solids, and dissolved solids from the upstream basin. This may account for the high levels of coliforms recorded in this section of the river [80]. Agreement 43 of 2006, issued by the Regional Autonomous Corporation (CAR), sets forth a maximum limit of 2.0×10^4 (MPN/100 mL) for Class IV. However, the values historically recorded by this station well exceed these objectives, as defined by the Corporation [78]. At Tequendama Falls, the Bogotá River leaves the savannah and enters the Tequendama archeological site in the province of Cundinamarca. The oxygenation it receives through this waterfall allows the river to recover part of its macrobiotic life [81].

As reported at the Quebrada La Cuy municipal discharge point, at this stage, high levels of TC and *E. coli* concentrations are recorded, mostly due to fecal contamination from animals. In 2010, the Regional Autonomous Corporation of Cundinamarca conducted a hog farm census of the area. The results revealed that 17,921 hogs were kept in 117 farms, none of which evidenced optimum waste-disposal systems. The discharges generated by hog farms in the area, in addition to producing bad odors, also directly affect the water in the middle basin of the Bogotá River and the waters near this section, which are used for animal consumption [82].

Finally, the Quebrada Honda No. 67 station is located in the last sections of the middle Bogotá River basin; the Quebrada Honda stream acts as a dissolution system for the pollutants that reach this point, considerably reducing both TC and *E. coli* levels. The Quebrada Honda stream is located within the Tequendama province in the department of Cundinamarca, mainly encompassing the municipalities of Tena and Bojacá. This sub-basin covers an area of ~1979.56 ha and runs at a height of 800–2550 masl [83]. These ameliorating effects are mainly due to the fact that a large part of the Quebrada Honda sub-basin is located in a protected forest reservation [84]; consequently, the anthropic effects on this body of water are minimal.

These agreements and measures were implemented to protect the Guacheneque Páramo, where the Bogotá River originates, as well as to manage the different industrial, agricultural, and livestock discharges, repair the river and its riverbed, and commission WWTPs [85]. As the consequences from river basin contamination increase, legal actions have become the go-to mechanisms for protecting environmental rights, even leading to work aimed at cleaning up the Bogotá River [85].

Throughout the entire middle basin of the Bogotá River, higher levels of coliforms and *E. coli* than the ones provisioned in Executive Order 1594 from 1984 on water and wastewater have been recorded. These standards establish a limit of 2.0×10^4 MPN/100 mL for TC and 2.0×10^3 MPN/100 mL for *E. coli*. All assessments included in this study are compared against these benchmark values. As evidenced in the aforementioned regulations, none of the sampling points comply with maximum permissible limits, except the Rio Frio station, No. 75, from 2009-02 to 2019-02, the downstream Jaboque station, from 2008-02 to 2019-02, the Quebrada Honda station, No. 67, from 2011-02 to 2019-02, and the Rio Chicú station, No. 74, from 2011-01 to 2019-02, where a decrease in fecal coliforms (*E. Coli*) is evidenced. The latter case is probably due to the conditions of the rivers that flow into this section of the river basin, as well as to a decrease in the contributions from the different municipal activities. For this reason, the water body becomes re-aerated, increasing by small amounts the presence of dissolved oxygen, especially after 109 km of the Bogotá River, exactly where it meets the Frio River [86]. Oxygenation helps the aerobic microorganisms in the water to breathe, which can then fulfill their function of naturally decontaminating the water. For this reason, the physicochemical conditions and the biological activity of the tributaries and effluents of this water resource are extremely significant [87].

5. Conclusions

This study concludes that, in the case of the middle Bogotá River basin, TC and *E. coli* concentrations are significant, since they exceed the permissible values established by current regulations. The analysis conducted for each year from 2007 to 2019 evidenced contamination in the water body, especially in the El Salitre WWTP, downstream Engativá, downstream Rio Fucha, and downstream Rio Tunjuelo stations, among others. Nevertheless, TC and *E. coli* concentrations have decreased in four stations—Rio Frio, Quebrada La Honda, the Jaboque discharge, and Rio Chicú—mainly due to the oxygenation, geomorphology, and aeration processes where anthropic impacts are minimal. In these sections of the Bogotá River, due to the natural characteristics of the water body and contributions from its tributaries, the concentration levels of these pollutants are considerably reduced.

Even though specific sections of the riverbed have been recovered over the years through different environmental programs conducted by the Regional Autonomous Corporation (CAR), as well as via an increased environmental awareness in some areas, the current state of the middle basin of the Bogotá River remains unsatisfactory. In fact, its current condition is unacceptable due to the different activities that occur near the riparian buffer zone of the river, which brings about uncontrolled domestic, industrial, and/or commercial wastewater discharges, an increased number of illegal settlements, and poor adherence to the Territorial Organization Plan (POT) in different municipalities. Likewise, inappropriate organic and inorganic solid waste management also favors the development of these fecal concentrations found in the surface waters of the river.

All these variables affecting the middle basin of the Bogotá River have a negative impact on public health and the environment, since this water is used to supply drinking water to a few communities outside Bogotá, as well as irrigation systems for crops intended for human consumption, causing gastrointestinal diseases to the human body due to its high content of coliforms and other toxic substances. For this reason, more WWTPs are expected to be implemented in the municipalities bordering the river, and significant improvements in the treatment capacities of each unit are required. In addition, new technologies should be implemented, such as solar water disinfection technologies in individual units and phytoremediation, where plant species such as algae are used to reduce the number of microorganisms favoring the development of communities.

Author Contributions: M.F.C.F. worked on data collection and conceptualization of information; I.R.C.M. worked on methodology construction, formal analysis and research; Y.E.D.C., D.E.M. and P.A.P.V. worked on data and information analysis and writing; C.E.M.M. and R.F.C.Q. worked on revision and writing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data provided by the Corporacion Autonoma Regional (regional autonomous corporation) (CAR).

Acknowledgments: The authors are grateful for the support of the Universidad Cooperativa de Colombia and the Partners Voor Water fund of the Dutch Government through the project Sustainable Water by floating solar energy powered Efficient reverse osmosis Treatment (SWEET).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

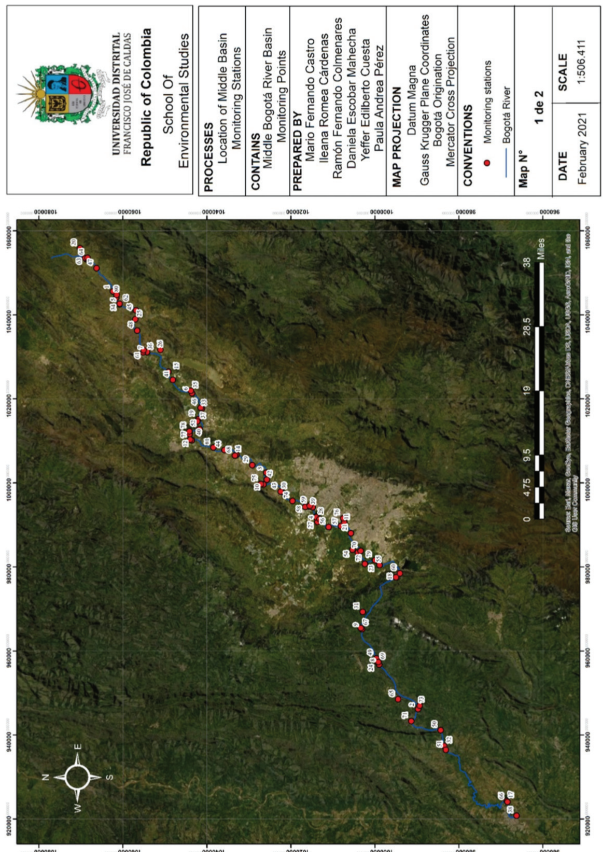

Figure A1. Bogotá River monitoring stations. Source: prepared by the authors, 2021.

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sustainability

Article

Stakeholder Analysis and Their Attitude towards PPP Success

Joanna Węgrzyn [1,*] and Anna Wojewnik-Filipkowska [2]

[1] Department of Economics of Real Estate and Investment, Cracow University of Economics, Rakowicka 27a, 31-510 Cracow, Poland
[2] Department of Investment and Real Estate, University of Gdańsk, Armii Krajowej 101, 81-824 Sopot, Poland; anna.filipkowska@ug.edu.pl
* Correspondence: wegrzynj@uek.krakow.pl

Abstract: The development of a wide range of infrastructure projects based on the idea of cooperation between the public and private sector, known as PPPs, contributes to fulfilling social and economic needs, rises the quality of life, and supports sustainable development. The expected results of these undertakings cannot be comparable; however, some PPPs are perceived as a success and some are not. The research is based on the stakeholder concept and the idea that different stakeholder groups present different attitudes to the success of PPPs and are motivated by different issues including economic, social, and environmental factors. Based on this assumption, a conceptual model of PPP stakeholders' identification and classification according to the attributes of preferred benefits, related to dimensions of sustainable development and engagement, including time and scope perspective, has been derived and tested. This exploratory analysis improves and tests the benefit–engagement conceptual model of PPP stakeholders' identification. This contributes to the theory and concepts of sustainable infrastructure investment and public–private partnership practice.

Keywords: stakeholder analysis; infrastructure; public–private partnership; PPP; Poland

Citation: Węgrzyn, J.; Wojewnik-Filipkowska, A. Stakeholder Analysis and Their Attitude towards PPP Success. *Sustainability* **2022**, *14*, 1570. https://doi.org/10.3390/su14031570

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 19 December 2021
Accepted: 24 January 2022
Published: 28 January 2022

1. Introduction

The idea of delivering infrastructure services via the cooperation between the public and private sectors has been extensively reshaped during the last few decades. In the early 1990s, the concept took the form of public–private partnership (PPP) and soon gained attention from policymakers around the world. In Europe, the PPP approach was pioneered by a private finance initiative (PFI) launched in 1992 in the United Kingdom. Since then, PPP was popularized in other European countries, especially France, Portugal, Spain, and Italy [1]. In Poland, the process of implementing PPPs began in late 2005.

The general rule standing behind PPP is that it combines the competencies of the public sector and both the financial and managerial commitment of the private entities in the process of delivering infrastructure goods and services [2] (hereinafter: infrastructure). A public party, also called a grantor, usually initiates a PPP project and provides support to the private party during the investment and operational phases. Typically, private investors tend to arrange their cooperation in the form of a consortium. In most cases, this consortium comes in a shape of a special purpose vehicle (SPV) created for the project [3]. In general, the PPP grantor (national or local government) provides the right to deliver infrastructure to the project company (SPV). In return, the grantor obtains the right to oversee management and regulates the services provided by an SPV. PPP financing is usually provided by project equity, loans, or bonds. All project financiers are involved in the financial structuring, drafting of the project documents, and certification of completion [4]. Financing may require a particular group of funding bodies. They are Multilateral Agencies (MLAs), Bilateral Agencies (BLAs), and Export Credit Agencies (ECAs), and they support PPP mainly by international agreements with the central government but they also provide direct lending or guarantees to the parties involved in PPP. The output of a project company can be contracted to the offtake purchasers to divert market risk. Before the goods or services reach the final client, they can be contracted by public utility companies. Finally, the PPP key project stakeholders are public sector clients including final users, unions, and media [5].

PPPs are considered a multifaceted challenge [6] due to more stakeholders than other types of infrastructure projects [7]. The set of stakeholders is dynamic (the stakeholders can change). These dynamic stakeholders also create dynamic relations during the PPP development and implementation (investment preparation, construction, and operation). Their engagement in the project may usually shift over time, not only because of the long-term nature of a PPP project but also because of changeable external conditions. These complex relationships between stakeholders pose a challenge to the successful management of a PPP project [8].

The broad scope of private participation in the process of delivering infrastructure, reinforced by the growing popularity of PPP, its contribution to fulfilling infrastructure needs, accompanied by the importance of infrastructure for sustainable development, reveals the need to adopt a more stakeholder-oriented perspective in project management and a need to go beyond results of the project. These are already happening by a shift of thinking: from the management of stakeholders to management for stakeholders; from GDP (gross domestic product) to sustainable development as an indicator of wellbeing. Scholars confirm that stakeholder involvement in infrastructure development plays a vital role in the success of an infrastructure project [9]; stakeholder involvement has already replaced the term of public involvement [10]. Stakeholder-oriented PPP strategy has already been identified as a prerequisite for success [6] in the sustainable development narration, which should and could be the guiding principle for infrastructure development [11]. PPP evaluation must be more systematic and integrated as the success or failure of a PPP requires taking into consideration the complexities of PPP projects and expanding existing approaches [12]. This research falls into the stream of the research concerning stakeholder management in public–private partnership infrastructure projects. There is still a limited amount of research concerning the issue of stakeholders' engagement in PPP projects. This research contributes to filling that research gap.

The assumption for the research is that the knowledge of project stakeholders, their power to influence the project, their interest (motivation), the urgency to implement the project, and the ability to create relationships with stakeholders is the condition for the project's success. However, is important to stress that the attempt to explain the concept of a PPP's success could be a challenge itself, as every PPP and every infrastructure investment is a complex and unique economic, social, and environmental phenomenon.

PPP in Poland is still an uncommon way of contracting infrastructure services, and comprehensive data on PPPs under the operational phase are hardly obtainable. As far as it is concerned, there is limited academic research analyzing the PPP market in terms of number, value, legal basis, and infrastructure-related sector. Załęczna et al. [13] proved that only a small number of PPP initiatives in Poland succeed in achieving the construction and operation phase (approximately 30%). There is also a lack of statistical information about the PPP projects that were terminated before the date scheduled in the PPP contract. However, market analysis indicates that early contract termination is not an uncommon way to end the cooperation under the PPP project. A new approach to the identification and classification of PPP stakeholders would shed light on the complex relations between PPP stakeholders.

The aim of the research is, therefore, a proposition of a refined conceptual model for the identification and classification of stakeholders in PPP projects. The research has instrumental rationality and looks for answers to the following interconnected research questions (RQ): 'Who are the PPP project stakeholders', 'What are the relations between PPP project stakeholders?', and finally 'How do different stakeholders groups perceive PPP success?' The attempt to answer these questions can contribute to a better understanding of what PPP means to the different stakeholders involved in PPP, and would allow decision-makers (representing public as well as private sectors) to engage under PPP with a greater understanding of motivations and expectations of the partners, which should lead eventually to successful cooperation. The research consists of subareas and three research questions; their interactions are presented below (see Figure 1).

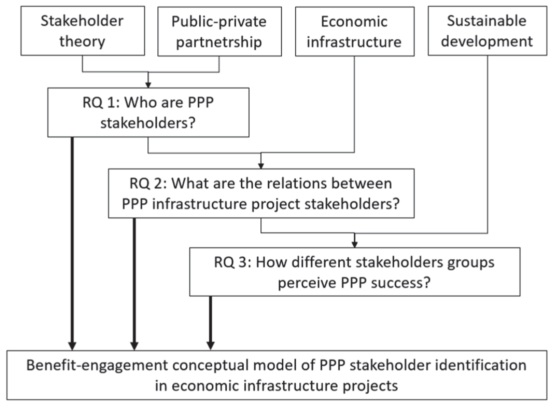

Figure 1. Research questions and aim (source: own study).

Although sustainable development has been presented as one of the research subareas, it is the fundamental assumption for infrastructure development. From the perspective of private sector partners, the idea of sustainable development might be implemented via strategy of corporate social responsibility (CSR) or the set of environmental, social, and governmental (ESG) factors. Still, the basic concept and the primary theory to the above-mentioned CSR and ESG is sustainable development, which forms the general research background.

The article consists of five sections. The methods and materials are presented in Section 2. Section 3 presents the literature review. Section 4 offers a framework for stakeholders' identification and classification in PPP projects. It is then verified via a selected case study in Section 5. Finally, conclusions are drawn and accompanied by a takeaway for practice, and also by research limitations in Section 6, which closes this research paper.

2. Materials and Methods

The study focuses on the presentation and discussion of the stakeholder approach to project analysis, and its possible utilization in defining PPP goals, which can be understood in terms of expected results or benefits contributing to project success. The paper is both conceptual and practical. Considering the theoretical concept of the article, this article refers back to the authors' earlier research [14]. First, this research includes a literature review and its constructive criticisms, which led to establishing the study objective and improving a conceptual model of stakeholder identification and classification in PPP projects. This research approach follows a general idea already established in the previous work of combining two components which are the perception of success in the public and private sector and the stakeholder engagement in PPPs. This research adds value to the conceptual sphere of the model by indicating sustainable development dimensions in the success perception and also to the practical sphere by testing the proposed model using the case study method and discussing the project of the underground car park. The selected project is the first PPP project procured in the form of a concession for the construction. The described case study has an instrumental nature and is focused on presenting how particular stakeholder groups can perceive a project's success and how it can affect their attitudes towards PPP management. The qualitative method of the case study enables for understanding and describing the case at hand in-depth and has already been selected as a research strategy [15,16].

Considering the research design, two main types of case studies can be distinguished, which are single and multiple-case studies. Both of them can be described in terms of their advantages and disadvantages [17,18]. Contrary to a single-case study, the evidence from multiple case studies is considered more compelling and the overall study is regarded as more robust. This view was formed based on a positivist approach that assumes examining the impact of specific variables on a particular phenomenon and attempts to explain obtained results, arranging them in a cause-and-effect sequence. At the same time, the rationale for a single-case design stems from the fact that it, by definition, concerns unusual or rare cases. Thus, the main flaws of single-case studies refer primarily to the lack of scientific rigor and reliability in the method and its inability to provide a basis for generalization of findings [19]. However, as [20] points out, the purpose of single-case studies is not to draw general conclusions. More specifically, the single-case study seems to be appropriate when it aims to describe and explain a kind of revelatory case that has not been sufficiently described in the literature yet [17]. The research focuses on relationships between several stakeholders, which corresponds to the approach used in interpretive research. In this particular situation, it was important to understand a rare event and analyze it from different perspectives to create a solid base for further theory building [21]. Finally, a research strategy that is well established in the PPP literature was followed. For example, ref. [22] support their findings on PPP stakeholder engagement with the use of a single case study. These arguments justify a single instrumental case strategy [23], that is used to illustrate the phenomenon at hand by applying concepts from theory.

A first step in designing and conducting a single-case study is defining the unit of analysis. This research discusses a unique infrastructure investment of an underground car park named 'Plac Na Groblach' located in Cracow in Poland (hereinafter: Project). The justification for this case-study selection is two-fold. The discussed Project is the first local government PPP project in Poland, which was procured in the form of a concession and reached the operational phase. Second, the Project has been operating since 2009, which allowed us a reflection over short and long-term challenges and reliable stakeholder analysis in its operation phase. In the second step, following the phases of stakeholder analysis proposed by Reed et al. [24], the context of the stakeholder analysis must be given. Then the research carries on stakeholder analysis concerning the attitude towards the Project's success and engagement.

Research methods include a combination of dialogic qualitative interview design, analysis of documentation, observation of the Project and its surrounding, and member validation [25]. In the beginning, tender documentation, local transportation programs, and other available data sources such as articles in the local press and website were studied. The next step included dialogic open interviews to give interlocutors flexibility to discuss issues they deemed most important. The interviewees included the representative of the City authority and of the Project's company. Directly relevant to the research at hand, interviewees were asked about the identification, attributes, and relations of stakeholders. To better understand the case, after preliminary analysis of the information from interviews and studies of shared internal documentation, a follow-up interview and member validation [25] with the managing director of the Project's Operator to verify that the facts presented in the case reflect reality took place. The interviews took place in April 2014 in the City Hall and in November 2019 in Cracow at the operator's location. The research strategy allowed to identify and classify stakeholders. It also enabled to investigate stakeholder relationships in the case study.

Finally, the material has been used to answer the research questions about stakeholder success perception, motivation, and engagement, and develop a proposition of an improved benefit–engagement-based framework for the identification and classification of stakeholders in PPP projects.

3. Literature Review

3.1. Stakeholder Theory

Stakeholder theory derives from corporate planning, systems theory, corporate social responsibility, and organizational theory. Elias et al. [26] distinguish three stages of the stakeholder theory evolution, namely, classical stakeholder literature, strategic management, and the dynamics of stakeholders.

In its classical shape, the concept of stakeholders was first introduced by the Stanford Research Institute in 1963. The concept relates to groups without whose support the organization fails to exist. Organizations were perceived as social institutions, with responsibilities going beyond shareholders, directors, and employees, and the manager's tasks were to protect various rights of all stakeholders [19,27]. A strategic approach to the stakeholder concept was created by Freeman [28], who defined a stakeholder as any individual or group who can affect, or is affected by, the achievement of the organization's objectives [26]. The strategic approach relates to three-level stakeholder analysis: rational, process, and transactional. Stakeholders' identification and their perceived stake are the issues to answer at the rational level. At the process level, stakeholders are identified and classified according to criteria of interest or stake and power. Finally, the organization management of the stakeholder's relations, the trade-offs, and understanding the legitimacy of stakeholders are the concerns relating to the transactional level. Donaldson and Preston [29] developed a normative, instrumental, and managerial approach to the stakeholder analysis. The normative approach is based on ethical, moral, and social frameworks. It presumes managers take action based on these values. The instrumental approach attempts to identify relations between stakeholders and the achievement of objectives. It verifies if organization success depends on organization responsiveness to its stakeholders. Descriptive studies define and sometimes explain characteristics and managerial behavior relating to stakeholders. The stakeholder theory is also managerial. It does not merely describe existing situations; further, it recommends courses of action to the managers.

Finally, the concept of the dynamics of stakeholders assumes that the mix of stakeholders and their stake may change over time. Mitchell, Agle, and Wood [30] used the attributes of power, legitimacy, and urgency to generate a typology of stakeholders and illustrated the dynamic of stakeholders by the change of stakeholders' salience (the degree to which managers give priority to stakeholder claims) according to attaining or losing the attributes. They identify seven groups (types) of stakeholders based on the above-mentioned attributes of stakeholders, who can change their classes by attaining or losing one or more of the attributes.

The dynamics may also be illustrated by the application of another mix of attributes. Vos and Achterkamp [31] developed a role-based stakeholder model (client, decision-maker, designer, and passively involved). Crosby [32] based stakeholder analysis on criteria of stakeholder interest and influence. According to Reed et al. [24], Freeman used attributes of cooperation and competition. Savage, Nix, Whitehead, and Blair [33] identified stakeholders based on their potential for cooperation or threat relating to the organization (mixed blessing, supportive, non-supportive, and marginal stakeholders). Callan, Sieimieniuch, and Sinclair [15] provide stakeholder classification based on different types of responsibilities (controller, executer, constraining advisor, and discretionary advisor).

To conclude, the stakeholder theory can be presented from different perspectives that involve very different methodologies, types of evidence, and criteria of appraisal. These several categorization models for identifying stakeholders have been criticized in prior stakeholder literature for their gaps between stakeholder theory and practice, among other gaps [9]. The gaps have been related to the definition of a stakeholder, identification, and stakeholder classification. In particular, in practice, stakeholders have been merely identified with entities benefitting from the project while those who are harmed by the project or have a negative influence on the project were not taken under consideration. There have been infrastructure-project gaps identified associated with stakeholder analysis in the investment cycle and related to investment motivation. Not only should stakeholders be managed at the stage of project construction but especially during the stage of conceptualization. This can help to avoid many problems during the next stages of investment and eventually increase the quality of the project. Finally, the long life of the infrastructure projects and their specific characteristics requires the identification of stages of maintenance and termination, during which stakeholders need to be managed as well. The dynamic nature of stakeholders requires not only whole life management but also management respecting different and changing motivations. This contributes to stakeholder relationship building, enables the provision of checks and balances, and ultimately increases the value of the project, at least in the case of the transportation project [34]. As the literature gaps are also related to the information that is not analytical enough and is not often aligned to PPP, the following part of the paper focuses on stakeholder theory tightly connected with the specific features of PPPs.

3.2. The Importance of Stakeholder Analysis in PPP Infrastructure Projects

The literature overview reveals that the utility of stakeholder analysis varies depending on its purposes, which might include defining success, risk management, stakeholder information provision, or stakeholder management [31]. Dalcher [35] states that the adoption of a stakeholder-centric approach enriches the research perspective and promises new insights relating to project management. Eskerod and Huemann [22] complain that current project stakeholder practices represent mainly a management-of-stakeholders approach, while a management-for-stakeholders approach may be more beneficial. The management-for-stakeholders approach assumes that all stakeholders have the right and legitimacy to receive management attention [36]. According to Hahn, Figge, Pinkse, and Preuss [37], although the management-for-stakeholders approach may lead to conflict-free solutions (win-win situations are characteristic for PPP projects), it might not be very ambitious, might hamper project progress, and finally delay benefits for all stakeholders [38]. The authors propose therefore to integrate management 'for' and management 'of' stakeholders to balance the necessity for stakeholder inclusiveness and the need to include new stakeholders. The last seems essential in the case of the infrastructure project, which is characterized by a long life cycle and economic, social, and ecological effects, also of external character. Jepsen and Eskerod [39] conclude that the current stakeholder analysis guidelines provide a conceptual framework but miss details. There is then a limited amount of research concerning the issue of stakeholders engagement in PPP projects. In this context, it is especially interesting to investigate how different stakeholder groups affect PPP success or PPP failure.

Some of these aspects have been studied in the literature on critical success factors (CSF). Stakeholders' issues relating to PPP projects, such as the relationship between partners and their experience in PPP, are perceived to be crucial to the success or failure of PPP projects [7]. A study carried out by Wegrzyn [40] also confirms that particular groups of stakeholders reveal a different attitude toward PPP success. The author examined the perception of PPP success factors among different stakeholder groups in different phases of PPP. Similar conclusions were drawn by Lop et al. [41] in their research examining the factors affecting the operational performance of PPPs. Lack of experience and understanding of PPP among stakeholders was identified as one of the main factors that hamper PPP management.

Discussed papers on PPP success factors prove the justification of stakeholder analysis. There are, however, only a few papers focusing on a broader context of stakeholder engagement in PPP. The dynamic relations among PPP stakeholders were described in an overall manner by [42]. The authors analyzed the process of stakeholder inclusion in PPP projects and ways of increasing stakeholder engagement. Schepper et al. [10] developed a more specific model for stakeholder identification. They focused on assessing stakeholder influence, which enables the allocation of responsibilities and accountability toward PPP stakeholders. By combining power and urgency, they identified three potential types of influence that each group can exert on the project. Some stakeholders have a minor influence on the project—they do not control critical resources, and their claims do not need immediate attention. Some stakeholders may have a potential influence on the project—they possess one of the attributes mentioned above. Definitive stakeholders have a direct influence on the project and its environment—they control critical resources, and their claims are urgent. Finally, ref. [5] examined the process of multi-stakeholder consultation and management in a PPP project environment. They highlight the problem of exclusion of the public sector client in PPP projects. The research, as mentioned earlier, exerts a significant impact on the analysis of stakeholder interactions in PPP projects. However, the analysis of these works leaves some questions relating to project success, stakeholder benefits, and engagement, which are addressed in this research.

4. Conceptual Model for Stakeholder Analysis in PPP Projects

4.1. Analysis of Stakeholders Based on Their Engagement

Stakeholder categorization is a complex issue that can be analyzed from different perspectives. In this research, three of the indicated stakeholder attributes create frames for analyzing PPPs and the potential engagement of stakeholders. Following Shepper, Dooms, and Haezendonck's stakeholder analysis approach [10], attributes of power and urgency were selected.

Stakeholder power can be defined as the relative access to critical resources for a specific stakeholder group regarding its focal organization [43]. In other words, possessing power in the organization is associated with access to funds, the reputation, competence, or ability to deploy power derived from the position in an organizational hierarchy or legal authority. There are two PPP project stakeholders, who can be perceived as 'focal'. They are the public initiator (the grantor) and a private partner as a sponsor, often aligned to a project company [10]. That is why the potential attention may be shifted from one group to another, and this depends on the development of the relationship between them. The imbalance between these stakeholders reflects a potential trade-off between market and social expectations as presented by Garvin and Bosso [44]. However, a central principle is that the dissemination of the PPP project's result must be consistent with rules dictated by certain PPP programs in a given jurisdiction, as the collective performance of all PPP projects determines whether the PPP program is useful as a strategy or policy for infrastructure development and management.

According to Mitchell et al. [30], urgency can be defined as the degree to which stakeholders claim to call for immediate attention. The component of urgency helps to move the model from static to dynamic. It is based on the following attributes: time sensitivity—the degree to which managerial delay in attending to the claim or relationship is unacceptable to the stakeholder, and criticality—the importance of the claim or the relationship to the stakeholder. In PPP projects, the responsibility to the claims is shared between the public and private sectors. On the one hand, it could mean that the range of arguments to influence the PPP project becomes wider. On the other hand, it limits the nature of the claim depending on the targeted focal stakeholder [10]. In general, public actor and project company may have distinct responsibilities, which are described in the contract, as so is the right to decide a particular case. This suggests possible obstacles which may occur while identifying a focal stakeholder responsible for taking action in a particular case.

A revised approach for stakeholder analysis is embedded in the concepts mentioned above of stakeholder categorization and management. By aggregating power and urgency, two types of engagement can be identified: indirect and direct.

4.2. Individual Perception of Success in the Public and Private Sector

According to Ambler and Wilson, success must be related to goals [27] which can also be conceptualized as interest and benefits gained [45]. In this context, the public sector that initiates PPP projects and private investor aligned in a project company is characterized by a potentially highest level of interest, although expressed in different ways. Public and private sector entities' goals are reflected in the strategic planning, and implemented via investment decisions and implemented investment projects. A private entity strives to maximize the benefits for its owners. The primary evaluation criterion is then the current value of the investment or the rate of return. In the case of projects implemented by public entities, the criterion is different, as public sector entities act in association with society. The purpose is not purely economic, and the effectiveness of the public sector should be assessed at macroeconomic and macro-social levels, including environmental impacts. The criterion for decision-making is represented by 'the public value', which should maximize the benefits for the citizens. Public sector decisions are therefore based on complex criteria and go beyond the functional and financial evaluation of the project itself, as proved by Hodge and Greve [46]. Eventually, the evaluation of the success in PPP relates to the success of public and private entities simultaneously.

There are several related concepts relevant to the research and development of the benefits–engagement model. Trocki [47] adopted the European Union approach [48] used for the assessment of structural funds employment. The EU concept identifies different types of project effects. There are financial or physical outputs (deliverables of the project), outcomes and results, and impacts. The EU success criteria include relevance (extent to which project effects are relevant to identified needs), effectiveness (extent to which project effects are achieved), efficiency (relation between resources required and project output), utility (benefits to target groups), sustainability (durability of employed effects), and community-added value (the extent to which project output, results, and impacts occur due to project intervention). Trocki [47] uses these criteria in the context of the project, organization, and environment.

Second, the criteria of efficiency and effectiveness, and in addition, differentiation between short-term output and long-term outcome (results), are used by Dalcher [35], who identified four levels of project success. Level 1, focusing on project management success, uses criteria of internal efficiency (profitability) and performance measures relating to the budget, schedule, and scope. Level 2 concerns project effectiveness in terms of quality and acceptability of the project output concerning shareholders. Level 3 focuses on the creation and delivery of internal value from the business perspective. Finally, Level 4 concentrates on prospects relating to project gains itself but also new ventures and opportunities concerning new skills, competencies, and capabilities. This connects Dalcher's approach with Hodge and Greve's approach, being the third concept building the grounds for the benefits–engagement matrix.

According to Hoge and Greve [46], governments expect that PPP would deliver a wide range of benefits relating to the project and technical concerns, and even political and cultural aspects. This presents a complex challenge for those interested in assessing the value and success of PPP [46]. Hodge and Greve's conceptual PPP model includes five levels of project evaluation: project, delivery method, policy, governance tool, and cultural context. There are goals relating to each level, and therefore the success of PPP might be judged separately at each level, which is similar to Trocki's approach. However, the levels and objectives are often overlapping, and much of the judgment resides outside the project itself. The project level relates to the objective connected with providing value for money. The delivery method refers to the promise of providing goods or services on-time, in-budget, and within scope. Objectives of infrastructure provision without growing public debt, transfer of risk, application of the more flexible private law, and support from private businesses relate to the sphere of policy. The governance tool means improving accountability and transparency. Cultural context refers, among others, to innovation, which Dalcher broadly calls future prospects.

Finally, success perception should be based on the criteria of sustainable development, which should form the general assumption for any activity. According to the concept, only a project that respects economic, social, and environmental requirements simultaneously can be sustainable, as presented below (see Figure 2).

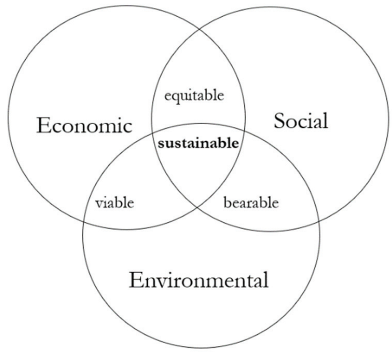

Figure 2. Dimensions of sustainable development as infrastructure project evaluation criteria Source: own elaboration based on [49].

The above concepts support the thesis that success can be perceived quite differently by the various PPP stakeholders. The perception of success depends strongly on the scope of assessment that can be conducted from an internal as well as from an external perspective. Overall, success perception relates to short and long-term perspectives, and financial and non-financial benefits relating to economic, social, and environmental dimensions of sustainable development.

Considering the differences between the public and private sectors and their perception of a project's success, it was assumed that PPP can bring two types of benefits: financial (economic) or non-financial (social and environmental).

4.3. A Conceptual Benefit–Engagement Model of Stakeholder Classification

The integration of the concept of engagement and preferred benefits allowed to distinguish four types of stakeholders (Table 1).

Table 1. The conceptual model for PPP stakeholders' identification and their classification. Source: based on [14].

		Preferred Benefits (Interests)	
		Financial(economic)	Non-financial (social and environmental)
Engagement	Direct	Type I	Type II
	Indirect	Type III	Type IV

Type I and Type II are the most influential stakeholders in the PPP project. They include two focal stakeholders, who are sponsors and a grantor. The relation between them is set up via a project company. There might be other key stakeholders, too. Their influence on a PPP project is most prominent as, if their support is withdrawn, the project is usually going to fail. This situation is not likely to happen in the case of Type III and Type IV stakeholders. They include operators or suppliers who may change during the operation phase, and this does not necessarily lead to the PPP termination. Equally, resigning from services by a single consumer probably would not cause substantial harm to the project. However, a single consumer may not have enough power to claim their own needs, but a group of consumers may have enough power to claim. Generally, lenders and bond investors are grouped in Type III, although the scale of economic engagement determines their particular influence. The bigger the financing leverage, the higher the engagement and therefore the possibility of their shift to Type I. These stakeholders evaluate the project mainly regarding efficiency criterion. Type IV are media, ecologists, and unions who influence the success perception in the broadest context. They are stakeholders focused externally without a direct financial interest in the project, and they concentrate on the social and environmental aspects of the project. Governmental supervisors and regulators are also Type IV stakeholders and they evaluate the PPP according to effectiveness, durability and socio-economic impact criteria.

Therefore, only the holistic approach on the project can provide infrastructure development along the criteria of sustainable development.

The matrix allows for demonstrating how the stakeholder's interests should be integrated into the PPP project by involving stakeholders in the decision process. The way of addressing a stakeholder's claim depends on the position of a stakeholder. However, the presented approach suggests that a focus on the stakeholders' attitude towards PPP success is also required. To meet sustainable criteria, engaged stakeholders should cooperate and delegate responsibilities to address those indirectly engaged stakeholders and their needs, who reveal a similar attitude towards PPP success.

5. Result and Discussion

5.1. The Underground Car Park 'Plac Na Groblach'—A Case Study's Results

Following the steps of stakeholder analysis [24], the context of the project must be given. The boundaries of the project are set by national regulations and local conditions based on the city transportation development strategy. In Poland, the process of implementing the cooperation under PPP was initiated in the year 2005 by introducing the Act on PPP. Cooperation with private partners started to be perceived as an attractive way of obtaining additional financing, especially for local governments. However, a vague policy of the central government, exemplified by the lack of executive acts to the Act on PPP, has deterred them from initiating PPPs. Therefore, public entities aiming to establish cooperation with the private sector had to look for other solutions. One of them was a concession for construction. The first project constructed in this model was the Underground Car Park 'Plac Na Groblach' in Cracow [50]. Mainly because of this reason, this project became the subject of the study.

The tender was announced in November 2005. After one year of negotiations, the City selected a concessionaire—Ascan Empresa Constructora y de Gestion—and signed the agreement in November 2006. The concession gives the private partner the right to occupy and use the car park for 70 years. The underground car park was completed in December 2009, and it offers 610 parking spaces.

The car park is located on the north bank of the Vistula river close to the most recognizable landmark of the Cracow city, namely the old city center, and Wawel Castle (see Figure 3).

Figure 3. Stakeholders' identification and relations in the Underground Car Park 'Plac Na Groblach' in Cracow—operational phase. Source: https://www.bip.krakow.pl/?dok_id=23247, accessed on 9 January 2022.

A paid parking zone covers this part of the city. In Poland, the functioning of the zones is determined by legal regulation, the Act on Public Roads (Dz.U. 1985 Nr 14 poz. 60). This regulation indicates that the institutions responsible for the creation and administration of the zones are local governments. The regulation also sets the maximal fees for car parking in the zones. However, the Act on Public Roads applies only to public facilities, and therefore private owners of car parks located in the zones are not obliged to follow these legal rules. Due to the nature of the contract, the Underground Car Park 'Plac Na Groblach' is treated as a private enterprise with a public stakeholder.

The cooperation between the private and public partners is shaped under the design-build-operate-finance 70-year contract (DBOF). The contract includes reconstruction of the existing sports field complex, and modernization of the surrounding streets, pavements, and green squares surrounding the area of investment. The complex of the Inter-school Sports Center "West" includes technical infrastructure and is located on the top surface of the underground car park. The concessionaire and sponsor, who is Ascan Empressa Construtructora, established the special purpose vehicle (SPV) (Ascan Joint Stock Company Branch in Poland). SPV took responsibility for the design, construction, operation, and financing of the underground car park. After construction, the SPV became the Project's Operator. This includes managing the system of tool collection, contracting services e.g., insurance, current repairs, technical audits, and energy supply, etc. Detailed terms of operating the car park are set up between SPV and the Department of Transport Infrastructure, which is an organizational unit of the local government of Cracow responsible for managing municipal infrastructure in the City. Simultaneously, in the City structures, the responsibility for operating parking zones belongs to Municipal Infrastructures Ltd., which is a municipal company. This company is responsible for providing information on the availability of parking lots and it has the right to collect parking fees. However, there is no formal contract between Municipal Infrastructures Ltd. and SPV, and they both operate within the same area. Finally, the stakeholders of the project include end-users, who are individuals and institutional clients. Institutional clients are hotels and companies located near the car park. They benefit from the available parking spaces on the basis of individually negotiated contracts. The individuals (such as inhabitants, sport facility users, and visitors) use the facility based on a long-term individual periodical fee or an incidental one-time payment. The Project stakeholders also include non-users of the underground car park. They are also inhabitants (primary and secondary neighborhood), sport facility users such as pupils, and the small businesses nearby.

The network of stakeholders of the Project includes stakeholders who are engaged in the Project directly and indirectly. The relations among stakeholders are centered but not limited to relations with SVP. There are two focal stakeholders who are the grantor—the City of Cracow, and the sponsor—Ascan Empressa Construtructora, represented by SPV. Direct engagement refers to the grantor and SPV—the recent being interested in the financial success of the investment, while the sponsor and grantor seek non-financial benefits. The sponsor is interested in implementing global strategy, value, and reputation increase for the whole company and prospective contracts due to the success of the Project. The grantor is interested in implementing the transportation policy and delivering infrastructure in time and of a good quality, thus increasing the quality of inhabitants' life. These briefly described relations constitute the background for further stakeholder analysis. All identified stakeholders and their relations in the operational phase are presented below (see Figure 4).

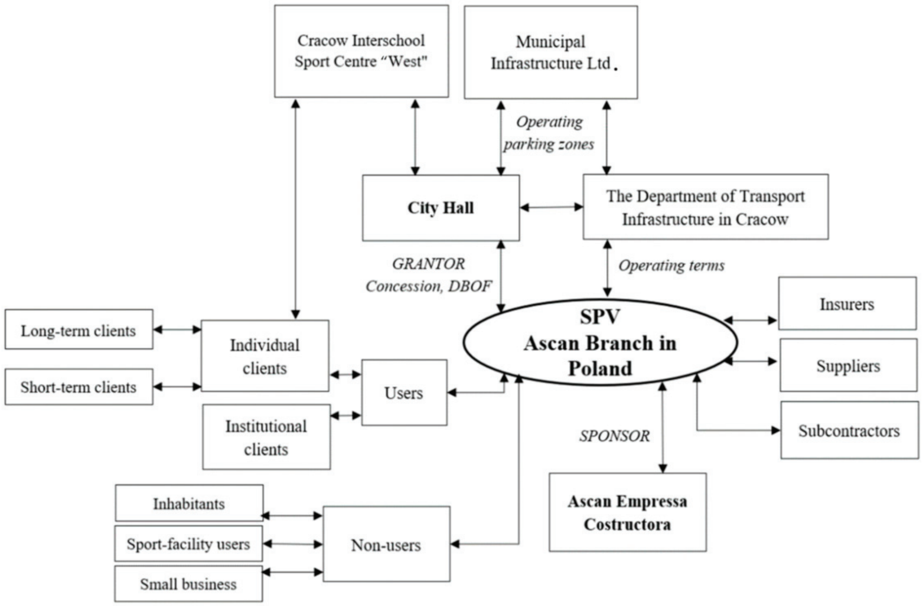

Figure 4. Stakeholders' identification and relations in the Underground Car Park 'Plac Na Groblach' in Cracow—operational phase. Source: Own elaboration.

5.2. Discussion

The Project sponsor (Ascan Empressa Construtructora) is not directly engaged in the Project and therefore in the stakeholder management. Since proceeding the Project to the operational phase, the sponsor has been focused on controlling the completion of established commercial goals from the global enterprise point of view. The responsibility for managing the Project rests primarily on the SPV (Ascan Branch in Poland). The SPV is responsible for arranging contracts and non-contract relations with stakeholders, including local inhabitants, sport facility users, and small businesses. At the stage of project construction, SPV guaranteed the use of parking for nearby inhabitants at preferred fees as they suffered the most from nuisance related to the construction of the Project. The SPV informs and presents offers to the individual and corporate clients, and negotiates and signs contracts with clients and other entities engaged indirectly in the project operations such as insurers, suppliers, and subcontractors. The engagement of the entities, including the Project sponsor and SPV, is on a commercial basis.

The grantor is represented by the City authorities and is responsible for formulating policy goals. The general aim of the policy is to limit the number of parking places, taking into consideration the capacity of the road network, which should lead to a shortening time of parking and more effective parking use. Above all, the policy should eliminate local street parking and make them walkable. The grantor focuses therefore primarily on the direct product, which is new infrastructure. There is less consideration of financial and technical issues of the project operational management as these issues, according to the DBFO contract, have been transferred to SPV. Simultaneously, the grantor's focus also has a long-term perspective as the Project is a component of a complex policy that would contribute to improving the transportation situation in the City for the interest of the inhabitants. The grantor is supported in the Project by its organizational unit, which is the Department of Transport Infrastructure in Cracow, and a municipal company, which is Municipal Infrastructure Ltd. Their engagement is also indirect, and the motivation is non-financial, i.e., society and environment-related.

The local community, including residents and Cracow Interschool Sports Center "West", were concerned that the investment would lead to an increase in parking costs and therefore the City authorities did not ban parking on the streets to prevent possible public opposition. Although being indirectly engaged in the Project, inhabitants create a powerful and urgent group of stakeholders even though they include non-users; this is a challenge, as they are non-financially motivated. Therefore, the City authority implements transportation policy and related changes gradually, so the actions hamper access to the City center mostly for those who do not live there, and prioritize the inhabitants' needs. Therefore, the Projects would not operate without end-users paying fees for using the underground car park and the entities delivering different services such as subcontractors, suppliers, and insurers.

The classification of the identified Project stakeholders based on the attributes which have direct and indirect engagement in the Project, and financial and non-financial motivations (benefits), which relate to dimensions of sustainable development is presented below (Table 2).

Table 2. Stakeholders' categorization in Underground Car Park. Source: Own elaboration.

		Preferred Benefits (Interests)	
		Financial (Economic)	**Non-Financial (Social and Environmental)**
Engagement	Direct	The project company—Ascan Branch in Poland	The grantor—Cracow City, represented by the City Hall
	Indirect	The sponsor—Ascan Empressa Construtructora Insurers Suppliers Subcontractors Institutional and individual clients	The Department of Transport Infrastructure Municipal Infrastructure Ltd. Cracow Interschool Sports Center "West" Community—local residents

The research strategy allowed to identify and describe the stakeholders, their relations, engagement, and motivation, determining success perception. This helps to understand how to construct relations to ensure the PPP project success, understood as obtaining the goals set by public and private partners. Simultaneously, the case study identifies potential challenges connected with the partnership (mainly focal partners) and the Project.

First, it is worth considering potential opportunities and threats of the Project to the local community. The residents were concerned that the investment would lead to an increase in parking costs. The gradual reduction of car traffic in the city center and restrictions for car parking imposed gradually were aimed toward citizens, not against them. Thanks to these gradual changes in the rule relating the street parking, the threat of public opposition was generally prevented. It occurred that the development and operation of the project did not significantly affect the situation of the residents living in the city center, as was previously expected. Moreover, the whole investment process made the residents more concerned about the city transport policy and its consequences for them. Although the evidence of direct cooperation between the private and public partners is hard to trace in this aspect, the local authority's policy contributes to the operation of the car park. The operation of the car park does not threaten the interests of residents who live in the neighborhood of the car park, and the car park becomes more attractive for those arriving in the city center by car.

Second, due to the law regulations, e.g., Act on Public Roads, the public–private cooperation between the Municipal Infrastructure Ltd. and car park operator is hampered. The operator of a car park has the right to charge fees on a commercial basis; however, the rules imposing the division on public and private facilities cause the local government and private owners of car parks to provide their services separately. As a consequence, main stakeholders are not motivated to cooperate under one car parking system in the city.

Third, the evidence of direct cooperation between the private and public partners in this Project is also "blurred" in the sense that the SPV company has been developed solely by the sponsor and the grantor representation has been fragmented by the engagement of two public entities. The local government is a concession grantor and the signature of the DBFO contract and is co-represented in the PPP by both an organizational unit (Department of Transport Infrastructure) and municipal company (Municipal Infrastructure Ltd.). Although the SPV structure gives benefits such as risk transfer (for instance market risk or financing risk), and in the situation of purely private SPV, also risk-avoidance (for instance in reference to moral risk), the concentration of responsibilities in one entity, which is one of Project Finance and PPP, has the most important advantages [51], and the local government engagement has been fragmented in this Project. This may raise the risk of losing control.

To summarize, the stakeholder analysis proved that PPP projects do not have to be treated as joint cooperation literally. This case study provides evidence that finding a balance in the cooperation of public and private partners could be considered as an important factor of successful stakeholders' management. The car park project is specific, too. The private partner retains the financial and technical responsibilities of a car park operation, whereas the city handles all the organizational tasks relating to the recognition of legal and political frames, pays attention to environmental risks, and takes responsibility for the policy and its acceptance by the citizens, all of which are critical for successful project preparation, realization, and operation. Nevertheless, the legal environment, including implemented regulations on PPP, and multiplicity of legal provisions relating to the actives undertaken by local governments (e.g., Act on Public Roads) impede the cooperation between the stakeholders, as is exemplified by the operator of city parking zones.

6. Conclusions

Since the introduction of cooperation under PPP, there are many successful projects as well as failures. Only approximately 30% of PPP projects in Poland are implemented [13]. The development of PPP literature has followed the growing experience in public–private cooperation. Currently, scholars tend to stress that the motives standing behind PPP can be highly polarized and PPP can no longer be perceived as just a solution to acquire additional capital that could satisfy everyone in an equal way. Due to these reasons, this research tries to offer a descriptive stance and to identify the main stakeholders in PPPs, examine their engagement in PPP, and define stakeholders' success.

The article was based on stakeholder theory, which indicates that there is more than one approach to project management and puts into light the importance of meeting stakeholder needs [52]. The conducted literature review reveals that the problem of joint cooperation between the public and private sector still requires stakeholders centered analysis. At the same time, growing research interest in project success and more specifically the perception of success by different stakeholder groups can be observed. This research approach combined two main ideas, which are the perception of success in the public and private sector, and stakeholder engagement. A conceptual benefit–engagement model for a new interpretation of stakeholders' identification and classification in PPP projects was proposed, which was then verified via a selected case study of a unique infrastructure investment taken from Cracow in Poland—a country characterized by development success in recent years.

The findings identified apparent discrepancies in the perception of PPP success between main PPP stakeholder groups, which can be classified into four groups (research question 1). Stakeholder Type I and Type II are the most influential in the PPP project. They include two focal stakeholders, who are sponsors and a grantor. Generally, lenders and bond investors are grouped in Type III. Type I and III evaluate the project generally based on its profitability. Type IV are stakeholders who perceive success in the broadest context.

They are stakeholders focused externally without a direct financial interest in the project. Type IV evaluates the PPP according to socio-economic criteria, long-term impact, and creating future opportunities.

This benefit–engagement classification, including the polarized goals of different stakeholder groups, justifies evaluating PPP project success as a whole. Through the use of the benefit–engagement model, public and private partners will be able to be more aware of who the stakeholders are and what the relations between them in terms of engagement and interest (research question 2) are. This will lead to more informed decisions, precision in their choice of project, and help in successful PPP delivery.

The criteria of benefits and engagement show how different stakeholder groups perceive PPP success (research question 3). The model distinguishes financial and non-financial benefits, which can be gained in the short and the long-term, and which became criteria for success evaluation of the sustainability of the project. The second dimension of the conceptual model is engagement. Engagement incorporates the attributes of power and urgency. Power refers to the ability to influence the definition of the project [30], and access to critical resources [43]. The urgency is defined in the model after Schepper et al. [10] as a degree to which stakeholders claim to call for immediate attention. This benefit–engagement model can be a tool for early and joint stakeholder management supporting individual motivation and attitude towards success, especially about, but not limited to, focal stakeholders.

The Underground Car Park case study confirms that a proper allocation of responsibilities between directly engaged stakeholders can cause uninterrupted cooperation with other indirectly engaged groups focused on two different types of benefits (financial or non-financial). The grantor—Cracow City—represented by the City Hall at the early stage of the project addressed the needs of the local community and other local organizations, whereas, during the operational stage, the stress was laid on addressing stakeholders focused on financial benefits. During that stage, the leading role was assigned to the project company. However, the City Hall still played an important role because it is responsible for shaping transport policy in the City. As a takeaway for practice, the research proves complex relations between different stakeholders and the diversity of PPs in terms of place and time. It is a prime issue especially for economies under transition, which are still gaining knowledge in the area of the management of and for their various stakeholders [53]. This research proves that only a holistic approach to PPP can lead to sustainable development, as only then does it cover economic, social, and environmental criteria. The success of the PPP project as a whole is then achieved when all stakeholders receive their benefits, which would simultaneously confirm the project's sustainability. Finally, the study proposes a background for further research on PPP success and important stakeholders groups of PPPs and their understanding of PPP success. By addressing these aims, a greater understanding of how PPP success dimensions can be measured and managed can be achieved.

The main limitation of the study arose from the broader need for empirical validation of the presented conceptual model. Although observations are made over a selected case study within a limited period, and the context of the analysis and stakeholder perception may change according to the dynamics of stakeholders, the research has a particular strength relating to its prospective dimension. It offers compelling evidence that stakeholder management is difficult under the best of circumstances, and becomes even more challenging in the presence of varying interests. Future research could consider characteristics of specific country circumstances and specifications of different types of PPP projects as the need to adopt a more stakeholder-oriented perspective in project management results from many participants involved, but also from different PPP forms, contracts, and country traditions.

Author Contributions: J.W. 55% and A.W.-F. 45%: Conceptualization, J.W. and A.W.-F.; Formal analysis, J.W. and A.W.-F.; Funding acquisition, J.W.; Investigation, J.W. and A.W.-F.; Methodology, J.W. and A.W.-F.; Project administration, J.W. and A.W.-F.; Resources, J.W. and A.W.-F.; Supervision, J.W. and A.W.-F.; Visualization, J.W. and A.W.-F.; Writing—original draft, J.W. and A.W.-F.; Writing—

review & editing, J.W. and A.W.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by Cracow University of Economics (agreement no. 5/EEN/2020/POT).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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Design of Social Responsibility Incentive Contracts for Stakeholders of Megaprojects under Information Asymmetry

Feng Xue [1,*], Guangyu Chen [1], Shanming Huang [1] and Huan Xie [2]

[1] School of Management and Economics, University of Electronic Science and Technology of China, Chengdu 611731, China; chenguangyu@uestc.edu.cn (G.C.); hsm@uestc.edu.cn (S.H.)
[2] Sichuan Provincial Branch of Southwest Regional Headquarters, China Communications Construction Company Ltd., Chengdu 610218, China; huanx1999@163.com
* Correspondence: xuefeng841116@163.com

Abstract: Social responsibility is essential to the sustainable development of megaprojects. A transparent and symmetrical information-sharing mechanism is an important guarantee for promoting megaproject stakeholders to fulfill their social responsibilities and improve project efficiency. Aiming at the problems of megaproject subcontractors concealing social responsibility information, which leads to unsmooth information channels and low project efficiency, this paper compares and analyzes the single-stage revenue-sharing model under symmetric and asymmetric information from the perspective of incentive contract design. Then, a two-stage incentive contract with multiple indicators under asymmetric information is designed using principal-agent theory. The research results show that the social responsibility effort level of the general contractor and the total project revenue is positively correlated with the input–output ratio, and is negatively correlated with the degree of information opacity of the subcontractor's social responsibility. Incentive contracts with multiple indicators in stages can effectively encourage subcontractors to disclose social responsibility information, and reduce information asymmetry, therefore enhancing social responsibility and improving overall project efficiency. This research transforms the research on the social responsibility of megaprojects from qualitative to quantitative. The research results provide theoretical methods and decision-making basis for megaproject general contractors to encourage subcontractors to improve social responsibility.

Keywords: megaproject; social responsibility; stakeholder; moral hazard; information asymmetry; incentive mechanism

Citation: Xue, F.; Chen, G.; Huang, S.; Xie, H. Design of Social Responsibility Incentive Contracts for Stakeholders of Megaprojects under Information Asymmetry. *Sustainability* **2022**, *14*, 1465. https://doi.org/10.3390/su14031465

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 29 December 2021
Accepted: 25 January 2022
Published: 27 January 2022

1. Introduction

In the context of the Belt and Road Initiative and the national strategy for sustainable development, China's major infrastructure projects (hereinafter referred to as megaprojects) are facing an unprecedented environmental sensitivity period, strategic opportunity period, and value reconstruction period. Therefore, in addition to paying attention to the progress, cost, and quality of the projects themselves, the stakeholders of megaprojects should also focus on project social responsibilities such as avoiding harm to public safety, maintaining ecological balance, and achieving sustainable development [1]. In reality, some project stakeholders excessively pursue their economic interests while neglecting social responsibilities, leading to frequent accidents. In 2013, the collapse of the Sava District Building in Bangladesh, which killed 1127 people, shocked the world. The main reason was the owners' lack of a strict review mechanism, and the project was multi-level contracted. Subcontractors cut corners and built-in violation of regulations; government departments had information asymmetry in those mentioned above lacking social responsibility behaviors, leading to government supervision and management dereliction, which eventually led to tragic accidents [2]. Even the consequences of general projects due to the lack of social responsibility are such serious, to say nothing of the megaproject. For megaprojects, the construction period is exceptionally long, the relationship is intricate, supervision is more difficult, and information asymmetry is more serious than ordinary engineering. Slight negligence of project stakeholders in the process of decision-making and implementation may lead to consequences beyond the project itself, which may evolve into a series of serious social problems, seriously restricting the sustainable development of megaprojects and the economy and society. Therefore, studying the social responsibility management of megaprojects under asymmetric information has important practical significance.

The social responsibility of megaprojects refers to the policies and practices adopted by megaproject stakeholders to fulfill their responsibilities for achieving broader social well-being during the entire lifecycle of the project [3]. Compared with general projects, megaprojects mainly have the following differences. (1) Project stakeholders must assume social responsibility [4]. General projects only need to carry out project construction following the contract (time, cost, quality, etc.), and there is no mandatory constraint on social responsibility. The megaprojects have far-reaching and irreversible impacts on environmental changes, economic development, and social progress. Therefore, stakeholders at all stages of the lifecycle of megaprojects must consider social responsibilities to ensure the sustainability of megaprojects. For example, the Hong Kong–Zhuhai–Macao Bridge project, while ensuring the quality of the project, is also required to take the social responsibility of long and durable design, green and low-carbon construction, and low-emission and low-consumption operation [5]. (2) Information asymmetry is more serious [6]. For megaprojects, the long construction period, complicated relationships, imperfect supervision system, and difficult identification of social responsibility efforts have caused serious information asymmetry. Moreover, megaprojects often adopt the general contracting model, i.e., the government (owner) is only responsible for overall management and control, and only signs general contracting contracts with the general contractor. The general contractor is responsible for all the work of the subcontractors to the owner [7]. Therefore, subcontractors have a weak sense of responsibility compared with the owner and contractor, and there are double opportunistic behaviors of moral hazard and adverse selection, which can easily induce project accidents.

In view of the two characteristics of social responsibility for megaprojects, serious information asymmetry will lead to opportunistic behavior and inhibit other stakeholders from promoting social responsibility. Therefore, this paper intends to encourage project stakeholders to disclose responsibility information and enhance social responsibility through contract design. In practice, the construction stage is the most important stage in the lifecycle of megaprojects, and it is also the stage most prone to accidents and hidden dangers. The main stakeholders at this stage include the owner (government), general contractors, and subcontractors. Therefore, studying the social responsibility incentive mechanism of the main stakeholders in the construction stage is of great significance to promote the project's success and reduce the project risk. In summary, this paper intends to study the following two issues. (1) Based on the perspective of the general contractor, we investigate how to design an incentive contract to solve the dual problems of adverse selection and moral hazard caused by subcontractor information asymmetry. (2) Based on the incentive contract model, we study the relationship and influencing factors of the social responsibility effort level, the revenue distribution ratio, and the total project revenue of the general contractor and subcontractors.

2. Literature Review

The social responsibility of megaprojects is the common responsibility of all stakeholders, and each stakeholder is part of the responsibility chain. This mainly includes economic responsibility, legal responsibility, ethical responsibility, and political responsibility [8]. Among them, the government's social responsibility (owner) is mainly reflected in realizing the value of the project, paying attention to public needs, formulating laws and regulations, and maintaining social stability. The general contractor's social responsibility is mainly reflected in ensuring quality and safety, controlling construction period and cost, innovating technology and process, optimizing resources and allocation, and coordinating interests and conflicts. The subcontractor's social responsibility is mainly reflected in the use and promotion of green materials, paying attention to employees' occupational health, and the protection of the construction site environment [9]. In the whole lifecycle of a megaproject, the social responsibilities of stakeholders are heterogeneous and interactive, and the highly integrated governance of government, enterprises, and the public can promote the creation of sustainable value of megaprojects [10]. The social responsibility of megaprojects has aroused great attention in academic circles, and many scholars have studied it from different perspectives. On the one hand, according to the characteristics of social responsibility of the megaproject, some scholars have constructed an indicator evaluation system of social responsibility of megaprojects [11,12]. On the other hand, some scholars have evaluated and analyzed the social responsibility risks of megaprojects based on social network analysis [13,14]. Moreover, some scholars have studied the relationship between the social responsibility of megaprojects and project efficiency and sustainability [9,15]. In summary, the existing research on the social responsibility of the megaprojects mostly focus on constructing the conceptual framework of social responsibility, establishing an indicator evaluation system, and sustainable development [14,15]. Few studies focus on social responsibility incentives for project stakeholders.

Megaproject features are high complexity, numerous stakeholders, and imperfect supervision systems, which have caused serious information asymmetry among project stakeholders, led to the double opportunistic behaviors of moral hazard and adverse selection of some stakeholders, and severely restricted the smooth implementation of the project and sustainable development [16,17]. Sheng et al. suggest that one of the issues of megaproject decision-making governance is to conduct an in-depth study on the process of megaproject decision-making governance to deal with adverse selection and other moral hazard issues [18]. Xiang et al. studied the probability and impact of information asymmetry among owners, contractors, and supervisors, and pointed out that opportunistic behavior caused by information asymmetry is the main cause of project loss and risk [19]. In the entire lifecycle of megaprojects, subcontractors are likely to cause double information asymmetry problems in the construction stage due to their weak sense of responsibility [20]. The study of pure moral hazard assumes that the agent's actions are not visible to the principal [21]. After Holmstrom proposed a general framework [22], many scholars have further developed it and applied it to different industries [23]. Based on PPP projects, Paez-Perez and Sanchez-Silva discussed a dynamic principal-agent model to solve the moral hazard problem caused by project information asymmetry [24]. The study of pure adverse selection assumes that the agent has some private information that is not visible to the principal [25,26]. Aiming at the adverse selection problem in the megaprojects' BOT model, Shi designed contracts to encourage companies to report information truthfully, therefore improving the BOT project's optimal capacity ratio [27]. The above studies provide ideas and methods for this research, but currently, few studies simultaneously study information asymmetry with the coexistence of moral hazard and adverse selection in the field of engineering.

A reasonable incentive mechanism plays a vital role in the construction of megaprojects. Qi et al. proposed that contract incentives, supplier selection, and collaborative cooperation play a positive role in constructing megaprojects' factories [28]. Shi et al. proposed that in the design of megaproject incentive mechanisms, stakeholders not only pay attention to revenue but also pay attention to reputation. A reasonable incentive model can encourage stakeholders to improve their effort level [29]. Through model analysis, Qiu et al. concluded that effective government supervision and incentive mechanisms could significantly improve the effort level of the construction entity and the overall benefits of the project, and the greater the supervision and incentive level, the harder the construction entity will work [30]. In the field of megaprojects, there are few studies on the promotion of social responsibility through the design of incentive mechanisms, and most of them are concentrated in the field of supply chain [31], such as revenue-sharing contracts [32], wholesale contracts [33], cost-sharing contracts [34], and multiple contract comparison [35]. These studies show that in the field of the supply chain, a reasonable social responsibility incentive mechanism can increase consumers' desire to purchase and consumption demand, therefore further increasing the revenue of supply chain members. The purpose of megaprojects to enhance social responsibility is to avoid later project risks, social conflicts, and hidden safety hazards. Therefore, to study the social responsibility of stakeholders in megaprojects, we should not only consider the revenues of stakeholders but also consider the overall benefits of megaprojects.

The existing research achievements provide ideas for further research on the social responsibility of stakeholders in megaprojects. However, through literature review, it is found that the current research on the social responsibility of megaprojects is mostly based on qualitative aspects, such as the establishment of a conceptual framework for social responsibility, the establishment of an indicator evaluation system, and the impact of sustainable development. By comparison, there is rare research carried out from a quantitative perspective. Therefore, this paper starts from the perspective of incentive contract design, combines the characteristics of megaproject social responsibility, and aims at the bilateral problems of moral hazard and adverse selection caused by subcontractor information asymmetry, uses principal-agent theory to design a two-stage incentive contract, and compares it with the single-stage revenue-sharing model. It is concluded that the two-stage incentive contract can significantly improve the social responsibility effort level of the subcontractor and the total project revenue. The research results provide theoretical methods and decision-making basis for general contractors of megaprojects to encourage subcontractors to improve social responsibility.

Compared with existing research, the main features of this paper are as follows: (1) to quantitatively study the information disclosure mechanism and influencing factors of megaproject subcontractors from the perspective of incentive contract design; (2) to design a multi-indicator two-stage incentive contract to address the dual information asymmetry problem of subcontractors' moral hazard and adverse selection; and (3) to prove that the multi-indicator two-stage incentive contract is more effective than the single-stage revenue-sharing model.

3. Single-Stage Revenue-Sharing Model

3.1. Problem Description and Model Assumptions

(1) Although there is more than one subcontractor during the design and construction of megaprojects, the nature and objectives of these subcontractors are similar, all for assisting the general contractor to complete the project objectives with high quality. Therefore, the decision-making body of this paper is the owner (government), a general contractor, and a subcontractor.

(2) The general contracting mode is a modern project management mode commonly used in megaprojects. The government (owner) is only responsible for overall management and control, and only signs general contracting contracts with general contractors. The form of the contract is a linear contract with a fixed total price plus bonus [36], i.e., $W = \overline{\omega} + \lambda M$, where W is the total contract price, and $\overline{\omega}$ is the fixed total price obtained after the general contractor reaches the lowest quality, construction period, and cost standards, and λM is an incentive bonus given by the owner to encourage the general contractor to make contributions to social responsibilities such as technological innovation, rational use of resources, and protection of the ecological environment. λ $(0 < \lambda < 1)$ is the incentive coefficient, and M is the total output of the cooperative cooperation between the general contractor and the subcontractor.

(3) Megaprojects are highly complex, especially for the "bottleneck problem". The general contractor needs to select some outstanding subcontractors to coordinate and cooperate to complete the project's tasks. To encourage subcontractors to improve their social responsibilities, the general contractor signs a fixed total price plus bonus contract with the subcontractors. The form of the contract is $P = \overline{p} + (1 - \beta)\lambda M$,

where P is the total contract price given by the general contractor to the subcontractor, $\overline{p}$ is the fixed total price obtained by the subcontractor completing the subcontracting project in accordance with the minimum requirements, $(1-\beta)\lambda M$ is the subcontractor's received incentive bonuses due to its contribution to the social responsibility of construction environmental protection, construction quality assurance, and promotion of green materials, etc. β and $1-\beta$ $(0<\beta<1)$ are the revenue distribution ratios of the general contractor and the subcontractor after receiving the owner's reward.

(4) Megaprojects, as a complex and huge system with far-reaching influence, not only need the general contractor and subcontractor to always pay attention to social responsibility, but also need their cooperation and joint efforts to overcome difficulties and promote sustainable development of the project. There are two common models in supply chain research to depict social responsibility. One is that social responsibility directly affects the demand function of products in a linear manner [37,38]. The other is that social responsibility is embedded in the consumer surplus function and indirectly affects demand [33,39]. The social responsibility of the megaproject is different from corporate social responsibility. Its demand for the quantity of product is determined and will not be affected by social responsibility. The social responsibility of stakeholders in the megaprojects mainly affects project output performance and project sustainability [3,15]. Based on empirical studies, He et al. and Ma et al. have concluded that the social responsibility of megaproject stakeholders has a direct and significant positive impact on project output performance [4,15]. With reference to the above studies and project background, we set the total output function for the cooperative cooperation between the general contractor and the subcontractor as $M=\eta e_c+\gamma e_s+\xi$. The output here refers to the joint efforts of the general contractor and the subcontractor in terms of social responsibility, including project quality improvement, rational use of resources, protection of the ecological environment, etc., where e_c and e_s are the social responsibility effort levels of the general contractor and subcontractor, η and γ $(\eta>0, \gamma>0)$ are the coefficients that characterize the influence of the social responsibility efforts of the general contractor and the subcontractor on the output, respectively, ξ is the output when social responsibility is not considered. Since this paper mainly examines the impact of information symmetry and asymmetry of social responsibility on output and revenue, based on not affecting the research and for the convenience of calculation, we set the expectation $E(\xi)=0$ [36,40].

(5) According to references [37,41], ke^{ρ} is the cost of social responsibility, where k is the coefficient of effort cost. Due to the increasing effect of cost and the marginal cost of social responsibility for megaprojects, when $\rho>1$, i.e., ke^{ρ} is the convex function of e, it conforms to the actual process of the social responsibility cost of megaprojects, and $\rho=2$ is the most common situation. Based on this idea, we suppose the effort costs of contractor and subcontractor are $c(e_c)=\frac{1}{2}k_c e_c^2$ and $c(e_s)=\frac{1}{2}k_s e_s^2$, where k_c and k_s (k_c, $k_s>0$) are the social responsibility effort cost coefficients of general contractor and subcontractor, respectively.

The symbols and related descriptions used in this paper are shown in Table 1.

Table 1. Symbols and related descriptions.

Symbols	Related Descriptions
W	The total contract price signed by the owner (government) and the general contractor
$\overline{\omega}$	The fixed total price obtained by the general contractor after reaching the lowest quality, construction period, and cost standards
M	The total output obtained from the collaboration of the general contractor and subcontractor in terms of social responsibility
λ	The owner's incentive coefficient for the general contractor and subcontractor's contribution to social responsibility
P	The total contract price signed by the general contractor and the subcontractor
$\overline{p}$	The fixed total price obtained by the subcontractor for completing the subcontracted project in accordance with the minimum requirements
β	The revenue distribution ratio of the general contractor after receiving the owner's reward
e_c	The social responsibility effort level of the general contractor
e_s	The social responsibility effort level of the subcontractor
η	The influence coefficient of the general contractor's social responsibility efforts on the output
γ	The influence coefficient of the subcontractor's social responsibility efforts on the output
ξ	Output when social responsibility is not considered
k_c	The social responsibility effort cost coefficient of the general contractor
k_s	The social responsibility effort cost coefficient of the subcontractor
$\overline{k}_s$	The upper limit of subcontractor's fixed cost under information asymmetry
ε	The degree of opacity of subcontractor's social responsibility information under asymmetric information

3.2. Single-Stage Revenue-Sharing Model under Information Symmetry

Under the symmetric social responsibility information, the deterministic revenue function of the general contractor is expressed as

$$\pi_c = \overline{\omega} + \beta\lambda(\eta e_c + \gamma e_s) - \overline{p} - \frac{1}{2}k_c e_c^2 \tag{1}$$

The deterministic revenue function of the subcontractor is expressed as

$$\pi_s = \overline{p} + (1-\beta)\lambda(\eta e_c + \gamma e_s) - \frac{1}{2}k_s e_s^2 \tag{2}$$

In megaprojects, the general contractor is the leader who has the dominant power. First, we determine the revenue distribution ratio β and its effort level e_c. The subcontractor is the follower, and then we determine its own effort level e_s after the general contractor makes a decision. By the backward induction method, the subgame-perfect equilibrium can be obtained.

Equation (2) takes the first-order derivative of e_s and we set it to 0, then

$$e_s = \frac{(1-\beta)\gamma\lambda}{k_s} \tag{3}$$

Substituting Equation (3) into Equation (1), we obtain

$$\pi_c = \overline{\omega} + \beta\lambda\left(\eta e_c + \frac{(1-\beta)\lambda\gamma^2}{k_s}\right) - \overline{p} - \frac{1}{2}k_c e_c^2 \tag{4}$$

For e_c and β, the contractor obtains the Hessian matrix $H^S = \begin{bmatrix} \frac{\partial^2 \pi_c}{\partial e_c^2} & \frac{\partial^2 \pi_c}{\partial e_c \partial \beta} \\ \frac{\partial^2 \pi_c}{\partial \beta \partial e_c} & \frac{\partial^2 \pi_c}{\partial \beta^2} \end{bmatrix} = \begin{bmatrix} -k_c & \lambda\eta \\ \lambda\eta & -\frac{2\lambda^2\gamma^2}{k_s} \end{bmatrix}$, when $2k_c\gamma^2 > k_s\eta^2$, the Hessian matrix is negative definite. The above model has an equilibrium solution. Therefore, the equilibrium solution is expressed as

$$\beta^{S*} = \frac{k_c\gamma^2}{2k_c\gamma^2 - k_s\eta^2}, e_c{}^{S*} = \frac{\lambda\eta\gamma^2}{2k_c\gamma^2 - k_s\eta^2}, e_s{}^{S*} = \frac{\lambda\gamma(k_c\gamma^2 - k_s\eta^2)}{k_s(2k_c\gamma^2 - k_s\eta^2)},$$

$$\pi_c^{S*} = \overline{\omega} - \overline{p} + \frac{k_c\lambda^2\gamma^4}{2k_s(2k_c\gamma^2 - k_s\eta^2)}$$

$$\pi_s^{S*} = \overline{p} + \frac{\gamma^2\lambda^2(k_c\gamma^2 - k_s\eta^2)(k_c\gamma^2 + k_s\eta^2)}{2k_s(2k_c\gamma^2 - k_s\eta^2)^2}$$

To ensure that the effort level and revenue of the general contractor and subcontractor are positive, it can be obtained that $k_c\gamma^2 > k_s\eta^2$, i.e., $\frac{\gamma^2}{k_s} > \frac{\eta^2}{k_c}$, i.e., the input–output factor of the subcontractor is greater than that of the general contractor. This is because megaprojects have high complexity, and the general contractor cannot complete some challenging projects alone. The general contractor will screen outstanding subcontractors in the industry to complete it in collaboration, so $\frac{\gamma^2}{k_s} > \frac{\eta^2}{k_c}$ is in line with the actual situation, and subsequent proofs on information symmetry are based on this condition.

Proposition 1. *In the single-stage revenue-sharing model with symmetric information*, (1) $\frac{\partial e_c{}^{S*}}{\partial k_c} < 0$, $\frac{\partial e_s{}^{S*}}{\partial k_s} < 0$; (2) $\frac{\partial \beta^{S*}}{\partial \eta} > 0$, $\frac{\partial \beta^{S*}}{\partial \gamma} > 0$; $\frac{\partial \beta^{S*}}{\partial k_s} > 0$.

Proposition 1 shows that in a single-stage revenue-sharing model with symmetric information, higher social responsibility cost will inhibit the enthusiasm of general contractors and subcontractors to invest in social responsibility; the revenue distribution ratio β has nothing to do with the owner's incentive coefficient, and is related to the effort output coefficient and cost coefficient of the social responsibility of both parties, i.e., it is related to the input–output ratio. The input–output ratio reflects the organization's ability and efficiency to some extent. Therefore, Proposition 1 shows that in a single-stage revenue model with symmetric information, the stronger the ability, the higher the distribution ratio.

3.3. Single-Stage Revenue-Sharing Model under Information Asymmetry

In reality, due to the long construction period and high complexity of megaprojects, it is difficult for the general contractor to measure the social responsibilities of the subcontractors in terms of the construction environment, green material use, and employee care. The subcontractors will conceal or falsely report relevant information to obtain higher economic benefits, so there exists serious information asymmetry. It may be assumed that the general contractor lacks complete information on the social responsibility costs of the subcontractors. However, the construction period of megaprojects is long, and the general contractor has a general understanding of the cost of the subcontractor based on experience. References [19,37] set the subcontractor's social responsibility cost coefficient k_s to be uniformly distributed, and its distribution function is $F(k_s)$, namely $k_s \sim \left[\overline{k}_s - \varepsilon, \overline{k}_s + \varepsilon\right]$, then the probability density function is $f(k_s) = \frac{1}{2\varepsilon}$, $0 < \varepsilon < \overline{k}_s$, where $\overline{k}_s$ is the upper limit of fixed cost, and ε represents the degree of opacity of the information. The larger the ε, the less transparent the subcontractor's cost information, and the lower the general contractor's grasp of the subcontractor's information. As the leader, the general contractor will first predict the reaction of the subcontractors, and then decide the distribution ratio and effort level. The following context re-adjusts the situation of information symmetry to deal with the situation of asymmetric information. From Equation (4), we know that $\pi_c = \overline{\omega} + \beta\lambda(\eta e_c + \frac{(1-\beta)\lambda\gamma^2}{k_s}) - \overline{p} - \frac{1}{2}k_c e_c^2$, and the expected revenue under uncertain cost information is given by

$$\pi_c^A = E(\pi_c) = \int_{\overline{k}_s-\varepsilon}^{\overline{k}_s+\varepsilon}\left(\overline{\omega} + \beta\lambda\left(\eta e_c + \frac{(1-\beta)\lambda\gamma^2}{k_s}\right) - \overline{p} - \frac{1}{2}k_c e_c^2\right) f(k_s)dk_s$$

$$= \overline{\omega} + \beta\lambda\eta e_c - \overline{p} - \frac{1}{2}k_c e_c^2 + \frac{\beta(1-\beta)\lambda^2\gamma^2}{2\varepsilon} ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}$$

Let $h(\varepsilon) = ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}/\varepsilon$, then

$$\pi_c^A = \overline{\omega} + \beta\lambda\eta e_c - \overline{p} - \frac{1}{2}k_c e_c^2 + \frac{\beta(1-\beta)\lambda^2\gamma^2}{2}h(\varepsilon) \tag{5}$$

We perform the second-order partial derivatives of β and e_c, respectively, and obtain the Hessian matrix $H^A = \begin{bmatrix} \frac{\partial^2\pi_c}{\partial e_c^2} & \frac{\partial^2\pi_c}{\partial e_c\partial\beta} \\ \frac{\partial^2\pi_c}{\partial\beta\partial e_c} & \frac{\partial^2\pi_c}{\partial\beta^2} \end{bmatrix} = \begin{bmatrix} -k_c & \lambda\eta \\ \lambda\eta & -\lambda^2\gamma^2 h(\varepsilon) \end{bmatrix}$. When $h(\varepsilon) > \frac{\eta^2}{k_c\gamma^2}$ is satisfied, H^A is negative definite. The equilibrium solution is obtained as

$$\beta^{A*} = \frac{k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}}{2(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)}, {e_c}^{A*} = \frac{\lambda\eta\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}}{2(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)} \tag{6}$$

Equation (6) is substituted into Equations (2), (3), (5) to obtain

$${e_s}^{A*} = \frac{\lambda\gamma(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - 2\varepsilon\eta^2)}{2k_s(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)}$$

$$\pi_c^{A*} = \overline{\omega} - \overline{p} + \frac{\gamma^4\lambda^2(ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2 k_c}{8\varepsilon(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)}$$

$$\pi_s^{A*} = \overline{p} + \frac{\gamma^2\lambda^2(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - 2\varepsilon\eta^2)(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - 2\varepsilon\eta^2 + 2k_s\eta^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})}{8k_s(k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)^2}$$

To ensure that the above revenues and effort levels are positive, we obtain $k_c\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} > 2\varepsilon\eta^2$, i.e., $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$.

Proposition 2. *In the single-stage revenue-sharing model with asymmetric information, when* $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$*, we have* $\frac{\partial {e_c}^{A*}}{\partial k_c} < 0$, $\frac{\partial {e_c}^{A*}}{\partial \varepsilon} < 0$, $\frac{\partial \beta^{A*}}{\partial\varepsilon} < 0$.

Proof. When $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, $\frac{\partial {e_c}^{A*}}{\partial k_c} = \frac{-\gamma^4\lambda\eta(ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2}{2(-\varepsilon\eta^2+\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2} < 0$,

Although $\frac{\partial {e_c}^{A*}}{\partial\varepsilon} = \frac{\gamma^2\eta^3\lambda(-2\overline{k}_s\varepsilon + (\overline{k}_s+\varepsilon)(\overline{k}_s-\varepsilon)ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})}{2(\overline{k}_s+\varepsilon)(\overline{k}_s-\varepsilon)(\varepsilon\eta^2-\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2}$, it is obvious that the denominator is greater than 0, in the numerator, Let $g(\varepsilon) = 2\bar{k}_s\varepsilon + (\bar{k}_s + \varepsilon)(\bar{k}_s - \varepsilon)ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}g(\varepsilon) = 0$, $\frac{\partial g(\varepsilon)}{\partial \varepsilon} = 2\varepsilon ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon} > 0$, so when $\varepsilon > 0$, $g(\varepsilon) > 0$, thus $\frac{\partial e_c{}^{A*}}{\partial \varepsilon} < 0$. Similarly, $\frac{\partial \beta^{A*}}{\partial \varepsilon} = \frac{\gamma^2\eta^2(-2\bar{k}_s\varepsilon+(\bar{k}_s+\varepsilon)(\bar{k}_s-\varepsilon)ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})k_c}{2(\bar{k}_s+\varepsilon)(\bar{k}_s-\varepsilon)(\varepsilon\eta^2-\gamma^2k_c ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2} < 0$. □

Proposition 2 shows that similar to the single-stage revenue model with symmetric information, in the single-stage revenue-sharing model with asymmetric information, higher costs will also inhibit the enthusiasm of the general contractor to invest in social responsibility. In addition, under the information asymmetry, the effort level and distribution ratio of the general contractor will decrease as the opacity degree of the subcontractor's social responsibility information increases, i.e., the greater the degree of opacity of the subcontractor's information, the more restrained the general contractor's investment in social responsibility investment, the lower the corresponding distribution ratio.

3.4. Comparative Analysis

To better compare the single-stage revenue-sharing model in the two situations of symmetric and asymmetric social responsibility information, Table 2 summarizes the equilibrium results.

Table 2. Comparison of the equilibrium results of the single-stage revenue-sharing model under the two situations.

Variable	Parameters of Symmetric Information	Parameters of Asymmetric Information
Subcontractor's effort level e_s	$\frac{\lambda\gamma(k_c\gamma^2-k_s\eta^2)}{k_s(2k_c\gamma^2-k_s\eta^2)}$	$\frac{\lambda\gamma(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-2\varepsilon\eta^2)}{2k_s(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)}$
General contractor's effort level e_c	$\frac{\lambda\eta\gamma^2}{2k_c\gamma^2-k_s\eta^2}$	$\frac{\lambda\eta\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}}{2(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)}$
Revenue distribution ratio β	$\frac{k_c\gamma^2}{2k_c\gamma^2-k_s\eta^2}$	$\frac{k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}}{2(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)}$
Subcontractor revenue π_s	$\overline{p} + \frac{\gamma^2\lambda^2(k_c\gamma^2-k_s\eta^2)(k_c\gamma^2+k_s\eta^2)}{2k_s(2k_c\gamma^2-k_s\eta^2)^2}$	$\overline{p} + \frac{\gamma^2\lambda^2(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-2\varepsilon\eta^2)(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-2\varepsilon\eta^2+2k_s\eta^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})}{8k_s(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)^2}$
General contractor revenue π_c	$\overline{\omega} - \overline{p} + \frac{k_c\lambda^2\gamma^4}{2k_s(2k_c\gamma^2-k_s\eta^2)}$	$\overline{\omega} - \overline{p} + \frac{\gamma^4\lambda^2(ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2 k_c}{8\varepsilon(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)}$

Proposition 3. *In the single-stage revenue-sharing model, the revenue difference $\pi_c^{S*} - \pi_c^{A*}$ of the general contractor under symmetric and asymmetric information satisfies: when $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, $\pi_c^{S*} - \pi_c^{A*} > 0$; when $h(\varepsilon) > \frac{2}{k_s}$, $\pi_c^{S*} - \pi_c^{A*} < 0$.*

Proof. $\pi_c^{S*} - \pi_c^{A*} = -\frac{\gamma^4\lambda^2k_c\left(4\eta^2\varepsilon^2-4\varepsilon\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c+2\gamma^2(ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2k_ck_s\right)-\eta^2(ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2k_s{}^2)}{8\varepsilon(k_c\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}-\varepsilon\eta^2)k_s(2k_c\gamma^2-\eta^2k_s)}$
where the denominator is greater than 0. For the parenthesis of the numerator, we extract $\frac{1}{\varepsilon^2}$ and then express it as $\frac{1}{\varepsilon^2}((2k_c\gamma^2k_s - \eta^2k_s{}^2)h(\varepsilon)^2 - 4\gamma^2k_ch(\varepsilon) + 4\eta^2$. This formula is regarded as a quadratic function of h(ε), and its quadratic coefficient $2k_c\gamma^2k_s - \eta^2k_s{}^2 > 0$, while

$$\Delta = (4\gamma^2k_c)^2 - 4 \times 4\eta^2(2k_c\gamma^2k_s - \eta^2k_s{}^2) = 16(k_c\gamma^2 - k_s\eta^2) > 0$$

Therefore, when $h(\varepsilon)$ falls between $\frac{2\eta^2}{2k_c\gamma^2-k_s\eta^2}$ and $\frac{2}{k_s}$, the numerator satisfies $(4\eta^2\varepsilon^2 - 4\varepsilon\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c + 2\gamma^2(ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2k_ck_s) - \eta^2(ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^2k_s{}^2 < 0$. Moreover, because $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, and $\frac{2\eta^2}{k_c\gamma^2} > \frac{2\eta^2}{2k_c\gamma^2-k_s\eta^2}$, so when $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, $\pi_c^{S*} - \pi_c^{A*} > 0$. On the contrary, when $h(\varepsilon) > \frac{2}{k_s}$, $\pi_c^{S*} - \pi_c^{A*} < 0$. □

Proposition 4. *In the single-stage revenue-sharing model, the subcontractor's revenue difference* $\pi_s^{A*} - \pi_s^{S*}$ *under symmetric and asymmetric information satisfies: when* $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, $\pi_s^{A*} - \pi_s^{S*} > 0$, $\frac{\partial(\pi_s^{A*} - \pi_s^{S*})}{\partial\varepsilon} > 0$.

Proof. when $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$,

$$\pi_s^{A*} - \pi_s^{S*} = \frac{\gamma^4\lambda^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}\left(-2\bar{k}_s\varepsilon + (\bar{k}_s{}^2 - \varepsilon^2)ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}\right)k_c\left(2\varepsilon\eta^2 - \gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c\right)}{8(\bar{k}_s - \varepsilon)\varepsilon^2(\bar{k}_s + \varepsilon)(\varepsilon\eta^2 - \gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c)^2} > 0$$

$$\frac{\partial(\pi_s^{A*} - \pi_s^{S*})}{\partial\varepsilon} = \frac{\gamma^2\eta^2\lambda^2(-2\bar{k}_s\varepsilon + (\bar{k}_s{}^2 - \varepsilon^2)ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})(\gamma^4 k_c{}^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon} + 2\varepsilon\eta^4 k_s - 2\gamma^2\varepsilon\eta^2 k_c)}{4(\bar{k}_s + \varepsilon)(\bar{k}_s - \varepsilon)(\varepsilon\eta^2 - \gamma^2 k_c ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon})^3 k_s}$$

Obviously, when $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, $\frac{\partial(\pi_s^{A*} - \pi_s^{S*})}{\partial\varepsilon} > 0$. □

Propositions 3 and 4 explain that: When $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, the revenue of the general contractor under information asymmetry is always lower than that under information symmetry. When $h(\varepsilon) > \frac{2}{k_s}$, although the revenue of the general contractor under asymmetric information is higher than that under information symmetry, the subcontractor will not negotiate with the general contractor. Because as long as $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, it is always beneficial to the subcontractor. With the increase of opacity degree ε, the subcontractor's revenue difference between under information asymmetry and under information symmetry will become increasingly larger, so the subcontractor will deliberately conceal or falsely report information to obtain greater revenue.

Proposition 5. *In the single-stage revenue-sharing model, the total project output under symmetric and asymmetric information satisfies when* $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, $M^{S*} > M^{A*}$

Proof. Total output under information symmetry satisfies:

$$M^{S*} = \eta e_c^{S*} + \gamma e_s^{S*} = \frac{\gamma^2\lambda\gamma^2 k_c}{(2\gamma^2 k_c - k_s\eta^2)k_s}$$

Total output under information asymmetry satisfies:

$$M^{A*} = \eta e_s^{A*} + \gamma e_c^{A*} = \frac{\gamma^2\lambda(-2\varepsilon\eta^2 + ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}(\gamma^2 k_c + \eta^2 k_s))}{2(\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c - \varepsilon\eta^2)k_s}$$

when $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$,

$$M^{S*} - M^{A*} = \frac{\gamma^2\eta^2\lambda(\gamma^2 k_c - \eta^2 k_s)(2\varepsilon - ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_s)}{2(\varepsilon\eta^2 - \gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c)k_s(-2\gamma^2 k_c + \eta^2 k_s)} > 0.$$

□

Proposition 5 shows that in the single-stage revenue-sharing model, when $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, the revenue of the general contractor and the total output of the project under asymmetric information are both lower than those under information symmetry. Therefore, the general contractor has an incentive to encourage subcontractors to disclose the cost information regardless of their own revenue or the total revenue of the project. In the single-stage revenue-sharing model, there is only one negotiation variable β, so the model's incentive adaptability is poor. Next, a multi-indicator two-stage incentive contract is constructed.

4. Design of Multi-Indicator Two-Stage Incentive Contract under Asymmetric Information

To encourage subcontractors to disclose their social responsibility information, a multi-indicator two-stage incentive contract is designed in this section. In addition to the distribution ratio β, the general contractor sets a fixed subsidy F which encourages the subcontractors to increase social responsibility, improve the overall efficiency of the project, and avoid project risks by coordinating the relationship between the two negotiation variables. It is supposed that the general contractor in the first stage first proposes the distribution ratio β and the subsidy F, and the subcontractor decides whether to accept it and, if not, then renegotiate, and if so, the subcontractor determines its own social responsibility effort level e_s. In the second stage, the general contractor determines its own social responsibility effort level e_c after knowing the effort level of the subcontractor. Therefore, the two-stage incentive model is constructed as follows:

$$\pi_c{}^{TIM} = \overline{\omega} + \lambda\beta(\eta e_c + \gamma e_s) - \overline{p} - \frac{1}{2}k_c e_c^2 - F \tag{7}$$

$$\pi_s^{TIM} = \overline{p} + (1-\beta)\lambda(\eta e_c + \gamma e_s) - \frac{1}{2}k_s e_s^2 + F \geq \pi_s^{A*} \tag{8}$$

$$e_s^{TIM*} \in \underset{e_s^{TIM}}{argmax} \pi_s^{TIM*} = \underset{e_s^{TIM}}{argmax} \overline{p} + (1-\beta)\lambda(\eta e_c + \gamma e_s) - \frac{1}{2}k_s e_s^2 + F \tag{9}$$

where π_c^{TIM} is the revenue of the general contractor under the two-stage contract, and π_s^{TIM} is the revenue of the subcontractor under the two-stage contract. Equation (8) shows the subcontractor's participation constraint, which guarantees that in the asymmetrical situation, the subcontractor's revenue under the two-stage contract is not lower than the revenue under the single-stage revenue-sharing. Equation (9) is the incentive compatibility constraint of the subcontractor. According to the backward induction method, the general contractor decides its effort level e_c to maximize the revenue. The first-order derivation of its revenue function is performed and is set to 0, then we obtain

$$e_c{}^{TIM} = \frac{\lambda\beta\eta}{k_c} \tag{10}$$

Substituting Equation (10) into the subcontractor's revenue formula, we obtain

$$\pi_s^{TIM} = p_0 + (1-\beta)\lambda(\frac{\lambda\beta\eta^2}{k_c} + \gamma e_s) - \frac{1}{2}k_s e_s{}^2 \tag{11}$$

Performing the first-order derivation of the subcontractor's revenue function and setting it to 0, we obtain

$$e_s{}^{TIM} = \frac{(1-\beta)\lambda\gamma}{k_s} \tag{12}$$

Substituting Equations (10) and (12) into the revenue $\pi_s{}^{TIM}$ of the subcontractor, we obtain

$$\pi_s^{TIM} = \overline{p} + (1-\beta)\lambda(\frac{\lambda\beta\eta^2}{k_c} + \frac{(1-\beta)\lambda\gamma^2}{k_s}) - \frac{1}{2}\frac{(1-\beta)^2\lambda^2\gamma^2}{k_s} + F \tag{13}$$

Tightening the constraints of Equation (8), we obtain

$$\overline{p} + (1-\beta)\lambda(\frac{\lambda\beta\eta^2}{k_c} + \frac{(1-\beta)\lambda\gamma^2}{k_s}) - \frac{1}{2}\frac{(1-\beta)^2\lambda^2\gamma^2}{k_s} + F$$

$$= \overline{p} + \frac{\gamma^2\lambda^2(\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - 2\varepsilon\eta^2)(\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - 2\eta^2\varepsilon + 2\eta^2 k_s ln\frac{\overline{k_s}+\varepsilon}{\overline{k}_s-\varepsilon})}{8k_s(\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon} - \varepsilon\eta^2)^2}$$

i.e.,

$$F = \frac{\lambda^2\left(2\beta\varepsilon\eta^2+(1-2\beta)\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c\right)\left((2\beta-3)\gamma^4 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c^2+4(\beta-1)\varepsilon\eta^4 k_s+2\gamma^2\eta^2 k_c\left(-(\beta-2)\varepsilon+(1-2\beta)ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_s\right)\right)}{8k_c(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s} \tag{14}$$

Substituting Equation (14) into Equation (7), we obtain

$$E(\pi_c^{TIM}) = \frac{\overline{\omega}-\overline{p}+(\lambda^2((3-4\beta^2)\gamma^6 ln(\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2 k_c^3-4(\beta-2)\beta\varepsilon^2\eta^6 k_s+2\gamma^4\eta^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c^2(2(2\beta^2-1)\varepsilon}{8k_c(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s} + \frac{(-1-2(\beta-2)\beta)ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_s)+4\gamma^2\varepsilon\eta^4 k_c(-\beta^2\varepsilon+(1+2(-2+\beta)\beta)ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_s)))}{8k_c(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s} \tag{15}$$

Equation (15) takes the first-order derivative of β and sets it to 0, then

$$\beta^{TIM*} = \frac{\eta^2 k_s}{\gamma^2 k_c + \eta^2 k_s} \tag{16}$$

Substituting Equation (16) into Equations (10), (12), (14) respectively, we obtain

$$e_c^{TIM*} = \frac{\lambda\eta^3 k_s}{k_c(\gamma^2 k_c + \eta^2 k_s)} \tag{17}$$

$$e_s^{TIM*} = \frac{\gamma^3\lambda k_c}{\gamma^2 k_c k_s + \eta^2 k_s^2} \tag{18}$$

$$F^{TIM*} = -\frac{\gamma^2\lambda^2(2\varepsilon\eta^4 k_s+\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c(\gamma^2 k_c-\eta^2 k_s))(3\gamma^4 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c^2+2\eta^4 k_s(\varepsilon+ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_s)-\gamma^2\eta^2 k_c(4\varepsilon+ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_s))}{8(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s(\gamma^2 k_c+\eta^2 k_s)^2} \tag{19}$$

Substituting Equations (17)–(19) into Equations (7) and (13), we obtain

$$\pi_s^{TIM*} = \overline{p} + \frac{\gamma^2\lambda^2(-2\varepsilon\eta^2+\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)(\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}-2\eta^2(\varepsilon-k_s ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}))}{8(\varepsilon\eta^2-\gamma^2 k_c ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2 k_s}$$

$$\pi_c^{TIM*} = \overline{\omega} - \overline{p} + \frac{\lambda^2\left(4\varepsilon^2\eta^8 k_s^2-4\gamma^2\varepsilon\eta^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c(\gamma^4 k_c^2+\eta^4 k_s^2)+\gamma^4 ln(\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon})^2 k_c^2(3\gamma^4 k_c^2+\gamma^2\eta^2 k_c k_s+2\eta^4 k_s^2)\right)}{8k_c(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s(\gamma^2 k_c+\eta^2 k_s)}$$

Proposition 6. *when* $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, $\pi_c^{TIM*} - \pi_c^{A*} > 0$.

Proof.

$$\pi_c^{TIM*} - \pi_c^{A*} = \frac{\lambda^2(-\gamma^6 k_c^3 k_s(\gamma^2 k_c+\eta^2 k_s)h(\varepsilon)^3+\gamma^4 k_c^2(3\gamma^4 k_c^2+2\gamma^2\eta^2 k_c k_s+3\eta^4 k_s^2)h(\varepsilon)^2-4\gamma^2\eta^2 k_c(\gamma^4 k_c^2+\eta^4 k_s^2)h(\varepsilon)+4\eta^8 k_s^2)}{8\varepsilon^4 k_c(\varepsilon\eta^2-\gamma^2 ln\frac{\overline{k}_s+\varepsilon}{\overline{k}_s-\varepsilon}k_c)^2 k_s(\gamma^2 k_c+\eta^2 k_s)} \tag{20}$$

where the denominator is greater than 0. In the numerator, we set $\varphi(h(\varepsilon)) = -\gamma^6 k_c^3 k_s(\gamma^2 k_c + \eta^2 k_s)h(\varepsilon)^3 + \gamma^4 k_c^2(3\gamma^4 k_c^2 + 2\gamma^2\eta^2 k_c k_s + 3\eta^4 k_s^2)h(\varepsilon)^2 - 4\gamma^2\eta^2 k_c(\gamma^4 k_c^2 + \eta^4 k_s^2)h(\varepsilon) + 4\eta^8 k_s^2$, $\varphi(h(\varepsilon))$ is the cubic function of $h(\varepsilon)$, where the cubic coefficient $-\gamma^6 k_c^3 k_s(\gamma^2 k_c + \eta^2 k_s) < 0$, $\varphi'(h(\varepsilon)) = -3\gamma^6 k_c^3 k_s(\gamma^2 k_c + \eta^2 k_s)h(\varepsilon)^2 + 2\gamma^4 k_c^2(3\gamma^4 k_c^2 + 2\gamma^2\eta^2 k_c k_s + 3\eta^4 k_s^2)h(\varepsilon) + 4\gamma^2\eta^2 k_c(\gamma^4 k_c^2 + \eta^4 k_s^2)$ is the quadratic function of $h(\varepsilon)$, $\Delta = 4\gamma^8 k_c^4(9\gamma^8 k_c^4 + 10\gamma^4\eta^4 k_c^2 k_s^2 - 3\eta^8 k_s^4) > 0$, and $\varphi(\frac{2}{k_s}) = \frac{4(\gamma^4 k_c^2 - \gamma^2\eta^2 k_c k_s + \eta^4 k_s^2)^2}{k_s^2} > 0$. It can be seen from the function image of the cubic equation, when $\frac{2\eta^2}{k_c\gamma^2} < h(\varepsilon) < \frac{2}{k_s}$, $\pi_c^{TIM*} - \pi_c^{A*} > 0$. □

Proposition 6 shows that under the information asymmetry of social responsibility, the revenue of the general contractor under the multi-indicator two-stage contract is greater than the revenue under the single-stage, and the revenue of the subcontractor is not lower than the revenue of the single stage.

Proposition 7. *Compared with the single-stage revenue-sharing model, the social responsibility effort level of the subcontractor under the two-stage incentive contract satisfies:* $e_s^{TIM*} > e_s^{A*}$, $e_s^{TIM*} > e_s^{S*}$

Proof.

$$e_s^{TIM*} - e_s^{A*} = \frac{\lambda\gamma(\gamma^4 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c^2 + 2\varepsilon\eta^4 k_s - \gamma^2\eta^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c k_s)}{2(\gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c - \varepsilon\eta^2)k_s(\gamma^2 k_c + \eta^2 k_s)} > 0$$

$$e_s^{S*} - e_s^{TIM*} = \frac{\lambda\gamma(\gamma^4 k_c^2 - \gamma^2\eta^2 k_c k_s + \eta^4 k_s^2)}{k_s(-2\gamma^2 k_c + \eta^2 k_s)(\gamma^2 k_c + \eta^2 k_s)} < 0$$

Therefore, when $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$, $e_s^{TIM*} > e_s^{A*}$, $e_s^{TIM*} > e_s^{S*}$. □

Proposition 7 shows that the design of a two-stage incentive contract is conducive to promoting the disclosure of information by subcontractors. Compared with the single-stage revenue-sharing model, subcontractors work harder, which greatly improves the level of social responsibility. This further verifies the effectiveness of the proposed two-stage incentive contract.

Proposition 8. *Compared with the single-stage revenue-sharing model, the total project output under the two-stage incentive contract satisfies:* $M^{TIM*} > M^{A*}$, $M^{TIM*} > M^{S*}$.

Proof. when $h(\varepsilon) > \frac{2\eta^2}{k_c\gamma^2}$,

$$M^{TIM*} - M^{A*} = \frac{\lambda(\gamma^2 k_c - \eta^2 k_s)(2\varepsilon\eta^4 k_s + \gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c(\gamma^2 k_c - \eta^2 k_s))}{2k_c(-\varepsilon\eta^2 + \gamma^2 ln\frac{\bar{k}_s+\varepsilon}{\bar{k}_s-\varepsilon}k_c)k_s(\gamma^2 k_c + \eta^2 k_s)} > 0$$

$$M^{TIM*} - M^{S*} = \frac{\lambda(\gamma^2 k_c - \eta^2 k_s)(\gamma^4 k_c^2 - \gamma^2\eta^2 k_c k_s + \eta^4 k_s^2)}{k_c k_s(2\gamma^2 k_c - \eta^2 k_s)(\gamma^2 k_c + \eta^2 k_s)} > 0.$$

□

Proposition 8 shows that the total output of the project under the two-stage incentive contract is greater than the total output of the project in the single-stage large-stage revenue-sharing model. The two-stage incentive contract can effectively improve the overall efficiency of the project.

5. Numerical Analysis

To compare the mutual influence of factors such as the revenue, effort level, and the degree of information asymmetry of the general contractor and the subcontractor under the two-stage incentive contract, the following numerical examples are used for demonstration. The previous discussion has verified the parameter changes and interrelationships of the revenue-sharing model under information symmetry and information asymmetry. Therefore, the main numerical analysis here regards the change of the revenue and effort level of the general contractor and subcontractor under the two-stage incentive contract with the cost coefficient, output coefficient, and degree of information asymmetry, as well as compare the revenue and effort level in the three situations.

The fixed total price can be obtained according to the requirements of the contract for cost, quality, and construction period. This parameter does not affect the comparison results and analysis, so the fixed total price of the owner to the general contractor is set as $\overline{\omega}=$ 1 billion, the fixed total price of the general contractor to the subcontractor is set as $\overline{p} = 0.5$ billion [36]. Because of the significant and far-reaching impact of megaprojects, if the efforts of the general contractor and subcontractors bring about breakthroughs in terms of social responsibility such as effective ecological environment protection and advanced technological innovation, the owner is willing to give higher rewards. For example, during the construction of the island tunnel project of the Hong Kong–Zhuhai–Macao Bridge, China Communications Construction Company (CCCC) and its subcontractor team stationed on-site for seven years continuously deepened and adjusted the preliminary design and optimized more than 90% of the initial design of the island tunnel project. They focused on solving the project's due service problem and achieving longevity and durability. For this reason, the island tunnel project increased the design cost by more than three times when the corresponding cost adjustment was restricted by the general contract [5], so λ cannot be too small, and we can set $\lambda = 0.8$. To study whether the cost coefficient and contribution weight affect the subcontractor's revenue and the degree of symmetry, we take $\gamma = 0.3, 0.5, 0.6, 0.8$, $\overline{k}_s = 0.4, 0.5, 0.6, 0.8$ to draw the figures reflecting the relationship between the revenue of the subcontractor and the degree of asymmetry ε. The results are shown in Figures 1 and 2.

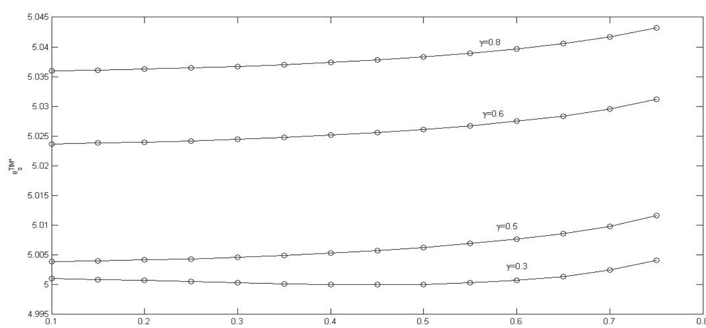

Figure 1. The changing trend of the subcontractor's effort level e_s^{TIM*} with γ and ε under the two-stage contract.

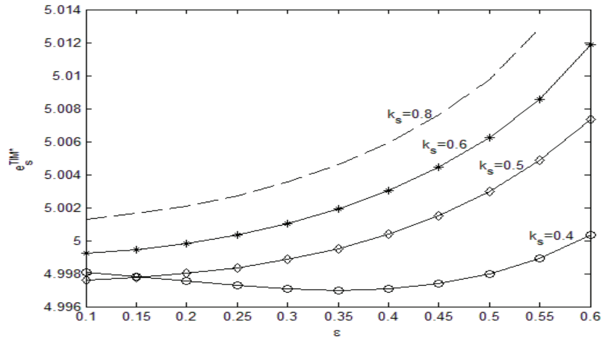

Figure 2. The changing trend of the subcontractor's effort e_s^{TIM*} level with $\bar{k}_s$ and ε under the two-stage contract.

Figures 1 and 2 show that under the two-stage incentive contract, the social responsibility effort level of the subcontractor increases with the increase of information asymmetry ε. This changing trend is not related to the social responsibility output coefficient γ and social responsibility cost coefficient $\bar{k}_s$. At the same time, the larger the subcontractor's output coefficient γ, the smaller the cost coefficient $\bar{k}_s$, the greater the subcontractor's social responsibility effort level. Therefore, the two-stage incentive contract takes into account fairness and efficiency to a certain extent.

The following part analyzes the revenue, social responsibility effort level, and the total output of the project with the degree of information asymmetry ε of the general contractor and subcontractor under three different models. As far as the cost coefficient and contribution weight of both parties are concerned, when selecting subcontractors, the general contractor must select the most outstanding subcontractor in the industry to collaborate. Therefore, the difference between the input–output ratios η/k_c and γ/k_s of the two parties will not be too large. We choose γ = 0.6, η = 0.5, k_c = 0.75, $\bar{k}_s$ = 0.8, k_s = 0.1 to observe the change trends of the effort level and return of both parties with the degree of asymmetry ε under the three different models. The results are shown in Figures 3–5.

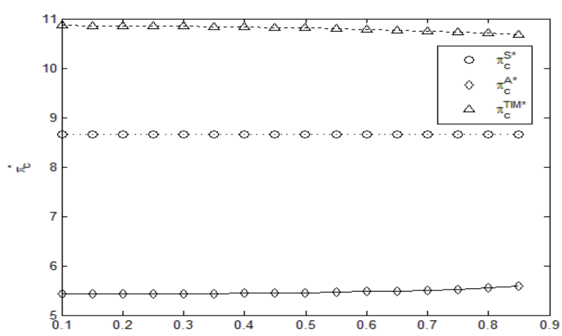

Figure 3. Change trend of general contractor's revenue π_c^* with ε under the three models.

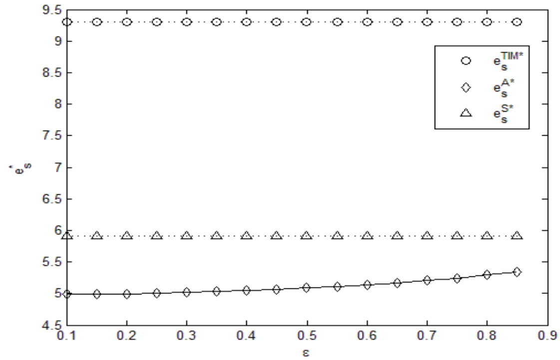

Figure 4. Change trend of subcontractor's effort level e_s^* with ε under the three models.

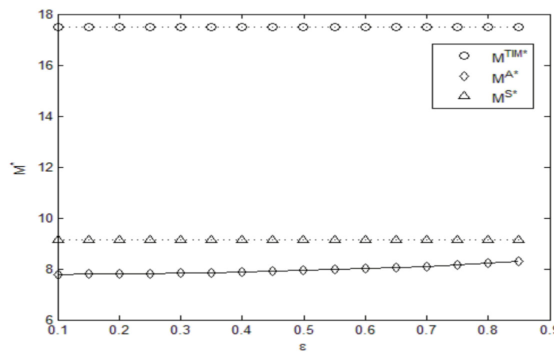

Figure 5. Change trend of total output M^* with ε under the three models.

Figure 3 shows that in the single-stage revenue-sharing model with information asymmetry, the general contractor's revenue increases with the increase in ε. However, it is always lower than the revenue in the single-stage model with information asymmetry, and even lower than the revenue under the two-stage incentive contract. Figure 4 shows that in the two-stage incentive contract, the effort level of the subcontractor is higher than that in the single-stage revenue-sharing model, which further shows that the two-stage incentive contract can promote the subcontractor's social responsibility. Figure 5 shows that under the two-stage incentive contract, the total output of the project is higher than that in the single-stage revenue-sharing model. It further shows that the two-stage incentive contract can improve project efficiency.

6. Conclusions

This paper aims at the problem of low engineering efficiency caused by the subcontractor's double information asymmetry behaviors, which are adverse selection and moral hazard. According to the principal-agent theory, this paper combined the characteristics of megaproject social responsibility and the single-stage revenue-sharing model under the situation of information symmetry and information asymmetry. After comparison and analysis, this paper found that subcontractors will deliberately conceal or falsely report social responsibility information to obtain higher profits. Therefore, this paper further designed the multi-index two-stage incentive contract to deal with information asymmetry and quantitatively studied the social responsibility information disclosure mechanism and its impact on the megaproject. The main conclusions are as follows: (1) Regardless of the model, the CSR effort level of general contractors and subcontractors is positively correlated with their contribution weight and the incentive coefficient of owners, but negatively correlated with the cost coefficient; (2) In the case of information asymmetry, the subcontractor prefers to conceal and exaggerate its social responsibility information, and this behavior will inhibit the enthusiasm of the general contractor to invest in social responsibility. (3) In the single-stage revenue-sharing model, the revenue of the general contractor under information asymmetry is always lower than that under information symmetry, and the profit difference decreases with the degree of subcontractor's information asymmetry. On the contrary, the income of subcontractors under information asymmetry is always higher than that under information symmetry, and the profit difference is increased with the degree of subcontractor's information asymmetry. (4) Compared with the single-stage revenue-sharing model, the revenue of both the contractor and the subcontractor in the two-stage multi-index incentive contract are not lower than those in the single-stage incentive contract, the social responsibility effort level of subcontractor and the total project output are significantly improved.

According to the above conclusions, the following management revelations and suggestions are made:

(1) Establish a social responsibility access mechanism, and strengthen examination and verification of qualification.

The megaprojects have a large investment scale, high construction difficulty, lasting influence, and great significance for the development of the country or region. The owner and general contractor should strengthen the qualification review during the bidding process, give priority to quality and technology, and moderately increase weight indicators such as reputation and social responsibility. In addition, the social responsibility records of subcontractors will be included in the bidding credit rating to ensure that participating organizations have sufficient ability and awareness to fulfill social responsibility, complete project construction, and improve project quality.

(2) Establish an evaluation system for social responsibility and strengthen supervision and management.

The main driving factors of social responsibility behaviors of different participants are different, and in the case of information asymmetry, there is a reverse conduction effect of social responsibility behaviors among participants. Therefore, it requires the owner or the general contractor to establish an operable and quantitative evaluation system of social responsibility and select scientific evaluation indicators, to improve the standardization and efficiency of the megaproject stakeholders' performance of social responsibility. In addition, project managers should constantly strengthen the awareness of social responsibility of subcontractors, strengthen supervision and management of subcontractors, and extend the supervision system from the original standardized operation to the promotion level of social responsibility of project stakeholders, therefore reducing information asymmetry and creating an excellent external environment for engineering construction.

(3) Establish a reasonable incentive mechanism for social responsibility and increase rewards and punishments.

For subcontractors, just as with enterprises, pursuing profit is the fundamental purpose of its business activities. Establishing a reasonable incentive mechanism of social responsibility to achieve the unification of economic interests and social responsibility can promote subcontractors to improve their social responsibility behavior. First, the owner and general contractor can change the "overall rationing system" budget management system, establish the budget management system of "basic cost plus performance reward cost", start from the source of budget management, connect the input of social responsibility with the value of project output, and then improve the effectiveness of incentive. Secondly, they are also supposed to explore the multi-index and staged dynamic incentive mechanism of fixed reward and performance reward, design a scientific and reasonable reward distribution coefficient, to balance the benefit relationship between the project participants and build a benign external environment. Furthermore, to establish a reward and punishment system, clear guidance has been gradually formed to encourage the advanced and spur the backward. Owners and contractors can increase rewards and penalties to stimulate project participants to improve social responsibility.

This paper quantitatively studies the social responsibility information disclosure mechanism and influencing factors of megaproject subcontractors, focusing on the design of multi-index and two-stage incentive contracts. The research results provide a theoretical method and decision-making basis for the megaproject general contractors to motivate subcontractors to improve their social responsibility. However, this study still has some shortcomings. First, the study considers the impact of social responsibility on the project output and the benefits of stakeholders, without considering the concerns of fairness among stakeholders, external spillover effects, and social attributes of social responsibility. In the follow-up study, it will become the focus of the research. Secondly, this paper considers the social responsibility incentive mechanism of stakeholders during the construction stage of megaprojects. Further research directions can be extended to the full lifecycle of megaprojects, from point-to-point enterprises to network level. With the help of stochastic game theory and complex network relevant theories, further research on the incentive mechanism of social responsibility of multi-stakeholder in the full lifecycle of megaprojects can be carried out.

Author Contributions: Conceptualization, F.X. and G.C.; methodology, F.X. and G.C.; software, F.X. and G.C.; formal analysis, G.C. and H.X.; investigation, H.X.; resources, G.C.; writing—original draft preparation, F.X. and G.C.; writing—review and editing, G.C. and H.X.; visualization, S.H. and H.X.; supervision, S.H. and H.X.; funding acquisition, S.H. and H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the National Natural Science Foundation of China (Grant No. 7153003), the National Natural Science Foundation of China (Grant No. 72101172), the project funded by China Postdoctoral Science Foundation (Grant No. 2021M692375).

Institutional Review Board Statement: No applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the anonymous reviewers for their criticisms and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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Sustainable Urban Development Strategic Initiatives

Margarita Panteleeva and Svetlana Borozdina *

Department of Economics and Management in Construction, Moscow State University of Civil Engineering, 26, Yaroslavskoye Shosse, 129337 Moscow, Russia; PanteleevaMS@mgsu.ru
* Correspondence: BorozdinaSM@mgsu.ru; Tel.: +7-905-585-17-34

Abstract: In order to ensure the implementation of the "Strategy for the Development of the Construction Industry of the Russian Federation until 2030" and the implementation of the UN resolution on sustainable development, there is a need to develop new strategic management initiatives. They should allow authorities to make inter-city comparisons, considering specific cities and their objects against the background of others undergoing similar development processes. In this article, the authors propose strategic initiatives for the management of urban facilities. In particular, the authors' approach to the assessment of the sustainable development of housing and communal service facilities in the city is proposed. According to the authors, the housing and communal city service objects mean capital construction objects in different forms of reproduction. Moreover, the article examines both residential buildings and structures, and utility networks. The authors' approach consists in the constant assessment of the city's housing and communal service facilities at different stages of their operation. For this, the authors use several types of analysis: ex post analysis, ex ante analysis, and foresight analysis. For each type of analysis, the authors form a set of assessment indicators and indicate the period of the analysis. The result of the study is the development of an indicator for the assessment of the level of sustainable development of housing and communal service facilities in the city, and a roadmap for their development strategy. The roadmap is formed considering the introduction of modern end-to-end technologies and digital tools into the work of state bodies. The proposed approach, on the one hand, considers the internal complexity and heterogeneity of the city's housing and communal service facilities. On the other hand, it is a simple tool for the making of effective management decisions by power structures, as it uses data which are available on a regular basis.

Keywords: housing and communal services; development; urban facilities; road map; strategy; end-to-end technologies; artificial intelligence

Citation: Panteleeva, M.; Borozdina, S. Sustainable Urban Development Strategic Initiatives. *Sustainability* **2022**, *14*, 37. https://doi.org/10.3390/su14010037

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 23 November 2021
Accepted: 17 December 2021
Published: 21 December 2021

1. Introduction

Currently, half of the world's population lives in cities and consumes three quarters of the world's resources [1]. Many of the modern capitals that play a dominant role in the life of individual countries can be called cities of global importance, due to their decisive contribution to the political, economic and social life of not only individual countries but the whole world.

The urban population growth projected over the coming decades is expected to lead to an increase in urban problems that are interconnected and complex.

Among the most important, promising problems are the problems of urban infrastructure, covering the main critical sectors of life: transport, energy, digitalization, waste, housing, and communal services. The relevance and complexity of solving problems related to the creation of sustainable urban infrastructure is often due to the complex nature of the organizational and economic relationships that arise during the functioning of its various elements [2].

"Sustainable development" is interpreted today as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." [3]. It should be noted that the combination of "sustainable development" was criticized by several scientists [4] as being contradictory in nature. Nevertheless, this term has become entrenched in political and scientific use to denote the balanced growth and development of humanity in interaction with the environment. In the resolution of the UN General Assembly No. A70/L.1 "Transforming our world: the 2030 Agenda for Sustainable Development" dated 25 September 2015, 17 sustainable development goals were identified, covering various aspects [1]. Among them, goal number 11 stands out: "To make cities and towns inclusive, safe and sustainable." To this end, the task of creating a stable living environment for the Russian Federation, set at the global level, began to be solved immediately. In December 2016, Rosstat became a member of the Interdepartmental Working Group under the Presidential Administration of the Russian Federation on Climate Change and Sustainable Development (IWG). Under the IWG, chaired by Rosstat, a Group of Experts on Information and Statistical Support for Monitoring Sustainable Development Goals was created. As a result, systematic work is underway in Russia to create conditions for the improvement of the quality of life and housing conditions of citizens. In this regard, we will consider the housing and communal service industry, which today occupies a leading role in the formation of a sustainable urban environment through the quality of the provided housing and communal services, and the management of housing and communal service facilities.

The analysis of the housing and communal services industry for the period from 1990 to 2020 showed that it does not meet the needs of the population in the main aspects [5]. The results of a study conducted by RIA NOVOSTI on the eve of the Day of Housing and Utilities Workers in 2020 states that the quality of housing services in Russia is not acceptable for 73% of respondents. Every fourth citizen of the Russian Federation (24%) assessed the activities of this sphere satisfactorily, and only 3% of the citizens had no complaints about housing and communal services, and were absolutely satisfied with its services [6–9].

However, when analyzing the housing and communal service industry, special attention should be paid to housing and communal services, in particular residential real estate, which is part of the basic needs of the country's citizens. It is the satisfaction of the need for housing that is the starting point of the country's economic development, as there is a direct relationship between labor productivity and the quality of housing. The able-bodied population—having the opportunity for normal, good rest, communication with family, and a comfortable life—more successfully copes with their responsibilities, and therefore, significantly affects the growth of the country's GDP.

Therefore, when managing the functioning of housing and communal services, it is important to pay special attention to housing and communal services, which are designed to meet the housing needs of people in various forms [10]:

(1) a room, apartment or individual residential building realizes the possibility of individual arrangement of space for a person or an individual family and the creation of household amenities inside residential premises, forms close interpersonal contacts of close people, and provides housing benefits for an individual household;
(2) an apartment building or a group of houses (complex) with an adjacent green area-allows one to make decisions together with neighbors and take specific actions to equip one's home and yard, and to create household amenities in common areas, determine the conditions for the personal communication of people, and provide housing benefits for those living in this house or complex.

We should note especially the state of living quarters today, in the era of the fourth industrial revolution and digital technologies, when robots can monitor the supply of water and electricity, and the analysis of the technical condition of capital construction facilities can be carried out using quadcopters or digital twins. It is during this era in the Russian Federation that the level of emergency and dilapidated housing, i.e., housing not suitable for normal life, continues to grow. According to Rosstat, in Russia, at the end of 2018 there were more than 101,000 buildings (about 25 million square meters) of dilapidated housing with more than 70% depreciation, and with 66–70% depreciation, i.e., more than 231,000 buildings (82 million square meters). Residential buildings recognized as emergency (that is, requiring demolition) at the end of 2018 already covered 12 million square meters. In order to relocate from unsuitable housing, a new house is needed, but the growth rates of budgetary construction projects are extremely small, and do not allow the provision of the required volume of residential premises; commercial housing does not correspond to the solvency of the country's population (Figure 1) [9,11].

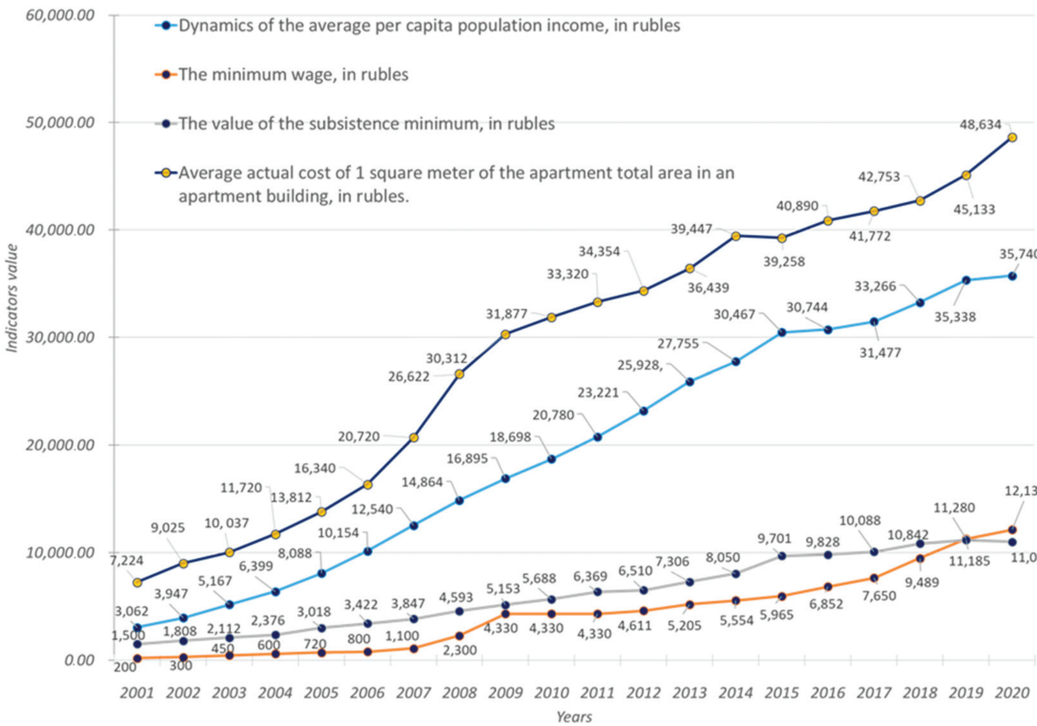

Figure 1. Characteristics of the population's standard of living and the average actual sq m total area of residential building construction costs (compiled by the authors based on [9,11]).

On 7 May 2018, the President of the Russian Federation, VV Putin, issued a decree "On the national goals and strategic objectives of the development of the Russian Federation for the period up to 2024" [12–14], which, in particular, spoke about the acceleration of emergency housing resettlement. Large-scale resettlement will be carried out within the project "Housing and Urban Environment" (Figure 2), on which the Russian authorities intend to spend over 1 trillion rubles in six years. The problem concerns almost all regions except Moscow. All other regions, for these purposes, are provided with more than 35 billion rubles annually from the federal budget within the framework of the national project.

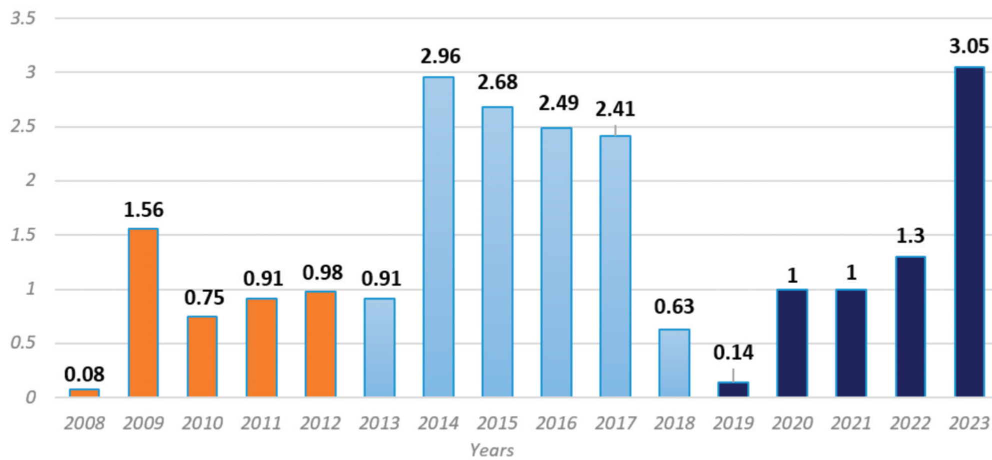

Figure 2. The schedule of emergency housing resettlement in the period from 2008 to 2018, and the planned resettlement from 2019 to 2024 according to the passport of the national project "Housing and Urban Environment" (compiled by the authors based on [9,11,14–16]).

However, as practice shows, not all regions of the Russian Federation succeed in fulfilling the Presidential Decree; in particular, the Pskov region and the Republic of Sokha became "anti-leaders" in the implementation of the federal project "Ensuring a sustainable reduction in the unsuitable for housing stock" under the Housing and Urban Environment Program as of 1 October 2021, according to the Fund for Assistance to Housing and Utilities Reform [14]. This is due to the three reasons discussed below.

Firstly, when analyzing the dilapidated housing stock, the rates of its growth due to the transition of dilapidated houses to the status of emergency ones are not taken into account. This growth averages about 2.3 million square meters per year. However, as 2017, Rosstat [9] stopped publishing data on dilapidated housing, which does not allow us to see an objective picture of the ongoing process, or to quickly assess the situation in the country according to this indicator. As a result, the volume of new residential real estate commissioned annually began to lag behind the rapidly growing volumes of emergency buildings and structures. In general, the balance of emergency and new housing in the country was upset (they should be equal);

Secondly, the efforts of the authorities towards the relocation of dilapidated housing stopped activities in relation to dilapidated housing and communal service facilities. As a result, a new disproportion appeared in the housing sector: a disproportion among the reproduction forms of capital construction objects. This is manifested in the significant predominance of new construction in comparison to other forms of housing renovation. A huge gap between the forms of reproduction of housing in general has been characteristic of the housing construction market in Russia for a long time. As such, in 2000–2019, in the structure of housing reproduction, the reconstruction of the housing stock accounted for no more than 1.3%, and major repairs accounted for no more than 12.9%, while the share of new construction in housing reproduction was no less than 86.7%. In 2019, in Russia, the share of new construction in the structure of reproduction of the housing stock was 84.7%, major repairs were 15.1%, and reconstruction only made up 0.1% (Figure 3) [9,17–19].

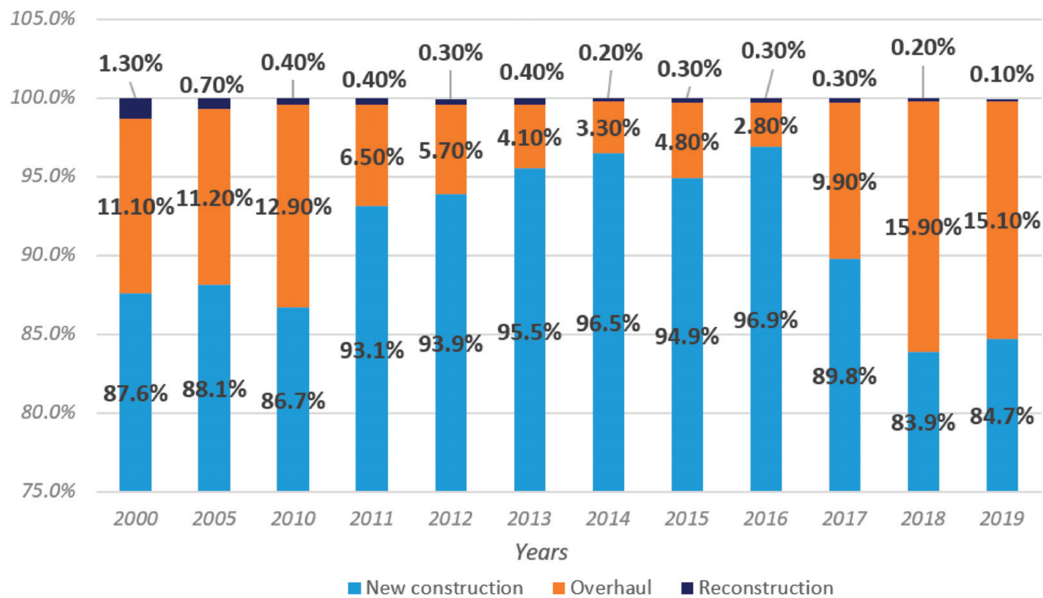

Figure 3. The structure of the housing stock renewal in Russia by reproduction methods (calculated by the authors according to [9,17–19]).

Thirdly, it is extremely important to ensure the continuity of the citizen resettlement processes from emergency housing stock and the renovation of dilapidated housing, as well as to continue systematic work on all projects for the modernization of facilities and systems in the housing and communal sector. This is hindered by the lack of constant contact and the coordination of actions between the citizens, government services and intermediary (resource supplying) organizations. Thus, recognizing a house as emergency is a matter of life and death for citizens. However, for municipal authorities, this is just a medium-term decision-making task with a high probability of transferring it to a long-term one, as, on the one hand, the "queue" of those in need of resettlement is only growing every year, and it is difficult to respond to all claims; on the other hand, indicators of the examination of a dilapidated building can be revised if, for example, the house was not recognized as dangerous to the life and health of citizens (Resolution of the Government of the Russian Federation of 28 January 2006 N 47). At the same time, resource-supplying organizations reduce their client portfolio, receive less planned profits, and do not have time to quickly revise their costs and increase the amount of utility bills for the remaining consumers [20].

In order to solve the problems identified above, various tools of the state management of housing and communal service facilities are used today.

The state management instruments of housing and communal services in the Russian Federation can be divided into two groups [21–23]:

1. The general government management instruments. These are aimed at managing the housing and communal service sphere of the country at the federal and regional levels. These instruments include: the legislation of the Russian Federation, federal and regional target programs of socioeconomic development, tariffs for housing and communal services, and strategies for housing and communal service development, etc.

2. Local government tools. These are aimed at managing state enterprises, institutions, and organizations in the housing and communal service sphere. The instruments of this group include regulations governing the activities of state authorities, charters of state unitary enterprises and state institutions, and the creation, reorganization and restructuring of state enterprises, institutions, and organizations, as well as their personnel management.

The main government management instruments for the management of the housing sector in Russia is "The Strategy for the Housing sphere Development of the Russian Federation for the Period up to 2025" [14], developed by the Construction Ministry, Housing and Communal Services of the Russian Federation.

In turn, "the Strategy for the Housing sphere Development of the Russian Federation" has its own implementation instruments. The main instruments for the implementation of the strategy are listed below:

(1) mortgage lending is the main instrument for acquiring home ownership;
(2) commercial rental housing is an instrument for both the short-term and long-term solution of the housing issue;
(3) non-commercial rental housing is an instrument to support socially priority categories of citizens;
(4) mortgage-backed securities are an investment instrument that provides an investment yield higher than federal loan bonds;
(5) instruments for the changing of the urban environment are instruments that have a direct impact on the achievement of the goals of forming a balanced ratio of supply and demand in the Russian housing market;
(6) standards for the integrated development of territories are an instrument for the transformation of cities;
(7) the "State information system of housing and communal services" (GIS housing and communal services) is an important instrument of government management in the field of housing and communal services. This system was created back in 2014 by the Federal Law of 21 July 2014 No. 209-FL "On the state information system of housing and communal services", and worked in test mode until 2017 [24]. GIS Housing and Communal Services is an information portal where one can create electronic voting on any issues related to the management of apartment buildings.

These instruments should help in solving the main task of the Russian Federation housing policy: providing the population with affordable housing in a comfortable urban environment [14].

However, there is a global difference in the composition of this toolkit in the Russian Federation and in foreign countries. This difference is mainly due to the rights of homeowners. In international practice, the priority in making decisions regarding the management of a residential building belongs to the owners [25–30]. These overseas homeowners unite in a non-profit consumer organization. This organization unites owners of real estate objects or shareholders. This organization's purpose is to manage the complex of the real estate, and to ensure the operation of this comple and the possession, use and disposal of property. The homeowner's association has become a generalizing concept of housing cooperation in various legal forms, such as Planning Unit Developments, Condominium Associations, and Housing Cooperatives in the United States and Canada; syndicates in France; and apartment joint stock companies in Finland [22,31–33].

In European countries, residents themselves monitor the house condition and receive financial support from the authorities. For example, in Germany, France and Holland, people have the right, in agreement with the municipality, to build (including with the involvement of investors) an object of shared ownership on their land plot, and to save money for overhaul during the operation [28,29,34]. Furthermore, in some countries, there are a state grants system and subsidies for major repairs of houses: they provide the authorities with a project of work, and, if it meets the approved criteria, they receive state aid [29,35–38].

The best world experience in the management of housing and communal services and housing construction belongs to Germany. Here, the townspeople themselves can act as customers for the construction of a residential building [28].

The French system of housing and communal service management is designed in such a way that about 60% of the townspeople can obtain social rental housing in multi-story buildings owned by the municipality. That is, residents are not at all burdened with worries about their own apartments. Instead, they gain confidence in the future and mobility: they choose a place of residence based on their professional interests. At the same time, social rental housing there is of higher quality than commercial housing. Municipalities are responsible for its renovation, and it is not profitable for them to save money during the construction phase, as this will lead to high costs in the future [39,40].

However, the most effective tools for changing the urban environment today are digital technologies in the foreign practice of housing and communal service management.

At present, intelligent systems are rapidly developing, and everywhere take the place of traditional information processing and control systems. The most significant successes have been achieved in the development of expert systems, intelligent systems for diagnostics, forecasting, planning, management, decision support, design, information retrieval, and the processing of natural-language information. Such systems are created using intelligent technologies, including software and hardware for the implementation of intelligent methods and algorithms [41,42].

A special place was given to the development of intelligent learning systems based on logic and neural networks, as well as cognitive systems that use the principles of the organizing structure, functions and behavior inherent in the human nervous system, possessing the ability, in particular, to accumulate knowledge in the process of functioning, and even to solve some creative problems. On this path, intelligent technologies become biological, which can significantly accelerate the development of intelligent systems.

Artificial intelligence can simplify and accelerate the process of the interaction between all of the participants in the management of housing and communal service facilities. It is the most popular disruptive technology in the digital marketplace around the world in the 21st century. It makes any activity more productive and smarter by integrating machine learning algorithms into various products and services. The global AI market is expected to reach $93.53 billion in 2021 [43,44].

Capgemini Research Institute, Intelligent Automation in Energy and Utilities, conducted the study “The next digital wave” in 2019. This study was devoted to the assessment of the implementation of artificial intelligence in housing and communal services. The study involved 520 companies from 16 countries. The AI technologies included in this study were speech recognition, natural language generation, context-aware computing, biometrics, image and video analysis, machine and deep learning, swarm intelligence, and chatbots or voice bots [26].

The study results showed that the dynamic growth in the number of companies developing AI solutions for housing and communal services began in 2015. The leaders in the development of AI in housing and communal services are North America and the EU, but the countries of the Asia-Pacific region, given their growth rates, may become new leaders by 2025. The implementation of AI in the housing and utilities sector of large cities around the world is usually not an industry priority for urban AI development initiatives [26]. Implementation takes place pointwise, depending on the problems of the city's development. Most AI projects are in the pilot phase.

The study noted that the most attractive areas for investment are groups of solutions focused on B2C or B2B2C segments (smart home systems, platforms, and applications for providing services to residents). Investors' interest in systems for the monitoring of the state of engineering infrastructure is also high [26].

The analysis of international experience shows that the basis of successful cases for the introduction of digital technologies is the creation of a basic infrastructure (sensors for the collection of data, platforms for their processing), as well as a high involvement of the authorities and residents of the city [45–48]. Leaders develop the sector by stimulating data sharing. However, Russia, in terms of most indicators, except for the high development of communication networks and 4G/5G penetration, is inferior to other countries in the world in terms of infrastructure development for the implementation of AI in housing and communal services [49]. As a result, the introduction of digital technologies is not yet a priority for the housing and communal services sphere of the Russian Federation, and is not included in the "Strategy for the development of housing and communal services until 2030" [26].

However, the solution to the above problems of housing and communal services is mostly associated with the use of digital technologies [49]. The inclusion of the procedure for the introduction of digital technologies into the basic tools of public administration could seriously change the general condition of housing and communal service facilities. The combination of artificial intelligence machines and human workers can increase productivity and reap huge benefits in this field.

As evidence of this trend, consider two options for the renovation of the housing stock in Russia: (1) using digital technologies, and (2) without using modern digital technologies (see Figure 4). It can be seen from the schedule that the use of artificial intelligence and digital technologies will increase the annual commissioning of housing in 5 years by 50%.

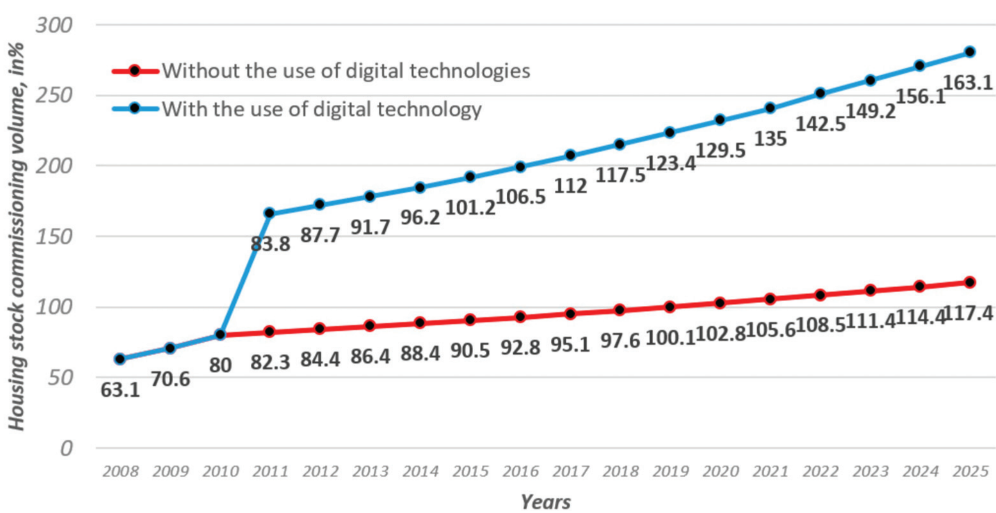

Figure 4. Dynamics and forecast of the housing stock commissioning volume in relation to 2008 with and without the use of digital technologies, as a percentage (calculated by the authors according to [9,50–53]).

This forecast (Figure 4) was compiled on the basis of the implementation results of digital technologies in several Russian regions and cities (Sakhalin Oblast, Udmurt Republic, Belgorod Oblast, Moscow, Nizhny Novgorod) [25]. In these Russian Federation constituent entities, digital technologies were next applied for the implementation of construction projects, e.g., the processing of digital technology of tender applications based on artificial intelligence, the technology for obtaining a digital construction order based on the use of online neural network video analytics to identify defects, etc. This has led to serious positive changes. Most of the processes have accelerated 5–10 times (preparation of documents, logistics of resources, training, etc.), and the cost of some types of work has decreased by 20–30% [26].

Summing up the issue of the relevance of the formation of management initiatives by creating conditions for the sustainable development of housing and communal service facilities based on the interconnection of the activities of all of the participants in this process and the use of modern digital technologies, it is important to note that work in this direction should take into account all of the existing industry problems and all of the stop factors and opportunities for their development [26]. Therefore, the scientific hypothesis of this study lies in the assumption that, for the sustainable development of urban objects facilities, it is possible to:

- formulate criteria for the assessment of the sustainable development of urban agglomerations;
- develop instruments for the management and assessment of the housing and communal services state, which at all of the stages of the sustainable development strategy will make it possible to form an up-to-date database of capital construction objects suitable for living.

Research objectives:

1. Analyze the current state of the housing and communal services industry in the Russian Federation in terms of the sustainable development concept of territories.
2. Assess the needs of the housing and communal service industry in the use of digital technologies.
3. Clarify the use of digital technologies in the management of the capital construction of housing and communal services.
4. Clarify the methods for the assessment of the development of cities and urban agglomerations.
5. Determine the criteria list that characterizes the sustainable development of housing and communal services.
6. Form organizational and analytical model for the assessment of the quality of the sustainable development of housing and communal service capital construction objects.
7. Determine the sustainable development goals (results) of urban agglomerations in the Russian Federation.
8. Form databases of housing and communal service objects suitable for habitation, considering the form of their reproduction (new objects, operated objects, dilapidated objects).
9. Develop a strategic roadmap for the sustainable development of object housing and communal services for the period 2021–2035, indicating the periods of implementation of digital technologies used in the management of housing and communal services capital construction objects.

In order to conduct the study, the following methods were used: the system analysis method, infographic modeling, aggregation, the process optimization method, synthesis, retrospective analysis, and forecasting.

2. Materials and Methods

An analysis of the housing and communal service industry showed that the main problem facing the state sector is the rapid growth of dilapidated housing. The government management tools used do not enable the control of this process. International practice shows that it is necessary to solve such a problem in a comprehensive manner. First, we need to progress and clarify general management tools for the housing and communal services sector of the country at the federal and regional levels [26]. Secondly, we need to modify old and create new local tools aimed at managing state enterprises, institutions, and organizations in the housing sector [54–56].

In order to solve the described problem, the authors of the study consolidated the following methods and end-to-end digital technologies based on artificial intelligence: (1) general methods of infrastructure facilities system analysis in some large cities and urban agglomerations; (2) infographic modeling; (3) intelligent decision support systems (decision intelligence); (4) methods of optimizing work within the urban ecosystem (automatic systems); (5) production optimization methods using artificial intelligence by automating data, model and application updates (artificial intelligence engineering/AI engineering).

2.1. General System Analysis Methods of Some Large Cities and Urban Agglomeration Infrastructure Facilities

All of the existing methods for the assessment of the development of cities and urban agglomerations can be divided into two types, depending on the purpose and scope of the study: "universal", aimed at assessing the development of large cities and agglomerations masses within a country or macroregion (hereinafter referred to as methods of the first type), and "individual", allowing the assessment of the development of one or more specific cities or agglomerations (hereinafter referred to as methods of the second type) [57,58].

The methods of the first type are more numerous. Their advantage is their relative simplicity of use. However, the flip side of these advantages is ignoring the internal structure of agglomerations (except, in some cases, the delimitation of the core and the periphery) and the variety of processes occurring in them. Such techniques are based on several basic indicators related to the agglomeration as a whole, which is thus interpreted, if not as a point, then, at best, as an aggregate of the nucleus and a peripheral zone that is homogeneous in terms of its characteristics. In addition, the universality requirements force the use of publicly available official statistics in the calculations, the set of which is limited, and the degree of reliability (especially in Russia) is often low. This imposes additional restrictions on the applicability of first-type techniques.

In Russian practice, the best known methods of this type were developed in the 1970–80s by the Central Scientific Research Institute of Urban Planning and the Institute of Geography of the Academy of Sciences of the USSR. They are similar in the approaches and methods used, but differ in their details [59].

The development of the agglomeration is assessed in these methods by calculating a special coefficient. In the methodology of the Institute of Geography, the coefficient of development considers the values of the population of cities and urban-type settlements in the agglomeration, and their share in the population of the agglomeration.

In the methodology of the Central Scientific Research Institute of Urban Planning, a similar coefficient is calculated as the ratio of the urban settlement number in an agglomeration to the product of the agglomeration territory area and the shortest distance between urban settlements in the agglomeration. In addition, in this technique, along with the development coefficient, the so-called agglomeration index is used, i.e., the ratio of the peripheral zone urban population to the entire agglomeration urban population.

Thus, both described approaches to the assessment of the development are based on the indicators of the settlement system, i.e., the population size, number, and population density of settlements, and—in the case of the Central Scientific Research Institute of Urban Planning methodology—density characteristics. According to these methods, the only indicator of internal connectivity within an agglomeration is transport accessibility.

In the post-Soviet period, individual researchers turned to the task of developing a universal integrated system of indicators for the assessment of the development level of agglomerations, but agglomerations were still most often regarded as territories that were homogeneous in their characteristics. Foreign experience in the assessment of the level of agglomerations development is richer, and often approaches the assessment of the agglomeration effect in the economy. However, the methods used by foreign researchers also, for the most part, involve the calculation of indicators and indices for agglomerations without taking into account the properties of their individual parts.

For example, Uchida and Nelson used three criteria in their proposed Agglomeration index of territories: the population density of the territory (urban area), the population of the core city (large city center), and the temporary accessibility to the core city [60–62].

Another example is the Sustainable Development Index calculated for US metropolitan areas. It includes 16 sustainable development parameters and sub-parameters, initially presented either as a percentage or in per-capita units. Each parameter is normalized so that it can be represented in the range from 0 to 100 using Formula (1) [63]:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \times 100, \tag{1}$$

where x' is the final normalized parameter value, x is the actual parameter value, and $\min(x)$ и$\max(x)$ are the maximum parameter values for the entire sample.

Thus, the agglomeration with the best value of this parameter recieves 100 points, and the worst one receives 0. In some cases, the indicators are additionally standardized for the upper and lower boundaries; for example, if target values are set for an indicator at the national level, then all of the agglomerations with higher values of these parameters receive 100 points, and the rest are normalized relative to the target value. The final index is determined based on the arithmetic mean for all of the parameters for each metropolitan area. However, the method does not consider the variation of the parameter values across the agglomeration territory.

The methodology for the assessment of the development of agglomerations in Germany works in a similar way. The assessment is based on 26 particular indicators, which are aggregated into 5 complex indices. Within each indicator, a ranking is built among all of the agglomerations; then, the ranking is performed again for each index, taking into account the rating by indicators within this index. The final "rating" (from 1 to 12) is graphically displayed on the corresponding axis of the pentagonal chart [64].

In the same relatively few cases, when researchers in one way or another assess the relationship between the municipalities of the agglomeration, the object of assessment is, as a rule, not the development of the agglomeration as a complex characteristic, but particular aspects of the agglomeration's functioning.

As an example, the Sprawl Index [41,65–67] is calculated for metropolitan areas of the United States in order to assess the degree of their extensive growth ("sprawl"). This index, however, considers such parameters as the connectivity of the street network, building density, and a variety of land uses. In this regard, we can also note the experience of the calculation of the Conurbation Index, evaluating (using the example of the Porto Alegre agglomeration in Brazil) the transport connectivity of the agglomeration parts among themselves and comparing it with the overall connectivity within the agglomeration [68].

In a few methods, in addition, indicators for the agglomeration as a whole and for the central city are calculated separately, which makes it possible to indirectly assess the role of the center in the agglomeration. An example is the city prosperity index, calculated for large cities and metropolitan regions (agglomerations) of the world according to the UN-Habitat methodology, based on weighted and scored values of private statistical indicators [69].

Techniques of the second type ("individual") are opposite to the techniques of the first type in terms of advantages and disadvantages. The enlarged scale of the study makes it possible to study in detail the structure of the agglomeration in all of the variety of ongoing processes and not be limited to official statistics, using non-standard and sometimes costly methods of collecting information (sociological surveys, visual observations, analysis of "big data", etc.). But this is precisely why such techniques are clearly applied in nature and work only for specific agglomerations, being limitedly applicable to others. As a rule, the methods of the second type use "thin" tools, and allow us to identify the real boundaries of the agglomeration with high accuracy, regardless of the network of administrative (municipal) units [59].

Research carried out by the methods of the second type has become widespread in Russia only in recent decades. This is due to the emerging demand from both society and the state to develop mechanisms for the management of the development of agglomerations. Such mechanisms cannot be developed without obtaining a detailed understanding of the boundaries, structure and nature of the agglomeration development. The most famous are the studies of the Irkutsk and Chelyabinsk agglomerations, carried out with the involvement of a wide range of experts from all of the over the country.

The results of the latter formed the basis of the monograph [70], which, along with a detailed analysis of the Chelyabinsk agglomeration, contains a systematic review of the theory and practice of managing the development of agglomerations abroad and in Russia. It is important to note that within the study, the authors did not stop at specifying the boundaries of the Chelyabinsk agglomeration, but approached the problem of the assessment of its development, precisely from the standpoint of its internal structure. Thus, the specialization of territories within the agglomeration was determined, and the so-called "integral development potential" was calculated (the integral development potential is formed, according to the presented methodology, by the "index of the achieved level of economic growth" (calculated on the basis of official statistics) and "development resource index" (determined on the basis of expertly evaluated indicators characterizing the administrative status, transport potential and the state of the economic and legal environment of the municipality) for each of the municipalities included in the agglomeration.

2.2. Infographic Modeling

Infographic modeling is an approach to construction design that allows one to visually perceive the image of a capital construction object. It can consider infographics as a visual interpretation of all of the kinds of data on the objects in question. Moreover, the quantitative or qualitative nature of the criteria describing capital construction objects does not matter [71–73].

In order to describe the complex interaction of all of the subjects of the housing and communal services system, infographics are the most effective tool, as they take into account different approaches to the formation of descriptive criteria for each subject of the housing and communal services system, and have no boundaries in relation to their dimensions.

2.3. Intelligent Decision Support Systems (Decision Intelligence, Autonomic System)

Intelligent Decision Support Systems (IDSS) are decision support systems that use artificial intelligence (AI) extensively. AI is a technique that allows machines to simulate human behavior. Artificial intelligence is the theory and design of computer systems capable of performing tasks normally requiring human intelligence, such as visual perception, speech recognition, decision making, and translation between languages. Decision intelligence (DI), or an intelligent decision-making system, is a modern approach in which the decision-making process is carried out with the help of additional analytics and artificial intelligence [46,74–78]. This approach enables leaders to make faster, more accurate, and consistent decisions based on analytics of complex data and the aggregation of all of the disparate stores within the organization. The goal of DI is also to maintain "explainability" with a clear emphasis on easy understanding and accessible meaning for each process of the organization in question. The decision analytics that this technology implements are largely action-oriented, and go beyond data analysis, as this allows one to make suggestions and recommendations on what to do for the manager in the future [79,80]. In fact, DI makes decisions on a par with the head, and, therefore, has a clear advantage in the management of the city's housing and communal services, as the latter presupposes the interconnection of large-scale databases of subjects and objects of the urban economy, and their constantly changing and newly emerging characteristics [46,81,82].

The second type of intelligent decision support systems that is actively used today in the work of a manager is the Autonomic System (AS) or autonomous systems. They are physical or software systems that are automatically trained on data from the environment and modify their own algorithms to optimize their performance within the ecosystem [83–87].

For the purposes of this study, the most interesting ecosystem is artificial intelligence, which is an attempt by humans to exploit the electronic, digital, or mechanical advantages of artificial intelligence technology to reduce the speed at which persistent and repetitive actions are performed.

2.4. Optimizing Production with Artificial Intelligence by Automating Data, Model and Application Updates (Artificial Intelligence Engineering/AI Engineering)

Artificial intelligence engineering is one of the new directions in the development of AI, focusing exclusively on the creation and development of intelligent tools, machines and systems to improve the living standards of society. AI Engineering covers a wide range of computing powers and massive datasets with the integration of machine learning algorithms. This approach helps businesses to create smart decision-making processes to meet customer needs and increase customer engagement. Engineering expertise is essential to effectively create, manage, and analyze AI functions [88–90].

Combined with data analytics, AI and machine learning facilitate predictive analytics: a technique that can provide predictions for strategic goals like business planning, or for practical applications like predictive maintenance. These technologies, embedded in software, can lead to the creation of expert systems that assist practitioners in fields such as medicine, exploration, and military applications [91–95].

What is artificial intelligence engineering? Essentially, artificial intelligence engineering is the use of algorithms, computer programming, neural networks, and other technologies in the development of artificial intelligence applications and methods. These methods and applications usually find practical application in commerce, science, and other areas of life [96–100].

Therefore, an artificial intelligence engineer must be able to efficiently extract data from various sources, design algorithms, build and test machine learning models, and then deploy those models to create AI applications that can perform complex tasks.

AI engineers can quickly add machine learning capabilities to mission-critical systems such as enterprise resource planning (ERP), customer relationship management (CRM), and mobile device management (MDM). They can also develop ad-hoc applications using artificial intelligence with the required level of security from scratch [47,92].

Artificial Intelligence Engineering enables organizations to build hybrid operating environments that combine data science, data engineering, and software development.

Depending on the industry, AI engineers also work with other AI and IT professionals to facilitate data management and process automation across the enterprise [101,102]. For example, in manufacturing, AI developers work closely with electrical engineers to develop software that builds artificially intelligent robots. In retail and other sectors, AI engineers develop machine learning models and collaborate with data scientists to manage large and complex datasets that enable predictive analytics [103,104]. At the strategic level, business intelligence (BI) developers design, model, and analyze complex data to identify industry patterns and market trends [54,105–108].

The consolidation of all of the above methods and approaches to the management and assessment of individual elements of the urban economy or urban agglomeration allowed the authors of this study to form the author's organizational and analytical model for the identification and assessment of the quality of the sustainable development of capital construction reproduction forms of housing and communal services (Figure 5) (capital construction objects are understood as buildings, structures, objects of construction in progress, and linear objects). Capital construction objects have the following main features: a strong connection with the ground, a buried foundation, and the inability to move them without causing disproportionate damage to their purpose [109]. It is important to note that this model is both quantitative and qualitative. It involves a multidimensional study of all of the capital construction objects' reproduction forms in housing and communal services, considering their condition at the time of the strategy formation's beginning, i.e., ex post analysis of housing and communal service objects for 2021. By analogy with macroeconomic analysis, ex post is an analysis of statistical data on the object under study or a set of objects. This analysis allows us to assess the current state of the object under study, identify problems and negative phenomena in its functioning, develop a policy to solve and overcome them, conduct a comparative analysis of similar housing and communal service objects located in other cities, and predict their state in the future (foresight analysis until 2035). Within the framework of this study, foresight analysis (foresight forecast) is a system of methods for the expert assessment of the strategic directions of the socioeconomic and innovative development of cities, identifying technological breakthroughs that can affect their economy and citizens in the medium and long term [40]), and their desired state in the future. The ex ante analysis of housing and communal services until 2024 and until 2027, by analogy with ex ante macroeconomic analysis, allows for the future-state predictive modeling of the object under study or a set of objects based on certain theoretical concepts and applied experience. This allows one to determine the patterns of development of housing and communal services, and to identify the cause-and-effect relationships between their changes and the sustainable development of cities. In addition, this approach makes it possible to introduce modern digital technologies based on AI into the implementation of the proposed strategy, and to form progressively a sustainable urban ecosystem.

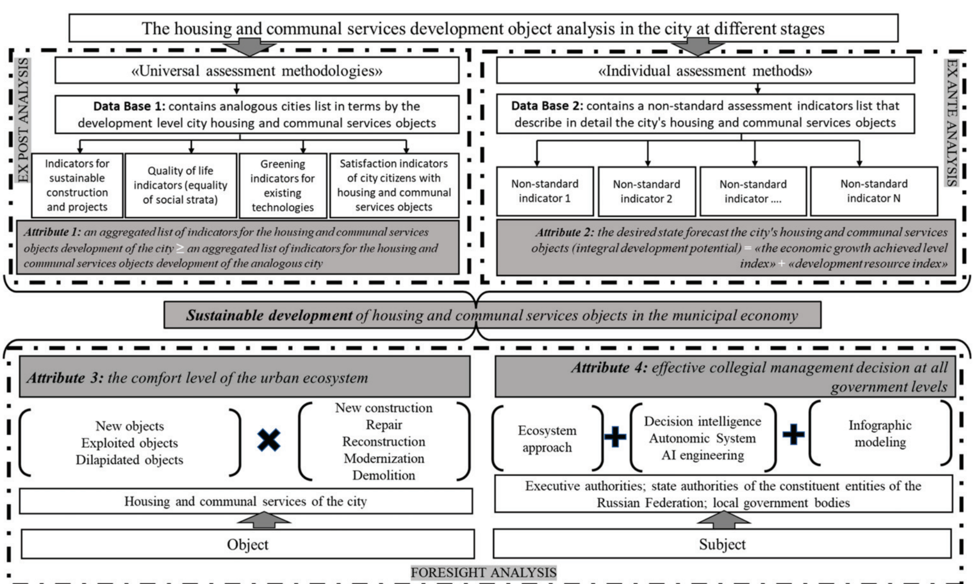

Figure 5. Organizational and analytical model of the identification and quality assessment of the sustainable housing and communal service object development of the municipal economy (compiled by the authors).

According to Figure 5, under the sustainability of housing and communal service object development of the municipal economy, the authors of the study understand such a state of the objects under consideration, which is characterized by the following integral list of properties that exist simultaneously:

(1) an aggregated list of indicators for the housing and communal service object development of the city $\geq$ an aggregated list of indicators for the housing and communal service object development of the analogous city;
(2) the desired state forecast of the city's housing and communal service objects (integral development potential) = «the economic growth achieved level index» (calculated based on official statistics) + «development resource index» (determined on the basis of expertly evaluated indicators characterizing the administrative status, transport potential and state of the economic and legal environment of the municipality));
(3) the comfort level of the urban ecosystem, which depends on the constant monitoring of the types of objects of housing and communal services in the aspect of the prospects for their transformation into one of the capital construction objects' reproduction forms;
(4) the effective collegial management decision of the executive authorities, the state authorities of the constituent entities of the Russian Federation, and local government bodies, formed using the ecosystem approach. This is a strategy for the integrated management of land, water and living resources that promotes their conservation and sustainable use in an equitable manner. It is based on the application of appropriate scientific methodologies focused on levels of biological organization that encompass the basic processes, functions and interactions between organisms and their environment, and end-to-end AI technologies for projected infographic models of municipal housing and communal service management.

3. Results

In order to apply the organizational and analytical model described above when developing a strategy for the sustainable development of housing and communal service object development (see Figure 5), the authors proceed from the assumption that the sustainability of the city depends both on the material and physical objects of housing and communal services, and on the social and environmental components of such a complex and dynamic structure as a modern city, as the sustainable development of each individual city should go along with the provision of both the national direction towards sustainability, and the global trend, which was set in 2015 by the UN General Assembly Resolution No. A70/L.1 "Transforming our world: the 2030 Agenda for Sustainable Development" [1].

In order to form a strategic roadmap for the sustainable development of housing and communal services in the municipal economy strategy of the Russian Federation (hereinafter referred to as the "roadmap"), the authors of the study selected two world goals from the UN General Assembly Resolution: No. A70/L.1 [2]-No. 11 and No. 9 (see Table 1). The selected goals are directly related to the problems of urban infrastructure's sustainable development, as they are aimed at achieving conditions for sustainable development through the joint efforts of governments, the private sector, civil society, and the inhabitants of the Earth. In Table 1, below, the goals selected by the authors correlate with the goals of the sustainable development of the Russian Federation at the federal, regional, and municipal levels [2,12,13,110–112], and the planned macroeconomic results of the road map.

Table 1. Compliance with the sustainable development goals for the federal, regional, and municipal levels and the planned macroeconomic results (compiled by the authors).

World-Class Goal Formulation	Formulation of Sustainable Development Goals at the Sectoral Level (Housing and Communal Services Industry)	Formulation of Goals for Sustainable Development at the Municipal Level (at the Level of Housing and Communal Services Facilities)	Planned Macroeconomic Results of the Roadmap Implementation
Goal 11. Make cities and towns inclusive, safe, sustainable [2]	Ensuring coordination of the activities of federal executive authorities, state authorities of the constituent entities of the Russian Federation, local governments, and development institutions for organizational and regulatory support for accelerating the development of housing and communal services in the Russian Federation [13].	Implementation of end-to-end digital technologies in the process of assessing and managing the city's housing and communal services objects.	Full results: - improving the places of Russian cities in the Mercer rating [84] in terms of the urban environment quality (quality of the population life): in 2019, Moscow was in 167th place, and in 2020, due to COVID-19, Mercer decided not to publish the rating; - the entry of 2–3 Russian cities into the number of world (global) cities in terms of parameters/indicators of the annual survey by Price Waterhouse Coopers "Cities of Opportunities" [113]; - the digitalization index "IQ of cities" (The index "IQ of cities" was developed by the Ministry of Construction of Russia in 2019 together with the Lomonosov Moscow State University within the framework of the departmental project "Smart City" (national projects "Housing and Urban Environment" and "Digital Economy") by 2035 (203 cities) 80% for 70% of cities [53]; - improving Russia's position in the DoingBusiness ranking: from 28th place in 2020 to move to the top ten countries by 2035 [50].
	Formation of a set of organizational, regulatory, and institutional measures that ensure the development of housing and communal services in the Russian Federation, coordinated in thematic areas and terms of implementation [13,20].	Adaptive AI models for housing and communal services, capable of continuously evaluating digital models of housing and communal services objects are creating.	
	Optimization of approaches to the development of housing and communal services due to the synergistic effect from the allocation of government regulation measures differentiated blocks [13,20].	A housing and communal services objects digital models are creating.	
Goal 9. Build resilient infrastructure, foster inclusive and sustainable industrialization and innovation [2]	Development of a concept for the development of housing and communal services in Russia as an integral part of the Strategy for the spatial development of cities and urban agglomerations of the Russian Federation and the Strategy for the development of the construction industry and housing and communal services of the Russian Federation until 2035 [2,13].	A virtual organizational and economic model for managing housing and communal services objects for the entire period of their life cycle is creating, based on the United Nations sustainable development principles.	
	Creation of conditions for real residents' participation in the processes of housing and communal services management [2,13].	The gradual formation period of a comfortable urban ecosystem.	

It should be noted that the selected targets for the formation of the "road map" were considered by the authors of the study only in terms of the development of housing and communal services in the medium and long term. In order to do this, all of the objects of housing and communal services of the municipal economy needed to be divided into three groups according to the criterion of their suitability for living:

(1) new capital construction objects (NCCO). These are new residential buildings, as well as new buildings and structures designed to perform various types of production processes, the storage of products, the temporary stay of people, and the movement of people and goods [109]. The database on new capital construction objects (Base NCCO) contains criteria for their investment attractiveness for all of the groups of stakeholders-IN_i, where $i \in [1; N]$, and N is the number of criteria for the investment attractiveness of housing and communal service facilities of the primary market/primary operation (for utility networks).

(2) exploited capital construction objects (ECCO). These are residential buildings, as well as buildings and structures designed to carry out various types of production processes, the storage of products, the temporary stay of people, and the movement of people and goods. For these construction objects, the effective operation minimum duration of load-bearing structural elements has expired. This duration is determined in Appendices 2 and 3 to the Order of the State Committee for Architecture of the State Construction Committee of the USSR of 11/23/1988 N 312 [114]. The database on exploited capital construction objects (Base ECCO) contains the criteria for their investment attractiveness for all of the groups of stakeholders-IE_k, where $k \in [1; M]$, and M is the number of criteria for the investment attractiveness of housing and communal service facilities of the secondary market/permanent operation (for utility networks).

(3) dilapidated capital construction objects (DCCO). These are new residential buildings, as well as new buildings and structures designed to perform various types of production processes, the storage of products, the temporary stay of people, and the movement of people and goods. The state of the structures of these objects, as a result of high physical wear and tear, ceases to meet the specified operational requirements [114]. The database on dilapidated capital construction objects (Base DCCO) contains criteria for their accident rate for all of the groups of stakeholders-ID_g, where $g \in [1; G]$, and G is the number of criteria for the accident rate of housing and communal service facilities of dilapidated housing stock/dilapidated utility networks.

Furthermore, the construction of the "road map" was associated with the process of the selected groups of housing and communal service objects reproduction. Each group of housing and communal service objects were assigned their own forms of reproduction (new construction, major repairs, current repairs, reconstruction, modernization, demolition in accordance with the criteria that characterize them (Figure 6 stage 1 and 2). This made it possible to obtain high-quality databases for all of the groups of objects of housing and communal services of the Russian Federation: Base NCCO = $\{IN_i\}$—new housing and communal service facilities; Base ECCO = $\{IE_k\}$—exploited objects of housing and communal services; and Base DCCO = $\{ID_g\}$—dilapidated objects of housing and communal services (Figure 6 stage 3).

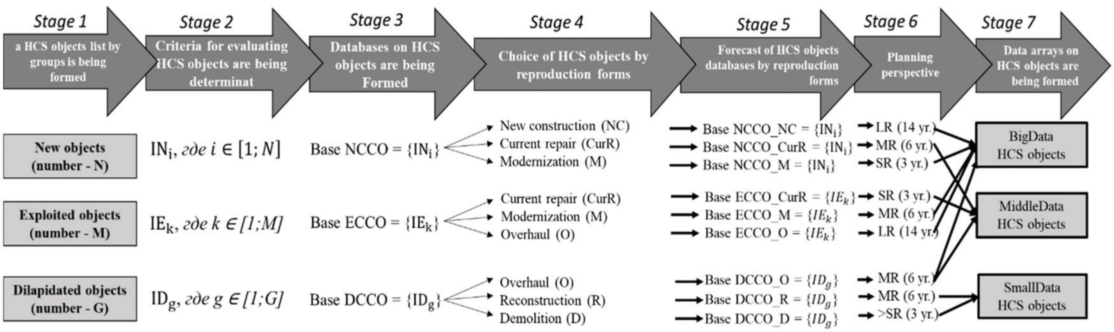

Figure 6. Detailing the formation of a database process to create a strategy for the sustainable development of housing and communal service objects (HCS) (compiled by the authors).

The obtained databases were used to distribute housing and communal service objects according to future possible forms of reproduction (see Figure 6 stage 4). As a result, the databases of housing and communal service facilities were predicted considering their forms of reproduction (see Figure 6 stage 5). Furthermore, the forecast databases were distributed over the planning periods necessary for the formation of the "road map" (Figure 6, stage 6). All of the planning perspectives are associated with individual stages of the roadmap proposed by the authors (see Figure 7).

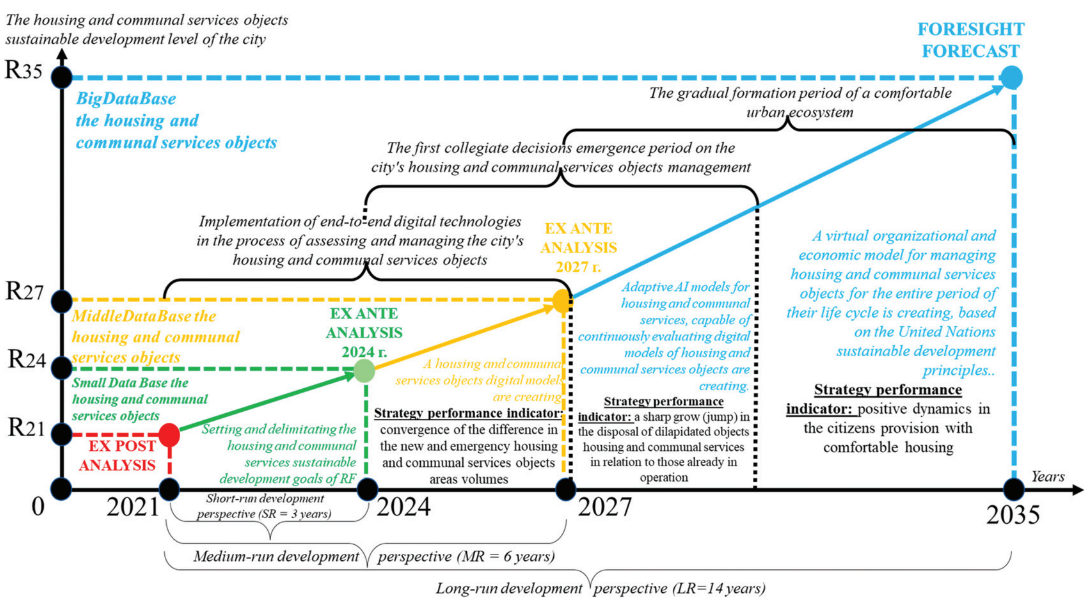

Figure 7. Strategic roadmap for the sustainable development of housing and communal service objects for the period 2021–2035 (compiled by the authors).

The short term (SR, short planning time) is from 2021 to 2024 (SR = 3 years). During this period, an ex post analysis of the city's housing and communal service facilities is carried out (see Figure 5). The medium term (MR, medium planning time) is the period from 2021 to 2027 (MR = 6 years). During this period, an ex ante analysis of the city's housing and communal service facilities is carried out (see Figure 5). The long-term period (LR, long-term planning time) is the period from 2021 to 2035 (LR = 14 years). During this period, foresight analysis or foresight forecast is carried out for the city's housing and communal service facilities (see Figure 5).

The final stage of the database formation process for the creation of a strategy for the sustainable development of housing and communal service facilities of the municipal economy was the stage of forming "living" databases of housing and communal services, which, in fact, will represent in the long-term structured datasets of small, medium, and large volumes: big data of housing and communal service objects, middle data of housing and communal service objects, and small data of housing and communal service objects (Figure 6 stage 7, Figure 7).

The detailing of the process of forming a database for the housing and communal service objects of the municipal economy is the basis for the "road map" formation based on the accounting principle for the forms of capital construction objects' reproduction.

However, the development of the "road map", in addition to considering the targets of sustainable development and determining the time perspectives for the creation of the database, takes place using end-to-end digital technologies. Starting from 2024, for effective interaction in relation to the housing and communal service facilities of the authorities, citizens and partner structures, it is planned to create digital models of housing and communal service facilities based on high-quality databases for all of the groups of housing and communal service facilities of the Russian Federation (Base NCCO = {INi}; Base ECCO = {IEk}; Base DCCO = {IDg}), which in the long term are modified using big data of housing and communal service objects, controlled by artificial intelligence.

Thus, the consolidation of modern methods of strategic analysis, methods for the assessment of the state of urban agglomerations, modern digital technologies, and infographic modeling made it possible to determine the criteria for the sustainable development of housing and communal service facilities, and to create a roadmap for their sustainable development strategy for the long term.

4. Discussion

Obviously, the identical management tool, all of the other things being equal, will work with different efficiency in different cities at different development levels, and will affect the urban infrastructure sustainability in different ways. Therefore, for the optimal effective implementation of the proposed initiatives ("road map"), the task of developing a methodology for the assessment of the level of urban development, including the construction of an indicator system that allows one to draw practical conclusions in terms of the adjustment of state and municipal policies, becomes relevant.

The effectiveness indicators for the implementation of the proposed "road map" can be considered absolutely achieved if, at the same time, we use a city or urban agglomeration, characterized, for example, by the list of parameters proposed in [115,116] (see Table 2).

An important condition in the formation of such a parameter list is to consider the effect of using the proposed tools for various stakeholder's groups. The most popular approach involves the assessment of the effect obtained in four directions: the economic effect, the social effect, the technological effect, and the environmental effect [31]. The authors' vision of these effects for the main stakeholder groups is shown in Table 3.

Table 2. Parameters of the investment attractiveness of the municipality [115].

Factors	Parameters
Geographical position	Profitable
Provision of natural resources and their availability	The level of natural resource endowment is high, and resources are available
State of the environment	The ecological situation is normal
The structural diversity of the economy	The structure of the economy is adequate to market requirements
The state and development of the market infrastructure	Infrastructure systems operate quickly and reliably
Development of culture and education of the population	The level of education and qualifications of the population is high and there are opportunities for training in the necessary professions
Socio-political stability	The socio-political climate is safe
Economic stability	Government controlled production costs are low; there is access to investment capital and credit resources; assistance to foreign economic activity is provided by the administration
Interaction of governing bodies with enterprises	Interaction between the city administration and city enterprises is mutually beneficial and transparent
Information and communication field	The level of equipment with advanced technologies is high
Regulatory and legal environment	The state of economic legislation and regulation does not limit the development of production
Investor incentive system	The tax system is acceptable and stable

Table 3. The effects from the proposed initiatives for different stakeholder groups (compiled by the authors).

Stakeholders Groups	Economic Effect	Social Effect	Technological Effect	Environmental Impact
Managing organizations of housing and communal services	The contracts cost optimization for the supply of utility bills. Reducing the cost of maintenance and overhaul.	Confidence growth of in the management organizations work of housing and communal services among the citizens.	Terms of work reduction by service organizations performance. The quality of provided utilities Improving.	Increase in efficient waste management and consumption.
Urban population/homeowners	The cost of utility bills is reducing or optimizing.	Satisfaction with living conditions among citizens increase. Accessibility barriers to many utility services are decreasing.	The procedure for interaction with housing and communal services service organizations is simplified.	Increase in efficient management of consumer waste.
Government	The budget is growing due to the reduction of debts on utility bills and due to the growth of investment attractiveness of the regions for small and medium-sized businesses.	Increased confidence in the government sector. A dialogue is being established between citizens, government, and business.	The number of emergencies at housing and communal services facilities is decreasing.	Introduction and implementation of the green economy concept in the regions. This concept leads to improved health and social justice of the population, as well as to a significant reduction in hazardous environmental impacts and to a decrease in environmental deficit.
Digital technology vendors	The revenue and capitalization of a digital technology company is increasing.	The quality of citizens life is improving.	Digital technologies are constantly improving.	The pressure on natural resources is reduced as their use is reduced.

In order to clarify the processes of introducing digital technologies (hereinafter referred to as DT) into the activities of the housing and communal service managing organizations in the Russian Federation, it is necessary to systematize them. Therefore, the prospects for the development of this study are associated with a large-scale analysis of digital technologies used in world practice for the management of capital construction projects in the housing and communal service sector. The systematization of DT is supposed to be carried out according to the following criteria:

(1) Developed and applied in practice:
- cheap/expensive
- free access/limited access
- secure for the storage of private data/vulnerable for the storage of private data
- easy to implement/difficult to implement
- easy to use/difficult to use

(2) Developed, but not applied in practice:
- cheap/expensive
- free access/limited access
- secure for the storage of private data/vulnerable for the storage of private data
- easy to implement/difficult to implement
- easy to use/difficult to use.

Carrying out the systematization of DT will allow the most correct determination of the periods and the sequence of their implementation, and will assess the effect of their use for the main stakeholders of this process.

5. Conclusions

As a result of the research carried out by the authors, a strategic roadmap for the sustainable development of housing and communal service facilities was proposed, considered from the aspect of ensuring (forming) a comfortable living environment for citizens. In the authors' roadmap, management initiatives were formed for practical use by state and municipal authorities on the main reproduction forms of capital construction objects of housing and communal services. The authors considered each form of reproduction for residential buildings and structures, and for utility networks, considering their transition from one form to another. In order to combine all of the proposed initiatives into a roadmap, the authors analyzed and selected end-to-end technologies based on artificial intelligence.

As a result, the proposed "road map" will make it possible to carry out the function of initiating and combining the organizational and institutional measures necessary to streamline and accelerate the development of housing and communal services in the city as a basic condition for the development of the post-industrial economy in Russia in the long term (for 14 years). The implementation of the "road map" should lead to the removal of restrictions and the smoothing of imbalances in the development of existing housing and communal service facilities in Russian cities and real local self-government.

The developed tool (a strategic roadmap for the sustainable development strategy) will make it possible to make operational management decisions within the framework of identified or anticipated socioeconomic problems of cities from the aspect of the strategic development of housing and communal services.

The proposed management initiatives, in the form of a strategic roadmap for the sustainable development of housing and communal services, will become the initial stage in the solution of the tasks set in the Strategy of the Scientific and Technological Development of the Russian Federation and the National Project "Housing and Urban Environment", from the aspect of the formation of an organizational and managerial mechanism for the implementation of digital hubs based on artificial intelligence.

Author Contributions: Conceptualization, M.P. and S.B.; methodology, M.P. and S.B.; validation, M.P. and S.B.; formal analysis, M.P. and S.B.; investigation, M.P. and S.B.; resources, M.P. and S.B.; data curation, M.P. and S.B.; writing—original draft preparation, M.P. and S.B.; writing—review and editing, M.P. and S.B.; visualization, M.P. and S.B.; supervision, M.P. and S.B.; project administration, M.P. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Ministry of Science and Higher Education, grant number 075-15-2021-686. All of the tests were carried out using the research equipment of The Head Regional Shared Research Facilities of the Moscow State University of Civil Engineering.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Data-Driven Methodology for Coliving Spaces and Space Profiling Based on Post-Occupancy Evaluation through Digital Trail of Users

Alicia Regodon [1,*], Maxime Armand [2], Carmen Lastres [3], Jose De Pedro [3] and Alfonso García-Santos [1]

[1] Department of Construction and Architectural Technology, Escuela Técnica Superior de Arquitectura de Madrid, Universidad Politécnica de Madrid, 28040 Madrid, Spain; alfonso.garciasantos@upm.es
[2] Urban Campus, 75002 Paris, France; maxime.armand@urbancampus.com
[3] Commuty, 28014 Madrid, Spain; carmen.lastres@wearecommuty.com (C.L.); jose.depedro@wearecommuty.com (J.D.P.)
* Correspondence: a.regodon@alumnos.upm.es; Tel.: +34-618-374-836

Citation: Regodon, A.; Armand, M.; Lastres, C.; De Pedro, J.; García-Santos, A. Data-Driven Methodology for Coliving Spaces and Space Profiling Based on Post-Occupancy Evaluation through Digital Trail of Users. *Sustainability* **2021**, *13*, 12607. https://doi.org/10.3390/su132212607

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 17 September 2021
Accepted: 4 November 2021
Published: 15 November 2021

Abstract: Sustainable spaces are those that are optimized, accessible, promote user experience and aim to reduce CO_2 emissions while enhancing users' well-being and comfort. The purpose of this paper is to present a methodology that was developed during the COVID-19 pandemic to understand and improve the use of coliving spaces based on remote Post-Occupancy Evaluation (POE) analysis of the digital trail generated by the users. Applying the POE methodology based on data collection from IT infrastructure enabled to identify opportunities to improve the future design of human-centered spaces. The residential market, design-wise traditional for centuries, is now facing a high-speed adaptation to the changing needs, accelerated by the COVID-19 crisis. New ways of living and shared spaces like Coliving are escalating. Technology is both an enabler of this shift in housing and the solution to operating and managing these new buildings. This paper demonstrates, through the case study of a Coliving space located in Madrid, Spain, the benefits of implementing data analysis of the digital trail collected from in-built IT systems such as smart locks, Wi-Fi networks and electric consumption devices. The conclusion is that analysing the available data from the digital infrastructure of coliving buildings can enable practitioners to improve the future design of residential spaces.

Keywords: coliving; COVID-19; digital trail; human-centered design; Post-Occupancy Evaluation; space profiling; sustainability; user experience

1. Introduction

Designing the perfect home for its resident has been architects' ambition for centuries, aesthetic perfection, functionality, which responds to the consumer's market. Today, the residential sector is experiencing a paradigm shift due to the changes in needs of its inhabitants: the incorporation of technology in spaces [1], remote working trends [2,3], workforce intercity and intercountry relocation and fluidity. Additionally, an unaffordable urban housing market [4] that makes houses non-accessible for part of the population and an increase in loneliness [5–7] are factors that are driving people towards diverse rental typologies with more shared spaces and innovative plug-and-play solutions, like coliving [8]. This is a trend that has been accelerated by the COVID-19 pandemic [9,10].

Before COVID-19, Europeans spent around 55%–66% of their time at home—home indoors—[11]; these ratios have increased during the pandemic, when we spent a considerably larger amount of time at home due to restrictions. In 2021, a new normality has brought new routines and evolving requirements for residential spaces.

COVID-19 has led to a redefinition of the way we live, how we use our residential spaces, our behavior and home responsibilities [12]. Loneliness, once said to be the illness of the XXI century, has risen exponentially, partly due to the regulations imposed by governments in response to pandemic [5,6,13]. According to the United Nations, community actions to reinforce social cohesion and reduce loneliness are needed to reduce the mental health consequences of the pandemic [14].

Coliving is an emerging residential typology, a "top down, modern form of housing where residents share spaces, activities, values, and/or intentions" [1,8]. These shared living solutions have shown ways of fostering human relationships and close networks that improve daily lifestyle, without imposing sharing behavior or patterns, simply by enabling users to choose what spaces to occupy and the levels of camaraderie they want to engage with. Monitoring and evaluating the use of these spaces has become essential to improving the future of spaces and promoting sustainable housing, tracking the factors of environmental, social, and financial sustainability [15,16]. Post-COVID-19 housing resiliency is related to flexibility, adaptability, reducing risk infection and ensuring user well-being [17,18], and has turned even more human-centered.

HCD defines a design based on human needs and experience [1]. HCD puts the end-users, humans, at the center of the design [19]; psychology and technology are implicit in its initial planning [1,20,21]—the human factor of buildings. Research that connected architectural design and behavioral patterns [18] has grown exponentially thanks to smart technologies and sensors [22].

The level of digitalization of buildings is also growing exponentially [23]; as buildings become smarter and more connected, the Architects, Engineers and Constructors (AEC) industry must adapt [1]. Smart buildings are living entities capable of adapting to the changing needs of the users and reporting to practitioners to improve the future design of spaces.

This research aimed to generate a methodology of spatial analysis using Post-Occupancy Evaluation (POE) of the spaces' performance and user behavior patterns based on the available technology infrastructure.

There were two primary objectives: the first was to identify the data provided from existing data sources that will offer valuable information for HCD spaces, and the second was to generate data-driven Space Profiles (SP) based on the methodology generated that can help AEC experts improve the design of future coliving spaces based on data-driven techniques.

The innovation of the current research also relied on the methodology fully performed remotely due to COVID-19, in real time and relying on the existing IT infrastructure of Coliving without adding other sensors.

1.1. Coliving

The residential sector is transforming quickly, accelerated by the COVID-19 crisis. Factors such as densification of cities, population growth, affordability, housing supply, demand dichotomy, rising prices [24] and lack of regulations [25] have impacted house prices and facilitated the evolution of new housing typologies. Coliving offers a more flexible leasing structure and increased engagement with the household to form more meaningful connections with housemates and the general community—regardless of the duration of stay [26].

Coliving operators, property managers and real estate investors have highlighted that their formula of success relies on providing the creation of fluid communities and neo-tribes [27], which are related to a state of mind and a lifestyle more than a membership or lineage [28,29]. Coliving also provides a variety of shared spaces mutualized by the whole community otherwise unavailable and unaffordable in a traditional way of living. Characteristics that made them have grown exponentially across Europe and other areas (Figure 1). For the new creative class, home means also an ideal place of work: it is mobile and social [30] with the communal spaces being key for the users [27]; additionally, the need for exterior and communal spaces, core spaces of coliving buildings, has also multiplied due to the COVID-19 crisis [18,31].

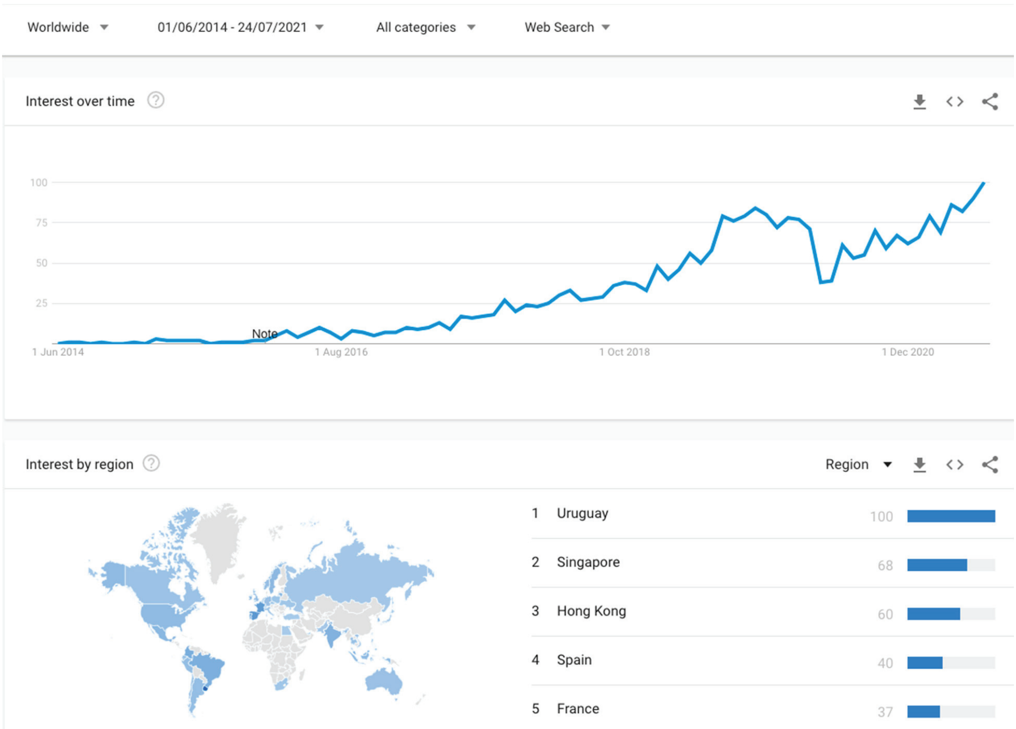

Figure 1. Evolution trend for the term 'coliving' Worldwide in the past 7 years 2014–2021 [32].

The rise in searches for the term 'coliving' in 2015 was likely due to an increase of these facilities in New York City and companies beginning to expand this typology outside of the tech world [33]. Spain is now the country with the fourth highest interest globally, according to Google, and the first in Europe. The current research was performed at Urban Campus, a coliving operator in Spain and France with several assets being operated under coliving and coworking and with a strong strategy for monitoring and optimizing buildings performance and user wellbeing.

One of the spatial strategies to encourage community is incrementing the shared amenities [34,35] and sharing these spaces with the whole community. The incidence of these spaces outside of the private room has promoted informal interactions, which in turn enhanced familiarity among residents and community [36].

Nevertheless, little architectural or interior design research is available to describe this emerging typology and scattered best-practices or guiding principles are appearing to aid designers in making informed decisions when designing or evaluating coliving spaces [8]. There has also been limited exploration into the houses to understand HCD approaches and climate adaptability of smart housing to meet user needs [1,37].

1.2. State of the Art Data-Driven Design through Post-Occupancy Evaluation (POE)

Using data for building design is not new ([38–40]). But incorporating qualitative and quantitative data in decision-making processes is a practice that has been recently incorporated into spatial design [41,42]. Post-Occupancy Evaluation (POE) is the methodology of obtaining feedback on the use of spaces in a building and its performance for the users [43,44].

Within this changing paradigm, a need for more advanced, digital methods to understand the use of space and improve its design has risen [45,46]; POE and other methods [47,48] are becoming essential to analyzing the current use of spaces, predict performance and ensure housing resiliency [17,49–53]. Recent studies have shown how POE could improve electricity performance predicted during the design of non-residential spaces [54]; a similar method has been applied for coliving residential spaces.

The POE is generally carried out a minimum of one year after the building is fully occupied [55] and includes several methodologies to perform holistic research of the building. The research studied a method of integrating technology and Internet of Things (IOT) data analysis as an added real-time assessment of end-users' electricity consumption patterns [56]. Remote comfort and well-being tracking systems and sensors enabled to collect and analyze data with little human intervention [28,57].

Innovation and new technologies facilitate a faster and more accurate understanding of the occupancy of and interaction with space [58,59]. IOT integrated entities of the physical world by making them addressable through the Internet and making the Internet accessible through physical objects. [60]. New ways of monitoring and data analysis have already provided real-time feedback as shown in different spaces like workplaces [46,61,62]. This paper reflects how residential spaces like coliving can undergo a similar transformation by incorporating in-built technology infrastructure POE data analysis to assess use of space.

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2. Materials and Methods

The study relied on available digital infrastructure designed for Urban Campus Colivings (smart locks, Wi-Fi, and electricity consumption devices) as data sources for operating coliving, defined as Post-Occupancy Evaluation (POE). The coliving spatial assessment evaluation framework in Table 1 sets a basis to understanding behavioral performance of spaces and to making informed decisions towards future sustainable and Human-Centered Design (HCD) of spaces. Behavioral patterns in space, experience, environmental consumption, and well-being were assessed.

In Figure 2, the 4 methodological stages were mapped based on the available IT infrastructure piloted in the study: (A) Electricity analysis, (B) Access analysis, (C) Network crosscheck, (D) Spaces profiling study. The mixing methods theory [76,77] was used to combine quantitative and qualitative inputs and was implemented during phase (D) to generate the SPs.

The data sample of the coliving spaces were collected during a 31-day period (1 May 2021–1 June 2021). Additional data were collected retroactively for the Electricity analysis for 1 year (1 June 2020–1 June 2021) in order to demonstrate the applicability of the methodology to explore and compare the use of spaces across different times and seasons. The data were extracted, cleaned, processed, and represented the data through PowerBI—a business analytics platform from Microsoft enabling user friendly visualization and interactions for behavioral analysis and sustainability decision making.

The subject group of study included the 72 residents of the coliving space with an age range of 25–40 years and coming from multiple nationalities including local Spanish colivers. For the current study, full authorization was granted by the residents and the data were treated in full compliance with the EU General Data Protection Regulation, (GDPR), being aggregated and anonymized accordingly to regulations. The analysis was performed in accordance with the principles outlined in the Declaration of Helsinki.

2.1. Spatial Definition

The current study analyzed a 3000 m^2 coliving residence in Madrid. The building has been operated as a Coliving by Urban Campus since 2019; the methodology that enabled the carrying out of remote research developed was fully compliant with regulations and COVID-19 restrictions in place in May 2021. Four different typologies of spaces in the Coliving were categorized into Table 2. There were three cluster spaces; a cluster is a shared flat consisting of individual or double studios with a private bathroom and a shared space with a shared kitchen and living room. Both the entrance door to the cluster and the door that separates the common cluster spaces from the private studio had a digital smart lock that managed entry permissions (see Figure 3). The shared kitchens and living rooms of all the clusters were open to the entire community from 07:00–23:59 and remain accessible only to cluster inhabitants during the night.

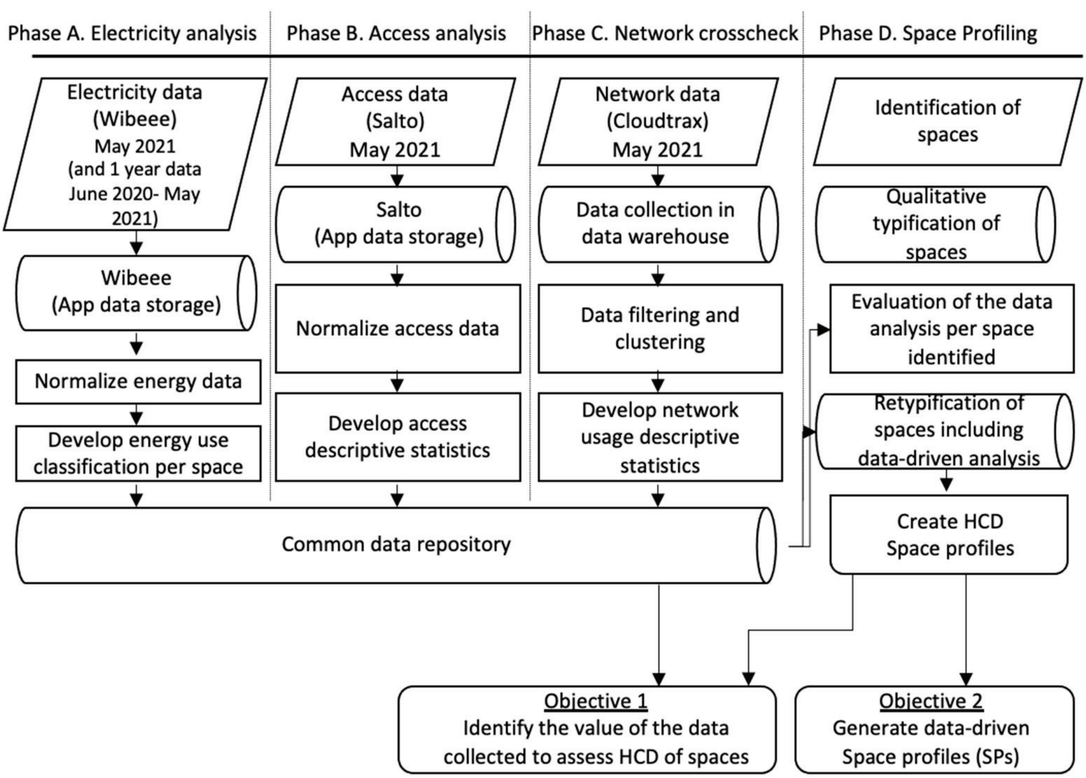
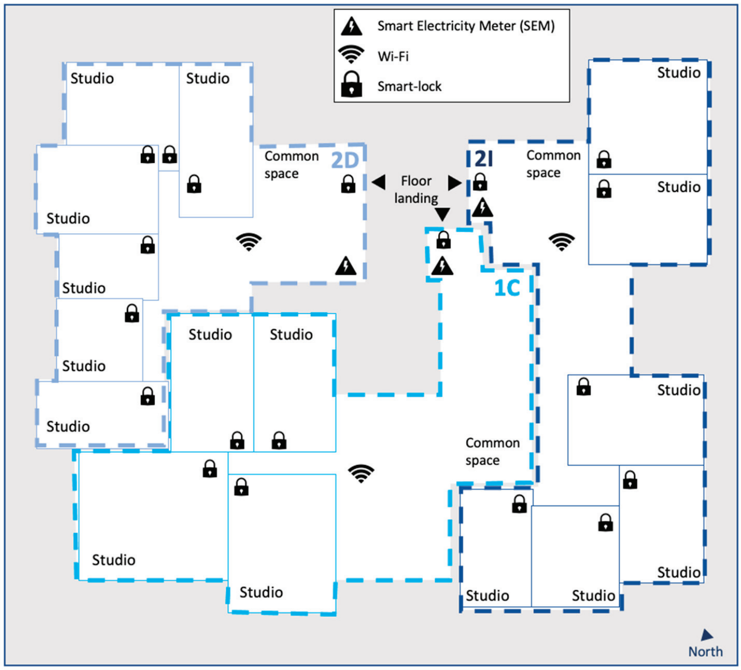


Figure 2. Flow chart describing methodology and the objectives of the study.

Table 1. POE coliving spatial assessment evaluation framework. The variable name is an acronym of the "Description" and a subindex that identifies the phase(s). (1C, 2D, 2I, 6C and 0I are the units of spaces analyzed through the current research).

Variable	Description	Unit	Evaluation	Device	Sustainability Indicator	Spaces Assessed in the Coliving	Literature
VE	Entries per coliver	# Entries per occupant	Ordinal, low, medium, high	Smart lock	Social	1C, 2D, 2I,	[63–66]
VH	Entry hours	in or out	Ordinal, out of hours	Smart lock	Social	1C, 2D, 2I, 0I, 6C	
PB	Presence (lights)	Hours	On/Off	SEM (Smart Electricity Meter)	Environmental Financial	6C	[67]
ECA	Electricity consumption	Hours	Activity time and appliances	SEM	Environmental Financial	1C, 2D, 2I, 0I, 6C	[68–71]
RWB	Computing laptop/data	Hours	Activity time	Wi-Fi	Social	1C, 2D, 2I, 0I, 6C	[22,72–75]
EB	Cooking/events home appliances	Hours	Activity time, appliances	Wi-Fi Smart-locks	Social	1C, 2D, 2I, 0I, 6C	[22,72–75]
Tc	Level of trust	% Open private spaces/Total private spaces	Open/closed	Smart-locks	Social	1C, 2D, 2I	[68–71]
AA	After-hours activity	Hours	Presence & use of appli-ances/devices	Smart locks-SEM	Social	1C, 2D, 2I, 0I, 6C	[68–71]
WABC	Week vs. weekend	Hours	Ordinal, not ordinal	All	Social	1C, 2D, 2I, 0I, 6C	All the previous

Note: # stands for "number of", % measures the percentage of private spaces left open against the total number of spaces.



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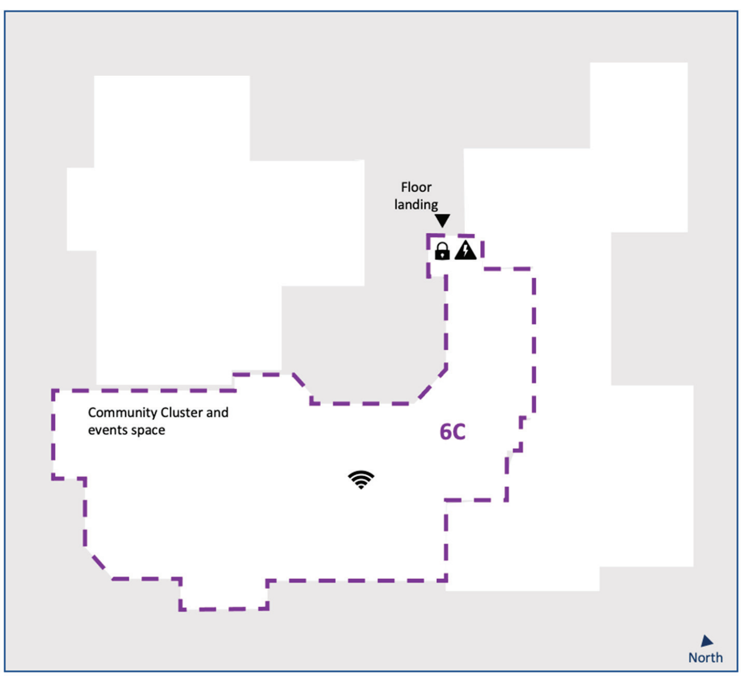

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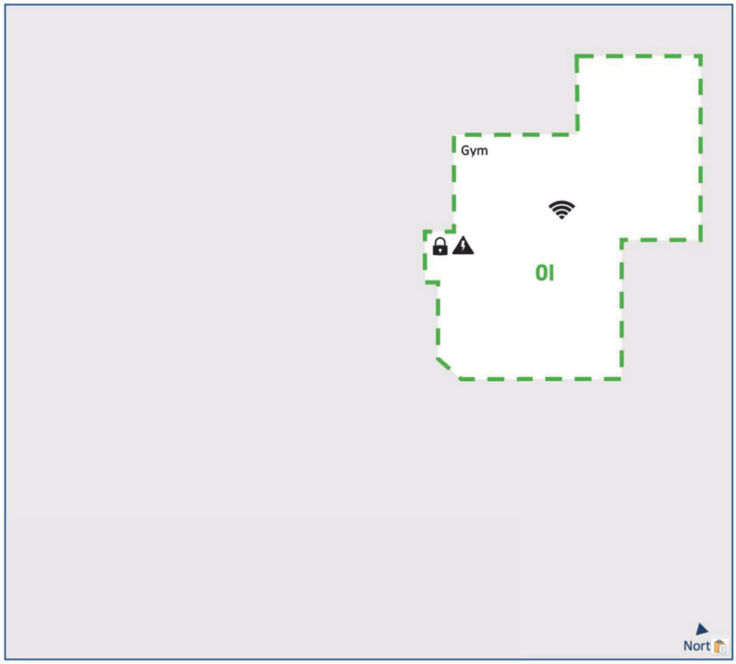
Figure 3. *Cont.*



(**c**)

Figure 3. Schemes of the different spaces studied: (**a**) Cluster apartments with studio subdivision 1C, 2I, 2D (**b**) Community Coworking space 6C; (**c**) Gym (0I).

Table 2. Physical classification of analyzed spaces. (Size in Net Usable Area NUA). The central cluster is the shared units that correspond to the central apartments in each floor of the building. The lateral cluster corresponds to the apartments situated at the left and right of the central apartment of each floor of the building.

Space	Typology	Residents	Uses	Access to All Colivers	Size of the Common Space
2I	Lateral Cluster	6	6 studios + kitchen/living-space	07:00–23:59 floor residents	22.88 m^2
2D	Lateral Cluster	6	6 studios + kitchen/living-space	07:00–23:59 floor residents	21.15 m^2
1C	Central Cluster	4	4 studios + Large kitchen/living-space	07:00–23:59 all residents	62.05 m^2
6C, 0I	Community Space	0	Coworking, social area, gym, terraces	07:00–23:59 all residents	6C = 156 m^2 0I = 60 m^2

2.2. Phase A: Electricity Analysis

Smart Electricity Meters (SEM), clamp-connected devices that measure the electricity consumption per apartment (cluster) and smartly classify the data of different appliances [56], were an essential adoption to guiding the transition towards sustainable use of resources such as water, electricity, and gas in residential spaces [78]. The innovation of the current research is that the information was collected to understand behavioral patterns and use of space, not only consumption dynamics. The data were then stored in a cloud platform designed for the visualization of the electricity consumption in almost real time. For the study, the data were extracted from the platforms and filtered by days and clusters selected to the study (I, C, D), community spaces and gym (0I).

Afterwards, the SEM were trained by the Urban Campus and IT teams to identify the different domestic appliances according to the SEM patterns for identifying appliances (Air-Conditioning (AC), home appliances, lights and plugs). The isolated use of each device and electricity consumption was collected in real time and transmitted through the Application Programming Interface (API) during the night.

2.3. Phase B: Access Analysis

The smart locks (from Salto) were connected to the digital network through Wi-Fi enabling remote opening of doors and transferring information of door status (open vs. closed) and entry times in real time and retroactively from the Salto platform. The research analyzed the patterns of aggregated users' digital trails and visiting of spaces in the building. The various doors—building main entrance, access to cluster doors and common spaces doors and individual doors to private studios—were configured with different accessibility permissions depending on the use of space and privacy. Central apartments were accessible to all residents (ex: tenant living in 1I has access to 1C, 2C, 3C, . . .), while side apartments were accessible to all residents living on a floor (tenant living in 1C has access to 1I, 1C and 1D but not 2I or 2D). Table 3 shows the 3 types of locks and the credentials according to the space works as follows.

Table 3. Categorization of locks according to the typology, location, and access permits.

Typology	Location	Position	Access Permits
Building access lock (password and digital key)	Building main entrance	Open-Locked	Everyone
Cluster Cylinder	Cluster access I-C-D/R all Coliving	Open-Locked	Cluster members 24 h Others 07:00–23:59
Private studio Gateway	Studio access I-C-D studios	Open-Locked-Unlocked	Individual

The data were downloaded from the Salto platform. The data were presented in charts that assess the use of space routines; the access analysis method enabled understanding of the use and entries but not occupancy as it does not provide information on different members accessing a space at the same time or exit time.

2.4. Phase C: Network Cross-Check

The Wi-Fi network connection structure was built using Cloudtrax software. There was one network, "Service Set Identifier" (SSID) with 1 or 2 Access Point (AP) per cluster space and per Community space—a total of 20 SSIDs in the building. Data from 5 SSIDs were analyzed (two Lateral Cluster spaces 2I and 2D, one Central Cluster space 1C and 2 Community Spaces: 1 Community Coworking (6C) and Gym (0I). The location of the APs in this study relied on original infrastructure and networks available and the places located.

The Wi-Fi network worked as a digital trail of any device that is present in the spaces and is identified by the APs without the need to be connected to the Wi-Fi. The current method implied identification of the members of the coliving space and association to the digital devices they own; each coliver has on average 2–3 devices and is then anonymized and aggregated according to GDPR laws. Analysis of any device that was not assigned to a person and mobile in space was eliminated, keeping laptops, tablets, smartphones, and smartwatches. Other devices like Chromecast and SEM were dismissed. The data collected enabled to identify patterns of use based on traffic data, number of devices connected and routines that served also as a cross-check for Phase A and Phase B.

2.5. Phase D: Space Profiling (SP)

Once the Electricity, Access, and Network analysis were concluded, the Space Profiles (SPs) were developed. An SP is a dynamic flashcard that integrates the description of spaces together with inputs from real time use of this space and users' behavior obtained through users' digital trails collected from the existing built-in IT infrastructure. The process relied on the mixing methods theory extracted from Phases A, B and C learning to conform the assessment. For the current paper, 4 SPs were developed: (A) Cluster Central (B) Cluster Lateral and (C) Community Space profiles. Assigning features and characteristics to the 3 profiles developed based on the previous phases enabled to understand how Coliving spaces worked. The potential of the SP was to understand the identity of spaces as an active space, that responds in different ways depending the user's needs and its specific design features. This methodology was tailored to the different spaces and local needs to be able to reproduce the best experience for colivers, for example reducing electricity consumption and therefore optimizing cost [79].

According to Williams [80], interaction between physical, personal and social factors has an impact on behavior, that can be used to evaluate the physical profile of shared housing facilities. The characteristics he identified include size, density, proximity, surveillance, ratio of private to communal spaces and affordances within each, and non-spatial factors such as formal and informal social factors.

The SPs were the HCD interpretation of space, adding the analyzed digital trail features to the traditional spatial space definition and working as an interface between users and spaces. For example, it is broadly understood that modifying the size of the bed or the capacity of a wardrobe changes the experience of a space; likewise, interfering with the digital network, access permissions or AC parameters also alters the experience and behavior of a coliver. Residential spaces have become something other than a bed and a kitchen; the digital dimension and how it shapes users' performance must be considered when defining spaces taxonomy.

Following Williams [80], the interaction between users and spaces Table 1 is needed to evaluate different typologies of spaces (Table 4) in order to have a complete assessment of experience in the space and be able to design future spaces. The SPs represented the standards to replicate conditions for future spaces; they are also an example of interaction with real studies to test how modifications or interfering with these spaces modifies behavior and likewise interfering with behavior affects the way we use spaces. Studying these conditions helped to better understand the community. The definition of SPs for coliving and studying evolutions was essential to improving sustainable design in the present and future of coliving spaces.

Table 4. Spaces classification according to William's parameters (Physical parameters). * Studios are private spaces, 1 per Coliving each cluster is connected to 3–6 studios (In Italic to differentiate from the common spaces that will be measured).

Space	Space Typology	Size (m^2)	% of the Total Building	Proximity (Distance to Studio)	Ratio (m^2/person)	Privacy Level	Equipment
Lateral Cluster (2I, 2D)	Cluster	18–22	11%	Same apartment (<1 min)	2.38	Semipublic (Open 07 h-00 h)	Kitchen + small living space
Central Cluster (1C)	Cluster	55–65	16%	Same apartment (<1 min)	3.57	Semipublic (Open 07 h-00 h)	Living room + Large kitchen
Gym (0I)	Community	75	4%	Ground-floor (<5 min)	0.89	Public	Fitness and exercise room
Community Coworking (6C)	Community	135	7%	Sixth floor (<5 min)	1.61	Public	Coworking, events, coffee corner sofa area, terrace
*Studio **	*Studio*	*8–18*	*59%*	*N/A*	*14.76*	*Private*	*Bedroom + Bathroom*

3. Results

3.1. Phase A: Electricity Analysis

Four spaces with a total count of 1,047,498 inputs were assessed: 1C (central cluster), 2I, 2D (lateral clusters) and 6C (community space, coworking and social life). Figure 4 shows the average electricity consumption per space: a clear difference in trends is highlighted for the cluster spaces (1C, 2D, 2I). The double peak linear trend showed an increase of the intensity during lunch and dinner times, particularly high in 1C. The Cluster Central was associated with having larger common spaces accessible to the whole community; colivers used this space for shared dinners with other colivers. Instead, the study identified that Community Coworking 6C showed a very different trend, with a single smooth one-lump shape with a peak at 6 pm that corresponded to a different use of this space. Figure 5 focused on 6C during the complete year: the electricity consumption shows a sensible increase from 9:00 to 23:00 in a plateau shape due to moderate electricity consumption related to use of laptops and lighting during autumn, winter, and spring seasons. During the summer season, the plateau shape stressed to a peak shape during the afternoons impacted by the use of air-conditioning (AC) because of the western orientation of the space that increased the temperature.

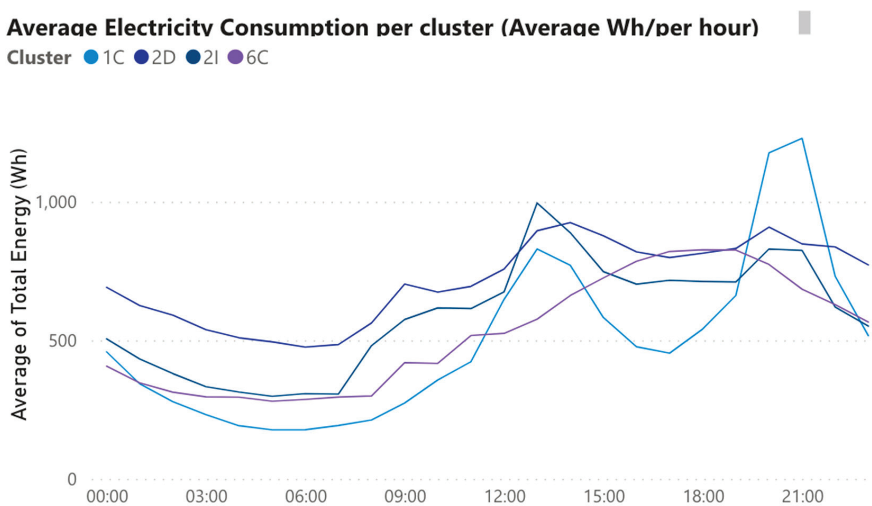


Figure 4. Average yearly electricity consumption per cluster (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI.

Figure 6 compares weekdays to weekend days. Cluster kitchens were being used more during weekdays than during weekends, especially dinners (Friday, Saturday, Sunday). Lateral clusters 2D and 2I and the Community Coworking 6C showed the only trend of a later start in activities from 9 h during the weekdays, up to 13 h during Saturday and Sunday.

3.2. Phase B: Access Analysis

In total, 75 different doors of the building (75 smart locks) were monitored; the spaces had different levels of access depending on the time of day (Table 2). The data respond to the different spaces: 1C Central Cluster with common kitchen, 2D & 2I Lateral Cluster with small kitchen, 6C Community Coworking and the other community spaces were also considered for this filtering.

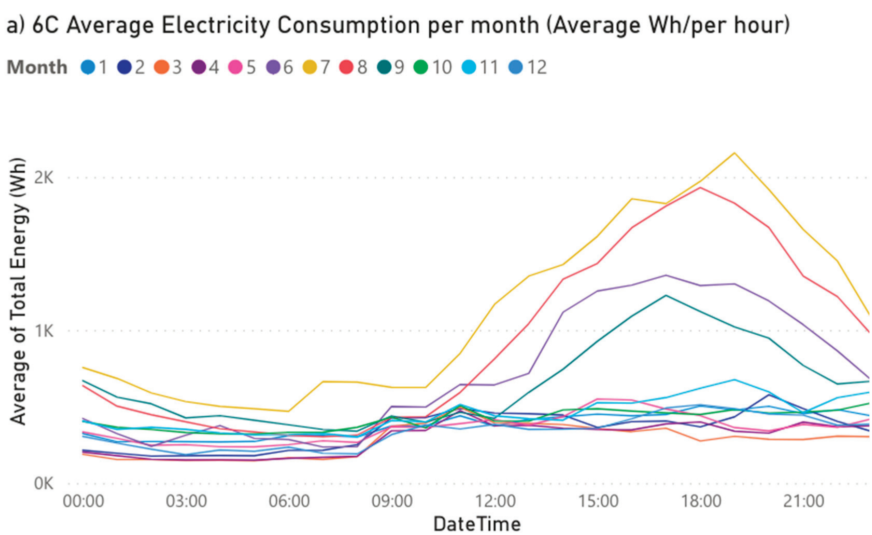
Data for 6C (community space for a coworking) were missing for Mondays, Tuesdays and Wednesday; this is a sample of colivers' interaction with space as they decided to leave that door open during the day for its constant use as a coworking and meeting space.

Each coliver visits an average of 3.58 shared spaces (excluding private studios) from the coliving space, apart from their own studio, with a range that goes from one to eight shared spaces (median of 3) per coliver. Table 5 shows that among all their favorite spaces, the most visited is the Gym(0I), being used by 68% of the inhabitants. After the gym, the central apartments (1C) are the most popular, despite hosting 25% of the private studios and colivers, visited by 67% members. These central apartments with larger kitchens and commons spaces act as a catalyst of communal activities such as dinners, reinforced in the electricity consumption records.

Table 5. Percentage of colivers visiting the different shared spaces per weekday, "S" is the % of colivers that visited a space at least once during the sample period. Entrance corresponds to the main gate of the building, therefore 100% of colivers transit it. Visualization from PowerBI. (The numbers are the ordinal representation of the weekdays 1 = Monday, 2 Tuesday . . .). 1 May 2021 to 1 June 2021.

Spaces	1	2	3	4	5	6	7	S
1C	16.7%	26.4%	22.2%	27.8%	25.0%	22.2%	16.7%	43.1%
2D	5.6%	4.2%	5.6%	6.9%	5.6%	6.9%	4.2%	11.1%
2I	%	6.9%	6.9%	6.9%	6.9%	6.9%	6.9%	8.3%
6C	-	-	-	1.4%	4.2%%	16.7%	18.1%	27.8%
Entrance	93.1%	93.1%	91.7%	94.4%	90.3%	90.3%	93.1%	100.0%
Gym	40.3%	44.4%	41.7%	44.4%	47.2%	19.4%	27.8%	79.2%
Any space	94.4%	95.8%	94.4%	95.8%	93.1%	91.7%	94.4%	100%

Table 6 shows the entries to the spaces. The number of colivers that share one cluster varies from 3 to 6. The most popular clusters visited were the central clusters "C" with the larger kitchens and living spaces. 1C was the most popular space with up to 31 colivers, 43% of the sample community visiting the space at least once—the average number of colivers that visit common spaces is 23% (1C, 2D, 2I). Figure 7 shows the habits and patterns of the visits, when and what are the most visited spaces and the comparison between weekdays when mobility increases within the Coliving from 8 to 9 am and at 8 pm and especially at the gym(0I) and weekends when the overall activity decreases and is concentrated opposingly during night hours and late morning.



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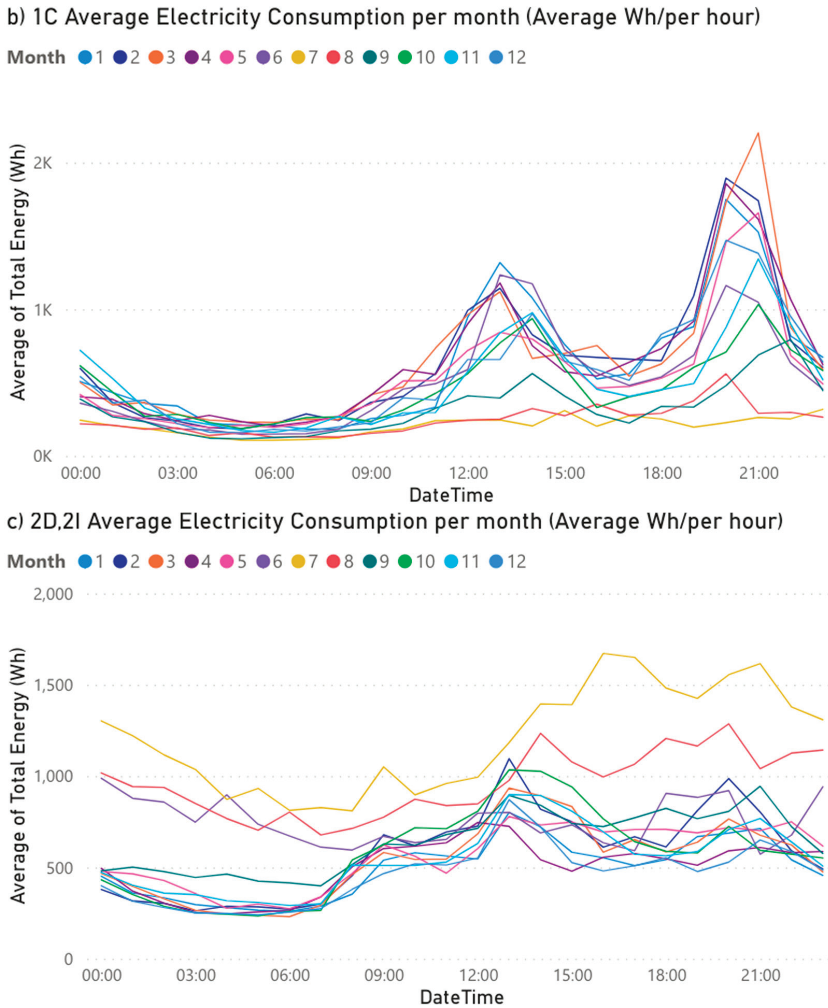


Figure 5. Seasonal electricity consumption. Electricity consumption per month (**a**) Community Coworking 6C (**b**) 1C Cluster Central Space (**c**) 2D, 2I Cluster lateral spaces in Community Space 6C (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI.

Table 6. Number of colivers visiting each space from 1 May 2021 to 1 June 2021. Visualization from PowerBI.

Space	Gym	1C	4C	5C	3C	6C	4D	1D	2C	3D	2D	1I	6I	2I	3I	6D	Average
Visitor count	57	31	25	21	20	20	12	10	10	9	8	7	7	6	5	3	16.6
(%) from total	79	43	35	29	28	28	17	14	14	13	11	10	10	8	7	4	23

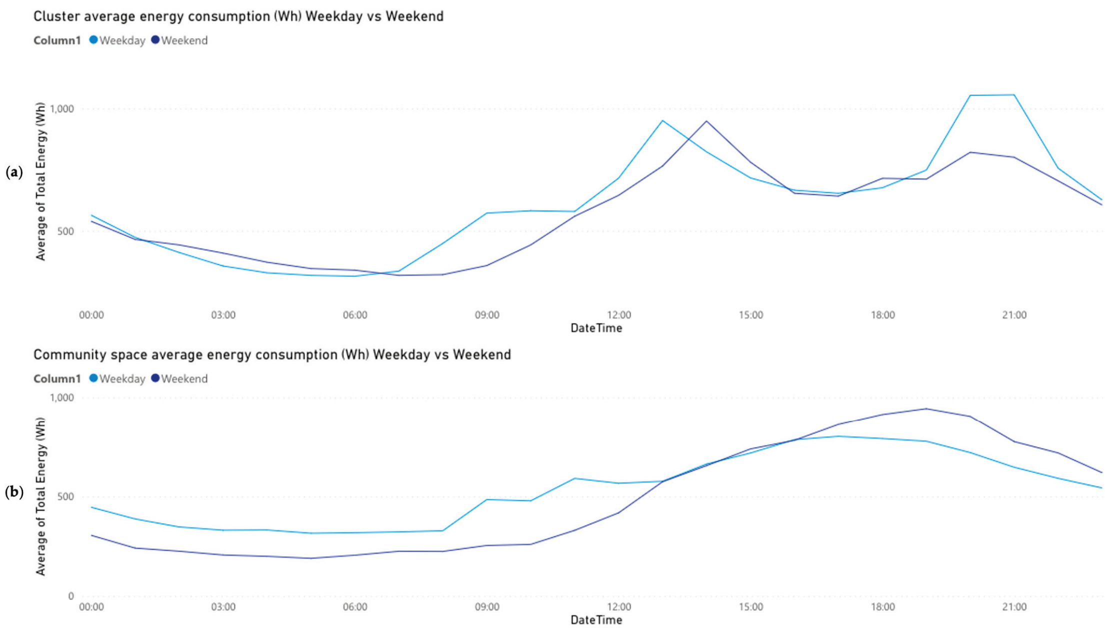
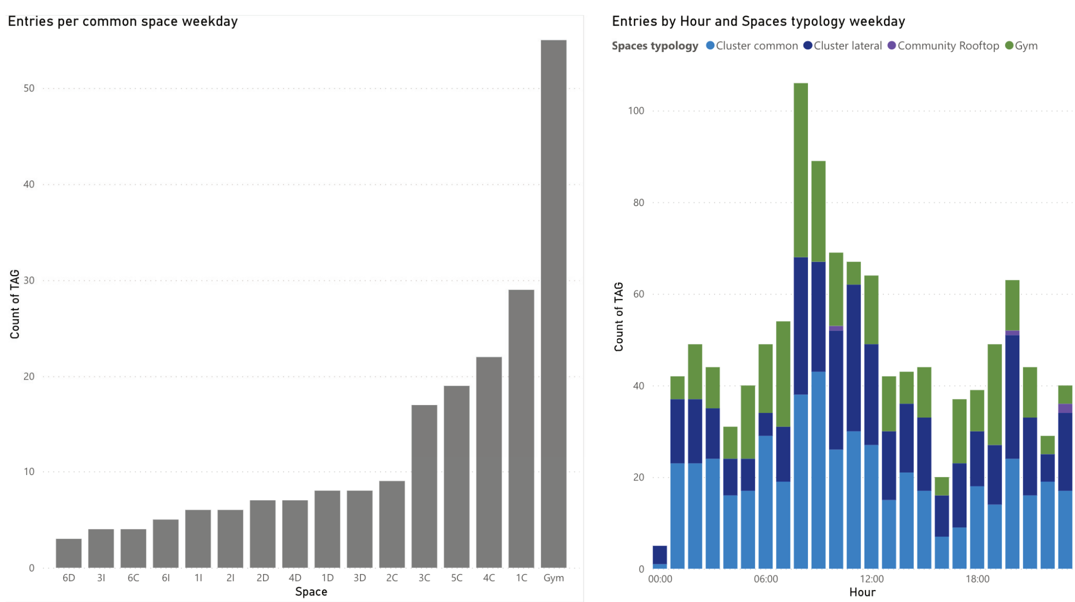


Figure 6. Average yearly electricity consumption per weekday (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI. (**a**) 1C Central Cluster with common kitchen, (**b**) 2D & 2I Lateral Cluster with small kitchen, (**c**) 6C Community Coworking space.



(**a**) (**b**)

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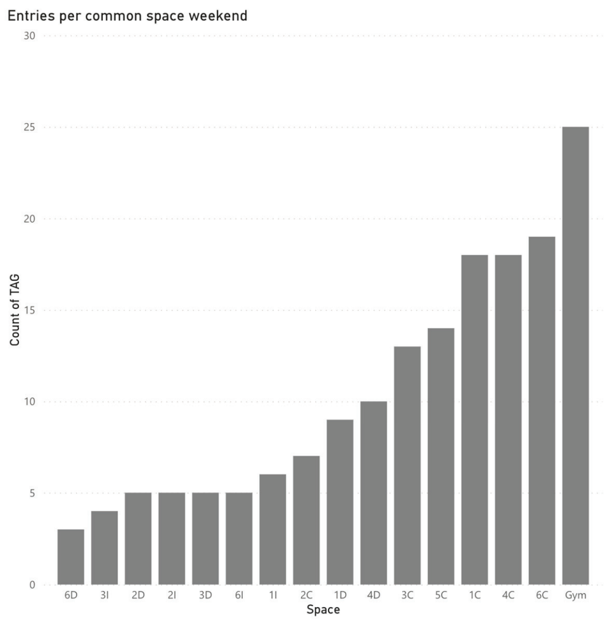

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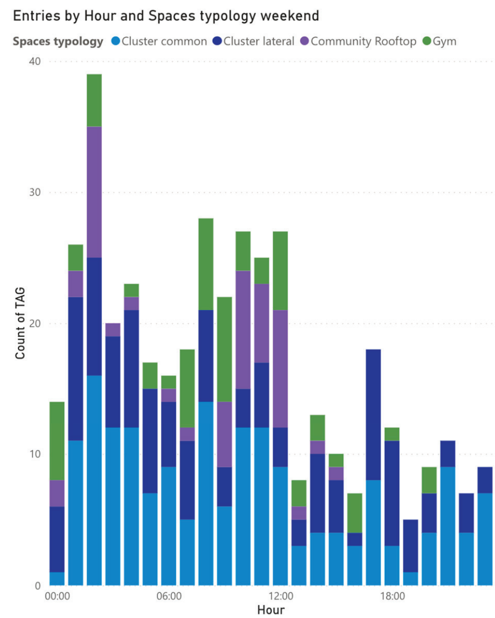

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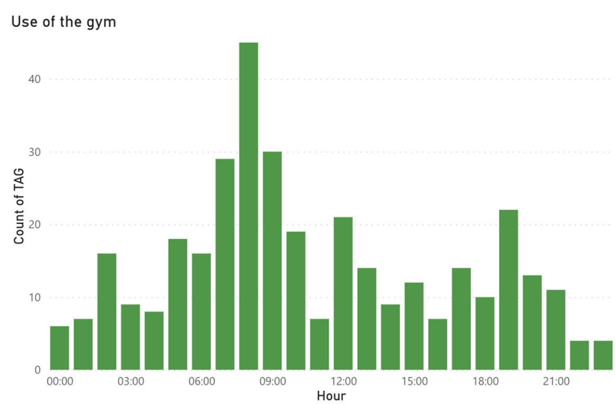


(**e**)

Figure 7. (**a**) Number of visitors per common space weekdays. (**b**) Visiting routines weekdays. (**c**) Number of visitors per common space weekends (**d**) Visiting routines weekends. (**e**) Visiting routines of the gym. (TAG is every entry by a coliver) from 1 May 2021 to 1 June 2021. Visualization from PowerBI.

3.3. Phase C: Network Cross-Check

The Wi-Fi had the advantage of seamlessly capturing data visualization of the co-livers mobile devices (laptop, mobile phone, tablet, watch) in each space, enabling the identification of different behavioral routines depending on the space. Figure 8 represents the devices seen per space and per hour as a daily average of the month. (a) shows the profile of all the spaces analyzed, (b) focused on the gym, with peak on activity at 1 pm and another peak the afternoon and evening during the weekdays (the night connections were also linked to the use of the common spaces next to the gym that had the Gym SSID as the closest network, highlighted by colivers, and cross-checked by the Access Analysis). (c) the Community Coworking area and events show a distributed activity starting at 12 pm until night in office working areas and dinner time more frequent during weekdays, but both charts were very different to (d) Cluster spaces 2I, 2D and 2I that all perform at low intensity during the day but peak between 9 pm and 11 pm during the weekdays, dinner and after dinner time, when colivers that are regularly active in their private spaces or common cluster spaces—this input is essential for the spaces profiling as it identifies the spaces clearly by the behavior within them. During the weekends, similarly to the access controls, there was considerably less use of internet and movement within the areas; 50% of connections in the coworking space 6C and even less in the Gym and surroundings and in the private spaces.

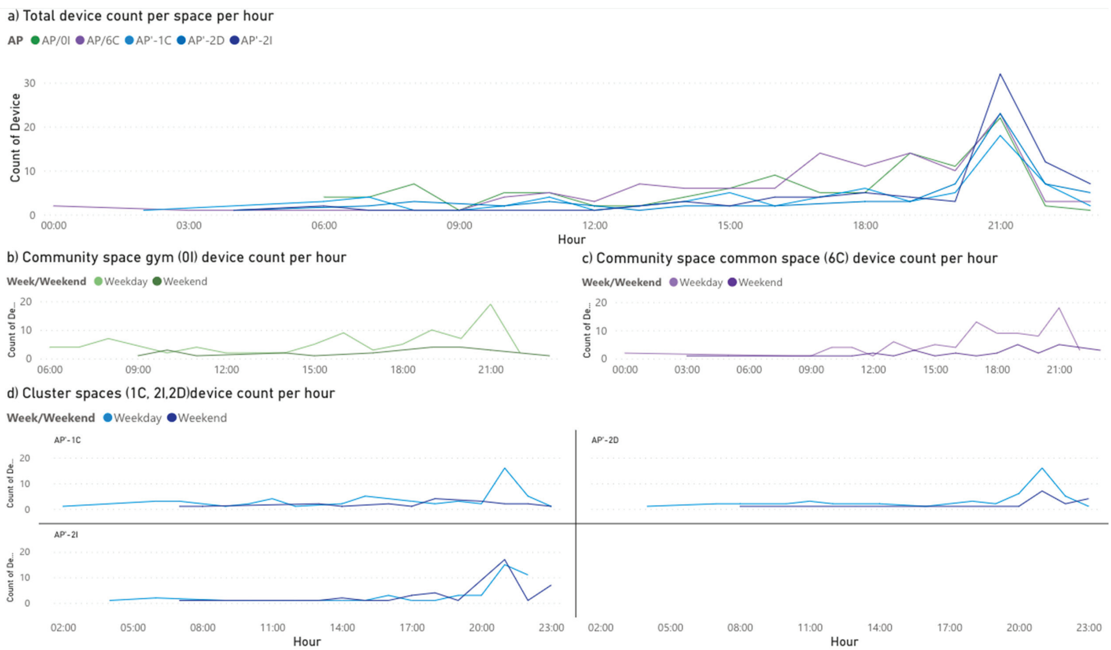


Figure 8. The graphs represent the daily average total devices seen by the APs per hour in the different spaces. (**a**) Average daily total devices seen per AP. (**b**) Total devices seen at the gym (0I) per hour, (**c**) Total devices seen at the Community space Coworking and events (6C) per hour, (**d**) Total devices seen in the different cluster spaces (2D, 2I, 2I) per hour, Count of De . . . (Count of Device). From 1 May 2021 to 1 June 2021.Visualization developed with Power BI.

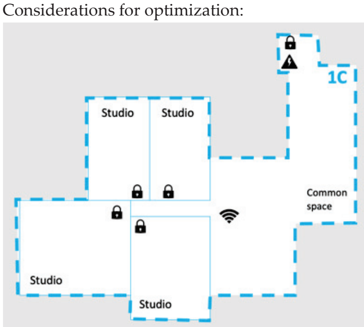
3.4. Phase D: Space Profiling

After concluding Phases A, B and C, the indicators of Table 1 were crosschecked with the space classification Table 4 and synthetized it to develop the SPs. The corresponding author developed the first SP and the co-authors, technology, head of local operations, IT expert, Chief of Operations and Head of Innovation reviewed and complemented the information. It was an iterative process complemented by adding details and helped understanding of the profiling Figure 9.

A) Central Cluster (1C)

Spatial characteristics: Shared spaces with large kitchen and living space.
Frequency: 1 per floor
Studios: 4 studios
Functionality: Living use with private studios and shared spaces
Network: Active use of network during the evenings by members of the cluster
Access and privacy: Gathering space visited by 43% of the community during the month.
Visiting times, Weekends, more emphasized in the mornings
Electricity consumption: Increased consumption during lunchtime and dinners, particularly due to kitchen appliances, showing a pattern of shared dinners among the inhabitants of the same cluster and other clusters

Considerations for optimization:

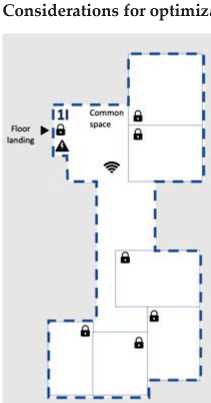


The Central Cluster spaces are essential for fostering informal communication and community gatherings across clusters, promoting their use for shared lunches and dinners by providing appropriate furniture and appliances. As they are the most used among the colivers, electricity saving appliances must be included and have the electricity power contracted to a variable rate adjusted to the consumption patterns//Provide good acoustic insulation between shared cluster space and studios in this cluster due to frequent social gatherings//Advice colivers the central clusters are more social and active, preferably for active users likely to engage in social gatherings.

B) Lateral Cluster (2D,2I)

Spatial characteristics: Shared spaces with small kitchen.
Frequency: 2 lateral cluster per floor
Studios: 3–6 studios
Functionality: Living use with private studios and floor shared spaces
Network: Active use of network during the evenings by members of the cluster
Access and privacy: Gathering spaces visited by 8.33% (2I)–11.11% (2D) of the community. Across the day weekends and mainly during the mornings during the week.
Electricity consumption: Increased consumption during lunchtime and dinners, particularly due to kitchen appliances.

Considerations for optimization:



The Lateral Cluster spaces are more optimized for supplying support space for private studios. Basic kitchen for quick and efficient breakfast lunch and dinner and discrete and silent spaces for colivers that want to live in independent spaces and chose when to gather with the rest of the community visiting other spaces//Appropriated for independent colivers less likely to look for frequent community gatherings.

Figure 9. *Cont.*

C) Community Spaces (6C,0I)

Spatial characteristics: Shared spaces open to the entire community, without associated studios and with a functionality different than traditional residential spaces.

Frequency: 1 Coworking per building 1 Gym per building

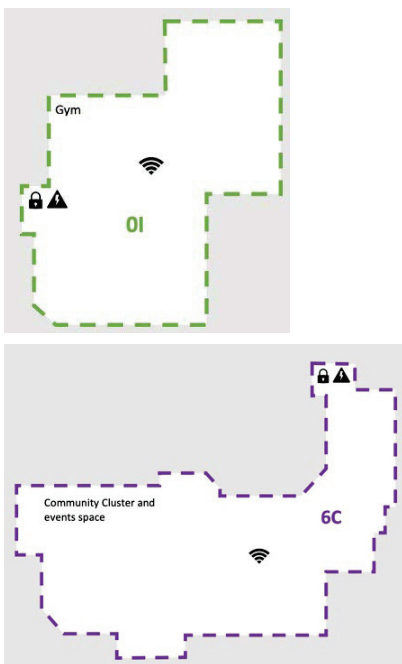
Functionality: Gym / coworking / event spaces / playground / terraces

Network: "Differs between spaces, should be tailored to each community space". Active use of network during the day for working and exercising and gathering during the night

Access and privacy: Design access and permits according to each space and COVID-19 (restrictions if applicable). Recommendation to maintain frequently used spaces like coworking without a lock. Shared spaces visited by upt to 79% of the colivers (gym)

Electricity consumption: AC has a big impact on electricity consumption in the spaces (6C)

Considerations for optimization:



Community spaces are the core gathering spaces of the Coliving. Monitor occupancy patterns, regulations and capacity of this spaces. Install booking systems or informative boards in those that require strict capacity regulations to ensure comfort and comply with regulations such as COVID-19, like coworking (6C) or gym (0I). In spaces more vulnerable to extreme temperature (6C) automatic windows and AC system to ensure climate comfort, review the design of terraces and building envelop design to reduce temperature variation // Ensure envelope acoustic insulation and impact sound insulation at (6C, above cluster spaces) for social gatherings to avoid interfering with neighbourhood // As these spaces are used by a large volume of colivers at the same time, ensure there is a clear understanding of the use of spaces and their functionality, implement coexistence guides to be designed and respected by the community

Figure 9. Space profiles (SPs). (**A**) Central Cluster (1C). (**B**) Lateral Cluster (2D, 2I). (**C**) Community Spaces (6C, 0I).

4. Discussion

As buildings are made smarter, AEC practitioners must integrate the latest technologies to adapt to a rapidly changing society and respond to sustainable HCD spaces [1]. The seamless Post-Occupancy Framework enabled to create a methodology to monitor and adapt the space to user needs over time. It is important to note that the SPs were not an objective itself, but a dynamic, interactive flashcard that provided inputs from the use of spaces. They are a means of dialogue between users and AEC practitioners to improve space design, iterate, modify physical characteristics of space, and analyze how it affected to colivers routines and the use of spaces through the digital trail of the users.

The SPs are therefore scalable and can be implemented globally, adapting to different buildings, locations and taking into consideration the different restrictions or regulations such as the COVID-19 restrictions in place during the time of study. The SPs are a powerful iterative, spatial tool to interact with residents use of space, and behavioral patterns to improve future design, optimize spaces and assess comfort and wellbeing.

Central Cluster spaces are visited by 14%–43%, an average of 29.7% (21.2 colivers), and the largest electricity consumption and visits are within weekdays at lunch and dinner hours, whereas the Lateral Clusters are visited by only 4%–17% of the community which meant an average of 10.3% (7.4 visitors from other clusters) and has a high consumption of internet at 21:00 h, mostly individual connections inside the private studios. Community Spaces like the gym had a visitor rate of up to 79% and coworking was preferred to be open without restricted access during the day.

Cluster spaces had a higher electricity consumption rate during lunchtime and dinner time mainly due to intensive use of appliances; community spaces like coworking spaces intensified electricity consumption gradually during the afternoon due to AC during the summer months—the rest of the months they encountered a plateau-shaped stable consumption trend. Central Cluster spaces acted as catalyzers of community, colivers visited an average of three to four common spaces, Central Clusters being frequented more by external visitors.

Our consultations with colivers were also essential to complementing and understanding their choices as key to HCD. Interviews and codesign to improve SPs is always recommended as a future line of research. For example, after identifying the electricity patterns and consumption habits of users, the results of the current research recommended modifying the electricity contract to be adjusted to match the peak hours of consumption of the Coliving in order to match their habits. In addition, other measures were suggested to improve wellbeing and use of spaces. Feedback also showed that colivers had a significant interest in the following: understanding building and performance, environmental sustainability, knowing how to improve performance and suggested visualization measures to reduce environmental impact. This interaction helped not only to improve the performance of current spaces but also to collaborate for a more conscious future society.

The use of space routine also differs depending on the day of the week: at weekends, the number of in-house common dinners was significantly reduced and mobility within the Coliving decreased and shifted towards late mornings and night-time rather than during the week when it is distributed more evenly along the day.

Colivers also showed different habits and patterns of use of space: more social colivers visit up to eight spaces apart from their private studios on average, others just one or two. After the study the Central Cluster spaces were recommended to colivers more interested in networking and community interaction and Lateral Clusters to others looking for more independence.

Future Lines of Research

In future lines of research, the researchers would complement and enhance the research by repeating the process in other buildings with a different typologies and other available data sources to be processed, such as open databases to track interaction with the city and sociodemographic data.

Including surveys to the colivers to enlightening colivers motivations for choosing coliving and their perception of the different spaces would be an additional value-added study for future research.

A post COVID-19 assessment of the building will also be performed to add additional feedback on the building and comparison of data during and post-COVID-19 crisis.

5. Limitations

Several limitations were encountered during the study: the first was to implement the study in a single building and geographic location in Madrid. Although colivers had an international background, the outputs and the SPs were therefore linked to the geographical context, target users and COVID-19 regulations. The methodology was designed to be iterated, replicated, and scaled to any kind of building and location, enabling the repetition of the process, the updating of the digital trail with the available data sources and replicating the SPs for other locations, users, and conditions.

At the beginning developing this methodology during the COVID-19 was a limitation due to difficulties to visit the space for data collection. This was transformed into an opportunity to take a step forward to POE analysis and adapt it to restrictions to develop a system that could be implemented fully remotely, which meant the process could be exported and scalated to other geographies, globally, without the need for geographic relocation; in addition, this methodology helped to understand the evolution of the use of spaces during and after the pandemic.

6. Conclusions

The current research demonstrated how POE techniques based on the digital trail can be employed to design a methodology for sustainable HCD Coliving spaces.

The infrastructure available in highly digitalized IOT-based buildings, like colivings, has proven to be a valuable resource to assess performance of spaces and behavioral patterns based on the already existing IT devices, without the need to install additional sensors, regarding the expected learnings.

The three SPs showed major differences in the use of spaces and enabled a comparative analysis of the use of spaces. The different data sources provided inputs to enable identification of the level of occupancy of the different spaces, average number of visitors and overall popularity of the spaces, differentiating between most occupied spaces and less occupied.

Data sources also provided insights into energy consumption and activities implemented in each space according to data consumption patterns.

A home is not a roof—walls and doors are physical divisions of space. This paper proved buildings go beyond the physical skeleton and shell, and strongly rely on digital networks and experience. The developed methodology and the use of SPs was essential for sustainable HCD interpretation of buildings to assess not only the behavioral patterns of the users but also the interaction of the building with the environment.

Author Contributions: Conceptualization, A.R. and A.G.-S.; methodology, A.R.; software, M.A. and C.L; validation, A.G.-S., M.A. and C.L.; formal analysis, A.R. and J.D.P.; investigation, A.R.; C.L.; resources, M.A.; data curation, A.R.; writing—original draft preparation, A.R.; writing—review and editing, A.R., A.G.-S., C.L.; M.A. and J.D.P. visualization, A.R.; supervision, A.G.-S.; project administration, A.G.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy.

Acknowledgments: The researchers of this project thank Urban Campus for their collaboration and access to the data as well as the community of colivers for their feedback and collaboration.

Conflicts of Interest: The authors declare no conflict of interests.

Abbreviations

Abbreviations

The following abbreviations are used in this manuscript:

AC	Air-conditioning
AEC	Architecture, engineering construction professionals
AP	Access Point
API	Application Programming Interface
HCD	Human-centered design
MDPI	Multidisciplinary Digital Publishing Institute
NUA	Net Usable Area
POE	Post-Occupancy Evaluation
SEM	Smart Electricity Meter
SP	Space Profiles
SSID	Service Set Identifier
TAG	Input entry by Coliver

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Review

Indicators of the Public Participation Exercise for Designing Public Parks in Malaysia: A Systematic Review

Ungku Norani Sonet [1], Mustafa Klufallah [1,*], Michael D. Peters [2] and Timothy J. Dixon [2]

[1] School of Built Environment, University of Reading Malaysia, Iskandar Puteri 79200, Malaysia; ungku.norani@gmail.com
[2] School of Construction Management and Engineering, University of Reading, Reading RG6 6AH, UK; m.d.peters@reading.ac.uk (M.D.P.); t.j.dixon@reading.ac.uk (T.J.D.)
* Correspondence: m.klufallah@reading.edu.my

Abstract: In an attempt to enhance democratic governance, sustainable development goals (SDG), and Local Agenda 21 (LA21), the notion of public participation exercise (PPE) presents a range of possibilities. The PPE is observed as a method of solving the constraints faced by public parks in Malaysia, which in general suffer from two main challenges, namely (i) the underutilisation issue of public parks and (ii) the weakness of the present top-down development policy. Consequently, the objective of this study is to develop indicators for PPE in designing public parks in Malaysia. The method implemented in this study is an assessment of the construct, variable, and indicator adapted from Lazarsfeld's scheme by conducting a document review of the Public Consultation Index (PCI), six sustainability assessment tools, namely LEED-ND, BREEAM, IDP, SITES V2, Green Mark-NRB, and GTI, and literature references. The variables and indicators were tabulated into the respective operational definition of the construct table and variables and measurement table. The findings include the identification of two main constructs, including public participation and public parks. Multiple variables were derived from each construct, including attributes of PPE in designing public parks in Malaysia, development stage, method of approach, type of public, and public parks design criteria. Subsequently, this study developed the fundamental basis for the PPE framework in designing public parks in Malaysia, which benefits the local development approach for public parks towards an integrated design framework.

Keywords: social sustainability; public participation; community engagement; sustainable development; Public Consultation Index; public parks

Citation: Sonet, U.N.; Klufallah, M.; Peters, M.D.; Dixon, T.J. Indicators of the Public Participation Exercise for Designing Public Parks in Malaysia: A Systematic Review. *Sustainability* **2021**, *13*, 12119. https://doi.org/10.3390/su132112119

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 21 September 2021
Accepted: 25 October 2021
Published: 2 November 2021

1. Introduction

This research is primarily derived from three core factors encompassing democratic governance, SDG, and LA21. Therefore, the relationship and association between these three factors and their significance to the public participation exercise (PPE) are further discussed.

Malaysia is a federal constitutional monarchy based on democratic parliamentary governance, which encourages citizens to participate and get involved in their public policies to serve the people and meet their needs [1,2]. This type of public policy displays a bottom-up development framework, whereby the involvement of the public and engagement level of the citizens is central and wide-ranging. Manaf [3] stated that increased public participation in government policies and decisions contributes positively to the enhancement of democracy. Hence, in order to emphasise democratic governance in Malaysia, the public is encouraged to have a role in the formulation and implementation of government civil policies.

In many instances, direct public participation in various governmental processes is intrinsically regarded as a means of democratic freedom of expression and procedural justice [4]. Public participation is strongly associated with democratic governance and is seen as a game changer in terms of decision making, shifting from top-down to bottom-up, with more participatory processes involving diversified factors [5–9]. An ideal democratic governance practise is that the public has a right to influence the decisions that affect them or the things they value [10]. By providing opportunities for citizens to participate in decision-making processes, public participation has proven to be a good exercise in strengthening democratic governance and expanding its horizons, as well as in shifting the present top-down framework for policy development to more participatory processes.

Sustainability is defined as "a process of change in which the exploitation of resources, the direction of investments, nature of technological development, and institutional reforms are consistent with the needs of the present and the future" [11]. According to the United Nations, sustainability refers to "the growth or development which fulfils the present needs whilst maintaining the ability of future generations to meet their own needs" [11,12]. Subsequently, the United Nations General Assembly adopted seventeen sustainable development goals (SDG), with the goal of enhancing the organisational operationalisation and integration of sustainability and, as a result, SDG address current and future stakeholder needs and ensure a better and sustainable future for all, while balancing economic, social, and environmental development [13]. SDG 17 specifically promotes the strengthening of implementation and revitalisation of the global partnership for sustainable development [14]. The discussion of SDG 17 includes eight major themes, including multi-stakeholder partnerships and voluntary commitments, which further elaborates the integration of decision making undertaken by the government, as emphasised in Agenda 21 (Johannesburg Plan of Implementation) [15]. SDG 17 acknowledges the importance of multi-stakeholder partnerships and encourages effective public, public–private, and civil society partnerships, building on the experience and resourcing strategies of collective action [14].

The Local Agenda 21 (LA21) was introduced in Malaysia in 1999 and the policy includes the involvement of the community and multi-stakeholders [15]. LA21 is a programme designed to forge partnerships between local authorities in Malaysia and the public, in the planning process and in maintaining the surrounding environment in achieving the SDG [16]. LA21 has mandated the encouragement of the local authorities to have dialogues within the community to achieve development and consensus on the LA21 action plan [15]. However, due to a lack of enforcement at higher levels of local government and the fact that implementation is solely dependent on the individual local authority, the implementation of LA21 activities in Malaysia is considered low [16]. Conversely, the LA21 outlined several aims focusing on people-centred development to achieve the sustainable development goals [3,17,18]. Ngah et al. [18] further highlighted that LA21 states that good urban governance demonstrates "people first" and "people-centric" schemes, emphasising the importance of allowing the public to participate in governmental decision-making processes.

Certainly, democratic governance, SDG, and LA21 have strong relationships in demonstrating the importance of the implementation of PPE in Malaysia. The anticipation of the public in various civil policies strengthens the diversity in obtaining a holistic consensus and decision towards the implementation of sustainable development. Volunteerism as a form of participatory action among the public has consequently been a key element of the progress made to date, including social leadership and higher awareness in implementing the doctrine of sustainable living policy. Undoubtedly, PPE holds great potential for Malaysia in contributing effectively to the global agenda towards sustainable development.

Therefore, the research aims to develop a set of variables and indicators in proposing a public participation framework in designing public parks in Malaysia. In relation to that, this paper identified two main research gaps identified in the Malaysia context, which consist of the following: (1) issues concerning the underutilisation of public parks and (2) weaknesses of top-down civil policies.

(1) Despite the presence of well-designed public parks landscapes, the issue of underutilisation of public parks in Malaysian urban areas persists [19,20]. The lack of public

participation in Malaysia's public parks indicates a failure in the design element of the public parks, despite the huge amount spent annually by the federal government [21]. Furthermore, the design factor is also believed to have an impact on the level of acceptance among the public, and the level of interest/engagement with its facilities [21].

(2) Malaysia's current landscape practise has a poor policy emphasis in responding to the required components of sustainable development, and it is critical to change this current conventional practise in order to adapt to new, more sustainable landscape practises. [21]. The top-down approach has proven to be a failure despite being based on professional estimators and assumptions as opposed to the opinions of the public. This has led to the development of unusable spaces that have failed to meet the needs of the public. In the late 1970s, the top-down approach was used in municipalities that adopted Western-style open space models under the "City Cosmetic Movement". Further, this caused major failures in most public park designs [22]. Ridings and Chitrakar [23] argued that the frameworks designed for public spaces in traditional cities were no longer appropriate. One of the major negative factors was the lack of direct public input during the establishment of the framework.

2. Literature Review

In order to identify the variables and indicators in PPE in designing public parks in Malaysia, the following sections are reviews of literature focusing on the PPE and public parks design criteria in Malaysia.

3. Public Participation Exercise—PPE

Human participatory development, which emphasises sustainably managing and restoring ecosystems, will have a simultaneous effect on promoting wellbeing whilst reducing negative environmental impacts [24]. The development of human participation in this context is related to public opinion and community decision making, as transparent communication may leverage support for certain policies, based on individual or social rationality, as long as people perceive the policy as appropriate to tackling the problem [24]. While the significant role of the community in promoting the sustainability agenda is readily apparent [25], the term social sustainability is not well defined, due in part to the difficulties in quantitatively measuring factors of social sustainability as compared to economic or environmental sustainability [26].

Sustainable development at the community level is defined as a dynamic process in which communities can anticipate and accommodate the needs of present and future generations by reproducing and balancing the local social, economic, and ecological systems to address global concerns [27]. In general, four main factors influenced social sustainable development, including social equity [17,28], sustainable community [29,30], community resilience [31], and community engagement [27–29]; thus, the significance of PPE in responding to social sustainable development is highlighted by community engagement factors.

Figure 1 depicts the connection between the governance policy, sustainable development pillars, and the social sustainable factors. PPE is supported at the local governance policy level by the three-governance policy, which comprises democratic governance, SDG, and LA21. The three pillars of sustainable development demonstrate that PPE has a significant effect on social sustainability factors, leading to sustainable development. The concept of community engagement is significant to PPE and emphasises the social sustainability components even more. As a result, PPE is essential to the three criteria mentioned, and this demonstrates the relevance and significance of PPE in Malaysian civil policy implementation.

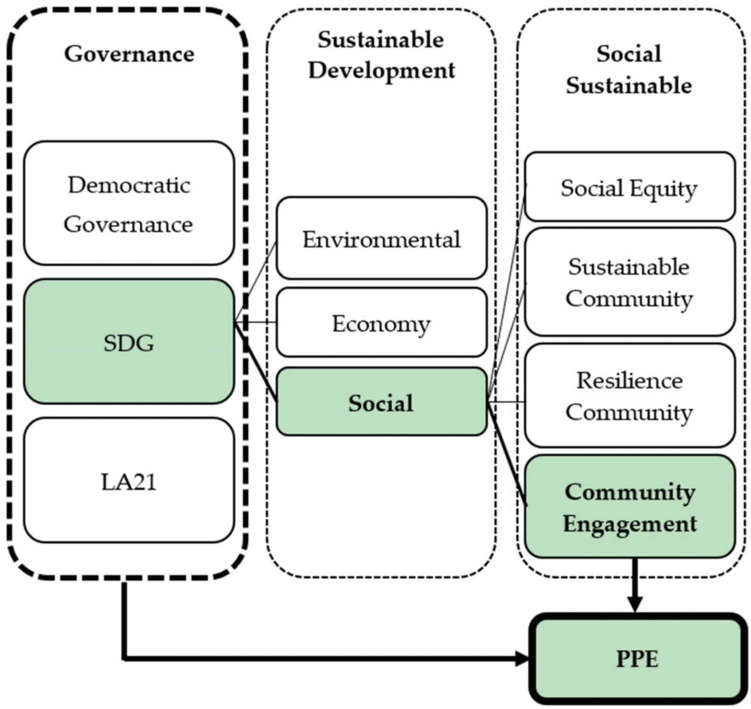

Figure 1. The significance of PPE in a Sustainable Development Framework.

PPE is defined as citizen participation and implies the involvement of citizens in a wide range of policymaking activities. These include the determination of levels of service, budget priorities, and the acceptability of physical construction projects in order to orient government programmes toward community needs, build public support, and encourage a sense of cohesiveness within neighbourhoods [32]. There are six concepts in implementing PPE which are labelled as functionalist, neo-liberal, deliberative, anthropological, emancipatory, and post-modern [33]. The concept is explained by the extent of the public contribution expected under the PPE. In general, each PPE is unique, whereby the location, type of public, type of policy, and the objective of PPE are main factors in identifying the characteristics of the framework to be implemented [5,34]. According to Jibladze et al. [34], there are five rising degrees of PPE on the International Association for Public Participation (IAP2) spectrum of public involvement. Inform is at the bottom, followed by consult, involve, collaborate, and empower. This spectrum illustrates the substantial degree of public decision-making capacity in PPE implemented by local governments.

The notion of PPE goes beyond just achieving consensus or obtaining mutual understanding in a decision-making context; rather, the PPE itself has considerable benefits to the public in terms of promoting interaction and engagement between the local authority and the citizenry [33]. Furthermore, the PPE is perceived as a pragmatic approach to cope with the complexity of modern societies, given that the public is more informed, educated, and interconnected. Thus, the public is better at accommodating new ideas, different perspectives, and innovative solutions to address issues attended by the local authority [5]. PPE is essential to generate public interest in participating in the local government process, as well as to increase public willingness to play an active role in development planning [33].

PPE has been proven to have a positive effect on public mental wellbeing [35–37] and in terms of good design practise in meeting the needs of the end user [38]. Payne et al. [38] highlighted that the implementation of PPE involving the end user should be at the beginning of the design process rather than during the post-occupancy stage, as it is important to ensure that the design meets the needs of the end user. The design brief, which indicates specific design factors during the PPE, is crucial in setting the scope and boundaries of the discussion [38].

It has been suggested that landscape architects integrate with the community in order to include social sustainability factors into the design scheme, as well as in establishing a design and development framework that involves the public [39]. Recent studies on public participation in landscape design have shown that it is superficial and insufficient, thus leading to difficulties in developing a design scheme for public spaces that meets the needs of the people [9].

Based on the current state of sustainable development, the development of an integrated design framework between public and civil policies for public parks is crucial. The role of the public is vital for the development of a design scheme that meets the needs of the public in public spaces. The PPE is an exercise that allows the public to directly contribute towards the decision-making process. Consequently, the PPE in local development projects will increase public awareness and knowledge of sustainable development, as well as motivate the public to care for the development's long-term upkeep [6,40].

PPE, which is also known as the integrated design process, is an iterative process that is inclusive from the very beginning, front-loaded (with time and commitment being invested from the start), and allows for full optimisation with decisions being influenced by the broader team. It also involves whole-systems thinking, requires life-cycle costing, seeks synergies, and continues throughout post-occupancy. In contrast, the conventional design process is a linear approach that involves team members only when it is essential, requires less time, commitments, and collaboration in the early stages, and involves decisions made by fewer people. Moreover, the systems are often designed in isolation and limited to constrained optimisation processes, have a reduced opportunity for synergies, emphasise up-front costs, and typically finish when the construction is completed [41].

PPE is commonly administered by the local authority [5,34] and in Malaysia, local authorities are mainly classified as city councils, municipal councils and district councils. Each of these local authorities has developed their own development framework as referred to the primary guidelines established by the federal government. The present PPE in Malaysia was established by the Department of Town and Urban Planning (JPBD), known as 'Publicity' (SERANTA) for the local development plan in Malaysia, which involves a public exhibition process where local citizens have the opportunity to express their personal opinions to the local authorities during the SERANTA process [42]. According to Ali and Arifin [42], the level of PPE in Malaysia is considered poor and viewed as top-down in the general system instead, whereas it should represent a bottom-up development framework system; thus, PPE in Malaysia at the moment reflects a non-holistic disciplinary approach and is not centralised [42]. Additionally, there is no trace and enforcement of PPE nor SERANTA in landscape departments within local authorities which are responsible for the development of public space projects, including public parks in Malaysia.

Therefore, a further investigation is needed to identify the variables and indicators for PPE by using the Public Consultation Index (PCI) as a main reference. PCI is one of the most referred to in the field of PPE globally [34]. There are six main criteria described in PCI [34] for developing a PPE, which include accessibility, openness, effectiveness of the public consultation process, accountability, diversity of participants, and public engagement/interest.

Table 1 shows that there are five variables identified in an effective public consultation process as referred to PCI. The five main variables are the announcement method, the consultation format, feedback, stages of policy development, and participants.

Consequently, the discussion on PPE and its relevance has led to the study of public parks in Malaysia. This is due to critical issues confronting the Malaysian public parks, which without a doubt have an impact on society, as the function of public parks in society is more than just a public infrastructure facility, but rather has a substantial impact on the development of sustainable communities. Public parks have proven to be beneficial to the general public's mental wellbeing and physical health [20]. Therefore, PPE is an important approach to be implemented in designing public parks in Malaysia.

Table 1. Extracted Variables of PPE from PCI [34].

Variable	Criteria
Announcement	• Announcement was disseminated reasonably. • Information in the announcement is sufficient.
Consultation Format	• Public consultations were conducted in at least two formats.
Feedback	• Multiple ways of feedback mechanism were ensured. • Sufficient time (minimum one week) was provided for feedback on policy document/brief.
Stages of Policy Development	• Public consultations were conducted at least at three different stages.
Participants	• Opportunity to participate in public consultation was open to anyone interested.

4. Sustainable Assessment's Tool

This study delves deeper into the independent variable, which was adapted from the six PCI criteria (the announcement method, the consultation format, feedback, stages of policy development, and participant). The sustainable assessment tools are widely used in built-environment research as the assessment tools list a rigorous measurable indicator as a guideline in complimenting sustainable development. According to Siew [43], several green rating tools have been employed to guide the design process and development of buildings, such as the Green Star Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environment Assessment Method (BREEAM), and Comprehensive Assessment System for Building Environmental Efficiency (CASBEE).

Wu [44,45] recommended the use of several sustainable assessment tools to evaluate both the environmental impact of construction projects and the systems for green development, which include the following: Life-Cycle Assessment (LCA), Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Building Environmental Assessment Method (BEAM), and Sustainable Building Tool (SB Tool). Larco [46] listed several rating scales that were used as sustainability-focused urban scale rating systems, which include LEED-ND, BREEAM communities, STARS, and SITES.

In total, nine sustainable assessment tools were reviewed in identifying the indicator for each variable derived from the PCI. Following this appraisal, out of nine assessment tools, only six of them have relevant indicators to the PPE as follows:

1. Leadership in Energy and Environmental Design Neighbourhood Development (LEED-ND)—United States [47].
2. Building Research Establishment Environmental Assessment Method (BREEAM)—United Kingdom [48].
3. Integrated Design Process (IDP)—Canada [49].
4. Sustainable Site Initiative SITES v2 Rating System for sustainable land design and development—United States [50].
5. Green Mark (For non-residential buildings NRB: 2015)—Singapore [51].
6. Green Township Index (GTI)—Malaysia [52].

The relevant indicators of PPE are abstracted and tabulated in Lazarsfeld's scheme method. Figure 2 shows the development of the dependent variable and the independent variable. The dependent variable is derived from the attribute of PPE in designing public parks as shown from the literature references, while the independent variable is developed from the PCI and the indicators are based on the documentation review of six sustainable assessment tools.

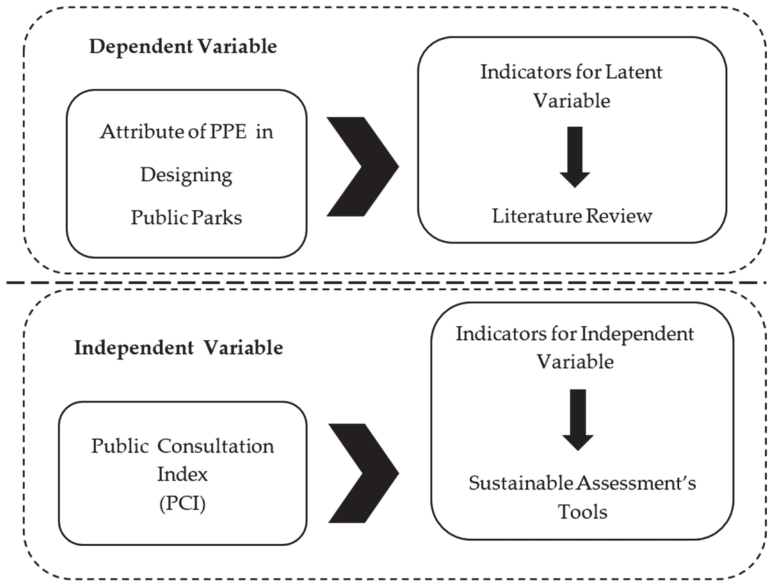

Figure 2. Variables and Indicators of PPE.

5. Public Parks Design in Criteria Malaysia—PPDCM

Adiati [53] stated that parks and green spaces are important components of recreation and relaxation. On the other hand, Ahmad [54] noted that public parks are essentially associated with open spaces and recreation activities. Public parks usually consist of three main components: (1) the parks and their facilities; (2) the landscape; and (3) the architecture of the parks. Sakip [55] emphasised that public parks are an integral aspect of an urban setting. The green spaces within the cities play an important role and provide several health-promoting benefits. In this regard, the public parks' components, which also include green spaces, potentially have a similar impact on the public [19].

Sakip [55] noted that the public parks categories in Malaysia are based on the Malaysian Town and Country Planning Department (TCPD) Planning Framework for Open Space and Recreation include the following: (1) national parks, (2) regional parks, (3) city parks, (4) local parks, (5) neighbourhood parks, (6) children's playgrounds, and (7) playgrounds. Ridings and Chitrakar [52] stated that various frameworks designed for public spaces in traditional cities were no longer considered appropriate. One of the major factors is the lack of direct public participation in the establishment of the framework.

Public parks in Malaysia have been developed in urban areas mainly for recreation and relaxation purposes [56], and they have provided significant benefits to the public's mental wellbeing, and facilities for physical activities [53,57]. Furthermore, Sakip [55] and Ngesan [58] stated that public parks not only offer health benefits to the physical body but also the inter-relationship between the community, and they increase the value of properties. Ridings and Chitrakar [23] stated that a successful public space requires the following components to be embedded: (1) people-friendly urban design factors, (2) human scale, (3) sightliness, (4) activated edges, (5) shelter, (6) seating, (7) engagement,

(8) legibility, and (9) permeability. Fu and Ma [59] discussed the significance of PPE and the integration between the community and the local governing system in designing public spaces. Tomlinson [60] highlighted that a successful public space requires the following: (1) places that trigger memories and (2) the cultural and historical meanings of places for individuals and the community.

Ridings and Chitrakar [23] elaborated that people-friendly frameworks were established through various studies by Lynch in 1960, Alexander in 1964, Alexander and Poyner in 1970, Gehl in 1971, Whyte in 1980, Jarvis in 1980, Carr in 1992, Srecnberg in 2000, Tibbalds in 2000, Carmona in 2003, and Crankshaw in 2008. These studies focused on approaches to encourage people to linger in public spaces which were designed for gathering and performing social activities [23]. However, Jan Gehl and Lynch noted that these frameworks do not provide a comprehensive set of rules for the design of public spaces [23].

Fu and Ma [59] argued that the efficient mobilisation of citizens and local governing institutions is required for a sustained interacting mechanism between urban space, social capital, and natural capital. A successful urban space results from a well-functioning community that positively engages with both local authorities and the public. Hence, PPE in decision-making for urban spaces will enhance the quality of urban spaces. Public parks play a crucial role in developing and maintaining the social identities of both individuals and groups [19]. Since public parks are used by various groups of people with diverse backgrounds, the landscape architect is responsible for designing public parks that respond to the needs of the end users. Furthermore, the design of a public park must respond to the local climate and surroundings of the site, historical value, cultural and social influences, as well as security and public safety factors [23].

Brown [61] mentioned that public parks, and in particular community parks, are crucial elements in urban development due to their social and ecological benefits. Hence, the role of the public is crucial and has equal importance with other stakeholders such as the local authorities and development consultants in terms of working towards achieving a public responsive design scheme for the development of public parks in Malaysia. The architectural and design elements of public parks carry social and cultural values for an individual, thus leading to social inclusivity and a sense of belonging to the public parks [25,62].

The discussion of public parks and the issues pertaining to Malaysian public parks demonstrate the significance of the implementation of PPE in designing public parks in Malaysia. An integrated design framework that incorporates PPE in the design of public parks promotes the sustainable development of the long-term growth of public parks in Malaysia. As a result, the PPE in designing public parks has the potential to address the issue of underutilisation of public parks by obtaining direct feedback from the public through the PPE. The PPDCM indicators discovered in this research are tabulated in Lazarsfeld's scheme for further analysis.

6. Methodology

In this study, the Lazarsfeld's scheme methodology was adapted for tabulating the identified variables into endogenous variables and exogenous variables. Even though Lazarsfeld's theory is commonly used in mass media communication studies [7], this research adapts a similar method to that of Lazarsfeld's, known for its technique of approaching public respondents about the attentive objective of this research. Lazarsfeld's scheme is mainly used for social science questionnaire-based studies [7]. Therefore, this research is oriented towards a public opinion.

Based on the scheme, the construct operational definition was developed by identifying the dependent variables (attribute of PPE in designing public parks in Malaysia) and independent variables (development stage, method of approach, type of public, and public parks design criteria) and relevant indicators in every variable of the study. The constructs (public participation and public parks) are the main keywords of the study. Additionally, a variable measurement table was developed for the measurement of indicators. The sequence of Lazarsfeld's scheme is shown in the results section. Operationalisation refers to the conversion of abstract concepts into measurable observations, in which there is a systematic data collection on processes and phenomena that are not directly observed. Operationalisation is important to remove ambiguity in concepts by specifying the operations that will be measured. Therefore, operationalisation translates the meaning of the constructs provided by the theoretical definition into a prescription for measurement. Operational definitions or prescriptions for measurements are statements that describe measurements and statistical operations. The three main components in operationalisation including: (1) social class, (2) morbidity, and (3) self-efficacy belief.

7. Results and Discussion

Table 2 shows the operational definition including two constructs identified as follows: (1) public participation and (2) public parks. Public participation is defined as an active public involvement in decision-making activities in policymaking, and physical development towards meeting the needs of the people. A public park is an open space that is associated with public and recreational activity among the public.

Table 2. Operational definition of the construct.

Terms	Definition of Terms	Reference
Public Participation	Citizen participation implies the involvement of citizens in a wide range of policymaking activities, including the determination of levels of service, budget priorities, and the acceptability of physical construction projects in order to orient government programs toward community needs, build public support, and encourage a sense of cohesiveness within neighbourhoods.	[63]
Public Parks	The term 'park' is frequently used in connection with open spaces. Park and green areas are part of an element of recreation and relaxation. Public parks are essentially linked to open space and recreation activities.	[53,64,65]

Table 3 shows the variables and measurements for each construct. There were five variables identified, including (1) attribute of PPE in designing public parks in Malaysia, (2) development stage, (3) method of approach, (4) type of public, and (5) public parks design criteria. The attribute of PPE in designing public parks in Malaysia is to measure public awareness of public participation activities in general.

Figure 3 shows the conceptual framework of this research, which is derived from the table of variables and measurement of PPE. There are two types of variables that have been classified under the conceptual framework which includes endogenous variable and exogenous variables. The endogenous variable (dependent variable) involves the attributes of PPE in designing public parks in Malaysia while the exogenous variables (independent variables) include the development stage, method of approach, type of public, and public parks design criteria. The conceptual framework demonstrates the relationship between the endogenous variable and the exogenous variable.

Table 3. Variables and measurement of PPE.

Variables	Construct and Operationalised Definition	Item Measurement	Indicator	Adapted Sources
Attributes of PPE in Designing Public Parks in Malaysia	Public Participation	Public perception towards the attributes of PPE in designing public parks in Malaysia	1. Democratic governance 2. Resilience community 3. Healthy mental wellbeing 4. Bottom-up public policy 5. Sustainable development 6. People-centred development 7. Interaction between public and local authority 8. Public to play significant role in the local governance 9. Enhance public awareness and responsibility	[1,2,5–8,10,14,18,19,24,30,31,33,35,36,38,40]
1. Development Stage (DS)	Public Participation	Public opinion on the development stage	1. Pre-design 2. Concept design 3. Construction stage 4. Post occupancy	[34,38,47–52]
2. Method of Approach (MA)	Public Participation	Public opinion on the method of approach	1. Public dialogue 2. Townhall presentation 3. Public meeting 4. Design charrette 5. Complaint's bureau 6. Formal consultation 7. Interactive workshop 8. Evaluation 9. Collaborative communication process 10. Public presentation 11. Web-based	[34,35,38,47–52]
3. Type of Public (TP)	Public Participation	Public opinion on the type of public	1. Business owner 2. Community 3. Property owner 4. Residents 5. Residents' representative 6. Residents' association 7. Non-governmental organisation	[34,47–52]
Public Parks Design Criteria (PPDC)	Public Parks	Public opinion on the design factor in designing public parks	1. The parks facilities 2. The landscape elements 3. Health promoting function 4. Psychological—benefits mental wellbeing 5. Interrelation between community 6. Recreation facility 7. Relaxation facility 8. People friendly design 9. Public engagement 10. Activated edges 11. Permeability 12. Place trigger memory 13. Cultural and historical meanings 14. Sociability 15. User and activities 16. Good accessibility and linkage 17. Degree of comfort and image 18. Self-identity public space 19. Group identity public space	[23,25,55,57–59,65–67]

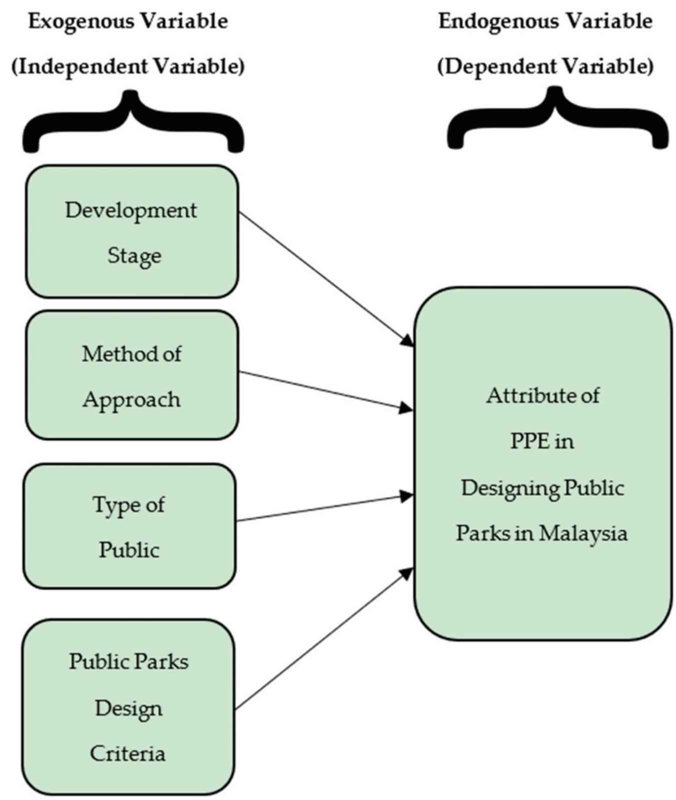

Figure 3. A conceptual framework of PPE in designing public parks in Malaysia.

8. Conclusions

PPE in general is not a common practise in local civil policy in Malaysia, despite the mandate given to the LA21 to support the SDGs and the notion of democratic governance. This research determines one dependent variable and four independent variables. The endogenous variable is the attribute of PPE in designing public parks in Malaysia, while the four exogenous variables are the development stage, method of approach, type of public, and public parks design criteria. The contribution of this paper includes public participation in civil policy in designing public parks as it demonstrates the public's responsive notion towards sustainable development in Malaysia. Consequently, the table of operational definition of the construct, the table of variables and measurement of PPE, and the conceptual framework of the variables for PPE in designing public parks in Malaysia represent the outcome of the research.

The process of obtaining the variables and indicators for PPE in designing public parks in Malaysia is shown in Figure 4. This research is limited to the context of Malaysia as the design framework is place-dependent. A further investigation into the PPE framework in designing public parks in Malaysia will be conducted to measure the relationship between endogenous and exogenous variables. Furthermore, it is highly recommended to further investigate the PPE design framework for other public facilities, such as sports facilities and health facilities.

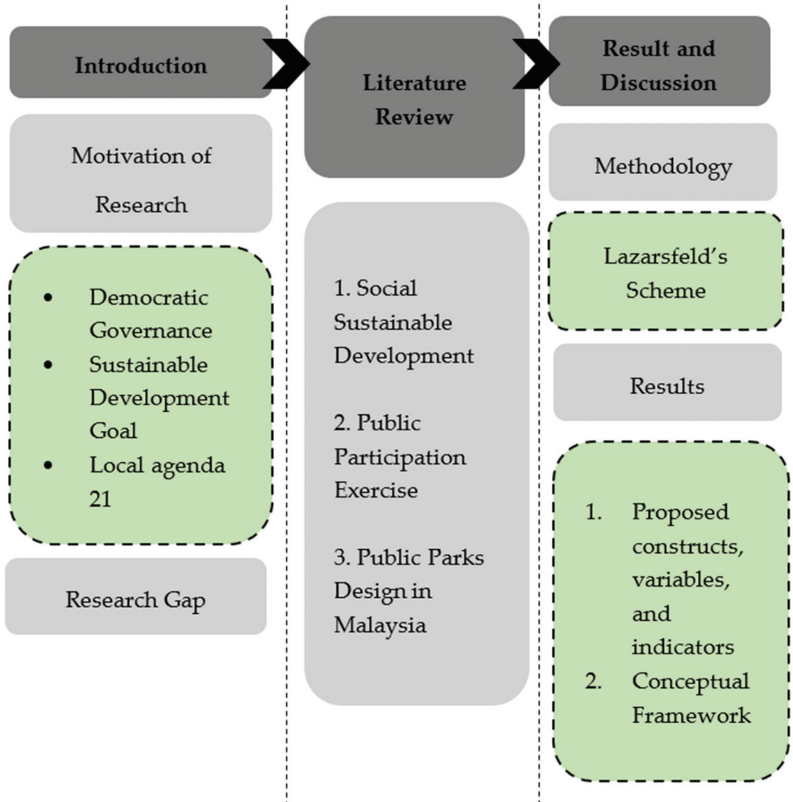

Figure 4. Structure of paper.

Author Contributions: U.N.S. carried out the study and the main drafter for the article; M.K., M.D.P. and T.J.D. involved in supervising the work and contributed to the revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by University of Reading-Malaysia.

Conflicts of Interest: The authors declare no conflict of interest.

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Environmental Footprint and Economics of a Full-Scale 3D-Printed House

Hadeer Abdalla [1], Kazi Parvez Fattah [1,*], Mohamed Abdallah [2] and Adil K. Tamimi [1]

[1] Department of Civil Engineering, American University of Sharjah, Sharjah P.O. Box 26666, United Arab Emirates; hadeer.s.abdalla@gmail.com (H.A.); atamimi@aus.edu (A.K.T.)
[2] Department of Civil and Environmental Engineering, University of Sharjah, Sharjah P.O. Box 27272, United Arab Emirates; mabdallah@sharjah.ac.ae
* Correspondence: kfattah@aus.edu

Citation: Abdalla, H.; Fattah, K.P.; Abdallah, M.; Tamimi, A.K. Environmental Footprint and Economics of a Full-Scale 3D-Printed House. *Sustainability* **2021**, *13*, 11978. https://doi.org/10.3390/su132111978

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 22 September 2021
Accepted: 26 October 2021
Published: 29 October 2021

Abstract: 3D printing, is a newly adopted technique in the construction sector with the aim to improve the economics and alleviate environmental impacts. This study assesses the eco-efficiency of 3D printing compared to conventional construction methods in large-scale structural fabrication. A single-storey 3D-printed house was selected in the United Arab Emirates to conduct the comparative assessment against traditional concrete construction. The life cycle assessment (LCA) framework is utilized to quantify the environmental loads of raw materials extraction and manufacturing, as well as energy consumption during construction and operation phases. The economics of the selected structural systems were investigated through life cycle costing analysis (LCCA), that included mainly the construction costs and energy savings. An eco-efficiency analysis was employed to aggregate the results of the LCA and LCCA into a single framework to aid in decision making by selecting the optimum and most eco-efficient alternative. The findings revealed that houses built using additive manufacturing and 3D printed materials were more environmentally favourable. The conventional construction method had higher impacts when compared to the 3D printing method with global warming potential of 1154.20 and 608.55 kg CO_2 eq, non-carcinogenic toxicity 675.10 and 11.9 kg 1,4-DCB, and water consumption 233.35 and 183.95 m^3, respectively. The 3D printed house was also found to be an economically viable option, with 78% reduction in the overall capital costs when compared to conventional construction methods. The combined environmental and economic results revealed that the overall process of the 3D-printed house had higher eco efficiency compared to concrete-based construction. The main results of the sensitivity analysis revealed that up to 90% of the environmental impacts in 3D printing mortars can be mitigated with decreasing cement ratios.

Keywords: additive manufacturing; life cycle assessment; life cycle costing; sustainable construction; concrete

1. Introduction

The construction sector is responsible for significant environmental stresses, consuming 48% of global supplied energy on an annual basis and depleting the natural resources [1]. In addition to exploitation of materials, manufacturing of construction materials and operational works are responsible for 38% of worldwide greenhouse gas emissions [2]. The sustainable development goals demand continuous monitoring of emissions and potential health risks of the implemented system. Understanding the environmental impacts of infrastructure and construction practices aids in developing efficient energy techniques. Moreover, low fatalities and injuries are common in the construction industry which encourages the automation of construction-related techniques. Furthermore, automation of construction activities is preferred to account for low productivity rates. More specifically, labour productivity, which is defined as construction workload expressed in units per man hour, plays a key role in the capital investment of the project as well as meeting the global housing demand [3]. Current rates of productivity combined with an increase in urbanization has been a concern in sustaining the increasing housing demand which is estimated to reach 230 billion m^2 in the next 40 years [4]. As a result, additive manufacturing has been proposed as an alternative to conventional construction. Additive manufacturing or 3D printing is being assessed as a potential solution to current methods of construction for energy reduction, automation of construction methods, mitigation of environmental impacts, and cost savings [2].

In addition to the consideration of materials, the construction industries face a continuous challenge of having to complete construction of the structures within the shortest time, while still having to maintain safety and work quality. Innovations in the construction industry have explored different techniques to account for the technical drawbacks and environmental impacts associated with conventional construction techniques. Automation of activities in the construction site have been proposed, particularly additive manufacturing or 3D printing technology, to improve construction practices [5]. The additive manufacturing process operates by continuously adding a layer-by-layer extrusion paste. It is also defined as a method of digitally fabricating materials via printers [6]. Each 3D printed layer is a 2D representation from the computer aided design (CAD) or building information modelling (BIM) model that is deposited to the printer [7]. Digital fabrication enables customization and assembly of complex designs. Attempts have been made to utilize 3D printing techniques in the construction industry and evaluate the sustainability and implications on the economic, environmental and social aspects [5]. A case study in China demonstrated the potential of large-scale 3D printing, whereby several houses approximately 200 m^2 have been built using high quality cement alongside glass fiber to enhance strength [8]. Another application represented the functionality of 3D printing by prefabricating the components of a 5 storey building and later assembled on site [9]. Wu et al. [7] asserted the importance of selecting appropriate material to attain the desired level of detailing and withstand the loading on the structure. A Complex design of a 12 m $\times$ 12 m $\times$ 12 m house with complex details has been successfully implemented using 3D printing [7]. The house was printed with glass reinforced plastic extrusion paste which was able to resist corrosion, aging and water seepage.

Digital fabrication foresees the potential of mitigating the environmental constraints and reducing the materials used in building sector [4]. Moreover, utilization of 3D printing technology in the construction industry can potentially lead to a reduction of energy supply and overall emissions up to 5% by 2025 in large scale projects (i.e., large filament size) [4]. The environmental performance of implementing additive manufacturing methods in the construction sector has been explored. Several studies investigated the environmental impacts of additive manufacturing in the construction industry using life cycle assessment (LCA) systematic framework. Sinka et al. [10] explored the environmental impacts of different 3D printing cement and gypsum binders. The results revealed that gypsum-based mixes had an overall reduction in GWP of 84% as a result of lower energy use. Other studies investigated the performance of different construction elements. Mrazović et al. [11] compared the environmental performance of conventional and 3D-printing of different metal building elements (such as steel frame and steel brackets). Additive manufacturing proved to be compatible for construction which achieved 40% lower environmental impact (compared to conventional manufacturing methods) [11]. Agustí-Juan et al. [12] utilized LCA to identify the viability of constructing walls with varying complexities using 3D printing compared to conventional construction techniques. The results revealed that complexity of structures did not increase the overall costs and the design of the structure was not responsible for environmental constraints as opposed to conventional building techniques. Moreover, the literature has been focused on studying the environmental impacts particularly, climate change potential and energy consumption as they have been reported to have the greatest effects [13]. The climate change impact of conventional walls was 75%, whereas the 3D-printed wall had negligible impact (2%). Climate change was reported to have significant environmental impacts as a result of the GHGs emissions during the material production, manufacturing, transport and construction phases [12]. Another case study assessed the environmental impacts from the materials production and operation of 3D-printed wall and roof structures [14]. Results highlighted the minimal impacts of operation of fabrication robots, while the mainstream energy consumption originates from material production. Mohammad et al. [15] also investigated the environmental performance of 3D printed walls compared to conventional reinforced concrete ones. The 3D concrete printing (3DCP) scenarios yielded lower emissions in terms of global warming potential and acidification potential. The study further combined conventional reinforcement with 3DCP, and the environmental impacts were still lower than conventional construction techniques.

All of the above mentioned studies only assessed the environmental impacts of different structural elements, on the other hand, Han et al. [16] developed a 3D model simulating a 3D-printed house. The emissions were calculated using equations from the literature. The findings of the study revealed that construction using 3D printing technology resulted in higher emissions when compared to cast in-situ conventional concrete. Moreover, the study attributed the high emissions to cement production processes. Another study compared the environmental impacts of 3D printing and conventionally built house [17]. The study utilized concrete and cob (a sustainable material) to run the analysis. The 3D printing technology acquired lower impacts compared to conventional concrete construction. In terms of materials, cob attained lower impacts, nevertheless, 3DCP binder consumed less energy. In terms of economic viability, a case study in the United Kingdom investigated the financial feasibility of 3D printed residential structures using life cycle costing analysis (LCCA). The findings of the study revealed savings up to 35% when compared to conventional houses due to lower material consumption and eliminated labour cost [18].

Conventional construction is responsible for significant environmental and safety risks which compels introduction of new efficient and feasible alternatives. Digital technologies, particularly 3D printing, have been successfully implemented in the field of construction. Evaluation of the systems encompasses quantification of environmental impacts using the standard LCA tool and economic value of building structures using conventional manufacturing methods versus 3D printed methods. The capital and energy costs incurred over the life cycle of the examined structural systems are estimated using life cycle costing analysis. An eco-efficiency analysis is used to combine the results of the LCA and LCC into a single framework to assist decision makers with the choice of the optimum construction method taking account the environmental and economic perspectives. A search of recent publications (Table 1) in this field showed that most of the studies focus primarily on developing the 3D printing mortar and utilizing sustainable materials. The literature lacks comprehensive and integrated environmental and economic assessment of large-scale 3D printed buildings. Since this technology is under development, more studies are needed to optimize the materials and methods used from both environmental and economic perspectives. This study aims to enrich the literature with comprehensive assessment of such a knowledge base which is essential to drive the shift towards digital fabrication construction. This study provides a comparative assessment of a 3D-printed structure compared to conventional concrete construction. The comparative assessment is applied on an actual single-storey house located in Dubai, United Arab Emirates (UAE).

Table 1. Summary of life cycle assessment-based studies in the construction sector.

References	Boundary	3D-Printed Unit	Stages	Impact Assessment Method	Software	Database	Functional Unit	Evaluated Impacts
[6]	-	Hypothetical house model	Material acquisition; construction Phase	Building Life-cycle Sustainability Impact Assessment Standard	-	Local data; Literature review	1 m^2 wall; 1 m^2 roof	Global warming potential; Acidification; Photochemical Pollution; Eutrophication
[10]	Cradle to gate	Cube Samples	Production	IPCC 2013 GWP100a	SimaPro 8	Ecoinvent 3; Previous studies	1 m^3 binder	Global warming potential
[15]	Cradle to gate	Wall structure	Production; Construction	TRACI	GaBi 9.2.1.68	GaBi 2020	1 m^2 external load-bearing wall	Global warming potential; Acidification potential; Eutrophication potential; Smog formation potential; Fossil fuel depletion
[17]	Cradle to Site	One-storey house	Raw materials; Transportation; Construction	ReCiPe Midpoint (H) v1.03	SimaPro 9.0.0.35	Ecoinvent v3.1; Literature; Local data	1 m^2 load-bearing wall	global warming; Stratospheric ozone depletion; Fine particulate matter formation; Marine eutrophication; Land use; Mineral resource scarcity; Water use
[11]	-	Metallic building components	Raw material processing; Manufacturing; Transportation	-	SimaPro	Local data	1 steel bracket	Energy consumption; Human health; Water source depletion; Abiotic depletion of fossil fuels
[12]	Cradle to gate	Wall Structure	Raw material extraction; Transport; Materials production; Robotic fabrication	Recipe Midpoint (H) v1.12	SimaPro 8	Ecoinvent v3.1	1 m^2 of wall	Climate change; Ozone depletion; Human toxicity; Terrestrial acidification; Freshwater eutrophication; Terrestrial ecotoxicity; Freshwater ecotoxicity; Water depletion; Metal depletion; Fossil depletion
[2]	Cradle to grave; Cradle to gate	Wall and roof structures	Materials production; Operation energy	Recipe Midpoint (H) V1.06	SimaPro 8	Ecoinvent v2.2	1 m^2 of wall and roof structures	Climate change; Ozone depletion; Human toxicity; Water depletion; Metal depletion; Fossil depletion

2. Methodology

In this section, the structural system components and configurations were discussed, followed by a description of the 3D printing technology utilized to construct the house understudy. Moreover, the standard methods of the environmental and financial life cycle analyses were presented.

2.1. Structural Systems

A single-storey detached house located in the UAE was selected as a case study. Figure 1 shows the plan and elevation layouts of the selected house with a net floor area of 90 m^2 and total height of 4.5 m. The proposed structural systems include (1) conventional construction method using cast in place concrete walls and flat slab with beams and columns, and (2) additive manufacturing using self-reinforced printable mortar. It should be noted that the construction time frame of the 3D printed house was approximately 2 weeks, whereas the conventionally built house was 4 months based on local engineering contractors. The timeframe excludes the HVAC, plumbing, and finishes works as they are similar in both houses.

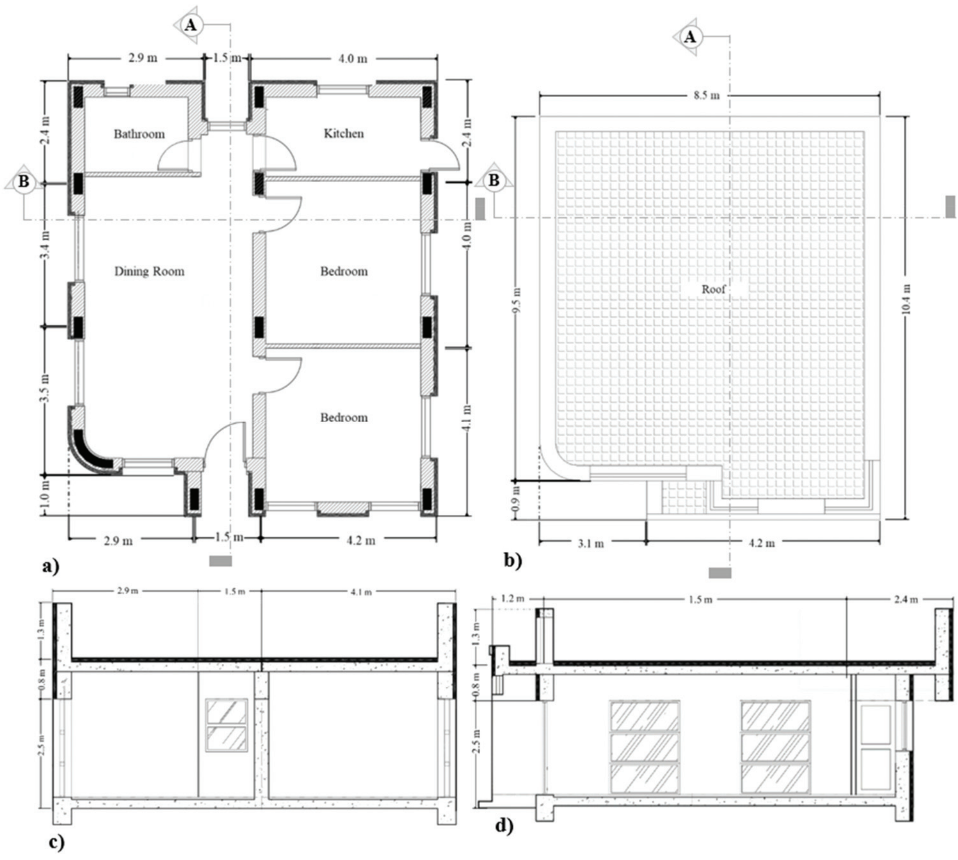

Figure 1. The technical drawings for (**a**) ground floor, (**b**) Site plan, (**c**) section A, and (**d**) section B.

Table 2 shows the details of the structural elements utilized for conventional concrete construction. The columns and beams have a cross-sectional area of 800 and 1600 cm^2, respectively, whereas the slab has a total area of 376 m^2. Wood formwork was utilized in construction of the columns, beams, and slabs of 3.8 m^2, 47 m^2, and 400 m^2, respectively.

There are 0.03, 0.04, and 0.245 m^3 of columns, beams, and slabs per m^2. The design of the steel reinforcement, confinement steel, and stirrups were conducted according to American Concrete Institute (ACI) standards [19]. Moreover, the considered primary loads in this study were the typical dead and live loads defined by American Society of Civil Engineers (ASCE) 7–10 [20].

Table 2. Dimensions and reinforcement of structural elements.

Element	Component		Value
External Wall	Specifications	Length (m) × Height (m)	37.8 × 2.95
		Required concrete (m^3)	6.19
		Total concrete bricks	15,478
Column	Specifications	Length (cm) × Width (cm) × Height (cm)	40 × 20 × 295
		Total number	13
	Reinforcement	Rebar size	10
		Spacing (cm)	25
		Total cross-sectional area (cm^2)	20.5
Beam	Specifications	Length (cm) × Width (cm)	40 × 40
	Reinforcement	Rebar size	22
		Number of rebars	6
		Total cross-sectional area (cm^2)	23.22
Slab	Specifications	Slab depth (cm)	0.25
	Reinforcement *	Rebar size	10
		Spacing (cm)	20
		Total number of main reinforcements	78
		Total number of secondary reinforcements	95

* The design details include main and secondary reinforcing rebars.

The specifications and properties of the cementitious mortar used for conventional concrete and 3D printing mixtures are summarized in Table 3. The conventional concrete mix has cement, sand, and aggregates ratio of 1 to 1.5 to 1.3, respectively, while the cementitious 3D printing mortar consists of 70% sand and 30% binder (cement and additives) [21]. Moreover, the mix of the 3D printing mortar is characterized by low sulphate and chloride content which was designed for structural and non-structural elements.

Table 3. Properties of 3D printing and conventional construction materials *.

System	Components *	Specifications
Conventional Concrete **	Ultimate Compressive Strength (MPa)	35
	Water/cement Ratio	0.5
	Maximum Aggregate Size (mm)	20
	Slump (mm)	20–80
	Mixing Water (kg/m^3)	200
	Density Concrete (kg/m^3)Vt	2355
3D Printing Mortar *	Grain Size (mm)	3
	Initial Set (min)	3
	Final Set (min)	5
	Layer Thickness (mm)	40
	Ultimate Compressive Strength (MPa)	40
	Tensile Strength (N/mm^2)	4
	Flexural Strength (N/mm^2)	6
	Specific Heat Capacity (J/g·K)	1.1
	Air Void Content (%)	5.3

* Compiled from [21] and ** [22].

2.2. Additive Manufacturing Technology

The application of a large-scale 3D printed structure entails using an extrusion method, in which the structure was built by adding layers of the prepared mortar through a nozzle. The digital STL (STsereo Lithography) formatted file was converted into several 2D layers by means of CyBe CHYSEL software [21]. Moreover, Table 4 summarizes the input parameters required for the operation of the mobile 3D printer. Furthermore, the printing process was regulated through a control unit which operates the mixing system to pump the mortar through a hose into the robotic arm. The mortar was added layer by layer at the specified coordinates via a 40 mm nozzle. The 3D printing filaments were characterized by a zigzag pattern and the printed walls were hollow (39 cm).

Table 4. Operating parameters of the 3D printer used.

Parameter	Value
Print Speed (mm/s)	50–600
Travel speed (km/h)	3
Precision (mm)	1:1:1
Layer resolution (mm)	10–50

2.3. Life Cycle Analysis

The environmental impacts and burdens on the ecosystem of production, construction, operation, and disposal stages over the life cycle of a system was quantified using the LCA systematic framework. The international organization for standardization (ISO) developed ISO 14044 and ISO14045 to unify the approach of evaluating the load on the environment, address the resulting ecological impacts and identify potential performance enhancement over the lifecycle of the systems [22,23]. Two LCA approaches are commonly investigated in the construction industry, namely, cradle to grave and cradle to site. The first method includes all materials and processes in a comprehensive assessment, while the second approach focuses on certain aspects of the construction project such as the materials [17]. In this study, a cradle to site approach was selected and the LCA was performed in four stages including, goal and scope, life cycle inventory (LCI), and life cycle impact assessment (LCIA) analysis, and results interpretation. Stage one of the LCA involves defining goal and scope as well as the system boundaries and functional unit. The LCI phase includes collection of data, while the third sage (LCIA) examines the contribution of these data to selected impact categories. Stage 4 involves assessment of the results and identifying study limitations. SimaPro 9.0 developed by PRé Sustainability was utilized to implement the LCA framework using Ecoinvent 3.0 [24].

2.3.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental performance of a 3D printed house compared to conventional construction techniques. Measuring the functionality of both construction techniques output was achieved by selecting a reference or a functional unit; 1 m^2 of the single-storey house surface area was selected for simplification of inventory data calculations. Figure 2 shows the boundaries of the examined systems including, production and manufacturing of materials, construction, operation, maintenance, and end of life phase. However, the LCA assessment was limited to material extraction, construction, energy consumption, and transportation during the operation phase. Similar components in both structural systems were excluded i.e., earthworks, HVAC systems and finishes. The labour and end of life phase were excluded from the study as they were found negligible [17]. Moreover, all of the reviewed literature (Table 1) excluded the end of life or demolition phase as a result of lack of available data.

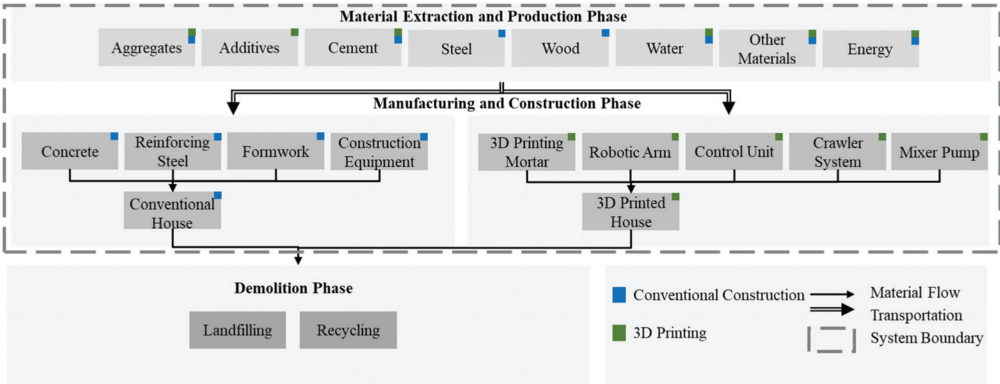

Figure 2. System boundaries of 3D printing and conventional construction of the examined house.

2.3.2. Life Cycle Inventory

The input data related to 3D printing and conventional construction were gathered from local suppliers, Ecoinvent database and the literature. Such technical data include foreground components such as quantity of materials, transportation, and energy consumption. Moreover, background data of the environmental burdens were assigned to the foreground processes and components. Table 5 lists the inventory data of the examined structural systems, in which energy consumption of the equipment utilized on-site can be measured from the power demand and operation time of such machinery.

Table 5. Life cycle inventory data of the examined systems per functional unit.

Data	3D Printing *	Conventional Construction **
Steel (kg) ***	-	200
Fly Ash (kg)	170	-
Micro silica (kg)	180	-
Superplasticizer (kg)	10	-
Viscosity modifying admixture	98,103	-
Cement (kg)	430	300
Coarse Aggregate (kg)	-	4680
Fine Aggregate (kg)	645	4680
Water (kg)	180	190
Concrete (kg)	-	340
Wood (m^2)	-	5
Energy Consumption (kWh)	21	68 ***
Material Transportation Distance (km)	100	100
Printer Transportation Distance	6500	-

* [25] ** [2,26] *** [27].

2.3.3. Energy Consumption

The energy consumption rates in the construction sector reach up to 40% of the total energy demand [28]. The primary electricity consuming sources are the cooling systems as a result of the harsh climate of the UAE with temperatures reaching up to 48 °C, hence the construction sector is constantly exploring efficient heat insulating materials to prevent overheating and humidity increase. The European commission has reported that buildings are responsible for at least 40% of the total energy consumption Particularly, air conditioning is a major energy consuming element in a building, hence reduction of cooling load demand by thermal insulation through construction materials inducing low heat transfer can save up to 50% of the building energy demand [29]. The energy savings for the 3D-printed and conventional concrete house were calculated based on the difference between the microclimate and the air temperature surrounding the structure as well as the thickness of the structural elements (external walls and roof). The ISO standard (EN ISO 6946:2008) reported the key factor to indicate the thermal properties of the building is heat transfer (U) in which lower U-value indicates higher energy savings [30]. The U-value [31] and the energy transfer or heat flow (Q) [32] were calculated using Equations (1) and (2) [33,34]:

$$U = \frac{k \times A}{l} \quad (1)$$

$$Q = \Delta T \times U \times A \quad (2)$$

where U is the thermal transmittance ($W/m^2 \cdot K$), k is the thermal conductivity of a material ($W/m \cdot K$), A is the plane area of (m^2), l is the thickness of material (m), Q is heat flow (W), and ΔT is the temperature difference between external and internal structural element surface (°C). The heat transfer through individual rooms of the house, the windows, and doors was calculated. The design temperature outside and inside the house was specified by local guidelines as 46 °C and 24 °C, respectively. Moreover, the U-value of the floor and roof slabs were obtained from local standards and they were compared to ASHRAE (American society of heating, refrigerating and air-conditioning engineers) specifications based on perimeter to area ratio and thermal resistance values [33,34].

2.3.4. Life Cycle Impact Assessment

The environmental impacts of the digitally fabricated and conventionally built house were estimated using ReCiPe 2016 V1.03 midpoint (H) indicators [35]. The method represents the impacts of a global representative and addresses 18 different categories. The impact mechanisms include climate change or global warming potential (kg CO_2 eq) ozone layer depletion (kg CFC-11), terrestrial acidification potential (kg SO_2), marine eutrophication (kg N), freshwater eutrophication (kg P), human toxicity (kg 1,4dichlorobenzeen), particulate matter formation (kg PM2.5), ionizing radiation (kBq Cobalt-60), photochemical oxidant formation (kg NMVOC), terrestrial, freshwater, and marine ecotoxicity (kg 1,4dichlorobenzeen), agricultural and urban land occupation (m^2), freshwater depletion (m^3 water consumed), mineral resource depletion (kg Copper (Cu)), and fossil fuel scarcity (kg oil) [35]. The impact categories represent the effect on the environment and are based on weighted and normalised factors [36].

2.4. Life Cycle Costing Analysis

The financial viability of 3D printing and conventional construction techniques was investigated by calculating the construction and energy use costs. The capital cost of the examined projects included procurement and manufacturing of construction materials e.g., cement, steel, wood, aggregates, and admixtures, as well as construction activities. The present value (PV) of the electricity costs of the systems was estimated for a period of 50 years, which was carried out via LCCA framework to estimate the present worth of the energy consumed in the 3D printed and conventionally constructed house. Moreover, the time value of the cashflow was considered in this study using a local-based discount rate of 3% [37]. Equation (3) is used to calculate the present value [38]:

$$PV = \sum_{t=1}^{T} C_{o,t}(1+r)^{-t} \quad (3)$$

where C_o is the cash outflow (USD) of year t, r is the discount rate (%), and T is the lifespan of the project.

2.5. Eco-Efficiency Analysis

Selection of an optimum alternative and identification system trade-offs can be accomplished through an eco-efficiency analysis. Such analytical framework functions by agglomerating LCC and LCCA results, which are plotted into a single portfolio [23]. The ratio method is the most commonly used approach to determine the eco-efficiency of a system or a product [39–41]. In this study, the ratio method was employed which is defined as the ratio of economic indicator to environmental performance of the examined system as shown in Equation (4) [41].

$$\text{Eco} - \text{efficiency} \; = \frac{\text{Environmental Performance}}{\text{Economic Value}} \tag{4}$$

The Environmental indicator in this research study was retrieved from the LCA SimaPro software represented by a normalized and weighted single value aggregating all the midpoint categories. Moreover, the present value was utilized which corresponds to the economic indicator of each assessed system. An eco-efficiency portfolio combining environmental and economic scores was plotted for the selection of the most eco-efficient system and assessing the trade-off among the studied alternatives.

3. Results and Discussion

3.1. Environmental Analysis

The LCA results analysed in this section represent a comparison of additive manufacturing and conventional construction techniques in terms of the environmental impacts. The environmental impacts of the studied scenarios were calculated via SimaPro in 4 stages—characterization, damage assessment, normalization, and weighing [24]. During the first stage (characterization), the materials were multiplied by a factor that represents the relative contribution. The damage assessment facilitates the use of endpoint categories, where impacts with the same units can be added. Normalization stage enables comparison among scenarios in which the impacts are divided by a reference. The weighing phase is typically performed by multiplying the impact categories with a factor and adding them to result in a single score. This score is an indication of the total impacts. Table 6 provides detailed environmental performance scores for each impact category of the 3D-printed and concrete-based house. Most impact categories had significantly higher values for the conventional construction method. Among the highest scored impacts in the conventionally built house were global warming, non-carcinogenic toxicity, water consumption, carcinogenic toxicity, and fossil resource scarcity. Cement production contribution to global warming potential (1154.2 kg CO_2 eq) was approximated to be 70%. Moreover, reinforcing steel production and manufacturing comprised 98 and 97% of the total emissions of non-carcinogenic and carcinogenic toxicity with relative impact of 675 and 169 kg 1,4-DCB, respectively. Furthermore, fossil scarcity (150 kg oil eq) was attributed to the manufacturing of steel (60%) and cement (38%), and the high-water consumption was mainly due to addition of water during concrete manufacturing. The Global warming potential and water consumption had relatively high impacts for the 3D-printed house. As for the concrete constructed house, global warming potential (609 kg CO_2 eq) was high due to production and manufacturing contributing 97% and water consumption with a volume of 184 m^3 per functional unit was attributed to water demand during 3D mortar preparation. The endpoint indicators were represented by a single score that combines all the inventory results in one factor. For the 3D-printed and the conventional house, the human health category had substantially higher impacts compared to effect on ecosystem and natural resources indicators. Human health category caused 93 and 88% of overall emissions of the conventional construction and 3D printing scenarios, respectively.

The obtained results from SimaPro were normalized and weighted to provide holistic assessment. Normalization enables for a coherent interpretation of the characterized environmental impact categories through referring to a reference scheme, followed by weighting which emphasizes the relative significance of the impact indicators. Figure 3 shows the relative environmental impacts of the examined systems analysed based on different impact categories. It is evident that 3D printing has an overall lower impact across all categories. The 3D printing scenario performed more than 50% better for the majority of the categories which may be attributed to the material efficiency compared to the conventional scenario. Typically, conventional building requires formworks and reinforcing steel, which are absent in the 3D printing scenario. Therefore, all emissions related to the production, manufacturing, transportation, and fabrication of materials are reduced. The damage to the ecosystem was minimal where the midpoint categories pertaining to freshwater marine, and terrestrial species had relatively low percentage (0–7%). Though all categories of 3D printing had lower impacts, the water consumption category was only 20% better for the 3D printed house due to high water use during cement production processes and electricity generation, which is common to both construction methods.

Table 6. Environmental inventory results of the examined structural systems.

	Impact Category	3D Printing	Conventional Construction
Midpoint Indicator	Carcinogenic Toxicity (kg 1,4-DCB)	4.30	168.60
	Fossil Resource Scarcity (kg oil eq)	2.90	150.00
	Fresh Water Ecotoxicity (kg 1,4-DCB)	0.23	23.90
	Fresh Water Eutrophication (kg P eq)	0.002	0.20
	Global Warming (kg CO_2 eq)	608.55	1154.20
	Ionizing Radiation (kBq Co-60 eq)	2.58	16.50
	Land Occupation (m^2a crop eq)	0.40	6.80
	Marine Ecotoxicity (kg 1,4-DCB)	0.34	33.60
	Mineral Resource Scarcity (kg Cu eq)	0.08	30.80
	Non-carcinogenic Toxicity (kg 1,4-DCB)	11.9	675.10
	Ozone Depletion (kg CFC11 eq)	1.90×10^{-4}	3.20×10^{-4}
	Particulate Matter Formation (kg PM2.5 eq)	0.02	1.70
	Photochemical Oxidant Formation (kg NO_x eq)	0.06	2.84
	Terrestrial Acidification (kg SO_2 eq)	2.50	4.10
	Water Consumption (m^3)	183.95	233.35
Endpoint Indicator	Human Health (Pt)	5.30	18.63
	Ecosystems (Pt)	0.64	1.30
	Resources (Pt)	0.05	0.20

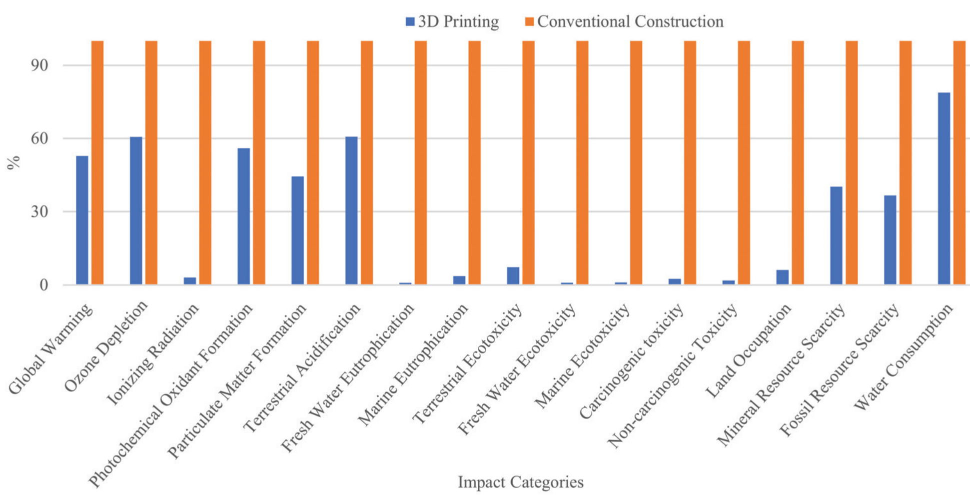

Figure 3. Relative environmental impacts of 3D printed and conventional constructed houses.

In the digitally fabricated house, cement production phase contributed (more than 95%) to most of the impact categories i.e., global warming, ozone depletion, terrestrial acidification and ecotoxicity, human carcinogenic impacts, and fossil and mineral resource scarcity as shown in Figure 4. Moreover, material extraction and production of the utilized admixtures was a major contributing process to land occupation, freshwater eutrophication, ionizing radiation, marine and freshwater ecotoxicity, and non-cariogenic human effects, with 99, 98, 97, 61, and 40%, respectively. Electricity and transportation obtained the lowest ratio in all environmental impact categories with impacts ranging between 0 to 2%.

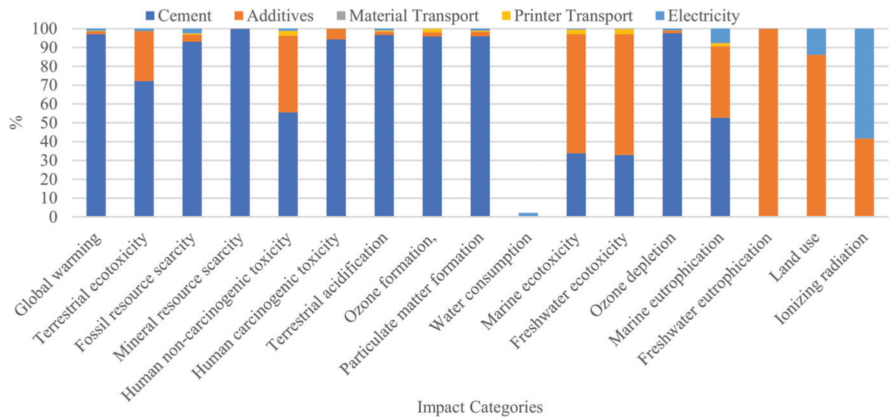

Figure 4. Contribution of 3D printing processes to the overall environmental impact.

The contribution of the different impacts i.e., production of cement and steel, manufacturing of concrete, transportation, as well as electricity production are shown in Figure 5. The cement production shows the highest contribution in all impact categories due to significant consumption of raw materials and energy, the greenhouse gas emissions during manufacturing phase, and the release of bulk amounts of waste. Moreover, the environmental analysis revealed that reinforcing steel production and manufacturing processes had a primary impact on freshwater eutrophication (99%), land occupation (98%), terrestrial and marine ecotoxicity (93%), carcinogenic, non-carcinogenic and freshwater ecotoxicity (89%), fossil resource scarcity (60%), and global warming (41%). Similar to the conventional house results, the electricity scored the lowest in all categories except ionizing radiation (11%). Overall, the exploitation of materials, energy use, and transportation during manufacturing of concrete components poses the highest environmental risks as can be deduced from Figure 5.

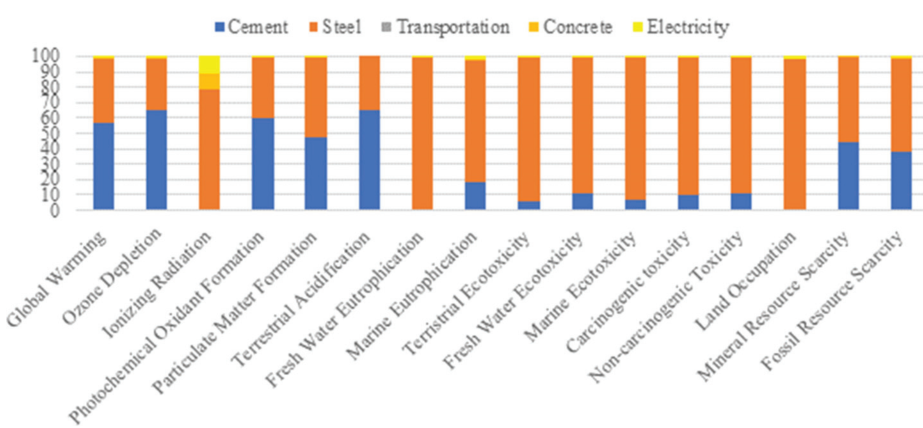

Figure 5. Relative contribution of conventionally constructed house processes to the environmental impact.

The results of this study agree with the outcomes of [2,12,17], which reveals that 3D printing structures outperform the conventional construction methods in terms of overall environmental impacts. The main difference in this study was conducting the analysis for the entire house, whereas [2,12] studied the impacts on individual elements (wall, roof, and a concrete slab) with varying design complexities and included the operation phase for the self-shading wall element. Moreover, the 3D printing mortar ratios and components in this study was tested for an implemented project in the UAE, while Agustí-Juan and Habert [2] adopted a fiber reinforced concrete from the literature and Alhumayani et al. 16 tested out three different mixes also compiled from the literature and compared the results. Furthermore, Agustí-Juan et al. [12] designed a high performance 3D printing concrete which was found to increase the GHG emissions when compared to conventional concrete mix.

3.2. Operational Energy

The cooling energy demand for the 3D-printed and conventionally constructed house was calculated considering the thermal transmittance of the construction mortars. Table 7 summarizes the cooling systems calculation results for the 3D-printed and conventionally constructed house. Overall, the total heat transfer (gain) of the conventional building system was 5% more than the 3D printed house. The 3D printed house acquired less heat gain due to higher material thickness and thermal transmittance (K). In other words, the lower thermal conductivity and thickness of materials the lower heat transmission. Another contributor to low heat conduction is U-value, where the slabs of a 3D-printed house had lower U-values compared to the conventional concrete house. On the other hand, the insulating properties of the 3D-printed wall including an air cavity had a much higher U-value (3.75 W/m^2·K) which is in close proximity to the concrete wall (3.6 W/m^2·K).

Table 7. Insulation parameters and cooling demand results.

Parameter	3D Printing						Conventional System					
	Wall				Floor	Roof	Wall				Floor	Roof
K (W/m·K)	0.92						0.55					
R (m^2·K/W)	0.08				0.33	0.16	0.09				0.46	0.45
Thickness (m)	0.08				0.3	0.15	0.05				0.25	0.25
U (W/m^2·K)	3.75 *				0.27	0.10	3.6 *				0.44	0.44
Q (W)	W1 2189	W2 3424	W3 3123	W4 2783	201	519	W1 2157	W2 3374	W3 3077	W4 3742	858	858
Σ Q ** (BTU/h)	49,269						52,098					

* The wall U-value includes air cavity with thickness 0.04 m and R of 0.12. ** The total heat gain includes heat from doors and windows.

3.3. Economic Assessment

The economic analysis findings of the selected structural systems are summarized in Table 8. The results comprise capital costs of materials (local-based) including civil works and operational expenditures of cooling systems. The conducted present value over a 50-year design period indicates that conventional construction technique was the most expensive alternative (USD81,064) which was double the cost of the 3D printing. This can be attributed to the cost of concrete, and formworks which comprise 51 and 24%, respectively. The capital expenditures of concrete are associated with the purchase and manufacturing of various sub-components, mainly aggregates (USD10,795). Although the steel cost rate (USD500/ton) was the highest, it had the least contribution to the overall cost. On the other hand, the 3D printing technology was found to be 49% cheaper than the conventional construction scenario. The 3D printing excludes multiple aspects including construction components, e.g., concrete and formworks, as well as labor cost, thus reducing the overall capital costs. These results are in line with [18], where the 3D printing of houses contributed to 35% savings compared to conventional construction.

Table 8. Capital costs of construction components and operational expenses.

Component	Rate (USD/ton)	3D Printing	Conventional
Cement	15	45	44
Additive	220	8	-
Aggregate	15	10,795	10,795
Steel	500	-	1308
Concrete	60/m^3	-	25,147
Formwork	27/m^2	-	11,933
Present Value (USD)	**-**	**−40,955**	**−81,064**

Note: Positive present values signify revenues, whereas negative values represent costs.

4. Eco-Efficiency Analysis

The depicted results of economic and environmental performance ratios were plotted in an eco-efficiency portfolio as illustrated in Figure 6. The top-right corner distinguishes the low eco-efficiency alternative, while the bottom left corner of the plot area identifies the high eco-efficiency option. The conventional construction house had significantly lower eco-efficiency compared to 3D-printing. Upon comparing the operation phases of both houses, the results reveal similar eco-efficiency scores, which coincides with the LCC and LCA analyses. Moreover, the eco-efficiency index diagram orders the alternatives from the highest (bottom) to lowest (top) eco-efficiency. The 3D printing method was found to be the highest and conventional construction acquired the lowest eco-efficiency. The findings of eco-efficiency analysis showed that operation phase alone was negligible in the selection process of the optimum alternative, nevertheless the combined construction and operation phase revealed 3D-printing as the most eco-efficient option.

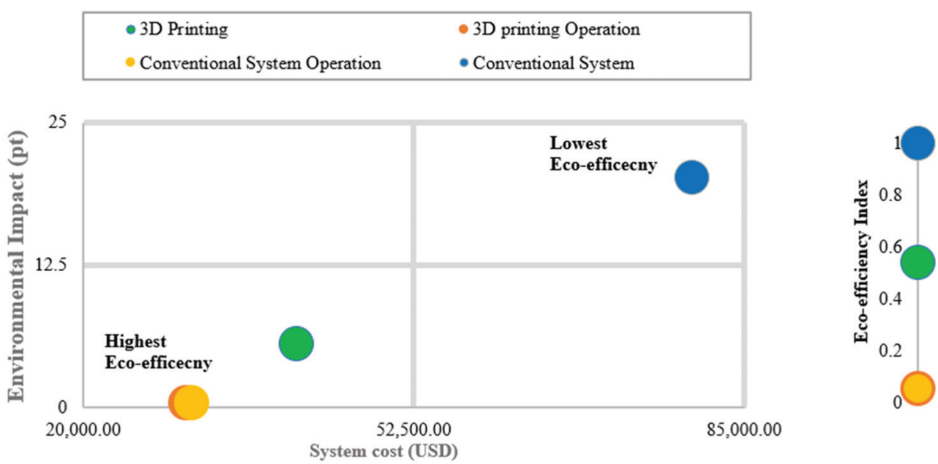

Figure 6. Eco-efficiency portfolio of 3D-printed and concrete-based house construction and operation phases.

5. Sensitivity Analysis

Several factors such as system boundaries, assumptions, and accuracy of inventory data affect the certainty of LCA and LCC results. Moreover, the 3D printing technology is still in the exploration and development stage and the data were compiled from the literature. A sensitivity analysis was conducted to account for the uncertainties in this study where the selected parameters are listed in Table 9. Different 3D printing binder mixtures were evaluated in the analysis to investigate the environmental impact of cement and coarse aggregates as they acquired the highest scores in the LCA results. The conventional concrete mix was also evaluated to investigate the effect of varying concrete and steel quantities [2,42].

Table 9. Parameters utilized in the sensitivity analysis for 3DCP and Conventional scenarios.

Parameter		Reference Value		Sensitivity Analysis Options			
				3D Printing *		Conventional	
		3D Printing	Conventional	Mix 1	Mix 2	Mix 1 **	Mix 2 ***
Life Cycle Analysis	Steel (kg) ***	-	200	-	-	560	61
	Fly Ash (kg)	170	-	165	165	-	-
	Micro silica (kg)	180	-	83	83	-	-
	Superplasticizer (kg)	10	-	8.3	8.3	-	-
	Viscosity modifying admixture	98,103	-	98,103	98,103	-	-
	Cement (kg)	430	300	580	300	53	10
	Coarse Aggregate (kg)	-	4680	1241	64	1135	1280
	Fine Aggregate (kg)	645	4680	-	-	-	2
	Water (kg)	180	190	232	190	231	822
	Concrete (kg)	-	340	-	-	7	140
	Brick (kg)					197	-
	Wood (m^2)	-	5	-	-	77	25
	Energy Consumption (kWh) ****	21	68	2.26	2.26	11	18
Life Cycle Costing	3D Printer (USD)	183,000	-	-	-	-	
	Electricity Tariff (USD/kWh)	0.081		0.07–0.101			

* Adapted from [15] ** [2], and *** [42], **** The energy consumed by machinery.

The concrete, steel, and cement production accounted for the highest environmental scores in the performed LCA. Figure 7 illustrates the results of the sensitivity analyses for the different 3DCP and Conventional mixtures. The results are presented relative to the conventional base scenario which obtained the highest impacts in all categories. The analysed mixtures had relatively small impacts contributing to 0–3% in all categories. Nevertheless, the 3DCP mix 1 and 2 contributed to the highest water consumption (474 and 391 m^3, respectively), followed by conventional mix 1 (390 m^3), conventional base scenario (233 m^3), the 3DCP base scenario (184 m^3), and the least water consumption was attained by conventional mix 2 (110 m^3). These results led to the conclusion that reducing cement quantities in 3DCP binder can reduce the overall environmental impacts by 90%. In conventional construction techniques replacing some concrete elements with bricks (such as conventional mix 2) can also reduce the environmental deterioration.

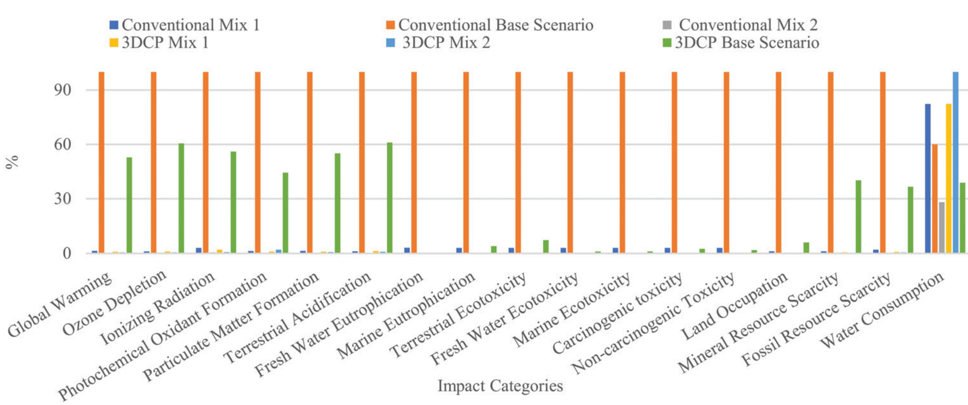

Figure 7. Sensitivity analysis results of different conventional and 3D concrete printing (3DCP) mixtures.

The LCC results of the different mixtures reveal significant differences from the original scenarios (Table 10). The 3DCP mix 1 and 2 showed almost similar results with a decrease of 20% from the original mix. This decrease can be attributed to the reduction of cement in mix 1 and mix 2. Conventional concrete mixtures 1 and 2 obtained a total cost of USD 33,073 and 31,451, respectively which is almost 60% less than the base scenario. Moreover, the cost of the 3D printer was added to the 3D printed house scenario while keeping all the other parameters constant. The present value was found to be USD 225,391 (82% increase in expenditures). Since the technology is still in the exploration stage, a renting cost is yet to be accounted for in future 3D construction projects. Different electricity tariffs ranging between 0.07 to 0.1 were investigated. For low electricity tariffs, the costs of the 3D printing scenario decreased by 5% and increased up to 25% for higher ranges. Similarly, the costs of the conventional scenario decreased by 7% and increased up to 7% for higher ranges.

Table 10. Life Cycle Costing of the different sensitivity analysis alternatives.

Sensitivity Analysis Options		Present Value (USD)
3DCP Mix 1		−32,664
3DCP Mix 2		−32,588
Conventional Mix 1		−33,073
Conventional Mix 2		−31,451
3D Printer		−225,391
Electricity Tariff	3DCP	−38,972 to −51,427
	Conventional	−75,741 to −87,483

Data uncertainty and limited availability typically affects the life cycle assessment results. Figure 8 shows a +10% variation of the LCC and LCA parameters studied in the current research. The figure revealed a correlation of operation of both 3D printed and conventional scenarios. Nevertheless, the construction of conventional system had the greatest environmental impact and greatest cost with the variation.

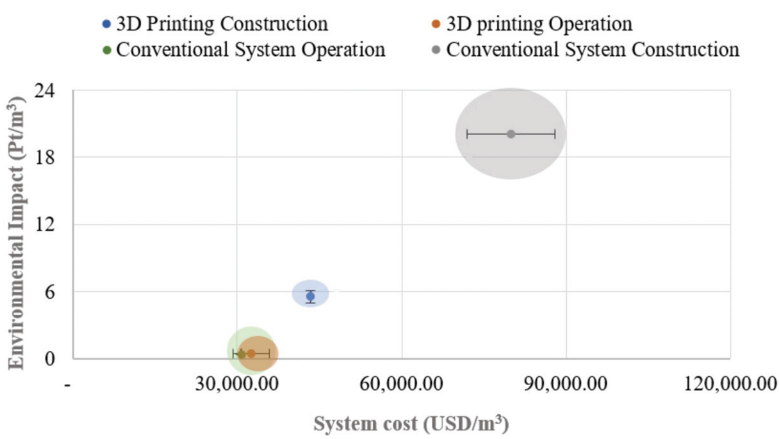

Figure 8. Uncertainty analysis of with +10% variation of 3D printing and conventional construction scenarios.

6. Study Limitations

Based on the conducted structural, environmental, and economic assessments, 3D printing is a viable alternative to conventional construction techniques. However, the findings of this comparative study were limited due to the unavailability of some important data, such as, (1) characteristics of the mortar used in 3D printing process, (2) varying ratios of conventional concrete ingredients, (3) limited number of investigated structural elements, (4) exclusion of sub-structure system and end of life phase, and (5) the common processes and components among the examined alternatives were not included, thus only relative environmental impacts were quantified, (6) inadequacy in 3D printing speicifc processing and (7) data inventory was calculated from diverse sources as a result of lack of data.

7. Conclusions

The evaluation of digital fabrication technologies, particularly 3D printing, has been adopted to enhance environmental performance and economics. This study compared (1) additive manufacturing by means of extrusion method and (2) conventional construction using cast in-situ concrete. The comparative analysis was performed on a single-storey house in the UAE from environmental and economic perspectives. The analysis utilized LCA using midpoint impact methodology ReCiPe 2016 to measure the relative environmental burdens. The LCCA analytical framework was conducted to determine the financial feasibility of the examined scenarios. The results of the LCA and LCCA analyses were combined using a ratio method to determine the system with the higher eco-efficiency. LCA analysis revealed better environmental performance of the 3D printing method due to the absence of several components, such as formworks, steel reinforcement and the lower use of materials, compared to conventional construction alternatives. From an economic perspective, the LCCA indicated that 3D printing is 78% more profitable than its conventional counterpart. The eco-efficiency analysis revealed that 3D printing was the optimum choice. The sensitivity analysis revealed that decreasing cement ratios in 3D printing mortars can significantly decrease the environmental impacts. In this study the 3D printing construction technology showed a better overall eco-efficiency. However, it is acknowledged that the number found in this study may differ for different comparative analysis conditions.

Author Contributions: The contribution of each author can be described as follows: Conceptualization, K.P.F., M.A., A.K.T.; Methodology, H.A., M.A.; Software, H.A., M.A.; Visualization, H.A., M.A., A.K.T.; Validation, H.A., K.P.F., M.A., A.K.T.; Writing-Original Draft Preparation, H.A., K.P.F.; Writing—Review & Editing, H.A., K.P.F., M.A., A.K.T.; Supervision, K.P.F., M.A., A.K.T.; Project Administration, K.P.F., M.A. All authors have read and agreed to the published version of the manuscript.

Funding: The work in this paper was supported, in part, by the Open Access Program and FRG20-M-E44 grant from the American University of Sharjah. This paper represents the opinions of the authors and does not mean to represent the position or opinions of the American University of Sharjah.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviations

3DCP	3-D Concrete Printing
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building information modelling
CAD	Computer aided design
GWP	Global warming potential
EI	Eco-efficiency index
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
ISO	International organization for standardization
LCA	Life cycle assessment
LCC	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact analysis
PV	Present value
STL	STsereo Lithography
UAE	United Arab Emirates

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Fading Attraction of the Shrinking City: An Empirical Study from an Urban Resource Perspective

Yuanping Wang [1], Mu Lin [2], Jingxin Gao [3,*] and Zhaoyin Zhou [1]

[1] School of Civil Engineering and Architecture, Chongqing University of Science and Technology, Chongqing 401331, China; ypwang@cqust.edu.cn (Y.W.); zzy@cqust.edu.cn (Z.Z.)
[2] School of Marxism, Dalian University of Technology, Dalian 116024, China; linmu258@dlut.edu.cn
[3] School of Economics and Management, Dalian University of Technology, Dalian 116024, China
* Correspondence: jxin25@cqu.edu.cn

Abstract: The accelerated flow of resources and the population has resulted in the coexistence of the expansion and shrinkage of cities. The shrinking city is not a new thing, but it is a new problem that needs to be solved urgently in China. Urban resources reveal the direct cause of the shrinking city: attraction, which reflects the competition for external resources and the endowment of the intrinsic resources of cities. Therefore, this paper established the Urban Resource Degree (URD) model to measure the urban resource degree of the shrinking city. Factors were then selected to analyze the ways in which they influence the shrinking cities. Given the spillover effect and heterogeneity of the influencing factors, a Spatial Durbin Model (SDM) and a Spatiotemporal Geographically Weighted Regression Model (GTWR) were used to conduct a spatial spillover (SSA) and spatial heterogeneity (SHA) analysis of the URD of the shrinking cities in Northeast China. The results show that the ability gap to compete for and control resources between prefecture-level shrinking cities and county-level shrinking cities is narrowed. From the SSA and SHA perspectives, the influence factors can be categorized into three types: "High West–Low East and Negative–Positive Spillover", "Low West and High East Positive–Negative Spillover", "Low Northwest and High Southeast Negative Spillover". Finally, policy implications are proposed to provide support for policy-making.

Keywords: shrinking city; urban resource degree; spatial spillover analysis (SSA); spatial heterogeneity analysis (SHA); policy-making

Citation: Wang, Y.; Lin, M.; Gao, J.; Zhou, Z. Fading Attraction of the Shrinking City: An Empirical Study from an Urban Resource Perspective. *Sustainability* **2021**, *13*, 11550. https://doi.org/10.3390/su132011550

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 3 September 2021
Accepted: 11 October 2021
Published: 19 October 2021

1. Introduction

The shrinking city is a young, crucial issue related to human sustainably development which needs to be given more attention. It is not a new thing, but it is a new problem that needs to be solved urgently. After the industrial revolution, cities grew explosively [1]. Both the number and the size of cities have shown a rapid growth which is unprecedented in human history. Since the 1990s, the urbanization rates of the United Kingdom, the United States, Germany, and France have far exceeded 50% [2–5]. However, at the beginning of the 20th century, some cities in these countries ended their growth process, and a series of problems such as urban population decline, economic recession, industrial imbalance, and a surge in unemployment appeared. For example, Leipzig, Germany, lost more than 100,000 people from 1951 to 1998, accounting for 20% of the total population [6]; Liverpool, the United Kingdom, began to experience a large-scale population decline in the mid-19th century. As of 2008, its population had decreased by 49% compared to 1931 [7]. Similar cases include the city of Hakodate in Japan, Detroit and Pittsburgh in the United States, and Leksa in Finland, etc. These cities all once flourished during the industrialization period, but they have all undergone a historic transformation from prosperity to decline.

The phenomenon of the shrinking city does not only appear in highly urbanized developed countries. In the process of large-scale urbanization, shrinking cities in China have begun to appear. China's urbanization has entered the turning point of the times, with large cities that cannot be contained on the one hand, and small cities that cannot be supported on the other [2]. Relevant studies have used different statistical calibers to identify and analyze shrinking cities. Due to the differences in the definition and the criteria of a shrinking city, the results obtained by related scholars are not in complete accord. After analyzing the data of the Fifth Census (2000) and the Six Census (2010), Zhang believed that more than 26% of the prefecture-cities and 37% of the county-level cities in China have experienced relative shrinking [3,4]; Long pointed out that between 2000 and 2010, 180 cities in China experienced negative population growth [5]. After analyzing the data of 663 cities in China from 2007 to 2016, Wu found that 84 cities had different degrees of shrinking [6,7]. Although the conclusions obtained by various scholars are different, it should not be ignored that these results show that the phenomenon of urban shrinkage has indeed occurred in China. Furthermore, the number and scale of the shrinking cities are still expanding.

In order to reveal the mechanism of the population loss and the series of problems, the "shrinking city" was formally proposed by scholars [8], and a few scholars have carried out in-depth research on it and achieved a series of fruitful results. As shown in Table 1, de-industrialization, suburbanization, and political system transformation have become the main reasons for the shrinking cities in European and American countries [9,10].

Table 1. Influencing factors of the shrinking city.

Author	Contents and Cases	Conclusion of Shrinking
C. Martinez-Fernandez et al. [11] J. Kotilainen [12] K. Pallagst [13]	Yubari, Japan Lieksa, Finland Flint, Michigan	Resource depletion, single industrial structure, natural disasters and environmental pollution
C. Freixas et al. [14] D. Camarda [15] C. Martinezfernandez [16]	St. Louis, USA Taranto, Italy 30 cities around globe	Deindustrialization, suburbanization and white people living in the suburbs for fear of public security in the city center (white flight)
R. Howe Steven [17] K. Pallagst [13]	Cincinnati, Cleveland, Dayton, and Youngstown, Ohio Flint, Michigan, USA	Suburbanization, regional transportation system promotion and restriction, regional unbalanced development, urban sprawl
T. Wiechmann [18] C. Cortese [19] T. Panagopoulos [20]	Schwedt and Dresden, Germany; Youngstown and Pittsburgh, USA Ostrava, Czech Republic; Génova, Itália e Leipzig, Alemanha Portuguese	The birth rate, population emigration rate, population density, total population and population structure change
Dga B [21]	Shaanxi-Gansu-Ningxia region, the Sichuan-Chongqing region, and the middle and lower reaches of the Yangtze River	population change rate
B. Hollander J [22] M. Bontje [23] D. Haase [24] A. Haase [25] M. Bernt [26]	Detroit, USA Germany Leipizig Halle Bytom	Social equity, policy system, system reform, ideology
A. Mallach [27]	Germany, Japan and the United States	conditions, discourse, policy and action
X. Meng [28]	5004 shrinking cities worldwide	population loss, economic decline, and decay in spatial quality
I. Kantor [29]	Bytom, Poland	city's policy, socio-economic situation
M. Rocak [30]	Netherlands	social aspects(resources, empowerment and participation)
A. Wichowska [31]	Poland	population decline, economic decline and the number of vacant homes

Due to the late start of urbanization in China, the shrinking city mainly occured in the 21st century, with the data explosion and rapid development of science and technology. Therefore, the phenomenon of the shrinking city in China not only has similar incentives to the developed countries but also has its unique side. The continuous construction and improvement of infrastructures such as transportation networks and telecommunications have greatly increased the flow of the population and resources in China. Besides this, many cities have abolished household registration restrictions, and some cities have provided excellent talent introduction policies to attract talents. The weakening and canceling of the restriction policy and the establishment and strengthening of the encouragement policy are gradually breaking the shackles of the population flow in China. According to China's national census data, in 2010, 261 million people left their registered places for more than half a year, with 82% of the total migrants being in eastern cities and 18% in being in central and western cities. Since the 21st century, China's population migration has become larger, faster and more frequent.

Urbanization is the process of population and resource agglomeration. In the urbanization process, some cities continue to expand, while others shrink. City shrinkage has many causes, such as economic development, climate, location, political factors and so on [32]. However, to sum up, the final reason is the city's decreased attraction. The gathering of resources accelerates the gathering of the population, and the value creation and consumption demand of the population gathering further promote the re-distribution of resources. Cities with strong "attraction" tend to gather a lot of excellent resources and become the inflow places of population, while cities with weak "attraction" naturally become outflow places. Therefore, we proposed the hypothesis that urban resources are a combination of the ability of cities to compete for external resources and the reflection of the endowment of urban resources. The level of urban resources is closely related to urban shrinkage. The level of urban resources determines the attractiveness of the city, reflecting the direct cause of urban shrinkage. However, few pieces of literature conducted an in-depth analysis of the shrinking city from the urban resource perspective. The objectives in this study are therefore to: (1) establish the URD model to measure the urban resource degree, and (2) to select factors to analyze how they influence the shrinking cities. Given the spillover effect and heterogeneity of the influencing factors, SDM and GTWR were used to conduct a spatial spillover (SSM) and spatial heterogeneity (SHM) analysis of the URD of shrinking cities in northeast China. Finally, policy implications are proposed to provide supports for policy-making.

2. Urban Resource Degree (URD) of the Shrinking Cities

2.1. Methodology

URD is the synthesis metric of the city's ability to compete for external resources and the resource endowment. Here, the resource is a general concept involving all of the tangible and intangible necessities for urban development, such as land, water, labor, culture, policy, and so on. Previous pieces of literature have focused on the URD from the perspectives of urban competitiveness [33–37] and sustainability development [38–42]. Although these focuses can reflect the URD to some degree, they are more comprehensive conceptual frameworks which are not limited to the URD. Therefore, they cannot be used to analyze URD accurately and pertinently. Besides this, some scholars have conducted an in-depth analysis of the resources between different cities [43–47] and different industries [48–51] in urban agglomeration through the gravity model. The gravity model can reflect the resource competence ability of two cities exactly, but cannot reflect the resource competence ability of one city compared to all other cities. From the concept of URD, it can be said that industrial agglomeration is the external performance of URD, and URD is the internal motivation of urban industrial agglomeration. Therefore, this paper proposed a weighted comprehensive industrial agglomeration model (WCIA) to measure the city's URD. The WCIA is as follows:

(1) Spatial Gini coefficient

$$G_i = \sum_{j=1}^{n} G_{ij} = \sum_{j=1}^{n} (x_j - s_{ij})^2 \tag{1}$$

G_i is the total Gini coefficient of industry i; G_{ij} is the Gini coefficient of industry i in city j; x_j is the percentage of the total employment in city j compared to the total employment in an urban agglomeration. S_{ij} is the ratio of industry i in city j to the total employment of industry i in an urban agglomeration. $G_i = 1$ indicates that the industrial agglomeration degree is high. Otherwise, $G_i = 0$ shows that the industrial distribution is balanced.

(2) Weight assignment

Suppose that there is an industry set of city i $E_i = \{e_{i1}, e_{i2}, \cdots e_{im}\}$ The Gini coefficient of industry j in city i at time t is recorded as $x_{tij} = (t = 1, 2, \cdots T; i = 1, 2, \cdots m)$. The decision sets are as follows:

$$X_t = \begin{bmatrix} x_{t11} & \cdots & x_{t1m} \\ \vdots & \ddots & \vdots \\ x_{tn1} & \cdots & x_{tnm} \end{bmatrix} \tag{2}$$

According to the numerical properties of x_{tij}, it can be divided into the positive index and negative index. In this paper, the range transformation method is used to normalize the positive index and negative index.

$$v_{tij}^{+} = \frac{x_{tij} - min(x_j)}{max(x_j) - min(x_j)} \tag{3}$$

$$v_{tij}^{-} = \frac{max(x_j) - x_{tij}}{max(x_j) - min(x_j)} \tag{4}$$

v_{tij}^{+} and v_{tij}^{-} are the positive normalization index and negative normalization index, respectively. $max(x_j)$ and $min(x_j)$ are the maximum and minimum values of the j-th index. The weight of industry j of the city i in time t is

$$P_{tij} = \frac{v_{tij}}{\sum_{j=1}^{n} v_{tij}} \tag{5}$$

where $0 \le v_{tij} \le 1; 0 \le P_{tij} \le 1$. The entropy of industry j in time t is

$$e_{tj} = -(1/L_n n) \sum_{i=1}^{n} P_{tij} L_n(P_{tij}) \tag{6}$$

The weight of the Gini coefficient of industry j in time t is

$$w_{tj} = (1 - e_{tj}) \Big/ \sum_{k=1}^{n} (1 - e_k) \tag{7}$$

(3) Urban resource degree (URD)

This paper combines the level of industrial agglomeration to form the overall concept of urban resources to reflect the city's resource endowment and its ability to compete for external resources. In Equation (8), N_i is the URD of city i at time t; G_{tij} is the Gini coefficient of industry i in city j at time t.

$$N_{ti} = \sum_{j=1}^{n} w_{tj} G_{tij} \tag{8}$$

2.2. Materials and Indicators Selection

The Shrinking City International Research Network (SCIRN) formally defined urban shrinkage as a city that has at least 10,000 residents, has experienced negative population growth for more than 2 years, and has undergone some structural crisis in economic structural transformation [52]. Since then, relevant research focused on urban shrinkage has achieved fruitful results. Oswalt defines urban shrinkage as cities that will lose a large number of residents, and stipulates that the annual population loss rate should be more than 1% [53]. After the establishment of the "China Shrinking Cities Research Network", scholars have systematically combed and summarized previous research and analyzed the development status of urban shrinkage in China. Zhang [54] and Long et al. [55] measured China's urban shrinkage through the data of the two national censuses in 2000 and 2010. Meanwhile, Zhang et al. judged China's shrinking cities as "one body, two wings and three dimensions" based on remote sensing data and geospatial data [56]. Liu et al. analyzed shrinking cities based on night light data [57].

Here, we can know that the academic community has not yet reached a consensus on the criteria for the determination of urban shrinkage, but the generally agreed upon view is that the decrease in the urban population is the core feature of shrinking cities. Professor Wu Kang of Capital University of Economics and Trade comprehensively interpreted the definition of the shrinking city, and based on the urban population data of municipalities directly under the central government, provincial capital cities, prefecture-level cities and county-level cities from 2007 to 2016, the cities with a lower population in 2016 than in 2007 and negative population growth in three consecutive natural years were identified [58]. Results showed that 80 out of 660 cities meet the criteria for shrinking cities.

There are 24 shrinking cities (see Table 2) in the three provinces of Northeast China, accounting for 30% of the total shrinking cities. The three provinces in Northeast China are an old industrial base in China. In the 1930s, the most advanced industrial system in Northeast Asia was built, which once occupied 98% of China's heavy industrial base. In recent years, there has been a slowdown in the speed of economic development and the phenomenon of population outflow, resulting in a large number of shrinking cities. Northeast China is an important industrial agglomeration and economic development pioneer in China. However, there is a lot of urban shrinkage in these areas. It is worth exploring the deep-seated reasons for this phenomenon. Therefore, 24 shrinking cities in Northeast China were taken as research objects, and the URD was measured.

Table 2. Shrinking cities selected in Northeast China.

Code	City	Code	City	Code	City	Code	City
R1	Anshan	R7	Bei'an	R13	Fuxin	R19	Ningan
R2	Fushun	R8	Nehe	R14	Jixi	R20	Jiamusi
R3	Qiqihar	R9	Tumen	R15	Beipiao	R21	Hegang
R4	Zhaodong	R10	Jinzhou	R16	Shulan	R22	Baishan
R5	Haicheng	R11	Yingkou	R17	Hailin	R23	Fujin
R6	Huadian	R12	Tonghua	R18	Ji'an	R24	Daqing

Data source: https://finance.sina.com.cn/china/gncj/2019-04-10/doc-ihvhiqax1466676.shtml (accessed on 1 october 2021).

2.3. Data Source

In China, there are 20 industry categories, 97 major categories, 473 medium categories and 1380 sub categories according to the *National Economic Industry Classification Standard* compiled by the National Bureau of Statistics. Given the research's purpose and operability, data-accessible, resource-intensive industries were selected as the sector indicators to measure the urban resource degree. Only the agglomeration of high-tech, high value-added and resource-intensive industries can truly reflect the level of urban resources. To reflect the URD of cities, we selected the manufacturing industry; mining industry; scientific research and technical service industry; information transmission, software and information technology service industry; and financial industry. The relevant data are from China Statistical Yearbook, China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, China Energy Statistical Yearbook, and the Urban Statistical Yearbook, the regional statistical bulletin, and some network data from some provinces, municipalities, prefecture-level cities and county-level cities.

2.4. Urban Resource Degree (URD)

The URD of 24 cities in Northeast China from 2007 to 2016 is listed in Table 3.

Table 3. The URD of 24 cities in Northeast China from 2007 to 2016.

City / Province	Region	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Liaoning											
Anshan	West	0.471	0.588	0.367	0.431	0.473	0.559	0.310	0.602	0.491	0.482
Beipiao	West	0.099	0.108	0.002	0.059	0.084	0.120	0.155	0.142	0.123	0.050
Fuxin	West	0.152	0.174	0.103	0.182	0.166	0.259	0.108	0.211	0.106	0.102
Fushun	West	0.395	0.473	0.300	0.389	0.468	0.550	0.160	0.501	0.326	0.321
Haicheng	West	0.256	0.257	0.047	0.300	0.374	0.407	0.564	0.586	0.473	0.162
Jinzhou	West	0.213	0.244	0.136	0.245	0.224	0.333	0.155	0.421	0.201	0.195
Yingkou	South	0.387	0.488	0.416	0.526	0.667	0.568	0.238	0.630	0.476	0.465
Jilin											
Baishan	South	0.193	0.313	0.146	0.114	0.103	0.193	0.052	0.122	0.123	0.120
Huadian	South	0.073	0.098	0.026	0.158	0.123	0.124	0.156	0.162	0.114	0.106
Ji'an	East	0.034	0.069	0.019	0.082	0.075	0.099	0.108	0.102	0.115	0.109
Shulan	North	0.109	0.112	0.014	0.100	0.102	0.100	0.124	0.139	0.105	0.062
Tonghua	South	0.211	0.245	0.127	0.122	0.131	0.146	0.074	0.170	0.118	0.077
Tumen	East	0.076	0.077	0.024	0.037	0.042	0.041	0.060	0.065	0.064	0.070
Heilongjiang											
Bei'an	North	0.111	0.109	0.025	0.087	0.076	0.121	0.150	0.160	0.175	0.188
Daqing	West	0.772	0.944	0.554	0.701	0.709	0.873	0.310	0.652	0.389	0.379
Fujin	East	0.010	0.072	0.011	0.049	0.057	0.090	0.101	0.093	0.093	0.108
Hegang	North	0.168	0.189	0.075	0.104	0.101	0.132	0.032	0.070	0.082	0.079
Hailin	South	0.052	0.078	0.036	0.094	0.101	0.135	0.165	0.181	0.190	0.212
Jixi	East	0.215	0.225	0.082	0.105	0.125	0.156	0.046	0.107	0.132	0.121
Jiamusi	North	0.193	0.229	0.065	0.083	0.094	0.121	0.078	0.165	0.164	0.159
Nehe	West	0.049	0.056	0.019	0.060	0.059	0.055	0.074	0.081	0.093	0.110
Ningan	South	0.105	0.109	0.005	0.022	0.047	0.057	0.062	0.064	0.091	0.094
Qiqihar	West	0.278	0.325	0.155	0.213	0.248	0.313	0.121	0.267	0.196	0.229
Zhaodong	South	0.074	0.069	0.003	0.064	0.093	0.129	0.148	0.149	0.145	0.164

From Figure 1, the overall performance of the URD in Liaoning province is in the state of being basically stable, with a small fluctuation from 2007 to 2016. For the five prefecture-level cities, the URD of Fuxin was at a low level from 2007 to 2016, with a small fluctuation between 0.1 and 0.26. Besides this, Jinzhou's URD also remained at a low level. Except for 0.33 in 2012 and 0.42 in 2014, the other years were below 0.3. The URD of Fushun decreased significantly in 2013, and remained around 0.4 in the other years. After the comparison of 2007 to 2016, the overall performance of Fuxin, Jinzhou and Fushun's URD declined slightly in the past ten years. Instead, the URD of Anshan and Yingkou was kept above 0.4, except in 2013, and presented a slight increase in the period. The URD of the only two county-level cities, Haicheng and Beipiao, of the seven shrinking cities in Liaoning Province changed greatly from 2007 to 2016. The URD of Haicheng experienced a great decline, a sharp rise, and then a substantial decline change: the URD of Haicheng (1) decreased from 0.256 to 0.047 in 2007–2009; (2) increased from 0.047 to 0.586 in 2009–2014; and (3) decreased from 0.586 to 0.162 in 2016. In contrast, the URD of another county-level city, Beipiao, was always the lowest in the seven shrinking cities in Liaoning Province. The changes of the URD are shown in Figures 2–4.

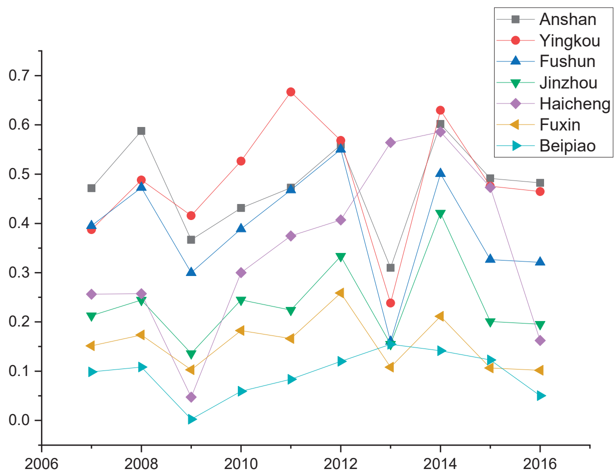

Figure 1. Changes of the URD of the shrinking cities in Liaoning.

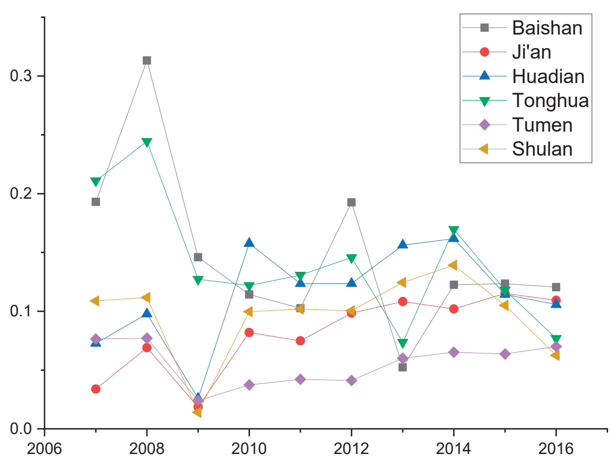

Figure 2. Changes of the URD of the shrinking cities in Jilin.

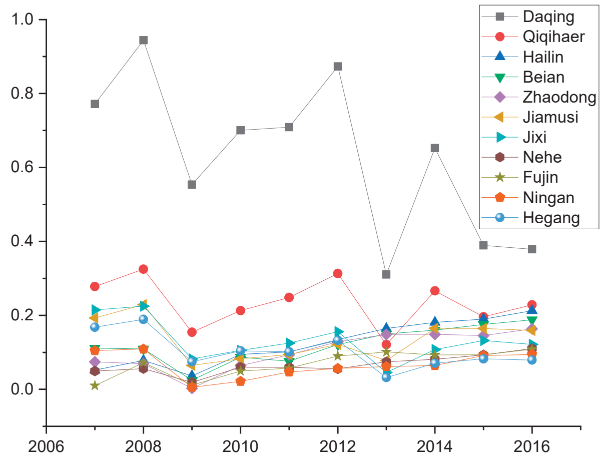

Figure 3. Changes of the URD of the shrinking cities in Heilongjiang.

From Table 3, the URD in Liaoning shows a trend of rising first and then decreasing. The resource degree of the cities in Jilin and Heilongjiang fluctuates slightly at a relatively low level.

Figure 2 illustrates the changes of the URD in the six shrinking cities in Jilin. Although the URD changes in the six cities are different, the differences are gradually narrowing and tending to converge. It is worth noting that the six shrinking cities were in a state of less than 0.2, except for Tonghua and Baishan in 2008. Tonghua and Baishan are the only two prefecture-level cities of the six shrinking cities in Jilin. As shown in Figure 3, the URD of Tonghua and Baishan were at high levels from 2007 to 2009, which were much higher than those of the other cities in the period. The URD of the two cities reached peaks which were 0.313 and 0.245, respectively. However, after 2009, compared with other shrinking cities, the URD of Tonghua and Baishan no longer existed. In 2016, the URD of the two cities was 0.077 and 0.120, respectively, and the difference with other cities almost disappeared. As for Huadian, Shulan, Ji'an and Tumen, the URD of the four county-level cities was less than that of the two prefecture-level cities. As of 2016, the URDs of Ji'an and Huadian were 0.109 and 0.106, which increased by 0.076 and 0.033, compared with 0.034 and 0.073 in 2007. However, the URD of Tumen and Shulan decreased from 0.076 and 0.109 in 2007 to 0.07 and 0.062 in 2016, respectively.

In conclusion, the URD of the six shrinking cities in Jilin Province had a short-term upward fluctuation from 2007 to 2016, but the overall trend was downward. Besides this, the gap of the URD between the prefecture-level city and county-level city gradually narrowed. Tonghua and Baishan lost the advantages brought by their administrative levels.

In Figure 3, there are six county-level cities and five prefecture-level cities in Heilongjiang Province. Notably, although it has decreased over the years, the URD of Daqing is far higher than that of other shrinking cities in Heilongjiang Province. Besides this, the URD of other prefecture-level shrinking cities, e.g., Jixi, Jiamusi, Qiqihar and Hegang, had different changes in the periods. The URD of Qiqihar was between 0.2 and 0.33, and ranks the second among 11 cities, only next to that of Daqing. Unlike that of Daqing and Qiqihar, the URD of Jixi and Jiamusi fluctuated slightly from 0.08 to 0.22, and always ranked the third to sixth among the 11 cities. Besides this, the URD of the final prefecture-level shrinking city, Hegang, declined sharply after 2013, and was the last in the 11 shrinking cities in 2013, 2015 and 2016. Compared with the prefecture-level cities, the URD of the six county-level cities of Hailin, Bei'an, Zhaodong, Fujin, Nehe, and Ning'an were all ranked behind the five prefecture-level cities before 2012. However, after 2013, the URD of

Hailin, Bei'an and Zhaodong increased significantly, and they always ranked second to sixth among the 11 cities.

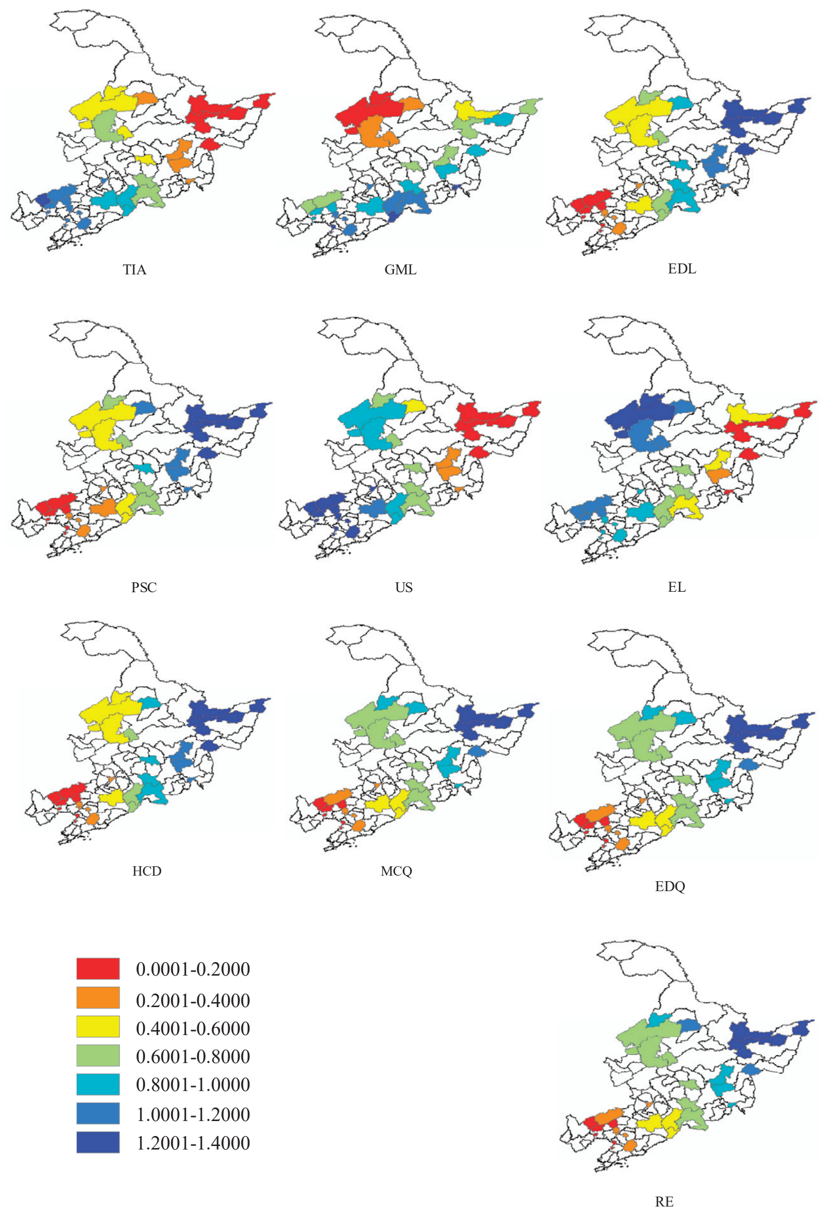

Figure 4. Spatial heterogeneity of the factors' influences on URD.

In summary, over time, the advantage of the URD of prefecture-level cities gradually weakened. On the contrary, the URD in county-level cities increased slightly, and the ability of cities to compete for and control resources increased.

3. Factors That Influence the URD and how, from the Spatial Spillover and Spatial Heterogeneity Perspectives

3.1. Influence Factors

In order to reflect various points of the previous pieces of literature from different perspectives, this paper conducted a literature review to extract the influence factors of URD. In order to avoid multicollinearity, this paper selects factors based on representativeness and the minimalist principle. We used the Factor Analysis Method (FAM) to reduce the dimension of 29 influences in Table 4. According to the relevant experience, the selected eigenvalues of the principal components must be greater than 1, and the cumulative variance contribution rate should be more than 80%. Therefore, given the results in 2007, 2011 and 2016, the top 10 principal components with cumulative variance contribution rates of 83%, 91% and 89% were selected. The rotating component matrix of the influencing factors of URD is shown in Table 4.

Table 4. Principal component rotation matrix of the influencing factors.

Factors	Factor Load									
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**
X1	0.91	−0.12	−0.01	0.18	−0.24	−0.02	−0.3	−0.03	0.23	0.08
X2	0.84	0.04	−0.29	−0.18	−0.22	−0.25	0.18	0.12	−0.05	−0.13
X3	−0.1	0.89	−0.22	−0.14	−0.01	0.13	0.26	−0.28	0.18	0.27
X4	−0.01	0.78	−0.09	−0.03	0.17	−0.28	−0.06	0.08	−0.15	0.09
X5	0.06	0.9	0.04	0.2	0.21	0.17	−0.11	−0.01	0.07	−0.14
X6	−0.08	−0.2	0.88	−0.02	0.02	−0.02	−0.1	−0.22	0.05	−0.11
X7	−0.02	0.22	0.92	0.17	−0.09	0.1	0.3	0.06	0.1	−0.16
X8	−0.17	0.16	0.95	−0.11	0.2	−0.29	0.14	−0.21	0.28	0.04
X9	0.25	−0.25	0.29	0.92	−0.21	−0.09	0.18	−0.27	−0.22	0.2
X10	−0.17	0.29	−0.25	0.67	−0.16	−0.09	0.05	0.24	0.24	0.28
X11	0.29	0.1	0.1	−0.19	0.79	0.17	−0.21	−0.08	0.16	0.03
X12	0.3	0.23	0.15	0.16	0.95	0.15	0.11	−0.09	−0.19	0.21
X13	0.08	−0.28	0.09	0.21	0.88	−0.05	0.19	−0.15	−0.16	−0.03
X14	0.27	−0.09	0.29	0.04	0.83	0.27	0.26	0.27	0.03	−0.24
X15	−0.07	0.11	−0.27	0.28	0.91	0.08	−0.02	0.17	0.03	0.06
X16	0.25	0.2	0.12	0.15	0.82	0.16	−0.23	0.16	−0.01	0.08
X17	−0.02	0.12	−0.25	−0.24	0.69	0.08	−0.12	−0.27	−0.08	−0.13
X18	0.15	0.28	−0.22	0.16	0.05	0.96	−0.25	−0.2	0.27	−0.21
X19	−0.13	0.09	0.04	−0.14	0.24	0.01	0.89	−0.19	−0.17	0.07
X20	−0.23	−0.19	−0.06	0.03	0.3	0.18	0.79	−0.17	−0.07	0.28
X21	−0.18	0.11	−0.11	0.08	−0.08	−0.17	0.8	−0.18	−0.05	0.01
X22	−0.18	−0.09	0.16	0.27	0.03	−0.13	0.9	0.109	0.09	−0.16
X23	−0.09	0.07	0.03	−0.29	0.14	−0.15	0.95	0.095	0.23	0.25
X24	−0.21	0.24	0.24	0.17	0.13	−0.21	0.74	0.08	0.09	−0.19
X25	0.05	0.16	−0.19	−0.12	−0.17	−0.11	−0.13	0.82	0.13	−0.29
X26	−0.11	0.23	0.01	−0.21	0.28	−0.26	0.06	0.21	0.74	0.09
X27	−0.02	0.01	0.26	−0.2	−0.26	−0.23	0.05	−0.25	0.91	0.34
X28	−0.11	0.23	0.23	−0.23	−0.12	0.28	0.13	−0.29	−0.17	0.83
X29	−0.04	0.11	−0.16	0.22	0.17	−0.24	0.22	−0.03	−0.26	0.64

Factors: X1—R&D investment; X2—Number of patent applications; X3—Actual use of foreign capital; X4—SME registration application approval cycle; X5—House price to income ratio; X6—GDP per capita; X7—Disposable income per capita; X8—The total retail sales of social consumer goods; X9—Proportion of secondary and tertiary industries; X10—Investment in the fixed assets of the whole society; X11—Amount of public transportation per 10,000 people; X12—Road mileage per capita; X13—Hydropower supply capacity; X14—Proportion of the education expenditure to financial expenditure; X15—Number of secondary schools per 10,000 people; X16—Proportion of the medical expenditure to financial expenditure; X17—Number of hospitals per 10000 people; X18—Urban population density; X19—Per capita garden area; X20—Greening rate of the built-up area; X21—Days of reaching air standards per year; X22—Industrial SO2 treatment rate; X23—Wastewater treatment rate; X24—Comprehensive utilization rate of solid waste; X25—Resource abundance; X26—Number of provincial cultural relic protection units per million people; X27—Number of cultural venues per capita; X28—Contributions per capita; X29—Average number of students in Colleges and universities per 10,000 people.

From Table 4, 29 influencing factors are divided into the following 10 principal components. The detailed information of the 10 principal components is listed in Table 5.

Table 5. Factors Affecting the URD.

Principle Indicators	Abbreviation	Indicators
City's technological innovation ability	TIA	R&D investment, Number of patent applications
Government management level	GML	Actual use of foreign capital, SME registration application approval cycle, House price to income ratio
The level of economic development	EDL	GDP per capita, Disposable income per capita, The total retail sales of social consumer goods
Economic development quality	EDQ	Proportion of secondary and tertiary industries, Investment in fixed assets of the whole society
Public service capability	PSC	Number of public transportations per 10,000 people, Road mileage per capita, Hydropower supply capacity, Proportion of education expenditure in financial expenditure Resource abundance, Number of secondary schools per 10,000 people Proportion of medical expenditure in financial expenditure, Number of hospitals per 10000 people
Urban size	US	Urban population density
Environmental level	EL	Per capita garden area, Greening rate of built-up area, Days of reaching air standard per year, Industrial SO2 treatment rate, Wastewater treatment rate, Comprehensive utilization rate of solid waste
Natural resources	RE	Resource abundance
Historical and cultural heritage	HCD	Number of provincial cultural relics protection units per million people, Number of cultural venues per capita
The moral and cultural quality of residents	MCQ	Contributions per capita, Average number of students in Colleges and universities per 10000 population

3.2. SSA and SHA for the Factors of URD

To reveal the spatial spillover and spatial heterogeneity of the URD in the 24 shrinking cities, we used the Spatial Durbin Model (SDM) and Spatiotemporal Geographically Weighted Regression model (GTWR) to perform the SSA and SHA.

(1) SDM for SSA

The SDM is as follows:

$$\begin{aligned} &y = \rho W y + X\beta + W\overline{X}\gamma + \varepsilon \\ &\varepsilon \sim N\left(0, \delta^2 I\right) \end{aligned} \tag{9}$$

where ρ is the marginal influence of the dependent variables of adjacent regions. β is the marginal effect of the independent variable on the dependent variable. γ measures the marginal effects of independent variables in adjacent regions on the dependent variables. $\overline{X}$ is a variable matrix of the independent variables.

(2) GTWR for SHA

Because the data may be non-stationary in time and space, the influence of the independent variable on the dependent variable is different in different times and regions; that is, there is heterogeneity in time and space. GTWR is an extended model of Geographically Weighted Regression (GWR), which embeds the time dimension into the regression model.

It takes into account the data changes of the URD of the shrinking cities in time and space. Therefore, GTWR is more in line with the actual situation.

$$Y_i = \beta_0(\mu_i, v_i, t_i) + \sum_k \beta_k(\mu_i, v_i, t_i)X_{ik} + \varepsilon_i \tag{10}$$

Here, Y_i is the URD of city i, μ_i is the longitude coordinate of city i, v_i is the latitude coordinate of city i, and t_i is the time coordinate of city i. Therefore, (μ_i, v_i, t_i) is the space-time longitude and latitude coordinates of city i. $\beta_0(\mu_i, v_i, t_i)$ is the constant term, and $\beta_k(\mu_i, v_i, t_i)$ is the independent variable regression coefficient. X_{ik} is the k-th independent variable of city i. ε_i is the random error. The coefficient estimation of GTWR is as follows:

$$\hat{\beta}(\mu_i, v_i, t_i) = \left[X^T W(\mu_i, v_i, t_i)X\right]^{-1} X^T W(\mu_i, v_i, t_i)Y \tag{11}$$

$$W(\mu_i, v_i, t_i) = diag(W_{i1}, W_{i2}, \cdots W_{in}) \tag{12}$$

$$W_{ij} = \exp\left[\frac{\left(d_{ij}^{ST}\right)^2}{h^2}\right] = \exp\left[\frac{\lambda\left[(\mu_i - \mu_j)^2 - (v_i - v_j)^2 + \mu(t_i - t_j)^2\right]}{h^2}\right] \tag{13}$$

H is the space–time bandwidth, which is selected according to the minimum cross-validation (CV).

$$CV(h) = \sum_i (y_i - y_l(h))^2 \tag{14}$$

3.3. Data Source and Processing

Part of the raw data comes from the China Statistical Yearbook, China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, China Energy Statistical Yearbook, Urban Statistical Yearbook, and some regional statistical bulletins and network data. Specifically, the R&D investment and social electricity consumption of the prefecture-level cities are from China's urban statistical yearbook. Instead, in 2011–2016, the R&D investment and social electricity consumption of county-level cities are from China's urban statistical yearbook. In 2007–2010, the R&D investment of county-level cities is from the statistical yearbook of local provinces and the relevant statistical bulletin. The social electricity consumption is from the Power Industry Statistical Data Collection, the Statistical Yearbook of local cities, and related statistical bulletins. Besides this, the raw data of the built-up area are from the China Urban Construction Statistical Yearbook and Regional Statistical Yearbook. The SME registration application approval cycle and the contributions per capita were obtained from the Internet and field questionnaires. The housing price income ratio was calculated according to the average price of commercial housing and the regional per capita income.

a. House Price to Income Ratio

$$HPIR = {TPH}\Big/{TIF} \tag{15}$$

$$TPH = RAP \times PP \times PHP \tag{16}$$

$$TIF = PP \times PTI \tag{17}$$

$HPIR$ is the house price to income ratio, TPH is the house price and TIF is the total annual household income. RAP is the residential housing area per capita, PP is the household size, PHP the average price per square meter, and PTI is the annual income per capita.

b Resource Abundance

The ratio of mining employees to the total number of employees is used to characterize the regional resource abundance.

c Hydropower Supply Capacity

The water and electricity supply capacity of each region is measured by the satisfaction degree of the residents with the local water and electricity supply.

d SME Registration Application Approval Cycle

Due to the large difference in the actual situation of each region, there is a gap in the registration approval process, integrated services, network information platform construction, and the scale and type of small and medium-sized enterprises. In order to facilitate the data collection and enhance the comparability of the data, this paper measures the SME registration approval cycle from the perspective of the interviewees' satisfaction, and collects the receipt of the SME registration approval cycle in each region by issuing questionnaires.

3.4. Results

In this paper, ArcGIS software and the GTWR plug-in were used to carry out the spatial-temporal weighted regression of URD in Northeast China Shrinking Cities (NCSC).

(1) Results for SSA

The test results of LM, Hausman and LR for the non-spatial panel data are shown in Table 6.

Table 6. Non-spatial panel model test of URD in Northeast China.

Test Estimator		St	*p*-Value
LM test	LM (error);	22.73	0.000
	Robust LM (error)	26.47	0.001
	LM (lag)	18.09	0.002
	Robust LM (lag)	27.79	0.001
Hausman test		300.44	0.000
LR test	Time fixed	216.29	0.000
	Space fixed	113.18	0.001

As shown in Table 6, the Hausman test is significantly positive. Therefore, we rejected the null hypothesis and selected the fixed effect model. The joint significance test LR time-fixed and space-fixed test results are 216.29 and 113.18, respectively. Therefore, LM (error), Robust LM (error), LM (lag), and Robust LM (lag) test of the space and time dual fixed model were selected to verify the specific form of the model. The results showed that there are spatial lag effects of both variables and error terms. That is, SDM is suitable to conduct the SSA. Table 6 is the results of the SDM for SSA.

In Table 7, the Wald test spatial lag and Wald test spatial error statistics passed the 1% significance test. Therefore, SDM cannot degenerate into SAR or SEM. The total effect, direct effect and indirect effect of SDM are listed in Table 8.

The direct effect, the indirect effect and the total effect of the influencing factors on the shrinking cities are shown in Figure 4.

a. The Direct Effect

From the direct effect perspective, TIA, GML, EDL, EDQ, PSC, US, MCQ have positive influences on the URD of the shrinking cities. Notably, EDL and EDQ have the greatest positive effects on URD, reaching 0.501 and 0.469, respectively. As we know, the development of EDL and EDQ requires the URD as the foundation. Therefore, it can be said that while URD promotes EDL and EDQ, economic development also has a significant role in promoting the URD. Besides this, the influence coefficient of TIA on URD is 0.401, revealing that technological innovation is an important motivation for attracting resource accumulation. In addition, GML can enhance the charm of cities and create a friendly environment for the entry of external resources. However, EL and HCD have no significant effect on the URD of the shrinking cities. This reflects that the natural environment and the human environment do not work on the URD of shrinking cities. It is worthy of noting that RE is the only factor that has a negative impact on the URD of the shrinking cities in Northeast China. The influence coefficient is −0.244, and has passed the significance test of 1%. It shows that the better the resource endowment is, the more unfavorable it will be to the URD, i.e., the "resource curse" proposed by relevant research [59].

Table 7. SDM model estimation results of both the time and space effects of URD.

Factor	Time-Space Fixed	Time-Space Random
TIA	0.162 **	0.303 ***
GML	0.335 ***	0.016 *
EDL	0.401 ***	0.461 ***
EDQ	0.209 *	0.502 ***
PSC	0.109 ***	0.011 *
US	0.604 **	0.264 ***
EL	−0.024	−0.059
RE	0.337 ***	−0.107 **
HCD	0.100	0.033 **
MCQ	0.331	0.002 **
W*TIA	−0.116 ***	0.373 **
W*GML	−0.019 **	−0.062 *
W*EDL	0.503 **	−0.109 ***
W*EDQ	0.011	−0.362 ***
W*PSC	0.601 ***	0.001 *
W*US	1.247	−0.205 ***
W*EL	−0.289	0.322
W*RE	0.303 **	0.091 **
W*HCD	0.609	0.102 ***
W*MCQ	0.114	0.091 ***
R2	0.9195	0.9356
Adj—R2	0.9260	0.4001
Wald test spatial lag	13.891 ***	215.339 ***
Wald test spatial error	74.113 ***	108.772 ***

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8. The total, direct and indirect effects of the SDM model of the URD of the shrinking cities in Northeast China.

Factor	Direct Effect	Indirect Effect	Total Effect
TIA	0.401 ***	0.394 *	0.795 ***
GML	0.202 **	−0.112 **	0.09 **
EDL	0.469 ***	−0.409 ***	0.06 ***
EDQ	0.501 ***	−0.497 **	0.004 ***
PSC	0.382 ***	−0.121 ***	0.503 ***
US	0.003 ***	−0.342 ***	0.345 **
EL	0.072	0.101 *	0.173
RE	−0.244 ***	0.305 **	0.061 **
HCD	0.103	0.007 **	0.11 *
MCQ	0.009 *	0.024	0.033 *

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

b. The Indirect Effect

From the indirect effect perspective, TIA, El, RE and HCD have significant positive indirect effects on the URD of shrinking cities. In other words, they have spill-over effects on URD. As we can see, the indirect effect of TIA on URD is 0.394, reflecting that the spill-over effects of technological innovation could improve the URD of the overall region. Instead, GML, EDL, EDQ, PSC and US have negative indirect effects on URD. That is, the negative spill-over effects of these factors would weaken the attraction of the shrinking cities for external resources, producing vicious competition.

(2) Results for SHA

In order to reveal the spatial heterogeneity of the factors' influences on the URD of the shrinking cities, GTWR is used to conduct the SHA. The results are shown in Figure 5.

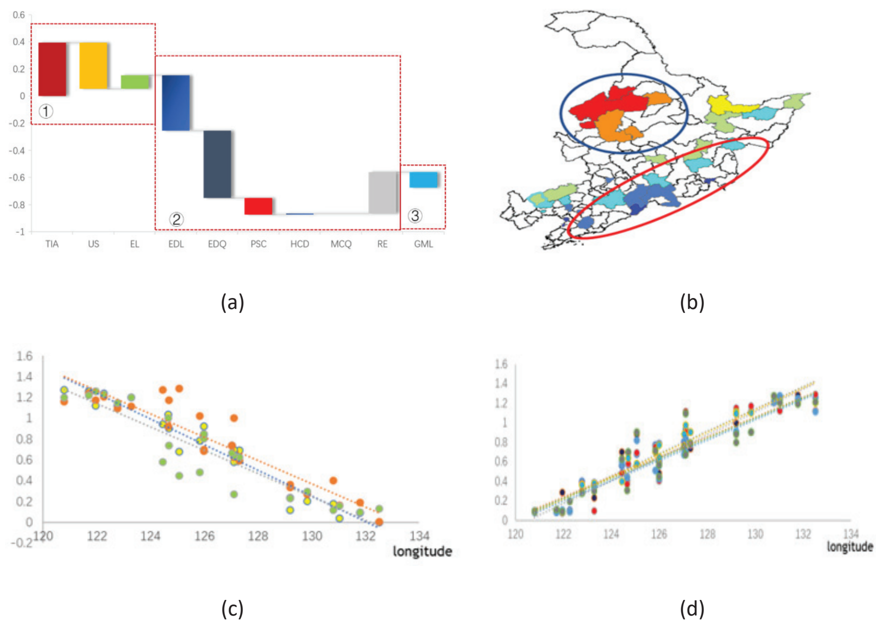

Figure 5. Influential factors and mechanisms of shrinking urban resources in Northeast China. (**a**) The coefficients of different factors. (**b**) The direct and indirect effects of GML. (**c**) The direct and indirect effects of TIA, US and EL. (**d**) The direct and indirect effects of EDL, EDQ, PSC, HCD, MCQ and RE.

Figure 4 illustrates the spatial heterogeneity of the influencing factors on the URD of the 24 shrinking cities in northeast China. The influence of TIA, US, EL on URD gradually weakens from the west to the east, and the coefficients are between 0.8 and 1.4 for the western cities such as Anshan, Fushun, Fuxin and Jinzhou. Instead, the influence of EDL, EDQ, PSC, HCD, MCQ and RE gradually strengthens from the west to the east, and the coefficients are between 1.0 to 1.4 for the URD of Hegang, Jiamusi, and Fujin. Notably, the influence of GML on the URD of the shrinking cities in Northeast China showed a trend of gradually increasing from the northwest to the southeast. The URDs of Qiqihar, Daqing, and Bei'an are influenced least. Anshan, Fushun, and Tonghua are the most affected, and the influence coefficient reaches more than 1.0.

4. Discussion and Policy Implications

From the above results of URD and the spatial spillover effect and spatial heterogeneity of various factors for the URD of the shrinking cities in Northeast China, the overall characteristics are summarized as shown in Figure 5.

From Figure 5, given the SSA and SHA, the influences can be categorized into three types:

(1) The "High West + Low East and Negative–Positive Spillover" of TIA, US and EL. Most cities in Heilongjiang and Jilin are less affected by these factors, while Fuxin, Jinzhou, Anshan, Fushun and the other shrinking cities in Liaoning Province are strongly affected by these factors. Meanwhile, TIA and EL have a strong positive spillover effect, while US will produce a negative spillover effect. Therefore, these cities need to focus on improving the ability of technological innovation and environmental governance, and take reasonable measures to avoid disordered competition among cities.
(2) The "Low West and High East + Positive-Negative Spillover" of EDL, EDQ, PSC, HCD, MCQ and RE. Most shrinking cities in Jilin and Heilongjiang, such as Hegang, Jiamusi, Fujin, Ningan, and Jixi, etc., are affected by these factors. Meanwhile, EDL, EDQ, PSC have a negative spillover effect on the URD of shrinking cities. Therefore, while developing the urban economy and improving its governance service and management ability, it is also necessary to create reasonable planning and layout within the region to avoid disorderly competition. In contrast, HCD and RE could produce a positive spillover effect on the URD of the shrinking cities. Therefore, while enhancing the soft power of urban culture, the regional synergy of positive spillover of these factors should be focused on in order to achieve the comprehensive effect of "1 + 1 > 2".
(3) The "Low Northwest and High Southeast + Negative Spillover" of GML. A few shrinking cities in Liaoning, Jilin and Heilongjiang are influenced by GML significantly. For these cities, in the adjustment of the urban development strategy, it is necessary to focus on improving the level of government management. Considering the negative spillover, it is also necessary to do a good job in the regional overall development planning in order to avoid disordered competition.

From the above findings, we proposed the policy implications as follows:

(1) Strengthen competitive industries and implement urban transformation and upgrading. The imbalance of development is serious in and between the regions of Northeast China for the similarity of the development strategy, the decline of the resource advantage under the new era and economic transformation, and the constantly strengthened competition in and between these regions. It is necessary, under these circumstances, taking these regions and cities into the overall national and social development framework, to clarify the advantages and establish development strategies of their own from a higher level and a larger region.
(2) Strengthen the system design and optimize the regional urban arrangement. In order to change the unbalanced regional development in the northeast, the system guarantees of the government are needed, with system design as the driving force, carrying out macro planning and arrangements from the overall perspective of the region, promoting regional coordinated development.
(3) Increase investment in science and technology, and enhance the innovation capabilities. The innovation of science and technology is always the most efficient means to drive the development of a city, and the only way to achieve sustainable development and enhance the competitiveness of a city. The innovation ability of science and technology is always needed for the city, no matter the development of the economy, the optimization of the industrial structure, or the establishment of a social security system and the upgrading of the urban function carrier.

5. Conclusion

In order to reveal how the factors influence the shrinking cities in Northeast China from the perspective of equality, this paper established the URD model to measure the urban resource degree. Given the spillover effect and heterogeneity of the influencing factors, SDM and GTWR were used to conduct an empirical analysis of the URD of shrinking cities. The findings are summarized as follows:

(1) In the study periods, the overall performance of the URD in Liaoning province is basically stable, with small fluctuation. Besides this, the URD of the six shrinking cities in Jilin Province has a short-term upward fluctuation, but the overall trend is downward. Notably, in the shrinking cities of Heilongjiang province, the URD of Daqing is far higher than that of other shrinking cities. On the contrary, Hegang's ability to compete for and control resources has declined sharply. Other cities have no drastic changes of the URD.
(2) The advantage of the URD of prefecture-level cities is gradually lost, and that of county-level cities is slightly improved. This reflects the fact that the ability gap to compete for and control resources between prefecture-level shrinking cities and county-level shrinking cities is narrowed.
(3) From the SSA and SHA perspectives, the influence factors can be categorized into three types, beginning with the "High West + Low East and Negative–Positive Spillover" of TIA, US and EL. Fuxin, Jinzhou, Anshan, Fushun and other shrinking cities in Liaoning Province are strongly affected by these factors. Next is the "Low West and High East + Positive–Negative Spillover" of EDL, EDQ, PSC, HCD, MCQ and RE. Hegang, Jiamusi, Fujin, Ningan, Jixi, etc are affected by these factors. Finally, there is the "Low Northwest and High Southeast + Negative Spillover" of GML. A few shrinking cities in Liaoning, Jilin and Heilongjiang are influenced by GML significantly.

From that above results, we proposed the policy implications from the perspectives of (1) strengthening competitive industries and implementing urban transformation and upgrading, (2) strengthening system design and optimizing regional urban arrangement, and (3) increasing investment in science and technology, and enhancing the innovation capabilities. URD indicates the resource endowment and the ability to compete with external resources of the shrinking cities. Therefore, it is indispensable to create reasonable planning and layout within the region in order to avoid disorderly development resulting from the negative spillover effect and make full use of the positive spillover effects of these factors to achieve the comprehensive effect of "1 + 1 > 2". We hope the findings can provide supports for related policy-making.

Author Contributions: Conceptualization, Y.W., J.G. and M.L.; methodology, Y.W. and J.G.; software, Y.W.; validation, Z.Z. and M.L.; formal analysis, Y.W. and M.L.; investigation, J.G.; resources, Y.W.; writing—original draft preparation, Y.W. and J.G.; writing—review and editing, J.G.; supervision, J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research has no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research has been supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (KJQN201801533, KJQN201801534).

Conflicts of Interest: The authors declare no conflict of interest.

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urban science

Review

Machine Learning Algorithms for Urban Land Use Planning: A Review

Vineet Chaturvedi * and Walter T. de Vries

Chair of Land Management, Technical University of Munich (TUM), 80333 Munich, Germany; wt.de-vries@tum.de
* Correspondence: vineet.chaturvedi@tum.de

Abstract: Urbanization is persistent globally and has increasingly significant spatial and environmental consequences. It is especially challenging in developing countries due to the increasing pressure on the limited resources, and damage to the bio-physical environment. Traditional analytical methods of studying the urban land use dynamics associated with urbanization are static and tend to rely on top-down approaches, such as linear and mathematical modeling. These traditional approaches do not capture the nonlinear properties of land use change. New technologies, such as artificial intelligence (AI) and machine learning (ML) have made it possible to model and predict the nonlinear aspects of urban land dynamics. AI and ML are programmed to recognize patterns and carry out predictions, decision making and perform operations with speed and accuracy. Classification, analysis and modeling using earth observation-based data forms the basis for the geospatial support for land use planning. In the process of achieving higher accuracies in the classification of spatial data, ML algorithms are being developed and being improved to enhance the decision-making process. The purpose of the research is to bring out the various ML algorithms and statistical models that have been applied to study aspects of land use planning using earth observation-based data (EO). It intends to review their performance, functional requirements, interoperability requirements and for which research problems can they be applied best. The literature review revealed that random forest (RF), deep learning like convolutional neural network (CNN) and support vector machine (SVM) algorithms are best suited for classification and pattern analysis of earth observation-based data. GANs (generative adversarial networks) have been used to simulate urban patterns. Algorithms like cellular automata, spatial logistic regression and agent-based modeling have been used for studying urban growth, land use change and settlement pattern analysis. Most of the papers reviewed applied ML algorithms for classification of EO data and to study urban growth and land use change. It is observed that hybrid approaches have better performance in terms of accuracies, efficiency and computational cost.

Keywords: urban growth; land use change; earth observation; modeling

Citation: Chaturvedi, V.; de Vries, W.T. Machine Learning Algorithms for Urban Land Use Planning: A Review. *Urban Sci.* **2021**, *5*, 68. https://doi.org/10.3390/urbansci5030068

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 2 August 2021
Accepted: 12 September 2021
Published: 14 September 2021

1. Introduction

The degree to which human actions have an effect on changes in the environment has been a key subject of study for land management researchers. One can measure these changes, which often have a spatial dimension, both qualitatively and quantitatively. Nevertheless, mapping of temporal and spatial changes of urban and rural land still remains a challenging task because the technological tools and instruments have so far not been adequate to support the daily practice and the spatio-temporal needs of planners and decision makers. The traditional methods used for land use planning such as field surveys and participatory mapping are time consuming, costly and labor intensive. Advancements in the data acquisition technologies and the availability of improved computational power has made it possible to make practical use of the algorithms which earlier could only be called theoretical solutions but could not be practiced [1]. The methods of imaging land use fall in the domain of remote sensing (RS) and processes by which they are utilized for their analysis is through Geographic Information Systems (GIS) tools. RS datasets are a vital source for assessing the land-use and land-cover processes. RS datasets provide large scale coverages right from the regional to the global scale. One of the ways to understand the status and changes in both natural and built environment is through interpretation of RS datasets. In recent decades, RS sensors and techniques have become increasingly sophisticated. They can provide a large volume of data with superior quality and high spatial resolution [2]. The availability of high-resolution data like LIDAR, RADAR, MSS, Hyperspectral, UAV borne data and other commercially available satellite data and data from other airborne platforms has improved the capabilities and understanding of land use planning. While classical methods compartmentalize graphic and non-graphic data for analysis, a combined use of advanced RS and GIS applications can integrate both spatial and socio-economic factors which may support a better understanding of the dynamics of the society needed to improve land use planning.

The spatial analysis underlying land use planning encompasses land use classification, growth, zoning, restrictions, allocation and change. There are various ML algorithms that make it possible to model aspects of land use planning. However, the algorithms differ in their performances, in terms of spatial accuracies and output possibilities. According to Hagenauer et al. (2019) [3] "ML comprises a set of inductive models that recognize patterns and/or minimize the prediction error of complex regression functions, by means of a repeated learning strategy from training data, linking an output such as land-use change to several underlying drivers. Once learned, the model can then be used to estimate previously unseen cases and predict future land-use change. There are many simulation models to model land use change and growth using ML techniques". In other words, the benefits of ML models are numerous, and have the ability of dealing with large amounts of data and a large number of variables, assigning relative importance to the variables, alongside the ability to model complex nonlinear relationships as well as interactions between drivers, while not being grounded in restrictive distributional assumptions of the input data that are hard to achieve in practice [3]. Despite these benefits, there is still limited literature which systematically compares the currently used ML algorithms in light of the specific needs and requirements of land use planning, classification, change, transition and growth.

The aim of this article therefore is to present the results of a comparative study of the commonly used ML algorithms against the background of the needs and requirements of land use planning and land use planning related decision making. The article identifies ML algorithms which give optimum results in terms of computation cost and accuracy levels.

The sequence of the article is as follows. We first present a theoretical grounding of the land use classification algorithms. Followed by discussion of the methodology adopted for reviewing the various ML algorithms for land use planning and finally conclude the findings after reviewing the functionalities, applications and computational power of the ML algorithms.

2. Theoretical Perspective

Land use planning is a process that ensures the judicious use of land by group of people who benefit from it. In order to make the best use of the limited available land and its resources, land use planners and policy makers need to intervene by incorporating guidelines/regulations on the use of land and to sustain the natural resources. The governments and administrative bodies involved in land use planning impose regulations on the use of land which include but are not limited to zoning, land use control, land use restrictions and allocation [4]. Rapid urbanization leads to substantial unplanned growth which is not healthy for the environment. It leads to degradation, air pollution and contamination of water resources. A major problem faced by urban planner and decision makers is to channelize this growth. In order to ensure the growth is planned and systematic spatial, non-spatial and temporal data has to be made available. To monitor and solve the problems of unplanned growth, EO and GIS data along with socio-economic data provide vital source of information for updating of land use maps.

In remotely sensed data, spatial resolution and temporal frequencies are the two important factors to study land use change. Proprietary and open-source data provided by various international and national agencies are custodians of EO and GIS data. The land administrators and land use planners need information on built-up area, non-built-up area, water bodies, green area, forests (urban), land use patterns, road network, drainage systems, etc. Most of this data can be obtained and/or extracted from images. Some types of data, such as open street map, USGS earth explorer, Sentinel hub, Copernicus open access hub, GHSL, etc., are repositories of open-source data and are utilized for spatial data requirements. Apart from open-source data, commercially available satellite images, aerial photographs, LIDAR data are used for various land use planning application such as cadastral boundary extraction, 3D feature extraction, 3D modeling, etc. The first step in the various stages of land use planning is to study the past data which is available in the form of master plan, census data and other statistical data available with various government and non-government agencies, the second stage is to study how far the plan has been fulfilled by studying with the help of EO based data against the master plan projections and the third stage will be projecting the land use plan for future, depending on the projection of the statistical data being generated as future projection, i.e., it will be geared towards fulfillment of those projections which will also be dependent on the government policies. A comprehensive geospatial database has to be developed to assess the existing land use and model the future changes. The type of data requirement depends on the type of land use planning problem in hand which needs to be addressed. Depending on the purpose, imagery could be of high resolution and in multi band or it may suffice to have imagery of low resolution as can be seen in Table 1 depicting the data requirements and the applications to measure the indicators.

Table 1. Land use planning indicators with measurements, data required and applications.

Indicators	Measurements	Data	Application
Urban expansion	Built-up density, settlement patterns, population distribution	EO based data, i.e., classified images, building footprints, urban heat islands	Classification and simulation (CA, spatial logistics regression, SVM, random forest, CNN)
Land restrictions	Land use/land cover change, built-up and non-built-up spaces,	Master plan, building by-laws, land use regulations	Classification, extraction of EO products like DEM, vegetation cover
Land allocations	Govt. policies, population growth, population distribution	Census data, socio-economic data	Spatial logistic regression, cellular automata
Zoning	Govt. policies and by-laws	Master plan, classified images	Planned development
Land use change	Settlement patterns, urban growth processes, (aggregated, compact, dispersed) population growth	Spatio-temporal EO based data	Spatial metrics, cellular automata, spatial logistic regression, agent-based modeling

2.1. Machine Learning Based Algorithms

Several ML algorithms have been tested for their performance on different kinds of datasets for land use classification and simulation of land use planning processes. The more popular algorithms are support vector machine, neural network, Markov random field, GANS and random forest. These algorithms are experimented on different data sets individually and in combination. The article is a review of the functionalities of these algorithms and their application in land use planning.

There is ongoing research for new methods of ML to take land use mapping to a higher plane. Support vector machines (SVMs) have been applied in a number of research papers and have been compared for their performance in land use classification with other ML algorithms such as random forest (RF), neural network. SVMs is a group of non-parametric ML algorithms. The core operation of SVMs is to construct a separating hyperplane (i.e., a decision boundary) on the basis of the properties of the training samples, specifically their distribution in feature space. In many instances, classification in high dimension feature spaces results in over-fitting in the input space, however, in SVMs over-fitting is controlled through the principle of structural risk minimization. The empirical risk of misclassification is minimized by maximizing the margin between the data points and the decision boundary [5]. In case of computational requirements SVMs work well with small data sets with fewer outliers [6]. Among the decision tree algorithms like CART (classification and regression tree), ID3 (iterative dichotomizer 3) more commonly used algorithm for land use classification is RF. One of the benefits of RF algorithm is that it can be used for both classification and regression. RF works as an ensemble learning algorithm based on decision tree classifiers, bagging, and bootstrapping. Each tree is trained by bootstrapping, using different samples from the training data. Additionally, each tree is trained using a random subset of the predicting variables. RF may use thousands of decision trees, where each tree casts a vote and the prediction of the class is decided by the majority vote. A big committee of randomly created decision tree determines the classification, hence the name, random forest [7]. RF can handle large number of variables without need of deleting any and bringing out the relative importance of each of the variables. As compared to SVMs, RF do not have hyperparameters to tune like choosing the right kernel, regularization, penalty, the slack variable, however, the complexity and computational cost increase with the increase in the number of trees in the forest. A list of some of the most commonly used variables is given in Table 2.

Table 2. List of image features.

Variables/Image Feature	Description	Examples	Description	Application in Land Use Planning
Spectral features	Provide information regarding the spectral response of objects, which differ for land coverage types, states of vegetation, soil composition, building materials [8]	NDVI (normalized difference vegetation index)—to measure/identify biomass	NDVI = (NIR−RED)/(NIR+RED)	Distinguishing built-up areas from non-built-up, green vegetation from barren land
		SAVI (soil adjusted vegetation index)	SAVI = 1.5 × (NIR-R)/(NIR+R+0.5)	Differentiate between vegetation and built-up
		BAI (built-up area index)	BAI = (B-NIR)/(B+NIR)	Built-up areas index has good performance in detecting asphalt and concrete surfaces
		NDWI (normalized difference water index)	NDWI = (G-NIR)/(G+NIR)	Enhances water features and helps in distinguishing water features from other ground objects
Texture features	Characterize the spatial distribution of intensity values of an image and data on contrast, uniformity, rugosity, etc. [8]	GLCM (grey level co-occurrence matrix)—specifically relevant when measuring, qualifying	GLCM is a tabulation of how often different combinations of pixel brightness values (grey levels) occur in an image	Measuring spatial patterns which are repetitive on the image like crop land and built-up

Table 2. *Cont.*

Variables/Image Feature	Description	Examples	Description	Application in Land Use Planning
Structural features	Help in identifying the spatial arrangement of elements in terms of the randomness or regularity of their distribution [8]	Edge detection filter specifically relevant when measuring, qualifying	Edge detection is a technique used to find the boundaries of features in an image. This uses an algorithm that searches for discontinuities in pixel brightness in an image that is converted to grayscale. ("Applying Edge Detection To Feature Extraction And Pixel Integrity," n.d [9])	For shape recognition, edge enhancement

Apart from SVM and RF, another ML algorithm which has been widely applied for land use classification is deep learning methods. In 2006, deep learning was introduced by Hinton et al. (2015) [10]. Deep learning methods are representation learning methods composed of multiple layers and each layer computes a new data representation from the representation in the previous layers of artificial neurons creating a hierarchy of data abstractions [10]. Among the group of deep learning methods is convolutional neural network (CNN) composed of convolution and pooling that are concluded by a fully connected neural network layer and a proper activation function, i.e., in models that directly reconstruct an output image prediction, such as U-Net and generative models, the fully connected network and activation function is not needed [11]. In deep learning, artificial neural network (ANN) has been gaining importance in land use planning studies. ANN is a computational ML model based on multilayer perception composed of processing elements forming three kinds of layer (input, hidden, output) which are called perceptrons [12]. Deep learning algorithms work well with relatively large datasets with supporting infrastructure to train them in reasonable time. There has been increasing interest in the Markov random field-based methods for land use classification and land use change as it helps in generating a smooth classification pattern. Markov random field (MRF) is a statistical model based on probability theory which efficiently represents dependency between pixels in a spatial domain. MRF is useful for characterizing spatial-contextual information and has been commonly used for image segmentation, texture analysis, edge detection and image restoration. MRF has been used for linear feature detection with satisfactory results. MRF for modeling spatial context relies on its relationship to Gibbs random field which is a useful way to apply MRF to deal with context [13]. In the paper "Identifying Urban Poverty Using High-Resolution Satellite Imagery and Machine Learning Approaches: Implications for Housing Inequality" [14], six types of image features perimeter, line segment detector (LSD), Hough transform, gray-level co-occurrence matrix GLCM, HoG, and local binary patterns (LBP) were extracted to identify urban poverty in Wuhan, China. The paper utilizes four machine learning regression approaches random forest (RF), Gaussian process regression (GPR), support vector regression (SVR), and neural network (NN) to study whether the features derived are helpful in differentiating urban poverty. It was concluded in the paper that textural features are important in identifying urban poverty in the study area.

In addition to the above-mentioned ML algorithms, there are several simulation models for the purpose of mapping and growth projections of land use. There are mainly two groups according to the key mechanisms to simulate the process of land use change rule-based/process-based models and empirical-statistic models [15].

2.2. Urban Land Use Models

Cellular Automata (CA)have been defined as discrete spatio-temporal dynamic systems based on local rules. In cellular models, geographic space is represented in the form of a geographic grid, such as the cells in a raster Geographic Information System. They are preferred when model states and the probabilities of transitions among those states are known and stable. They are most suitable for measuring, detecting and predicting change processes such as land use change and urban growth [16].

Cellular automata have capacity to handle temporal dynamics. Cellular automata have the following basic features:

- States: each cell can take an integer value that corresponds to the current state of that cell. There is a finite set of states.
- Neighborhood: is a collection of cells that interact with the current one. To perform simulations on a satellite image we normally take the eight surrounding pixels as neighborhood.
- Transition function (f): takes as input arguments the cell and neighborhood values and returns the new state of the current cell.

The transition function is applied to each cell of the grid across several iterations. Therefore, cellular automata have an evolution process because some cells are changing their states across the different iterations [17]. The most commonly used cellular automata model is the Slope, Land cover, Exclusion, Urban growth, Transport and Hill shade (SLEUTH) model which has been in application for a long time. SLEUTH model has been widely used for simulating urban growth and land use change. SLEUTH is open source and has been developed in C programming language. As described by Berberoğlu et al. (2016) [18].

> *"The program involves as a series of nested loops: the outer control loop repeatedly executes each growth "history", retaining cumulative statistical data, while the inner loop executes the growth rules for a single iteration, assumed to be a "-year-." The rules apply to one cell at a time and the whole grid is updated as the iterations complete".*

Statistical modeling methods are widely used for modeling, assessing, qualifying, quantifying and predicting the degree/extent/direction of land use change and growth. An example of a statistical model is the logistic regression model. Logistic regression is a predictive statistical modeling technique which applies multivariate regression to predict future land use based on historical land use changes, their spatial (change) characteristics and other potential drivers [15]. It is easier to model land use change using statistical modeling methods as their calibration is not so computationally intensive compared to rule-based models like cellular automata [19]. In logistic regression, social and economic factors like population density, accessibility to services, distance to commercial and industrial area, mean incomes, etc., can be incorporated in the model. Logistic regression analysis has been one of the most widely used approaches in the past two decades for predictive land use modeling by means of variation of inductive modeling [19].

Agent-based modeling (ABM), which is a forward-looking simulation technique which calculates "agents," each of which represents an actor and how they interact with their "environment" or the total system. The models represent real and imagined scenarios, which allow for the discovery of potentially emergent issues or phenomena. Such models have increasingly been used to analyze complex issues like land use change. Agents are independent entities which have set goals to achieve. The agents can be countries, landowners, land tenants, citizens, etc. ABM is used to simulate human behavior in cities, for example whereby policy makers, planners or citizens are entities (agents) which interact with the city environment and are capable of making urban planning decisions [16]. In a rule-based approach, their behavior is fixed, meaning that decision-making functions and algorithms remain unchanged (i.e., they always react in the same way when confronted with a particular situation). While agents react to changes in their spatial and social environment, they neither adapt their rules in response nor intelligently learn from previous experiences. ABM can be useful to study the changes in the land use and to evaluate the projections.

The various development environment used for agent-based modeling are Anylogic, Cormas, Cougaar (via OpenMap) Framsticks, Janus (using JaSIM), MASON, Repast, SeSAm, VisualBots, and NetLogo. These environments provide tools to develop an agent-based model and provide a platform to represent model components, control model function, and evaluate and visualize model output [20].

Hybrid approaches have been developed by integrating different ML methods which has resulted in better performance and assessment. An example of a hybrid method is the integration of logistic regression, Markov chain and cellular automata [21] to model urban expansion in the metropolitan area of Tehran, Iran. The results of the simulation were compared with the actual land use map and the result matched 89% between the simulated and the actual. Another example is integration of cellular automata Markov chain (CA-MC) with artificial neural network [22] to enhance the simulation capacity in predicting the changes in land use. The study integrates ANN and CA-MC to incorporate several driving forces (economic, spatial and environmental variables) that impact land use change. The integration and the influence of the driving forces improved the model prediction. Among the hybrid approaches Kamusoko and Gamba (2015) [23] tested random forest–cellular automata to study urban land change in Harare metropolitan province, Zimbabwe. Cellular automata was used to calculate multiple-step transition rates from land use/land cover maps (1984, 2002 and 2008). RF model was used to compute transition potential maps. The study then compared this model with SVM-CA and logistic regression (LR) and CA. The result showed that RF-CA outperformed SVM-CA and LR-CA models. Hybrid Urban Expansion Model (HUEM) was used by Mustafa and Cools (2018) [24] that integrates LR, CA, AB to simulate future urban development in Wallonia, Belgium. The urban expansion is simulated between 1990 and 2000. The calibration results are analyzed by comparing the projection for the 2000 simulated map with the actual 2000 land use map. The HEUM model uses three agent sets, developer agent, farmer agent and planning permission authority agent. The performance of HEUM is compared with other spatial expansion models, i.e., Logit model, CA model, CA-Logit model. The comparison shows that the performance of HEUM model is better than other models in terms of allocation ability.

3. Materials and Methods

3.1. Research Approach

The review article is based on an integrative approach relying on secondary data. It is a concept-centric qualitative approach drawing on deductive logical reasoning to create new scientific knowledge from the existing facts in literature and inform future research, policies and decision making. The researchers use their own knowledge about the topic in order to critically analyze and synthesize the existing knowledge about different concepts, theories and principles and deduct their own conceptualization from the reviewed general facts. Webster and Watson [25] and Torraco [26] argue that this approach adopts critical review, analysis and synthesis of existing knowledge about the topic under research, with the object of devising possible relationships among various research variables, identifying knowledge gaps and contradictions, and seeking opportunities for future research. The aim of the research is the potential to reconceptualize the expanding and diversified knowledge base of the topic as it develops over time [25]. Spatial and temporal limitations (boundaries) were not considered throughout the review process for internal validity purposes. This led to review of both old and new geographically unlimited available literature material on the topic as an appropriate method for this type of research approach which requires comprehensive and broad literature. For the purpose of avoiding various conceptual deviations, misuse and linguistic bias, both empirical (primary) and review (secondary) literature were limited to English language. The following subsection explains the process and method for identification of literature (search, selection criteria and its sources, database, repositories) screening, eligibility and inclusion (Figure 1).

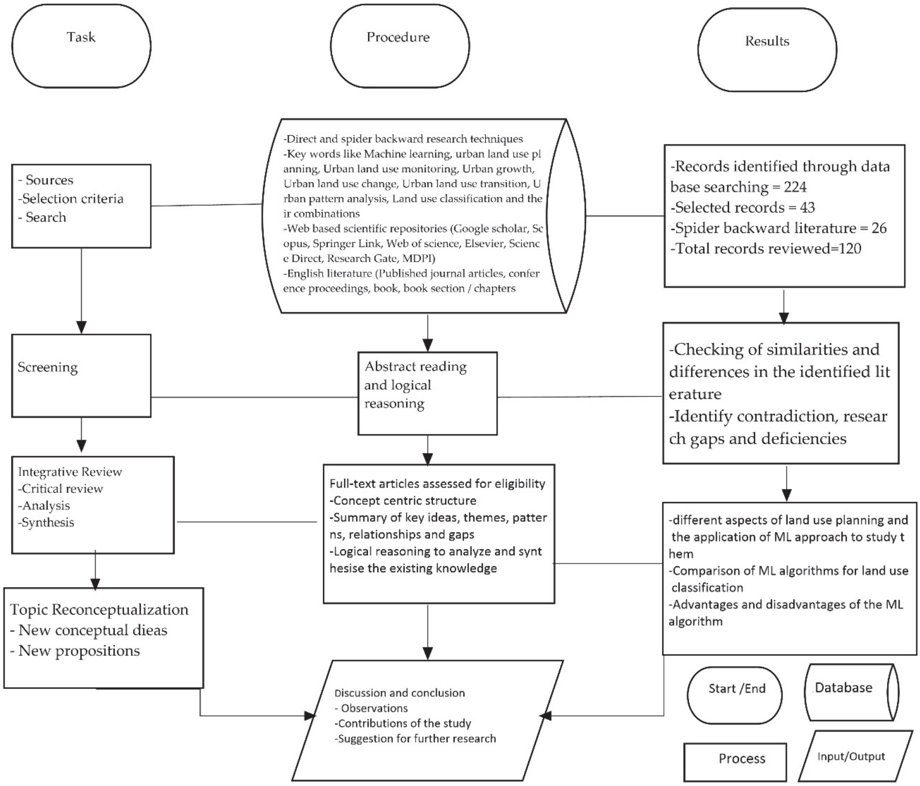

Figure 1. PRISMA showing the steps of methodology.

3.2. Data Sources and Research Method

Once the limits of the literature search were defined, we conducted the literature identification. The search strategy involved keywords and their combination. The list of keywords and their structure is given in Table 3.

Table 3. Keywords and related terms.

Keywords	Description	Related/Alternative Keywords
Land use planning	Spatial arrangement of land between competing and conflicting uses	Urban planning, land allocation, urban design
Urban growth modeling	Statistical model that involves economics, demography, geography, sociology to explore the mechanisms of increase in urban areas	Urban agglomeration, built-up density
Machine learning	Type of knowledge engineering	ML algorithm, neural network, SVM, random forest
Urban land use change	Conversion of type of use of a piece of land by humans	Land use conversion, land use transition, land use transformation
Urban land use classification	Grouping of land into different categories based on their use	Zoning, urban land management
Urban land use patterns	Layout or arrangement of uses of land	Urban form, framework, urban structure, arrangement, urban fabric
Urban expansion	General increase in the land area or the population size of an urban area	Sprawl, urbanization, urban development

Table 3. *Cont.*

Keywords	Description	Related/Alternative Keywords
Artificial intelligence	Algorithm developed to perform tasks by learning or identifying patterns	Machine learning, deep learning, neural network, pattern recognition
Urban built-up area extraction	Extraction of building footprints and other manmade features	Classification, aggregation, conurbation, urban spread
Urban land use monitoring	To detect changes in land use over a period of time	Land development, land regulation, land management

The methodology adopted consisted of selecting books, articles, journals, review papers and research papers dealing with land use planning and the various ML applications adopted for studying and analyzing the various components of land use planning. The objective of literature search and selection was not to derive an all-encompassing list of author-centric publications referring to specific ML algorithms, but to derive a content-specific review of publications which most adequately describe specific ML algorithms, specifically the procedures, popularity (i.e., frequency of use, frequency of citation, etc.), advantages and disadvantages, applicability, functional and interoperability requirements. The framework of the paper is designed on the basis of both test case and use case approach [27]. Research papers where the algorithm is a function of the commercial software and also where it has been independently developed by the user wherein functional requirements are taken care by the developer were examined.

Land use planning is a flexible, adaptive and iterative process and is based on the needs, capacities and the institutional guidelines in place. There are two approaches to land use planning, one is systematic or top-down approach which is institutionalized and is based on technical surveys and the other is collaborative/participatory planning also known as the bottom-up approach which is based on people's participation and is in accordance with the socio-cultural, economic, technological and environmental conditions.

There is limited interoperability among the ML methods. The data types are generally incompatible. Some of the programming languages in which ML tools are written are java, R and python. ML tools are supported on third party environments and can be run in the background without the user having to write a code. The selected ML algorithms can be reviewed for their functionality, interoperability requirements and their applications in land use planning. The emphasis is given on land use growth, land use zoning, land use classification, land use restrictions, land use allocation. These ML algorithms were chosen because of their popularity (i.e., frequency of use, frequency of citation, etc.), in land use planning phases, processes and/or decision making. There is awareness of the chosen algorithms among researchers and they have wide range of application. For the purpose of reviewing the algorithms, relevant literature was selected where the algorithm is used as an application and the functionalities of the algorithm are used and analyzed for their performance. For the comparison of the algorithms/models the advantages and disadvantages are discussed. The papers range from classification of data to simulation models for land use change and growth.

A comparison of various ML algorithms/models for land use planning which includes land use classification, land use change and land use growth indicates that each of the algorithms have their own advantages and disadvantages. Selection of the appropriate algorithm/model depends largely on the objective and the quality/type of data sets available (both graphic and non-graphic).

4. Results and Discussion

Machine learning algorithms are listed in Table 4 with their advantages and their applications.

Table 4. Machine learning algorithms and their advantages.

Machine Learning Algorithms	Advantage/Useful When/Appropriate for Applications Related to
Support vector machines (SVMs)	- Once the hyperplane is found SVMs tend to generalize well - Once the boundary of hyperplane is established most training data is redundant - Powerful algorithm for land use pattern recognition - Capability of contextual feature extraction
Markov random field (MRF)	MRF combines both pixel information and region information
Convolutional neural network (CNN)	Local spatial coherence in input image makes CCN suited for feature extraction
Random forest (RF)	- Can deal with large number of features - It incorporates spectral bands and other feature selection layers like soil index, water index, NDVI - It incorporates texture features for classification which include metrics like entropy, variance, morphology, line feature, etc. - It avoids overfitting

Support vector machine (SVM) is popular because of its ability to use nonlinear boundaries and locate boundaries of training data. Classifying algorithm SVM does not require very large training samples. Sensitivity of SVM algorithm is experimented on rapid eye images in [28] for land use classification. For comparison, the traditional maximum likelihood classification was also performed in the same set of images. The results of the research indicated that model parameters and kernel type play an important role in the accuracy of the classification using the SVM algorithm. However, it can be deduced from various research papers that the results of the SVM depend on the choice of the kernel and the regularization parameters.

ANN approaches have a distinct advantage over statistical classification methods in that they are non-parametric and require little or no a priori knowledge of the distribution model of input data. Additional superior advantages of ANNs include parallel computation, the ability to estimate the nonlinear relationship between the input data and desired outputs, and fast generalization capability. Many previous studies on the classification of multispectral images have confirmed that ANNs perform better than traditional classification methods in terms of classification accuracy, such as maximum likelihood classifiers [29].

Random forest algorithm is used for satellite and aerial image classification. Its ability is to handle large numbers of features like texture, contextual, spatial, spectral and structural without affecting the overall accuracy of the classification. In an experimental study, the authors [7] integrate the random forest method with spatial metrics and texture analysis and find that the use of this method seems to be limited to flat cities with a small number of high-rise constructions. In the research by Belgiu et al. (2014) [30], building types are classified by means of domain ontology and machine learning using airborne laser scanner data. In the study, RF classifier has been applied to select the relevant features for predicting the classes of interest. RF classification model has been used to study the urbanity index between Germany and France [31]. The study involved defining urbanity on the basis of travel behavior. The aim of the study is the identification and comparison of different urban structures at zip code level across Germany and France. It was concluded that the adaptation of the RF model provided an effective methodology for the automated assessment of level of urbanity of different areas.

Cellular automata models are sometimes described as a type of agent-based model. The key difference is that, for cellular models, spatial entities are the basic units of simulation and the topology (or connection) between those units remains fixed, whereas agent-based models described in Table 5 represent decision making units that have a flexible and dynamic relationship with land units [20]. Specific advantages of agent-based models include their ability to represent individual decision makers and their interactions, to incorporate social processes, non-monetary influences on decision making, and to dynamically link social and environmental processes [32]. A relevant example of an agent-based model is simulation of informal settlement growth in Dar es Salam, Tanzania [32] where a vector based, micro scale housing model is developed to simulate the growth of informal settlements.

Table 5. Statistical modeling approaches.

Machine Learning Models	Advantages	Disadvantages	Particularly Useful for Applications of
Spatial logistic regression	-Can incorporate socio-economic and demographic factors -Logistic regression allows multi-scale calibration due to less demand of computation resource	-Lack of temporal dynamics -Does not consider location preferences, policies	Urban growth, land use change, land allocation
Cellular automata	-Phenomena of sprawl can be efficiently simulated in CA models -CA models produce outputs according to the transition rules	-High demand of computation power -Capability to handle temporal dynamics	Land use change, land allocation
Agent based modeling	- It incorporates human behavior - Bottom up approach	-Variability in the results because of randomization of agents at initialization for combination of parameter settings -Hard to calibrate	Urban growth and land use change

Some of the research work carried out using different methods of ML and modeling by the researchers is given in Table 5 with the advantages, disadvantages and their applications.

4.1. Machine Learning Models and Their Applications

4.1.1. Algorithms/Models to Study Urban Growth, Patterns and Land Use Change

Several studies have been carried out using empirical data sets to compare the performance of machine learning/statistical models to study the aspects of land use planning. Most of the studies focus on urban growth/expansion, land use change and patterns of land use. The most commonly used models to study urban growth and change are logistic regression and cellular automata. The performance of some of the machine learning algorithms and statistical approaches for the studies reviewed is shown in Table 6.

Table 6. Machine learning algorithms and their performance.

Author and Year	Study Area	Data Used	Method	Performance
1.Urban growth pattern modeling using logistic regression [15]	Jiayu County, Hubei Province, China	Vector data, map of the county, topographic map, DEM and data on population, agriculture, industrial from secondary data sources	Logistic regression modeling	Less demand of computation resources, vector-feature-based spatial analysis has higher accuracy, procedure is most effective when group membership is a truly categorical variable
2. Support vector machines for land use change modeling [33]	Calgary, Southern Alberta, USA	Chronological land use data Landsat TM and ETM, demographic data, and transportation data (major roads and LRT lines), elevation data, community map, city amenity map, community service center map, and shopping center distribution map	Support vector machine (SVM)	Improved SVMs can greatly improve the accuracy and reliability of land use change modeling especially when the underlying data distribution is unknown and the dataset is significantly unbalanced
3. Modelling urban growth with GIS based cellular automata and least squares SVM rules [34]	Qingpu–Songjiang area of Shanghai, China	Landsat images covering the study area acquired on 18 July 1992 and 24 March 2008 were used, topographic map at a scale of 1:50,000 as the reference data for georectification	MachCA model which is cellular automata (CA) with nonlinear transition rules based on least squares support vector machines (LS-SVM)	LS-SVM method is relatively complex in its theory and implementation. Therefore, it requires an understanding of the mechanisms of urban dynamics as well as mastery over the requisite mathematical and computer knowledge for its application
4. Land cover and land use classification performance of machine learning algorithms in a boreal landscape using Sentinel-2 data [35]	Uppsala in South-Central Sweden	Sentinal-2 multi temporal images was used covering an area of 10 × 12 km mixed-use landscape	SVM, RF, extreme gradient boosting (Xgboost), and deep learning (DL)	The results show that the highest overall accuracy was produced by support vector machines closely followed by extreme gradient boosting, RF and finally deep learning
Urban expansion in Centre County, Pennsylvania: spatial dynamics and landscape transformations [36]	Centre County, Pennsylvania	Landsat TM images of the county for 1993 and 2000	Cross-tabulation; logistic regression; CLUE-S regional modeling framework	Although the model is able to simulate urban land use location at the county level, it is less able to simulate these locations at the sub-county level due to non-availability of data at the appropriate scale

Table 6. *Cont.*

Author and Year	Study Area	Data Used	Method	Performance
Modeling urbanization patterns with generative adversarial networks [37]	Global training samples of 30,000 cities (urban footprints)	Global training samples of 30,000 cities (urban footprints) https://github.com/adrianalbert/citygan (accessed on 4 April 2021).	Generative adversarial networks (GANs)	GAN model is able to generate realistic urban patterns that capture the great diversity of urban forms across the globe

In addition to the above commonly used ML algorithms and statistical models, several other published papers have applied not so common ML algorithms to obtain their results. To study the factors contributing to urban land use patterns, Decraene et al. (2013) [38] developed a dynamic urban growth model that aims to construct artificial cities from the bottom-up using the measure of spatial entropy and index of dissimilarity. The study applies a CA model which relies on the range of influence of different land use sectors (residential, business and industrial). Four statistical modeling approaches are compared for modeling land use change; they are Markov chain, logistic regression, generalized additive models and survival analysis [39]. The methods were compared on the basis of accuracy (overall and by land use type, sample size and spatial independence by means of conventional and spatial cross-validation). Logistic regression and survival analysis were more accurate for specific land use type. It was concluded that hybrid approaches outperformed individual statistical approaches. SVMs have been used in a variety of application domains including land use change modeling. SVM based land use modeling technique is applied to study the change in land use classes for the municipality of Zemun, Republic of Siberia for a 10 year time period [40]. The SVM modeling procedure entails finding a function which maps attributes of a grid cell at a time point to its land use class at time + 1. The population change index (PCI) was used as an attribute and it was calculated as the ratio of change in the number of inhabitants per each cell between two censuses: 2001, 2011. Correlation based feature subset reduces the number of initial attributes to an informative subset for a more efficient model less sensitive to the SVP parameter changes. It is concluded that the SVM based LUC model is sensitive to the choice of datasets used for training and validation, the selection of attributes and optimal learning parameters.

4.1.2. Commonly Used Algorithms for Land Use Classification

RF algorithm is evaluated for its performance in land use classification (Rodriguez-Galiano, Ghimire, Rogan, Chica-Olmo, & Rigol-Sanchez, 2012) [41] using multitemporal Landsat-5 thematic mapper data of a large heterogeneous area. The study area selected for the project is the province of Granada in Southern Spain. The study also compares the performance of the RF algorithm with conventional classification trees (CT). It was concluded that RF provides more significant differentiation of land cover categories. A hybrid approach of classification has been adopted by [42]. In the modified method, the object-oriented approach is combined with deep convolutional neural network (COCNN). The object-oriented method is used to construct a multiscale sample set to provide high precision training data. Ten land use types are classified using remote sensing images covering an area around Fuxian lake. Convolution kernels is regarded as the most sensitive element of the CNN and is responsible for directly extracting the lowest level feature on the original image. The result of this approach has been compared with the outputs obtained from CNN and the modified approach has shown to improve the results. It is concluded in the paper that the result is dependent on the kernel size and for the object-oriented training sets a kernel size of 3 × 3 has been used.

4.1.3. Limitation

The research cannot be exhaustive as the number of papers which have been published on urban land use planning using ML algorithms and statistical models majorly focus on two aspects of urban sprawl/growth and land use transition/change. The author was interested in other aspects of urban land use planning like zoning, land allocation, land restrictions but sufficient published literature was not available to cover these aspects. There are numerous published research papers on use of classification algorithm to classify land use but the majority of them are covering algorithms like deep learning, SVM, random forest and very few papers on algorithms such as logistic regression, MRF, k-nearest neighbors, naive Bayes, etc.

5. Conclusions

This comparative study is an analysis of the various ML methods used in land use planning along with their advantages and disadvantages. The study also has brought out the applicability of ML algorithms to specific task of land use planning. Some of the articles deal with the testing of the performance of specific ML algorithms and while others have dealt with specific requirements of land use planning. In particular, the aspects of urban land use change, relevant to understand the spatio-temporal patterns of urbanization are prominent in the literature. To a lesser extent, the socio-political reasons and causes of these patterns are part of these studies, although it can be imagined that ML algorithms could also address part of these via other types of data repositories. The review of various publications on ML algorithms and their applications in land use planning demonstrates that most of the ML algorithms operate at the pixel level and have limited practicality when working with VHR imagery, in contrast to object-based image analysis. In general, non-parametric algorithms are computationally more expensive compared to linear models. The efforts are more towards minimizing the complexity and lowering the computational cost. The comparison of the various algorithms indicates further that random forest is relatively more robust for classification. The choice of the ML methods relies largely on the type of datasets and understanding of the researcher. It has been seen that hybrid approaches like pixel based and object-based approaches are gaining popularity to get the optimum/desired results for modeling urban growth, land use change, settlement patterns and classification.

The benefit of this review is that it enables the boundary work between practitioners and future researchers in either land use planning or in the application of technical spatial and information scientific tools. The overview tables present the links.

Further research should go in the direction of utilizing empirical data sets and applying the algorithms to analyze their performance and suitability for studying aspects of land use planning. Experiments on deep learning, SVM, random forest and GANS for land use classification should check the overall classification accuracy of each of the algorithms. In addition, experiments with spectral, texture, structural and contextual image features should be undertaken to improve the accuracy of classification. The performance of the hybrid approach should be tested to get best results in classification, modeling of urban land use growth, change and transition.

Author Contributions: Conceptualization, V.C. and W.T.d.V.; methodology, V.C. and W.T.d.V.; investigation, V.C. and W.T.d.V.; writing—original draft preparation, V.C. and W.T.d.V.; writing—review and editing, V.C. and W.T.d.V.; supervision, W.T.d.V. Both authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TUM open access publishing fund.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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buildings

Review

Mining the Built Environment: Telling the Story of Urban Mining

Faisal Aldebei * and Mihály Dombi

Department of Environmental Economics, Faculty of Economics and Business, Institute of Economics and World Economy, University of Debrecen, 4032 Debrecen, Hungary; dombi.mihaly@econ.unideb.hu
* Correspondence: faisalaldebei@mailbox.unideb.hu; Tel.: +36-204-387-285

Abstract: Materials are continuously accumulating in the human-built environment since massive amounts of materials are required for building, developing, and maintaining cities. At the end of their life cycles, these materials are considered valuable sources of secondary materials. The increasing construction and demolition waste released from aging stock each year make up the heaviest, most voluminous waste outflow, presenting challenges and opportunities. These material stocks should be utilized and exploited since the reuse and recycling of construction materials would positively impact the natural environment and resource efficiency, leading to sustainable cities within a grander scheme of a circular economy. The exploitation of material stock is known as urban mining. In order to make these materials accessible for future mining, material quantities need to be estimated and extrapolated to regional levels. This demanding task requires a vast knowledge of the existing building stock, which can only be obtained through labor-intensive, time-consuming methodologies or new technologies, such as building information modeling (BIM), geographic information systems (GISs), artificial intelligence (AI), and machine learning. This review paper gives a general overview of the literature body and tracks the evolution of this research field.

Keywords: urban mining; material stock; circular economy; building information modeling (BIM); geographic information systems (GISs)

Citation: Aldebei, F.; Dombi, M. Mining the Built Environment: Telling the Story of Urban Mining. *Buildings* **2021**, *11*, 388. https://doi.org/10.3390/buildings11090388

Academic Editor: Pierfrancesco De Paola

Received: 21 June 2021
Accepted: 14 August 2021
Published: 1 September 2021

1. Introduction

There has been a surge in interest in the circular economy as a research subject in recent years [1]. According to the present authors, sustainability issues, resource scarcity, waste management, and progressive policies are driving this interest. The traditional economic model takes a linear approach to resource utilization, beginning with extracting raw materials from the natural environment and transforming them into products; these products are discarded as waste in the end-of-life phase. The pollution generated at each step receives little to no attention. In this linear economic model, economic goals take precedence over environmental and social concerns [2]. Economic growth, according to researchers, leads to the depletion of natural resources and a reduction in the natural environment's generative ability [3]. As a result, the circular economy was developed to decouple economic growth from natural resource depletion [4]. However, the term circular economy does not have a fixed definition [1]. It was initially portrayed as a way to achieve a closed-loop material flow within the economic system [5] or a "cradle-to-cradle" system, as McDonough (2007) describes it [6]. One consequence of this interpretation of the circular economy is that it fails to distinguish between distinct types of circularities. As a result, the academic community has primarily focused on closing material loops, where the value of resources is maintained through recycling in what can be described as a "traditional" approach to cleaner production, with much less attention paid toward slowing down the loops [1]. According to Graedel (2011), the recycling efficiency of metals is the sum of the efficiency of each step leading to the production of secondary raw metal [7]. 75 percent of waste metals will not be recycled due to losses at each stage. Therefore, it is important to reduce the number of steps by using other forms of circularity.

According to Sauvé et al. (2016), the circular economy model can be a production model that aims to extend the useful life of products by favoring the possibility of repair, refurbishment, and reuse [2]. Slowing materials loops entails creating long-life products, starting with a durable product design; then, its value is extended through remanufacturing, repair, refurbishment, and reuse practices [8]. Many researchers nowadays prefer reuse to recycle or backfilling practices [9,10].

A linear economy based on the take, make, and dispose approach subsequently led to a linear material flow. Coupled with urbanization, an unprecedented amount of material has accumulated in urban systems. The accumulated materials are known as "anthropogenic resources" [11]. In order to describe the size of anthropogenic resources, suffice to imagine that over three hundred years of mining, more than 80 percent of the world's natural resources—resources that could be used for production—were extracted and accumulated above ground. A substantial portion of it is now waste [12]. The anthropogenic stock of gold, silver, lead, and zinc exceeds the known natural deposits, while the anthropogenic stock of copper and iron is equal to known natural deposits [13–17]. Moreover, half of the extracted amounts of copper and iron are no longer in use [18,19]. Furthermore, Krausmann et al. (2017b) estimated that 35 percent of the in-use materials in 2010 will be disposed of as waste by 2030, which is approximately the same amount of waste generated in the last 110 years combined [20]. It is, therefore, safe to assume that the linear model is unsustainable and will lead to the depletion of non-renewable virgin resources. Due to this linear consumption pattern, urbanization, and industrialization, humans have extracted vast amounts of materials, most of which accumulated in urban areas [20–23]. On the one hand, urban areas are considered economic powerhouses, accounting for 85 percent of global GDP [24]. On the other hand, they account for 75 percent of natural resource consumption, 50 percent of global solid waste generation, and 60–80 percent of greenhouse gas emissions [25]. In line with the above, attention was drawn to the exploitation of these anthropogenic resources through a process known as urban mining to replace and complement the extraction of unrenewable natural resources [22,26].

In this paper, we review the development of urban mining as a research subject. Following the introduction section, the research methodology is presented in Section 2. Section 3 introduces the metabolism concept in industrial ecology, the theoretical root for urban mining. In addition, we aimed to organize and classify the literature body to identity urban mining research. In Section 4, an extensive review of urban mining literature from conception until present-day state-of-the-art research and future possibilities is presented. This paper's contributions include (1) analyzing the leading academic research in academic databases and classifying them based on research objectives into four categories: waste management, production and consumption, environmental impacts, and urban mining and secondary resources; (2) comparing related articles concerning their methodologies, research objects, and scopes to track the research evolution and results; and (3) identifying the current research gaps and potential future research directions.

2. Research Methodology

Due to the interdisciplinary nature of research on urban mining and material stock and the lack of unified definitions and terminologies, we decided that a systematic review was not the best approach to collect literature; instead, selective snowballing methods were used, as snowballing studies are less affected by diverse terminologies [27]. We started by searching Scopus, Web of Science, and Google Scholar databases for the terms "Urban Mining" and "Material Stock" and after reviewing the results one by one, we chose the most cited paper that matched our scope [14], which was the seed paper for this review. The reason for choosing only one paper was that most of the search results were on e-waste mining. Therefore, these papers did not fall into this review scope. We started a backward snowballing search by looking at the references list from the seed paper and selecting the most related paper to our scope. Then, we performed a forward snowballing search from the seed paper and the set of papers extracted from it using the Google scholar "cited by" filter. We continued with the same process, and we stopped the snowballing when no paper relevant to this research could be found. A major drawback of the snowballing methods is that snowballing is affected by the authors' subjective judgments on which papers are worth exploring, and this may result in missing some literature that still falls within the scope of the paper.

3. Industrial Ecology and Urban Metabolism

Baccini and Brunner defined the anthroposphere as a "complex system of energy, material, and information fluxes" in their book *The Metabolism of the Anthroposphere* [26]. They coined the term "anthropogenic metabolism" to describe human society's material and energy turnover, similar to that of living organisms. They noted that the anthroposphere is constantly changing due to man's "biological and cultural needs." Material stock is built up over time as goods that serve as "carriers of materials" accumulate. They also viewed cities as an unhealthy form of accelerated anthroposphere expansion that would eventually collapse due to resource scarcity and pollution.

In this context, the concept of metabolism is not new. Several authors used various approaches to interpret metabolism from a social and industrial standpoint [28]. The term "urban metabolism" was coined by Wolman (1965), who defined it as "the materials and commodities needed to sustain the city's inhabitants, ... The metabolic cycle is not complete until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard" [29]. According to Fischer-Kowalski (1998), this definition was the first attempt to conceptualize metabolism in industrial societies [28]. Later, in 2007, Kennedy et al. (2007) defined urban metabolism as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" [30]. The concept has evolved; the term "socio-economic metabolism" was coined to describe the extended notion of metabolism [31] as the set of all anthropogenic flows, stocks, and transformations of physical resources, as well as their respective dynamics [11,32]. Wolman used mass balance principles to quantify urban metabolism in his 1965 study [33]. This study was a driving force behind creating economy-wide energy and material flow accounts [31]. Studying urban metabolism has gained popularity worldwide, showing the importance of understanding material flows and accumulation processes and how they are critical to cities' sustainability. The result was a perfect storm in academia that propelled material flows and stocks to the forefront of industrial ecology and metabolism research. Today, industrial ecology is a well-established research field that is specifically interested in analyzing material flows and quantifying stocks (both in and out of use) to better understand social, economic, and ecological real-world issues [11,32–35].

The Role of Material Stock in Industrial Ecology Research

Material stocks are considered the building blocks of society due to their essential social, economic, and ecological roles. Material stock, such as buildings and infrastructures, deliver services to society, such as shelter and transportation. At the same time, they are considered capital containers that require significant monetary investments. Most resource use and emissions that are generated arise from buildings through using and maintaining these stocks [32]. Therefore, the literature on industrial ecology and urban metabolism has a diverse set of goals and drivers. It is also constantly branching out into new fields and applications, with one of these being urban mining. Therefore, categorizing the body of the literature solely based on purpose is difficult. Nonetheless, in Table 1, we attempted to organize the literature into four main categories based on the purpose of each article for the sake of simplicity. However, these categories are interconnected, and many articles fell into more than one category.

Waste management: This category included all waste and resources efficiency concepts [34,36,37], current recycling and recovery rates, and the future potentials in light of policy frameworks and/or management systems, which are themes that are generally addressed in this category of research. For example, Graedel's (2011) study evaluated the recycling potential of metals in the periodic table and discussed factors influencing recovery rates [7]. Similarly, [35,38] examined copper and zinc global anthropogenic cycles, respectively, to estimate the end-of-life recycling rates. Ciacci et al. (2017) investigated the stock and flow of PVC in the EU-27 countries. Its findings showed that two-thirds of PVC stock are still in use, while one-third is wasted and mostly landfilled with a low recycling rate. Thus, the author proposed several policy interventions [39]. Similar findings were presented in another study [40]. Furthermore, the literature shows an interest in quantifying the current and future waste flows. The general methodology of such research can be described as a retrospective stock pattern estimation that allows a prospective forecasting model for future waste generation to be created [41–53].

Production and consumption: This category included research that focused on the evolution of stocks and flows over time, highlighting the increasing consumption and accumulation of stocks [20,22,49,54–67]. Typically, it included forecasting future demand, similar to the general methodology described in the previous category. Several studies provided indicators based on stock levels, such as materials' saturation in industrialized countries [63–66], and socio-economic indicators, such as the decreasing housing stock in developed countries [67] in contrast to a housing deficit in developing countries [68]. In other words, researchers here attempted to explore and understand the relationship between stock levels and production, consumption, social welfare, population, and income, along with other parameters [60,68–74].

Environmental impacts: A significant part of the literature addressed the ecological implications of material flows and stocks. Many studies examined the correlation between GHG emissions and material stocks [46,75–80], while others estimated wood-based materials or "carbon stock" [81–83], and there was also an interest in analyzing energy use retrospectively [20,84–86] and estimating future energy demand [87–92]. In short, this part of the literature is significant because it presents various scenarios that demonstrate the magnitude of environmental harm that can be averted [52,93], especially in the context of renovation activities and retrofits that extend the life of building stock rather than end it [94–96]. Furthermore, they provide a road map to meet global climate targets [43,97]. In addition, there are several growing trends in terms of energy generation technologies and the transition to clean energy. Stock levels, materials requirements, and materials efficiencies are all factors to consider [98–101]. Other studies were more concerned with natural disasters: earthquakes, tsunamis, and floods. They estimated the losses in material stocks that are considered an unexpected waste flow. They also estimate the amounts of material needed to restore previous levels of economic growth [102–105].

Moreover, some studies examined the effect of global warming on the economy, e.g., by estimating lost stock due to the rising sea level [106,107] and the effect of war on stock levels [108,109]. However, those might be better suited under the "urban immune system," which is a unifying framework for urban resilience that expands industrial ecology research on urban risk management [110].

Urban mining and secondary resources: This last category includes research that looks at material stock from a future secondary resources standpoint. Any research can be considered an asset for urban mining literature independent of whether the authors refer to urban mining. According to Graedel (2011), three main questions must be answered to assess the potential of urban mining. How many materials are there? When is it going to be available? What form does it take? [7]. Thus, any research that answers one or more of these questions is critical to urban mining as a developing field.

Table 1. The four categories of material stock research.

Category	Purpose	Geographical Scope and Materials	Methodological Approach	Forecasting Model	Examples
Waste Management	Forecasting and comparing future input and output flows. Recycling and recovery rates and policy and management systems are reoccurring themes.	Geographical scale: national and global. Materials: metals, construction aggregates, and plastic.	Top-down retrospective dynamic flow analysis is commonly used, unlike a bottom-up analysis.	Yes	[7,38–40]
Production and Consumption	Studies the evolution of stocks and flows over time. Forecasting and comparing future input and output flows, e.g., demand for metals.	Geographical scale: national and global. Materials: metals, construction aggregates.	Top-down retrospective dynamic flow analysis.	Yes	[20,41,49,67]
Environmental Impacts	Examines the correlation between GHG emissions, energy demand, and material stocks. Global climate change and natural disasters are also reoccurring topics	Geographical scale: regional, national, and global. Materials: metals, construction aggregates, and wood.	Top-down retrospective stock analysis.	Yes, especially energy demand and scenario-based forecasting.	[56,77,79,91]
Urban Mining and Secondary Resources	Estimating material stock for future exploitation	Geographical scale: urban and regional. Materials: metals, construction aggregates, and wood.	Bottom-up static stock analysis and occasionally a retrospective dynamic analysis are performed.	No, instead, some studies estimate the demolition curve.	[111–114]

4. Urban Mining

In 1969, Jane Jacobs put forward the seed of what would later become urban mining. In her book, *The Economy of Cities* [115], she mentioned that future cities "will become huge, rich and diverse raw materials mines. These mines will differ from any now to be found because they will become richer the longer, they are exploited; new veins, formerly overlooked, will be continually opened." Years after Jacobs, in 1988, Japanese professor Randolph Nanjo noted that the grade of the metals used in products accumulated in the anthroposphere exceeded the grade of natural deposits. He referred to the area of accumulated materials on the Earth's surface as "urban mines" [17]. Mining, which in its traditional sense refers to the extraction of minerals from natural deposits in the Earth's crust, was used to refer to the process of anthropogenic resources utilization and exploitation. Urban mining is, therefore, a metaphor for describing these activities. Similar to traditional mining, which consists of several stages of prospecting, exploration, development, and exploitation, the stages of urban mining begin with prospecting, which entails researching areas with urban mines, then exploration, which entails quantifying the stock, and finally, determining the feasibility of exploitation [22,116–118].

Urban mining is considered one of the strategies for transformation to a circular economy [15,60,119–122]. Urban mining, however, does not have an exact definition but generally refers to the recovery of materials from anthropogenic resources [13]. The term may include energy recovery [123] and product design [7,11]. The concept is known throughout the literature; however, authors used different terms to describe it, such as secondary mining, waste mining, mining above ground, and landfill mining [13]. Although the latter refers to the processing of accumulated waste that is located in waste dumps and structured landfills [124], it originated from the waste management field [14]. According to Cossu et al. (1996), landfill mining differs from urban mining; the author argues that the main driver of landfill mining is not the recovery of materials [125]. Urban mining, therefore, extends landfill mining to the process of the recovery of materials [118,126]. Perhaps the most comprehensive and inclusive urban mining definition comes from Johansson et al. (2013), which includes in-use stocks, landfills, tailing ponds, slag heaps, hibernating stocks, and dissipated metal resources [13]. However, the literature is still quite divided on what is an appropriate definition for urban mining. For instance, Cossu and Williams (2015) stated that "urban mining should refer to the exploitation of anthropogenic stocks"; the authors further add, "the term is widely used for describing almost any sort of material recycling." The authors argued that material stocks in a defined location, such as buildings and infrastructure, may not vary over time. In contrast, material flows may change from year to year, depending on the economic situation, trends, and technical innovations, making it difficult to estimate the flow since accurately estimating quantities is crucial for urban mining because it is firmly based on economic feasibility [15].

4.1. Materials under Study

The urban mining of material stock initially focused on e-waste, motivated by the high concentration of expensive rare earth minerals [15]. In other words, urban mining was considered where economic incentives were high [7]. Then, the focus shifted to hibernating stocks, which are abandoned material stocks that have yet to be collected for waste management [23]. These stocks were soon estimated and realized to be relatively small, accounting for less than 10% of the anthropogenic stock [127–129]. Again, the focus shifted this time toward in-use stock, driven by industrial ecology and socio-economic metabolism studies [32]. In-use stock, namely, buildings and infrastructure, is the largest anthropogenic stock and the most prominent product of the urban environment. However, in-use stocks are considered the black box of anthropogenic resources [130] due to the difficulty of estimating stock depositories. Several studies have estimated that buildings and infrastructure account for more than 50 percent of all metals used [131], making it the largest urban mine compared to other anthropogenic stocks.

4.2. Urban Mining Benefits

The benefits of urban mining go beyond reducing the extraction of non-renewable resources and reducing or eliminating waste to mitigate the environmental impacts of traditional mining [11,14,132]. Graedel (2011) stated, "It should be clear at this point that the successes to date are not very significant or exciting, and that enormous challenges remain. Nevertheless, urban mining does matter. Every kilogram recovered and reused displaces a kilogram that must be mined and processed, with all the environmental, social, and economic implications those actions entail" [7]. In China, for example, aluminum extraction and production accounted for 17,000 kg of greenhouse gases (GHG) per ton in 2008, while recycled aluminum accounted for 715 kg, or 237 times less [133,134]. Furthermore, according to another study [135], recycling iron was predicted to save 96.3 million tons of coal and 32.0 million tons of aluminum by 2020, while recycling copper was expected to save 1305.5 million tons of water and eliminate 1255.9 million tons of solid waste. In conclusion, urban mining is essential in the transition toward a circular economy and sustainable cities. Furthermore, it might just be the answer to some deeply-rooted global problems.

4.3. The Methodological Framework for Urban Mining

Material flow analysis (MFA) is one of the most widely used methods for examining a specific socio-economic system's material and energy flows. Based on the first law of thermodynamics, "in any process of physical transformation, matter can neither be created nor destroyed". Material inputs are always equal to material outputs plus the material that is stocked, i.e., the build-up, in the system. MFA is defined as "a systematic assessment of the flows and stocks of materials within a system defined in space and time". It connects the material's sources, pathways, and intermediate and final sinks [136]. MFA can be applied to any socio-economic system at any scale, such as global and national economies, a specific economic sector, a company, a city, or even a household [20,52,60,74,137,138]. In terms of time, static analysis can capture the material flow and/or stock over a specific period, usually a year, although this is less common [132,139]. Alternatively, dynamic analysis can be used to capture the evolution of material flow and/or stock over a more extended period [20,45]. MFA characteristics make it an attractive tool in resource, waste, and environmental management, as well as secondary resources utilization [34,136]. In urban mining, two main methods are typically used: a bottom-up method and a top-down method. Both methods are used for analyzing material flows and stocks with varying degrees of detail [140].

4.3.1. The Top-Down MFA

A top-down method is used for larger areas at a macro level, such as global and national economies, over extended periods. Typically, the in-flow data are obtained from macroeconomic statistics, which are typically available. However, outflows are harder to obtain. Therefore, the top-down approach is used in combination with the product's lifetime estimations [141,142]. The results of this method are highly aggregated and lack spatial resolution. Therefore, it has significant limitations and uncertainties when analyzing small geographical areas, such as cities, where there are insufficient statistics [57,143,144]. The general theory behind using the top-down method in urban metabolism is that stock accumulation follows per capita wealth. Thus, national figures can be scaled to urban regions, e.g., per capita gross domestic product [7,137].

4.3.2. The Bottom-Up MFA

A bottom-up method is a coefficient-based approach for quantifying material stocks and identifying flow behavior [60,114]. It entails splitting the stock into distinct material compartments based on their usage (e.g., buildings, vehicles) and then calculating the amounts of material in those compartments by multiplying the material composition indicators, such as the material intensity coefficient, by the physical parameters that define the size of the compartment (e.g., floor area and height). A bottom-up model offers high levels of detail, and the results are typically more accurate than a top-down model. However, this approach is labor- and time-intensive [138,141]. To measure the building stocks, the bottom-up method requires field inspections and construction plan analysis, among others. Thus, it is usually used on a narrow scope to evaluate a specific material in a specific year for small geographical areas [49,141]. The accuracy of this method is determined by the material under study, the chosen compartment, and the knowledge of material compositions [22]. Therefore, data availability is a significant limitation. A broad scope of research would necessitate a massive amount of data; insufficient or poor-quality data would result in a high amount of uncertainty and inaccurate stock estimations [141]. As a result, a bottom-up approach was used in only 6 studies out of 60 that were reviewed by Müller et al. (2014) [145]. Nonetheless, bottom-up MFA is advantageous in terms of spatial resolution provision. It provides all the necessary details and accurate results for stock estimation or urban mines. In the 2015 study, Professor Tanikawa and his research team emphasized the importance of bottom-up efforts for country-specific studies [138]. This approach, we believe, is the best fit in terms of urban mining and quantifying urban mines because urban mining is a practical tool for change; after all, "Man can think globally but must act locally" [26].

4.4. The Evolution of Urban Mining Research

Early research that was focused on forecasting future waste briefly discussed this future waste's availability as secondary resources. Müller (2006) [41] developed a model for forecasting the material demand and waste flow of concrete in Dutch dwellings. Hu et al. (2010) [48] considered iron and steel in Chinese residential buildings in a similar manner.

Both studies found a decrease in demand and an increase in waste output eventually. Both studies attempted to explain these findings from a variety of perspectives. However, both agreed that the main factor was that the rate of stock accumulation was faster than the rate of waste generation in the early stages of economic development. As the economy expands and more materials accumulate in the system, more waste from aging stocks is generated until the economy reaches a point of material saturation or full economic development. It does not require as many material inputs as it did previously. Because of the long lifespan of durable stocks, such as buildings, demand begins to decline, and the waste generated from old stock increases; however, a recent study showed that the demand for materials in some countries remained high, even after saturation levels, due to maintenance requirements [146]. Muller explained, "stocks are essentially integrals of flows, meaning that relatively small changes in stocks have significant consequences for the flows." This was especially evident in Hu et al.'s findings, which showed that iron and steel waste scrap from residential buildings, if efficiently recycled, could cover or exceed the future demand. A similar approach was used by Hashimoto et al. (2007) [42] to investigate construction minerals and aggregates in Japan for buildings and infrastructures. However, despite the fact that the research revealed a similar trend of decreasing demand, the authors concluded that the amount of waste generated would remain lower than the demand; this indicates a consistent increase in stock or that a significant amount of materials that were previously accounted for as stock are now in their final sink as dead or dissipated stock. It is not always the case that all input materials generate a waste flow in the future. In order to address these constraints in a later study [47], the authors classified construction minerals' input flows into four categories: potential wastes and secondary resources, potential dissipated materials, dissipatively used materials, and permanent structures. This classification system assumes that not all material inputs and stock will generate waste in the future and by excluding non-waste-generating materials, such as missing or dissipated stock, future waste flows and current material stock can be more accurately estimated. However, these studies remain insufficient for accurately quantifying future waste as secondary resources due to many shortcomings. It can be inferred, for example, that this model is highly dependent on the material under study and its pathway. Concrete in infrastructure is more likely to be abandoned and left as hibernating, dead, or dissipated stock. Furthermore, it lacks the spatial resolution of the material compartment, making it impossible to determine the physical location of these missing or dead stocks. This is attributed to the methodological framework since these studies take a top-down approach at a macro-level by considering various parameters that negatively affect the final result, where perhaps the most important examples are the lifespan assumptions [142]. Moreover, a dynamic top-down model requires a long temporal scale for the data to provide an accurate projection. However, this does not consider the variation of material content over time, e.g., renovation activities.

Meanwhile, Lichtensteiger and Baccini (2008) [147] and Wittmer and Lichtensteiger (2007) [44] used a bottom-up approach, what they called the "ark-house method," to study the copper stock in Swiss buildings. This method consists of three steps. It starts with identifying the stock; then, a sample of the stock is physically surveyed and inventoried to determine critical parameters, including the copper content. Finally, a dynamic top-down MFA model was compiled to describe the copper stocks and flows. The goals are to estimate the quantity and quality of copper in building stock and the variations in quantity and quality over time, thus providing more accurate estimates of future availability as secondary resources. Although they chose Switzerland as the system boundary for the data availability at a national level, they argued that Switzerland has the size of a region. Therefore, the method is applicable on a regional or urban scale. Similarly, [46] took the same approach to investigate the Chinese building and infrastructure stock. However, it is still not spatially detailed enough for realistic urban mining estimations.

4.5. Overcoming Methodological Limitations

Despite its shortcomings in quantifying future secondary resources, early studies were essential for opening the black box of stocks and better understanding their behavior. These studies paved the way for more accurate quantifications of stocks. In other words, they provided a proof of concept for urban mining and are considered to be urban mining's early stage of prospection [118]. Nowadays, the bottom-up MFA is described as the second stage of exploration in urban mining. Detailed information about the stock is calculated based on micro-level studies [118]. However, as we pointed out earlier, bottom-up MFA is a time-, labor-, and data-intensive method. Material intensity coefficients (MICs) are needed to calculate the amount of material within the stock when using the bottom-up MFA. MICs are multiplied by the volume of the compartment to calculate the mass of stocked material, which are then aggregated to provide an estimate of the total mass. MICs are similar to density (kg/m^3). While the compartment volume represents the actual parameters of the selected compartment, e.g., in building stock, the volume of the building is given in cubic meters. For example, if the steel in a building were to be calculated, the MIC for steel specific to the building and the building volume is needed to calculate how much mass of steel is used in that building. This is a straightforward explanation for a couple of complicated issues. The first is the MICs' availabilities, which will be discussed first in the next section, while the second issue concerning the compartment's physical parameters, e.g., the building's volume and how to acquire such data, will be discussed in the following section.

4.5.1. Bottom-Up MFA and Material Intensity Coefficients (MICs)

The MIC datasets are not readily available; they are site-specific and highly affected by local conditions (architectural trend, economic development, etc.) [143]. Therefore, authors typically need to extrapolate MIC data from multiple sources, including a site investigation, architectural data, construction codes and standards, construction blueprints and documents [114,144,148–152], company data [153], energy requirements [130,149], and cadastral maps [111,112]. Using a combination of sources is the norm since the data content and quality of information vary considerably between different sources [148], making it an essential practice to reduce uncertainties [154]. MICs research often focuses on residential buildings considering that most of the building stock comprises these buildings [143]. On the other hand, non-residential buildings received less attention [144]. Nevertheless, the general procedure is similar. It can be summarized as follows: buildings are categorized according to several features and characteristics, e.g., building types, such as single-family or multiple-families in case of residential buildings [143,155], or in terms of energy use or energy efficiencies, such as heated non-domestic buildings or social infrastructure in the case of non-residential buildings [144]. Other features include the type of structure [53,119,154,156], or what is generally known as "archetypes" [96,141]. Typically, a few buildings of each category are samples. Then the physical size of the buildings is calculated, e.g., volume (m^3). Then, the MIC specific to each material is calculated by the means mentioned above as a density (kg/m^3). Finally, the result gets generalized to the whole stock, and estimates of material quantities are made. To overcome this complexity, researchers have developed several frameworks that link the materials cycle to the services provided by the products containing the materials while in use rather than the products or the compartments themselves [36]. Instead of investigating a building by volume, it can be done by its service unit, e.g., the floor area (m^2); in that case, MICs would be in kilograms per service unit. It is worth noting here that, recently, several studies have taken a novel approach driven by circular economy principles. This approach focuses on components that are complex assemblies of materials within buildings, e.g., windows and bricks, rather than focusing on the materials that make up these components to avoid down-cycling. In other words, this approach breaks the building into several components of pre-mixed materials. When estimated and quantified, it gives an idea of the total stock, reducing or eliminating the need for country-, city-, or building-specific MIC calculations [10,114,156–159]. As a result, the units of measurement of MICs frequently differ from one study to the next, depending on the material under investigation, the scope of the study, and the availability of data. Therefore, tremendous effort has gone toward collecting and organizing a comprehensive and harmonized MICs database as in [150,160] and [154]; in the latter, for example, the authors collected MIC data from 33 studies and harmonized and reported their findings in a unified unit of kilograms per gross floor area. In a similar context, over the last decade, building information modeling (BIM) has grown in popularity [161]. It can be defined as a digital representation of built objects' physical and functional characteristics [162]. BIM is the backbone of several recent initiatives, such as the EU-funded Buildings as Material Banks project [163]. This project creates "material passports" to provide full and transparent information about buildings, including their material compositions [164]. There are also other commercial projects, e.g., Madaster [165]. However, all the previously mentioned projects involve BIM databases that are primarily populated with newly constructed buildings. In Volk et al.'s (2014) research, the authors reviewed 180 publications on BIM. They concluded that, despite the increasing BIM usage for newly constructed buildings, BIM implementation in existing buildings is still limited. This is due to several factors, such as the effort needed for data collection, modeling, and handling uncertain data and/or objects in buildings [161]. Cheng et al. (2013) presented several BIM systems for existing buildings as a tool for C&D waste estimation and renovation planning [166]. Recently, Rose and Stegemann (2018) proposed E-BAMB (Existing Buildings as Material Banks), which is an effort to collect and organize free access knowledge about materials stocks in existing buildings [167].

4.5.2. Material Compartments' Physical Parameters in Bottom-Up Methods

As discussed earlier, one of the limitations facing the mass adoption of the bottom-up method in studying material stock is acquiring the physical parameters of the stock, primarily pre-existing old stock, which typically lacks proper documentation and requires significant amounts of individual investigation. Modern technologies have significantly aided in the collection and processing of these essential data, where remote sensing was one of the first technologies to be used in this context. For example, the research by Meinel et al. (2009) used topographic maps and geographic information systems (GISs) to analyze building stock [168]; although no MFA was used or a specific material investigated, their study is worth noting because they introduced a new approach to calculate the parameters of urban structures using topographic, digital, and analog maps, combined with statistical data at the municipality level. They mentioned that their method can be used for material flow modeling; they also pointed out the possibility of using maps representing different time slices to analyze the temporal development of the buildings' stock. In the pioneering research of Tanikawa and Hashimoto (2009), a GIS was used to spatially analyze material stock in buildings and infrastructure in combination with a time-series database for temporal analysis. The authors called it a four-dimensional GIS (4D-GIS). The first spatially explicit bottom-up MFA covered 8 km^2 in Manchester, UK, and 11 km^2 of Wakayama city center, Japan [111]. Although it discussed material availability as secondary resources and the recyclability of materials, this research had a broader scope of investigating the construction materials' distribution in space and time, which enabled the authors to estimate the demolition curve of buildings, hence estimating the average lifespan of the buildings, and finally, to elucidate material accumulation with respect to its vertical location. Several authors have since utilized the same approach in their research. The following summarizes how this technique evolved and was used in different cities, sometimes with significant modifications. Chen et al. (2016) applied a 4D-GIS to estimate the demolition curve in Ezhou City, China [169], while Wang et al. (2019) investigated Longwu village in Shenzhen [170]; Miatto et al. (2019) investigated the city of Padua, Italy [112]; and Guo et al. (2021) investigated Tiexi district, China [171] using the same method. Heeren and Hellweg (2019) used a similar approach but instead of estimating the demolition curve, they provided several scenarios of building renovations in Switzerland [172]. Krook et al.

(2011) used a GIS to analyze the power infrastructure in Gothenburg and Linköping in Sweden, differentiating between in-use and hibernating stocks of copper in the power networks [23]. Similarly, Wallsten et al. (2015) used a GIS to analyze the hibernating stocks of copper, aluminum, and iron in buildings and infrastructure in the city of Norrköping, Sweden, in which the hibernating metal stocks were mapped using urban districts as the area unit [173]. Marcellus-Zamora et al. (2016) utilized a similar land-use approach [153]. Köhler and Schnitzer (2014) provided an urban mining cadaster using a GIS consisting of industrial and commercial buildings of Darmstadt, Germany [174]. Zhu and Yu (2016) used GIS to form a spatial database of copper, zinc, and steel stocks, which was presented at multiple spatial scales in Australia [137]. Kleemann et al. (2017) calculated the material stock of all buildings in Vienna, Austria, using a GIS [175]. Similarly, Mesta et al. (2019) calculated the material stock of residential buildings in Chiclayo, Peru [151] and Oezdemir et al. (2017) used the same method on residential buildings in Rhine-Ruhr, Germany [130]. Meanwhile, Schebek et al. (2017) calculated material stocks of non-residential buildings in that same area [149]. Cheng et al. (2018) used GIS-based hot spot analysis to detect material stock clustering in Taipei, Taiwan [22]. Similarly, Guo et al. (2019) used the same approach for 14 Chinese metropolitan areas [176]. Gontia et al. (2019) also utilized a similar approach to analyze material stocks with clustering algorithms within GIS software for the city of Gothenburg, Sweden [177].

Other remote sensing methods are used in material stock research. For example, nighttime light (NTL) [141], where early NTL studies found significant correlations between NTL and socio-economic indicators, such as population and GDP [178–181]. These findings are also supported by recent studies based on a new generation of NTL [182–184]. NTL data eliminates the need for the physical parameters of buildings. However, NTL stock studies are often carried out on a large macro-scale using top-down methods, resulting in aggregated estimations that lack spatial detail [182,185]. Although several authors attempted to address this issue by narrowing the geographical scope or using NTL in conjunction with MICs at the regional scale, theoretically, the archetypes and typologies are the same [186]. However, as we discuss, these methods are not suitable for urban mining, as it is not spatially detailed enough for accurate stock estimations.

4.6. Future Research and New Technologies

With technologies becoming more advanced and affordable, other tools and remote sensing methods that once were exclusive to governments and big corporations are now available to researchers, such as light detection and ranging (LiDAR) technologies [52,187], high-resolution satellite imagery (HRSI) [138,188], and low-altitude drone photography [189,190]. All these technologies can capture highly accurate building parameters, footprints, heights, and other dimensions, which subsequently enable accurate stock estimation through bottom-up approaches. Moreover, remote sensing coupled with information and computing technologies, such as big data, artificial intelligence, and machine learning [191] enables the automated, low-cost classification of land use and building typologies. They are making the process of capturing and extracting building parameters in a spatially explicit fashion at all geographical levels an easier task. Nowadays, there are several projects and initiatives in this field, such as SpaceNet.ai, which is an open project that was started in 2016. It offers a repository of freely available precision-labeled buildings and infrastructure on high-resolution satellite imagery as training data for image classification, segmentation, and computer vision. Their datasets include 101 geographical locations, covering 41,000 m^2 and a little over eleven million buildings. SpaceNet encourages crowd engagement by organizing challenges anybody can participate in to solve a task or other specific goal, such as building detection, road network detection, and the most recent temporal urban development [192]. The benefits of these new technologies in an urban mining context are that it enables fast, relatively easy, and accurate building parameter detection and thus accurate estimation of the in-use material stocks [193]. We believe that urban mining research will benefit from these technologies in many ways, for example, material estimations and localization will only get more accurate. We also predict a widespread adaptation of bottom-up methodologies at a larger geographical scale. Developing countries where traditional urban planning data is lacking will likely join the trend.

Author Contributions: Conceptualization, methodology, investigation, writing—review and editing, F.A.; supervision, M.D. Both authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Research, Development and Innovation Office—NKFIH, K-135907.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Statistical Modelling of the Market Value of Dwellings, on the Example of the City of Kraków

Elżbieta Jasińska and Edward Preweda *

Department of Integrated Geodesy and Cartography, AGH University of Science and Technology, 30-059 Krakow, Poland; elzbieta.jasinska@agh.edu.pl
* Correspondence: edward.preweda@agh.edu.pl; Tel.: +48-126172251

Abstract: The analysis of a city's spatial development, in terms of a location that meets the needs of its inhabitants, requires many approaches. The preliminary assessment of the collected material showed that there was real estate in the database whose price did not have market characteristics. For the correct formulation of the valuation model, it is necessary to detect and eliminate or reduce the impact of these properties on the valuation results. In this study, multivariate analysis was used and three methods of detecting outliers were verified. The database of 8812 residential premises traded on the primary market in Kraków was analyzed. In order to detect outliers, the following indices were determined: projection matrix, Mahalanobis distances, standardized chi test and Cook distances. Critical values were calculated based on the formulas proposed in the publication. The probability level was P = 0.95. The article shows that the selected methods of eliminating outliers—the methods of standardized residuals and the Cook's distance method give similar regression models. Further analysis (with the use of classification tree methods) made it possible to distinguish zones that are homogeneous in terms of price dispersion. In these zones, a set of features influencing real estate prices were determined.

Keywords: outlier observations; Cook's distance; statistical analysis; classification tree; real estate valuation model

Citation: Jasińska, E.; Preweda, E. Statistical Modelling of the Market Value of Dwellings, on the Example of the City of Kraków. *Sustainability* **2021**, *13*, 9339. https://doi.org/10.3390/su13169339

Academic Editors: Pierfrancesco De Paola and Brian Deal

Received: 3 July 2021
Accepted: 16 August 2021
Published: 20 August 2021

1. Introduction

Kraków is the second largest city in Poland by population and is undergoing a housing boom, particularly in apartment development. It is an important centre in Poland for many sectors of the economy, including higher education, start-ups, outsourcing, business, tourism and culture. The motive of some of the purchasers of apartments is to derive income from renting, attracted by its high profitability compared to low-interest bank deposits. The average rental yield was over three times higher than that gained from bank deposits. Today, the real estate market is facing the COVID-19 (coronavirus) pandemic that has been ongoing for several months [1]. The tourism industry has been particularly affected by the pandemic, which has meant that private short-term rentals have suffered [2]. Long-term rentals have also deteriorated because of the increasing popularity of remote learning and working. Rental prices in large agglomerations have decreased significantly. Most of the apartments for rent are empty so their owners often consider selling. Thus, the supply on the secondary market is increasing [1].

The housing market provides random information. Random factors disaggregate into the type of characteristics that shape the market value, which obliges the application of statistical rules. One of these features is the location of the property [3]. The work in the present paper characterizes the original market of residential real estate in Kraków. The research, covering the period 2015–2019, aims to determine the market processes in 18 districts of the city (Figure 1).

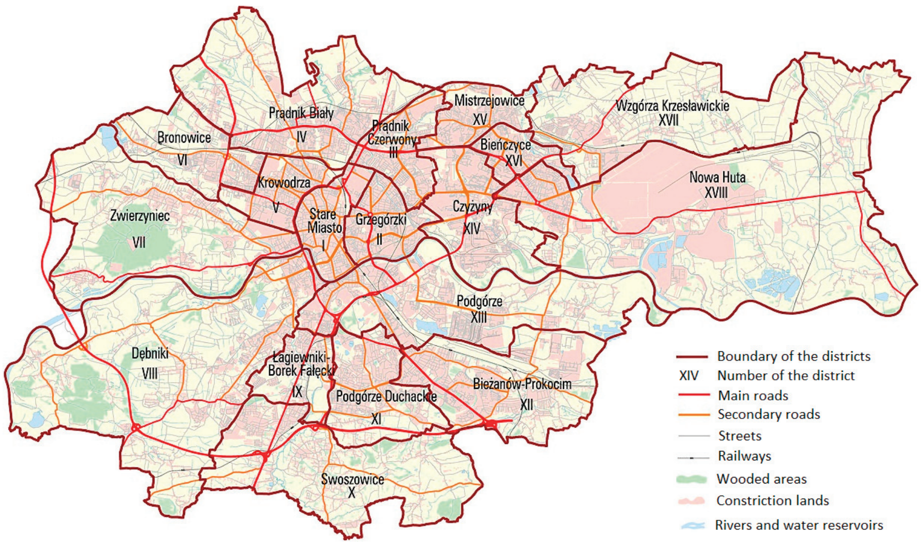

Figure 1. District of Kraków [4].

One of the most important market process is to estimate the value of real estate in individual city zones. Short descriptions of the zones are written below (based on [5] and subpages linked in the text on this website).

District I, Stare Miasto (English name: the Old Town) is the oldest district of Krakow, the heart of the city. Because of the large number of monuments, there is the greatest tourist traffic here. The district has been inscribed on the UNESCO World Heritage List. The Old Town is also the center of entertainment and cultural events in Krakow. There are many clubs, pubs, cafes and restaurants around the Main Square. In the Old Town, there is the Regional Bus Station and the Main Railway Station. Apartments in this district are among the most expensive in the Krakow real estate market.

District II Grzegórzki (English name is not used)—a small district next to the Old Town from the east. The construction of Grzegórzki is extremely diverse. There are many historic buildings on their premises. The area in the center of Krakow attracts more residents and developers who introduce modern buildings to the district. The biggest disadvantages of the district, apart from high prices, include too fast development and traffic jams at rush hour in some regions. However, this does not adversely affect the popularity of Grzegórzki. The prices of apartments in this district are in third place, right after the Old Town and Zwierzyniec.

III Prądnik Czerwony—next to Grzegórzki and the Old Town, it is in Śródmieście, the former district of the city. It is located close to the center, but away from the hustle and bustle of the city. High residential buildings and modern office buildings dominate here, with lower buildings in several places. There are many green and recreational areas in Prądnik Czerwony. The district is very well connected to the center of Krakow. The biggest disadvantages of the district are traffic jams and air quality. Despite this, Prądnik Czerwony is very popular among both people looking for a flat and developers. Prices in the district are lower compared to other districts of Krakow, and the location is exceptionally favorable.

IV Prądnik Biały—the most populous district of Krakow in the city's north. It is one of the most dynamically developing districts of Krakow. Every year there are more and more housing investments in its area. Prądnik Biały used to be the bedroom of Krakow, now it is becoming one of the most modern districts. There are many green areas in the district where the residents like to spend their time. Unfortunately, there are also exit streets to other cities, which increase the volume of traffic. This has a negative impact on the air quality, which frequently exceeds the dust norms. For some, Prądnik Biały may also be too quiet a district, as there is a shortage of pubs and nightclubs.

V Krowodrza—because of the proximity of the Old Town and the AGH campus, Krowodrza is quite a busy district of Krakow. The nearby Błonia (large grassy area surrounded by bicycle paths) and the beautiful Jordan Park are an ideal place for walks and sports. The district is characterized by a very large number of new residential investments. It is a kind of compromise between the bustling Old Town and the quieter surroundings that are ideal for the elderly and families with children. As a result, real estate prices in Krowodrza are much higher than the average.

VI Bronowice—a sparsely populated district on the outskirts of the city. It is currently one of the most popular districts of Krakow. Residents appreciate this district, it is a more intimate neighborhood, adapted mainly to families with children and people looking for peace. There are many green and recreational places. Unfortunately, the district suffers from an insufficient number of nurseries, kindergartens and cultural centers. In Bronowice, there are both modern apartments in apartment buildings, slightly larger and cheaper premises in blocks of flats, as well as single-family houses. The district is very well connected with the rest of Krakow. VII Zwierzyniec—is one of the greenest, most prestigious and the most beautiful districts of Krakow. In its area there are, among others, two mounds: Kościuszko and Piłsudski, the monastery complex in Salwator, the Zoo, Lasek Wolski and Błonia. The district can boast excellent medical and educational facilities, interesting premises and interesting events. The Zwierzyniec housing estates are very diverse. There are both compact urban buildings, modern blocks and villas. Typically, large-city construction is only found in a small area. Zwierzyniec is the least populated district in Krakow. Apartment prices are second only to the Old Town.

VIII Dębniki—one of the prettier and quieter districts of Krakow. Dębniki is on the southern side of the Vistula River, on which it borders and which separates it from Zwierzyniec and the Old Town. The proximity to the city center makes it an interesting location for living. The air here is much cleaner than in the center of Krakow, which makes it possible to stay outdoors more often. Currently, many new investments, housing estates, educational, entertainment, service and commercial facilities are being built here. The district has a wonderful connection with other districts through many tram and bus lines. Dębniki is one of the most dynamically developing districts of Krakow. Developers currently offer thousands of apartments for sale here.

IX Łagiewniki—Borek Fałęcki—a district known mainly for the Sanctuary of Divine Mercy, to which Catholics make pilgrimages. It is characterized by vast green areas and a recently launched suburban railway. The buildings are diversified, but the farther from the city center, the faster it moves from multi-story apartment blocks to single-family houses.

X Swoszowice—a district built up with single-family houses, and is rather quiet. It is not of particular interest to real estate market participants rather than tourists, although there is a health resort in this district and council flats have been built there in recent years (because of cheap land); it is a district on the border of Krakow.

XIII Podgórze—one of the oldest districts of Krakow, although it was connected to Krakow in 1915. The area of mainly pre-war buildings, modernized over time, supplemented with new facilities in recent years. Next to Kazimierz, it is a painful memory of the Second World War (the forced labor camp in Płaszów, the Kraków Ghetto). It is a well-urbanized area, enabling the use of local transport; it is full of parks (Bednarski Park, Jordan Park) and green areas (the former Korona stadium, area next to Vistula River) and is one of the pleasant parts of Krakow, both for residents and tourists. XI Podgórze Duchackie, XII Bieżanów—Prokocim—two districts built in a similar period (1950–1980 of the 20th century), with the assumption of providing housing facilities for the developing Krakow. They have good public transport and green areas. However, it is mainly about housing estates, not parks. Bieżanów is connected to the city center by a suburban railway, which significantly shortens the transport time.

XIV Czyżyny—there are 5–15-storey multi-family apartment blocks with pure social infrastructure (kindergarten, school, playground, medical clinic, park), as well as the Polish Aviation Museum, which has been open since 2003. The aviation park is a large green area enjoying great popularity by residents. However, recent housing investments are assessed negatively—there is a lack of green areas and parking spaces.

XV Mistrzejowice, XVI Bieńczyce, XVII Wzgórza Krzesławickie—districts of single-family houses with a small share in the Krakow real estate market.

XVIII Nowa Huta—the largest district of Krakow in terms of area. Designed in the 1950s, it is well thought-out for housing. Low (4-storey) blocks are surrounded by advantages of the district, including greenery, very good city communication, parks, a lagoon, green areas. It was once intended to serve the employees of Huta im. Tadeusz Lenin (later Sędzimir). Although it is at a distance from the center of Krakow, it is practically self-sufficient and now and then you hear voices about the proposal to disconnect it from Krakow.

The basic source of data on real estate in Poland is data from the Price Register, but the information contained often requires appropriate analysis before starting the study of statistical relationships [6–8]. The analysis is based on data from the Register of Prices. This is a public register which contains data on the prices of immovable property specified in the notarial deeds and the value of the property as estimated by the property valuers. Over 9000 (exactly 9312) residential properties from the primary market were surveyed. 500 were eliminated because of incomplete data (8812 left). The reason for removing the property from the database was the lack of information about the location (25%), transaction date (25%), usable area (20%), and number of rooms or storeys (30%). The preliminary analysis of the collected material showed that the database registered observed values since 2015. Outliers may be caused by errors in the data or may be present because the set contains unusual observations, for example, motions intended for speculative purposes, with very small or very large areas compared to the cut value of the set [9]. A large number of outliers may also indicate incorrect model selection. Methods and estimators based on the assumption of a normal distribution and linear relationships are particularly resistant to outliers, so it is necessary to remove them from the set or minimize their impact [10]. The problem of rejecting outlier properties is not limited only to the study of price volatility, it also finds its way into the analyses of consolidation and replacement of land [11,12]. The identification of outliers was carried out based on the rest of the model [13], using the Mahalanobis distance metric [14,15] and by determining Cook's distance [16,17]. The Mahalanobis distances were used for real estate market analyses, mainly as a verification of bank portfolios [18,19], however, the authors did not find the application presented in this publication [20,21]. The method of the smallest squares was determined by the regression model for individual districts of the city, before and after the elimination of outlier observations. The regression and classification measures used in the further part of the work confirmed the results of analyses carried out by multiple regression. Hedonic modeling of real estate values is the subject of many studies [22–26]. Some of them concern the detection of outliers with selected methods, e.g., [18–20], others use solutions minimizing the impact of outliers [27,28]. A certain gap in the analyzed works is the lack of a precise definition of the criterion allowing for the recognition of the real estate as an outlier. This applies especially to Cook's distances in real estate market analysis. Based on the Fisher–Snedecor distribution, the authors precisely defined the Cook's distances criterion.

The article uses 4 methods of detecting outliers; we present them in points 2.2–2.5. Section 2.6 presents classification and regression trees. In Section 3, outliers were identified and C&RT and CHAID tree models were constructed after eliminating outliers from the base. The conclusions can be found in Section 4.

2. Materials and Methods

2.1. Multidimensional Regression

Forecasting the market value of a property is often carried out according to the classic multi-regression model. According to the classic linear regression model, explanatory variables should be correlated with the explained variable and not correlated with each other. For a simple model with one y-explained variable and two explanatory variables, the following dependencies should occur: (x_1, x_2)

$$\mathrm{cov}(y, x_1) \neq 0 \qquad \mathrm{cov}(y, x_2) \neq 0 \qquad \mathrm{cov}(x_1, x_2) = 0 \tag{1}$$

In practice, these assumptions are very rarely met. Real estate data are always correlated to some extent, so regressors are colinear. The variance of each model estimator can be saved as:

$$V\left(b_j\right) = \frac{\sigma^2}{\left(1 - r_{12}^2\right) \times \sum_{i=1}^{n}\left(x_{i,j} - \overline{x}_j\right)^2} = \frac{\sigma^2}{\left(1 - r_{12}^2\right) \times V_j} \qquad (j = 1 \ldots 2) \tag{2}$$

If the explanatory variables of the model are strongly correlated (the correlation coefficient tends to 1), then the estimator variance tends to infinity. Equation (2) can be generalized to multiple explanatory variables. If it is a vector of explanatory variables and a correlation coefficient of the *k*th regressor with the others, then the variance of the estimator can be saved as: $(x_1, x_2, \ldots, x_k) r_k^2 b_k$

$$V\left(b_j\right) = \frac{\sigma^2}{\left(1 - r_{j.}^2\right) \times \sum_{i=1}^{n}\left(x_{i,j} - \overline{x}_j\right)^2} = \frac{\sigma^2}{\left(1 - r_{j.}^2\right) \times V_j} \qquad (j = 1 \ldots k) \tag{3}$$

It follows that the variance of the parameter estimator increases with the correlation between the *j*th regressor and the others and decreases with the variance of the *j*th variable. In practice, there are often cases where there is a relationship between explanatory variables, but this is not a strictly linear relationship. Then, although the assumptions of the classic linear regression model are met (as we are dealing with a linear relationship, the number of observations must be greater than or equal to the number of parameters derived from the regression analysis, the variance of the residuals, the random component is the same for all observations, there is no autocorrelation of residuals, residuals have a distribution close to the normal distribution, and there is no predictor collinearity) [13,29,30]. There are other problems, the most important of which are two:

1. small changes in the database result in large changes in the value of estimators;
2. regression equation coefficients have large standard deviations, thus they may be statistically insignificant, despite even a high R^2 determination factor (together they are relevant).

Both of these problems may be due to outliers in the database. In regression analysis, we mean atypical values of explanatory (independent) variables, unusual values of a dependent variable (explained), or unusual values for both variables. Outliers can be caused by data errors, such as mistakes when entering information in the property price and value register. They may also exist because the database contains unusual observations, for example, properties with very small or very large areas compared to the average value of the set. Methods and estimators based on the assumption of a normal distribution and linear dependencies are particularly resistant to outliers, so it is necessary to remove them from the set or minimize their impact. In the case of linear multidimensional regression, diagnostic tests to detect outliers are most common: standardized model residual analysis, Mahalanobis distance and Cook's distance. It has been noted that on different databases, these tests detect observations as outliers slightly differently, although all are based on a similar principle.

To detect outliers, descriptive statistics were set out in the first stage, broken down by the district of Krakow (Table 1).

Table 1. Descriptive statistics of the database.

	Number of Properties	Average Unit Price [PLN/m^2]	Median [PLN/m^2]	Min. Unit Price [PLN/m^2]	Max. Unit Price [PLN/m^2]	Standard Deviation [PLN/m^2]
Bieńczyce	70	4662	4535	3733	6383	474
Bieżanów	711	5273	5210	3400	6805	478
Bronowice	106	6606	6718	5054	8321	605
Czyżyny	1029	5356	5311	3999	8279	813
Dębniki	937	6570	6173	2790	18,043	2107
Grzegórzki	1281	7634	7395	2166	15,688	1459
Krowodrza	464	7527	7389	4736	11,629	1015
Łagiewniki	99	6002	6246	2990	7516	992
Mistrzejowice	352	5116	5096	3999	6799	490
Nowa Huta	94	4507	4466	2735	5921	432
Podgórze	996	6787	6712	2510	11,979	1302
P. Duchackie	360	5855	5826	3367	7511	593
Prądnik Biały	1276	6204	6221	3585	12,006	825
Prądnik Czerwony	439	6111	5962	3276	9100	841
Stare Miasto	424	10,051	9473	2467	20,446	3030
Swoszowice	42	4907	4951	4298	6170	338
Wzgórza K.	35	4755	4490	2853	6258	890
Zwierzyniec	97	8709	8888	3100	13,393	1926

Figure 2 presents the boxplot, presenting information on the location, dispersion and shape of the distribution of data from individual districts of the city.

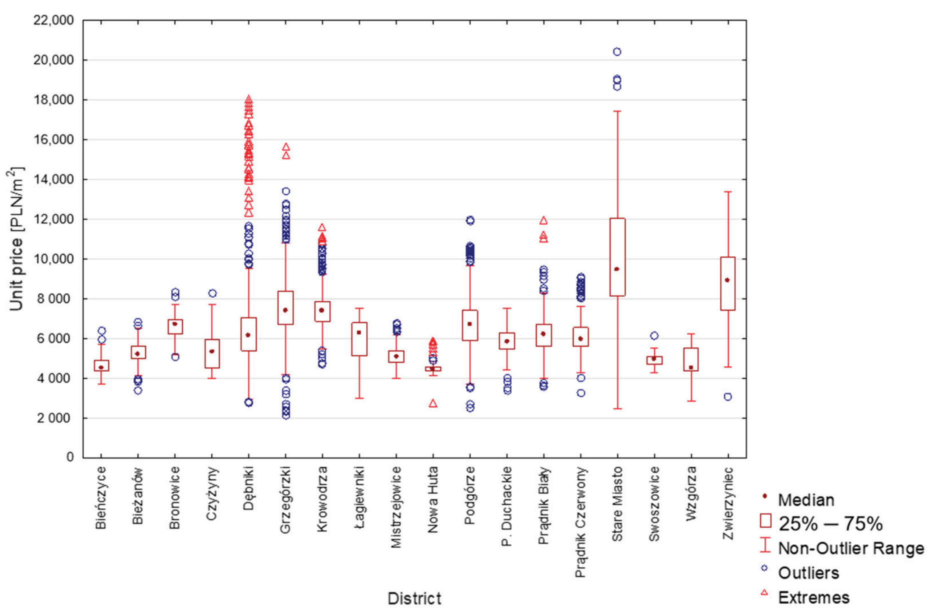

Figure 2. Box plot of unit price grouped by district—8812 properties.

Extreme and outlier unit prices are noted. These values must be verified and removed from the database so that they do not interfere with the further modelling process. It should be noted, however, that these values may be due to the characteristics of the property in question, which are more or less favourable than the average characteristic. In the first place, it is necessary to verify the statistic distributions of property prices in the following specific districts. The authors verified the hypothesis of normal distribution using the Shapiro–Wilk (SW-W) test, because of its eminent power compared to other tests, low sensitivity to autocorrelation and variance of variance. The hypothesis was verified for the entire city and separately for individual districts. Selected results of the analyses are presented in Figures 3–21.

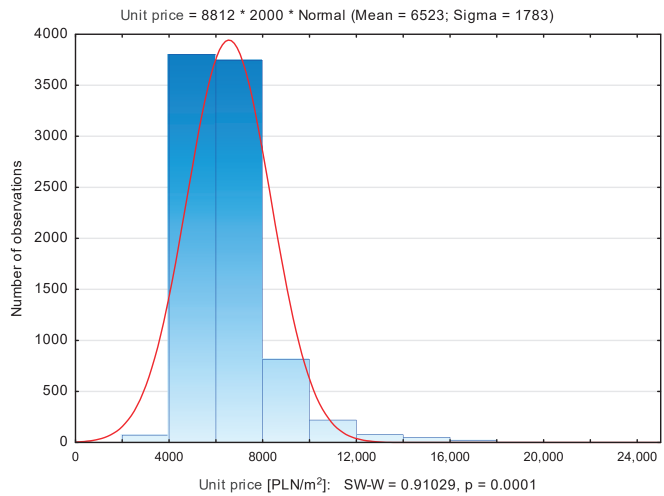

Figure 3. Histogram of unit price—Krakow, the whole city.

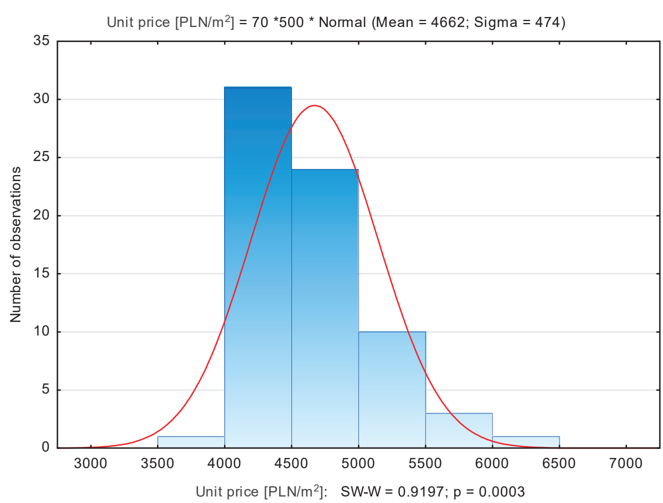

Figure 4. Histogram of unit price—district Bieńczyce.

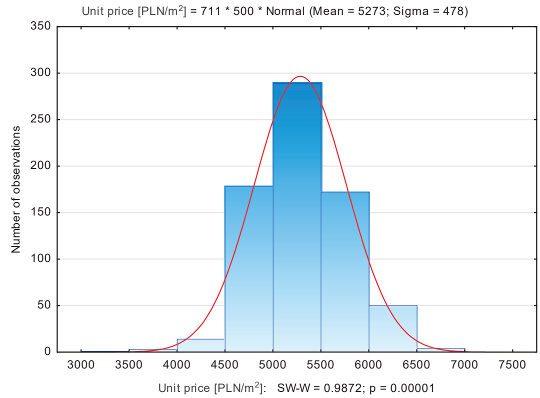

Figure 5. Histogram of unit price—district Bieżanów.

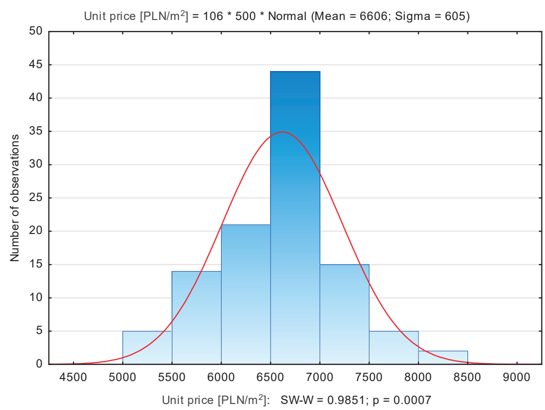

Figure 6. Histogram of unit price—district Bronowice.

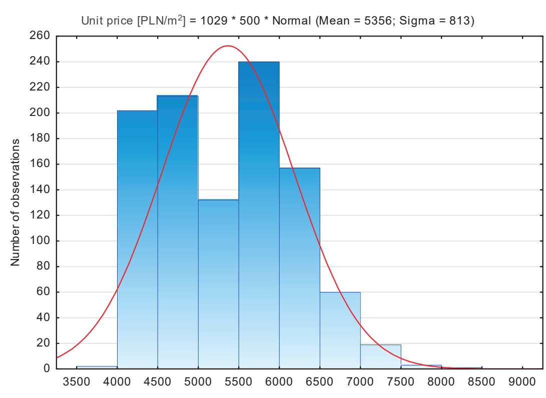

Figure 7. Histogram of unit price—district Czyżyny.

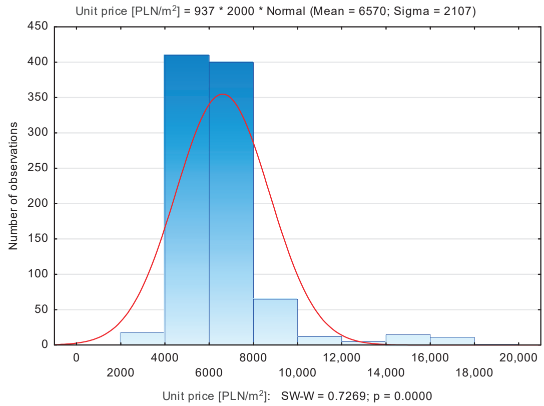

Figure 8. Histogram of unit price—district Dębniki.

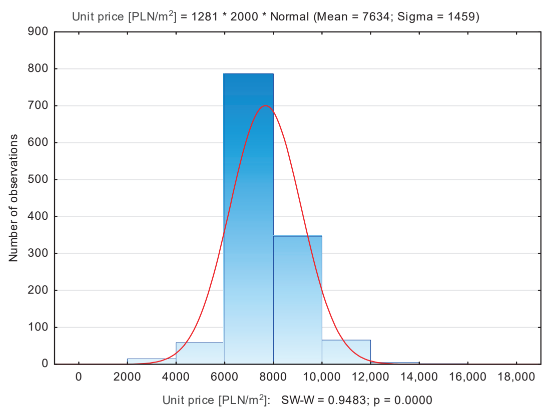

Figure 9. Histogram of unit price—district Grzegórzki.

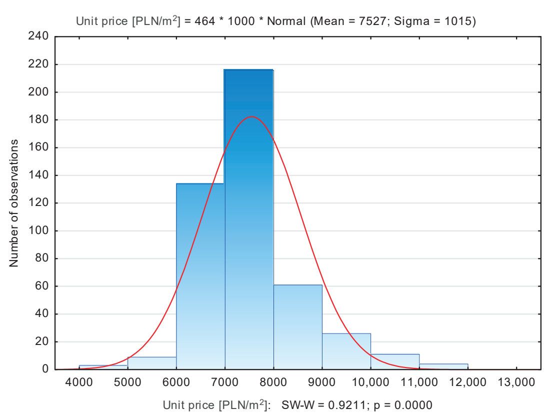

Figure 10. Histogram of unit price—district Krowodrza.

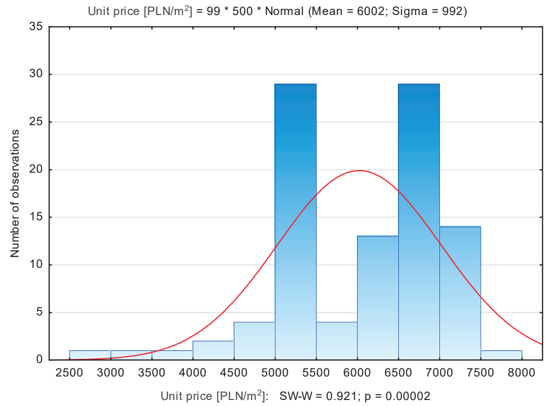

Figure 11. Histogram of unit price—district Łagiewniki.

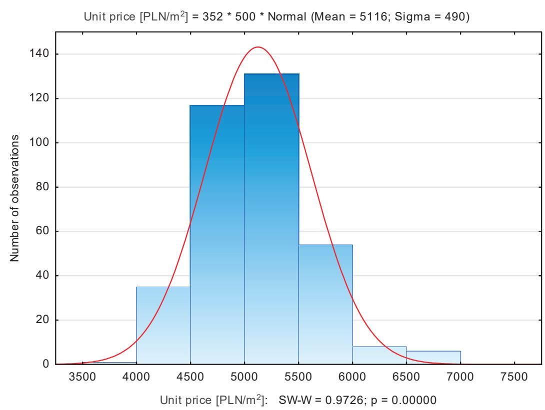

Figure 12. Histogram of unit price—district Mistrzejowice.

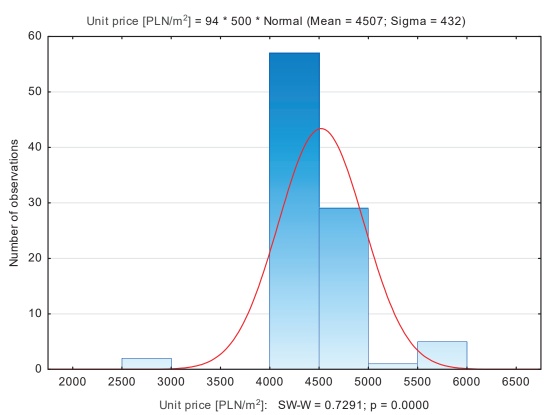

Figure 13. Histogram of unit price—district Nowa Huta.

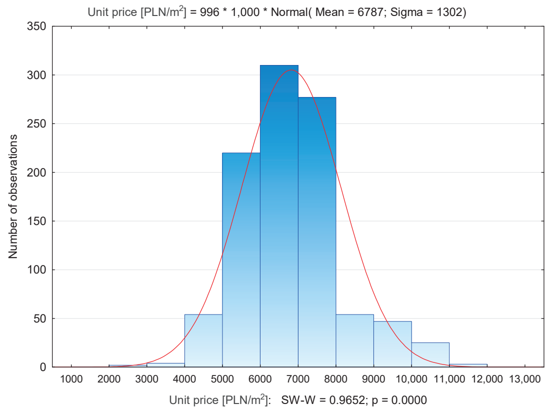

Figure 14. Histogram of unit price—district Podgórze.

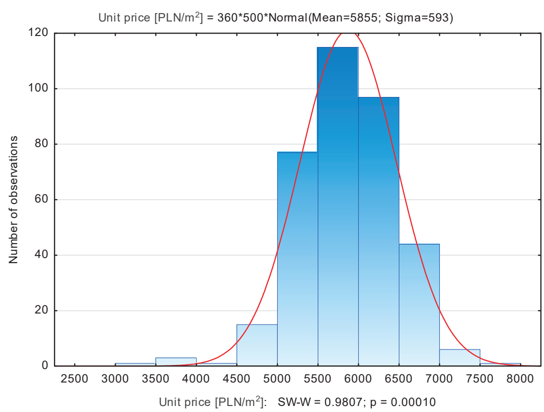

Figure 15. Histogram of unit price—district Podgórze Duchackie.

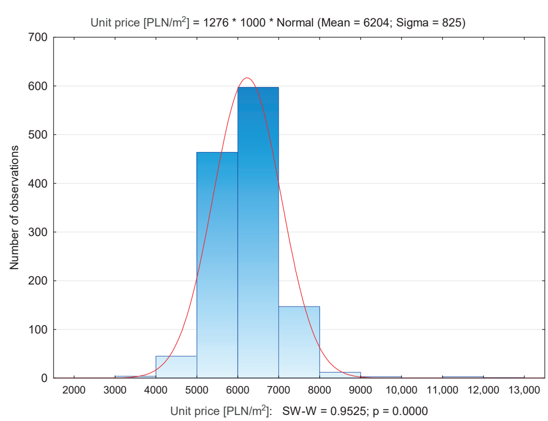

Figure 16. Histogram of unit price—district Prądnik Biały.

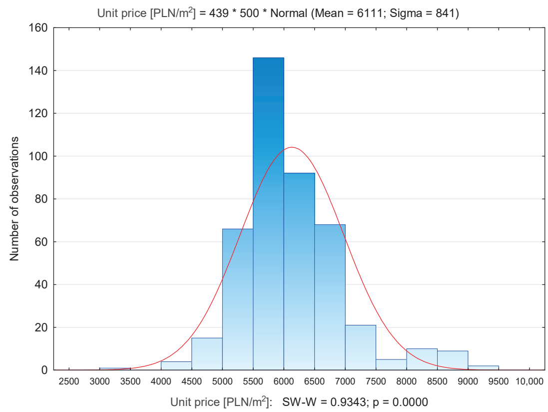

Figure 17. Histogram of unit price—district Prądnik Czerwony.

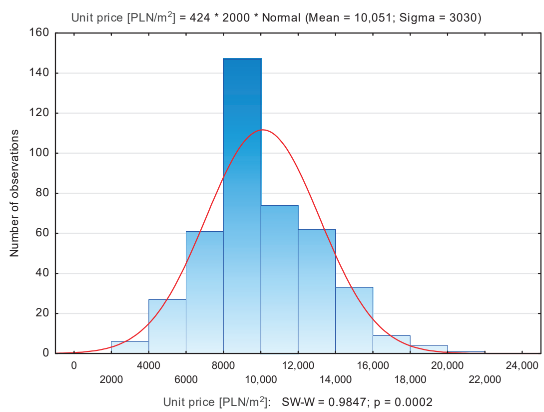

Figure 18. Histogram of unit price—district Stare Miasto.

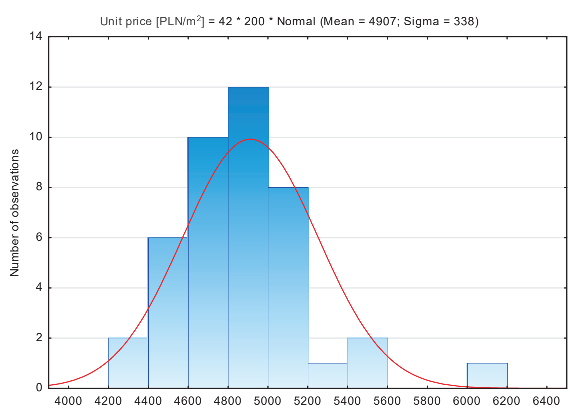

Figure 19. Histogram of unit price—district Swoszowice.

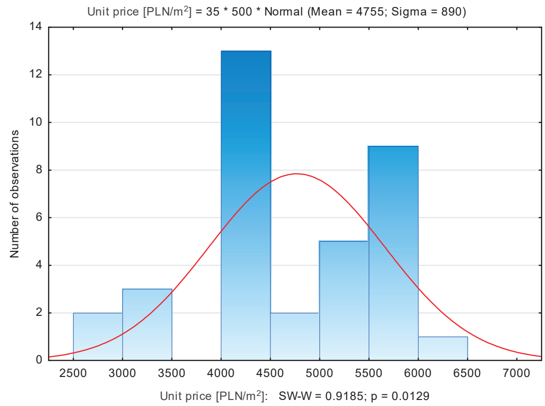

Figure 20. Histogram of unit price—district Wzgórza Krzesławickie.

The analysis of the results allows the conclusion that with the assumed significance level (P = 0.05) there are no grounds to reject the hypothesis of a normal distribution of unit prices only for the Zwierzyniec district. This proves the occurrence of outliers. The aim of further research is to eliminate observations outliers from the database.

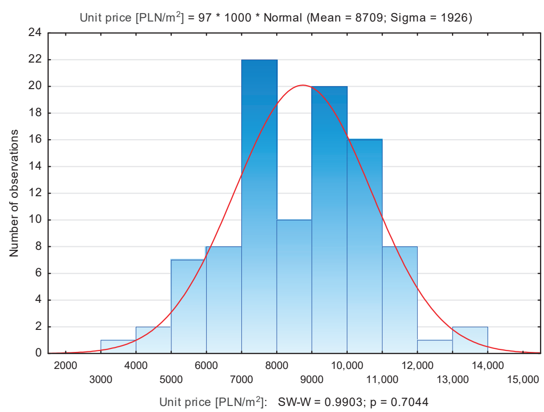

Figure 21. Histogram of unit price—district Zwierzyniec.

2.2. Rule of Thumb

It is necessary to examine the characteristics of the set of data to take any further action based on inference. Even if the model does not have a co-linearity problem or a data problem (for example, data shortages), it is prudent to see which observations have a big impact on regression results. Impact observation diagnostics provide information on the reliability of conclusions drawn from an estimated model. To pre-detect influential observations in a property database, an R-projection matrix can be used, as follows:

$$\mathbf{R} = \mathbf{X}\left(\mathbf{X}\mathbf{X}^{\mathrm{T}}\right)^{-1}\mathbf{X}^{\mathrm{T}} \tag{4}$$

where **X** is a matrix of coefficients of multiple regression model equations. Elements from the diagonal **R** matrix determine the effect of the *i*-th observation on model parameter estimates. The **R** matrix is idempotent, therefore these elements will always be contained in the range [0, 1]. The well-known 'rule of thumb' principle states that if $\mathbf{R}_{i,i} > 0.5$ is observed, it should be considered influential. Based on analyses of many lands and residential property bases [31,32], the authors conclude that to detect influential observations in property bases, the value should be $\mathbf{R}_{i,i}$ reduced to around $\mathbf{R}_{i,i} > 0.07$. This is because this parameter depends solely on the values of explanatory variables, the number of which is small relative to the number of observations obtained from the register. It should be emphasized that the matrix does not depend on the transaction prices of the property, therefore, it is possible to determine only which properties in terms of characteristics (attributes) have a significant impact on the regression model.

2.3. Mahalonobis Distance

Methods for identifying outliers based on Mahalonobis distances use the following criteria [14,33]:

$$MD_i{}^2 = (\mathbf{x}_i - \overline{\mathbf{x}})\mathbf{Cov}(\mathbf{x})^{-1}(\mathbf{x}_i - \overline{\mathbf{x}})^{\mathrm{T}} \tag{5}$$

MD_i—Mahalonobis Distance,
$\mathbf{x}_i$ —a vector containing the ith explanatory variables,
$\overline{\mathbf{x}}$—vector of the average explanatory variables,
$\mathbf{Cov}(\mathbf{x})$—covariance matrix for explanatory variables.

The Mahalanobis distance can also be determined by means of levers (leverage) h_{and}:

$$MD_i{}^2 = (n-1)\left(h_i - \frac{1}{n}\right) \tag{6}$$

where

n—number of observations,
h_i —the value of leverage for the first observation.

This measures the distance of a given observation from the mean of the independent variables. In practice, it is difficult to determine the cut-off point for influential cases. In the literature, it is difficult to find a clear answer to the question of how this criterion should be determined. This approach also has the disadvantage that the value of the criteria itself (6) is very sensitive to the occurrence of outliers. To determine the cut-off point of influential observations, it should be noted that these criteria should depend on the number of model parameters and the number of observations. Based on the theory of square forms, it is concluded that Equation (6) has a distribution of o $(n - u)$ degrees of freedom, where u is the number of parameters of the model. Observations with high statistics, i.e., a square of the Mahalanobis distance compared to the critical values of the distribution, can be considered as influential observations. In this case, the data need to be checked and the appropriate limit value selected. In the case of a large number of degrees of freedom, the authors propose to set the cut-off criterion at:

$$k\_MD = \frac{n/u}{\sqrt{\chi^2(n-u,\alpha)}} \tag{7}$$

2.4. Analysis of Standardized Model Residuals

If each residual is divided by its standard deviation, i.e., as follows:

$$RS_i = \frac{v_i}{\sigma_i} \tag{8}$$

then it will generate a statistic that points to the impact of observations. It is customary to consider that if the absolute value of t is greater than 2, then it is influential. However, this is an approximate criterion. In practical applications, it is worth applying stricter or milder conditions. This is because the model is exuded by the least-squares method, the residuals have a normal distribution and the statistics (8) of the Student's t-distribution are o $(n - u)$ degrees of freedom, where n is the number of observations and the number of parameters of the model is estimated. By assuming any level of materiality α, the residuals can be considered to be inputs to the model and thus the observation may be considered as an outlier by comparing the statistic (8) with the Student's *t*-distribution.

$$RS_i > k\_RS_i;\ k\_RS_i = t_S\left(1 - \frac{\alpha}{2}, n - u\right) \tag{9}$$

Figure 22 shows graphs of critical values for selected probability levels of value P, depending on the number of degrees of freedom.

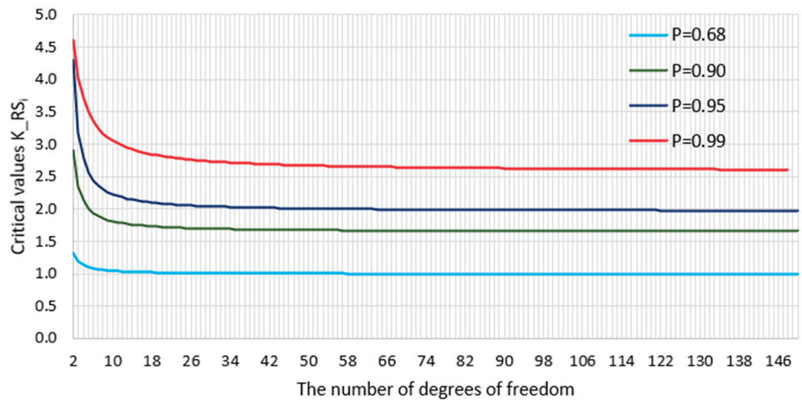

Figure 22. Critical values K_RS_{and}.

It follows from the above statements that at the set probability level P = 0.95 it can be approximately assumed that observations for which standardized residuals exceed twice the quantum value of the Student's *t*-distribution, but with at least 25 to 30 degrees of freedom, can be considered outliers from the model. For P = 0.99 and with degrees of freedom above 30, this value is on the order of 2.7–2.6. The exact value of the criterion can be calculated on a case-by-case basis according to the given algorithm. It should be noted that increasing the probability level results in fewer observations being detected as outliers, while a decrease in the probability level makes the criterion more stringent. Figure 22 indicates that for P = 0.68 outliers will be considered as observations whose residuals exceed the standard deviations directly determined by the least-squares method. Based on several experiments conducted by the authors, it is concluded that the elimination of observations from the model should be carried out individually, even if a larger group of outliers is detected in a given iteration. This is particularly important in the case of a more stringent criterion. This is because in a regression model even a single outlier can significantly change the form of the model and observations that did not match the primary model can meet the criteria of the second model after eliminating even one observation.

2.5. Cook's Distance

Cook's distance measures the change in regression coefficient values when a single observation is eliminated from the model. In the case of the Mahalanobis distance [33,34], the distance of the case from the centre of gravity determined by the independent variables is measured. Standardized tests determine the distance from the regression line. Cook's distances combine these two distances and are a cumulative measure of the effect of individual observations on the regression line [16]. To determine whether the vector of independent variables x and for the ith observation is unusual against the background of the other x, the lever hand can be determined by the following form:

$$h_i = \boldsymbol{\delta}_i^{\mathrm{T}} \mathbf{X} (\mathbf{X}^{\mathrm{T}} \mathbf{X})^{-1} \mathbf{X}^{\mathrm{T}} \boldsymbol{\delta}_i = \boldsymbol{\delta}_i^{\mathrm{T}} \mathbf{P}_X \boldsymbol{\delta}_i = \mathbf{x}_i (\mathbf{X}^{\mathrm{T}} \mathbf{X})^{-1} \mathbf{x}_i^{\mathrm{T}} \tag{10}$$

where

$$\mathbf{P}_X = \mathbf{X}(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}, .\boldsymbol{\delta}_i = [0, \ldots, 0, 1, 0, \ldots 0]$$

There is a dependency for each model. Informal rules say that ‘if, then’ observations can be considered unusual. The fact that the observation is unusual does not yet indicate that it does not fit the model. However, if unusual observations, i.e., large levers, have high residual values at the same time, then this may indicate that they are outliers from the model. Since the variances have chi-squared distributions of $(n - u)$ and $(n - u - 1)$ degrees of freedom, respectively, the statistics are as follows:

$$0 \le h_i \le 1 \quad h_i \ge \frac{2u}{n} \hat{\sigma}^2, \hat{\sigma}_i^2$$

$$CD_i = \frac{1}{u} \frac{\hat{\sigma}_i^2}{\hat{\sigma}^2} \frac{h_i}{(1 - h_i)} \quad \sim \quad F_{(1, n-u)} \tag{11}$$

where

CD_i—Cook’s distance,
$\hat{\sigma}^2$—variance estimator calculated based on all observations,
$\hat{\sigma}_i^2$—an estimator of variance calculated after elimination of *the first* observation,
n—number of observations,
u—number of model parameters.

In practice, Cook’s distance with modified residues is determined in the form of:

$$CD_i = \frac{\sum_{j=1}^{n} \left(\hat{y}_{j(i)} - \hat{y}_j \right)^2}{u \hat{\sigma}^2} \tag{12}$$

where

$\hat{y}_j$—the value predicted by the model for the jth observation determined in the full model,
$\hat{y}_{j(i)}$—the value predicted by the model for the jth observation determined based on the model from which the ith observation was removed.

It is generally assumed that if $\mathrm{CD} \ge 4/n$ then you should look at such observation because it can be an outlier observation. This approach is correct if the significance level is set at 0.05 and the number of observations is large. Based on (11), by employing the Fisher–Snedecor distribution, the critical value can be specified precisely. The authors propose that the criterion be determined based on dependencies:

$$k\_CD_i = \frac{F(\alpha, 1, n - u)}{n} \tag{13}$$

Figures 23 and 24 show Cook’s distance values for three probability levels, depending on the number of observations and the number of degrees of freedom.

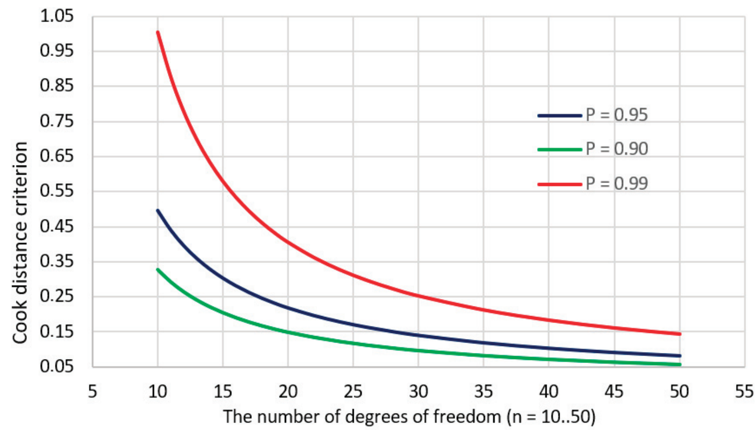

Figure 23. Cook distance criterion for 5 model parameters depending on the number of observations (n = 10 to 50) and the probability level.

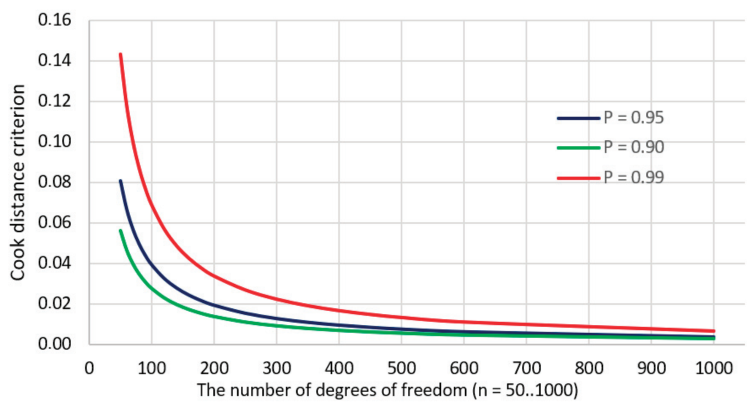

Figure 24. Cook distance criterion for 5 model parameters depending on the number of observations (n = 50 to 1000) and a fixed level of probability.

2.6. Classification and Regression Tree Models

Classification and Regression Tree (C&RT) models provide a significant solution to regression and classification problems. The method is described in detail elsewhere [35–38]. In the C&RT method, there are several basic steps:

- Tree building: the process occurs through the recursive division of nodes,
- Stopping the construction of the tree: at this stage, the tree is as extensive as possible, usually containing redundant information,
- Pruning of the tree consists of removing redundant branches,
- Choosing the right tree: some branches are restored to increase the effectiveness of the method.

3. Results

3.1. Identification of Influential and Outliers in the Kraków Database

The database of 8812 premises traded on the primary market in Kraków was analysed. Initially, based on correlation analysis, five characteristics were found that shaped property prices and at the same time represented variables explaining the multiple regression model.

The regression model was determined by the least-squares method. Based on the original base, the following model parameters were obtained, drawn up for the entire city and separately for each district (presented in Table 2):

Table 2. Regression model parameters—base.

Object	R^2	σ	Distance	Usable Area	Storey	Rooms	Transaction Date
Bieńczyce	0.04	471	-	−0.090	−0.550	−0.120	−0.330
Bieżanów	0.11	451	0.234	−0.030	0.279	−0.160	−0.180
Bronowice	0.28	522	−0.450	0.150	0.150	−0.310	0.119
Czyżyny	0.29	612	−0.380	0.457	0.061	−0.680	−0.160
Dębniki	0.45	1577	−0.550	0.387	0.071	−0.150	0.061
Grzegórzki	0.32	1203	−0.510	0.087	0.149	−0.190	0.055
Krowodrza	0.18	925	−0.050	0.406	−0.020	−0.690	−0.030
Łagiewniki	0.24	885	−0.020	0.140	−0.170	−0.490	−0.160
Mistrzejowice	0.28	417	−0.480	0.034	0.172	−0.270	−0.310
Nowa Huta	0.12	414	−0.014	0.013	0.043	−0.280	0.212
Podgórze	0.36	1009	−0.460	−0.170	0.155	−0.220	0.002
P. Duchackie	0.19	514	−0.270	−0.420	0.146	0.085	−0.110
Prądnik Biały	0.05	804	−0.010	−0.050	0.094	−0.140	0.118
Prądnik Cz.	0.24	736	−0.400	0.345	0.147	−0.330	0.032
Stare Miasto	0.27	2552	−0.420	0.274	0.161	−0.330	0.214
Swoszowice	0.03	350	−0.010	0.295	−0.080	−0.340	0.120
Wzgórza K.	0.48	685	−0.150	−0.080	0.029	−0.630	−0.080
Zwierzyniec	0.11	1863	−0.140	−0.420	0.086	0.321	−0.300

The statistically significant parameters are marked in red. The results of the analysis show that it is not possible to use a multiferroic regression model based on a raw database. The coefficients of determination R^2 are unsatisfactory for each of the analysed districts of Kraków. Outliers should therefore be eliminated. To detect outliers, for the entire city and each district separately, the following indicators were set: projection matrix, Mahalanobis distance, standardized residuals of Ri and Cook's distance (Table 3). Critical values are calculated based on Formulas (7), (9) and (13). The probability level of P = 0.95 is assumed. Table 4 highlights selected observations that have been identified as influential or outliers for the example district of Dębniki. This district has the highest number of outliers (Figure 2). The number of observations in the Dębniki district is 935. Based on Formula (7), the criterion for outliers determined by the Mahalanobis distance is $k\_MD_{and} = 6.45$. As proposed by (13), Cook's distance criterion was set at

$$k_{CD_i} = \frac{F(0.05,\ 1930)}{935} = \frac{3006}{935} = 0.00321$$

The number of detected influential observations in the analysed district varies, depending on the method used. For Cook's distances it is 6.5%, the standardized residual of the model is 4.9% and Mahalanobis and 'rule of thumb' distances are about 6.2%. None of the 18 districts exceeded 8% of the total number of properties. The elimination of outliers was carried out based on Cook's distance. The rule of thumb method and Mahalanobis distance should only be considered as supporting the decision to treat observations as an outlier. The standardized residual method overlaps approximately 90% with the Cook's distance method. Figure 25 shows the plot box after eliminating outliers.

Table 3. Influential properties identified by the Mahalanobis distance, projection matrix, standardized model rest and Cook distance.

Case	Cook's Distance	Standard Residual	Mahalanobis Distance	R_{ii}
873	0.134967	−3.65	40.45	0.14
567	0.098323	4.04	24.66	0.11
565	0.079709	3.99	20.52	0.10
845	0.064456	1.47	104.04	0.09
563	0.057482	3.37	20.66	0.14
372	0.056316	3.84	15.6	0.12
562	0.055229	3.33	20.41	0.10
566	0.044671	5.22	6.28	0.11
371	0.043808	3.94	11.39	0.08
165	0.043595	3.83	12.04	0.14
352	0.041662	2.48	27.65	0.12
373	0.040856	5.08	6.02	0.08
...	...	...	...	....
834	0.007834	−2.19	6.27	0.08
809	0.005884	−2.14	4.71	0.10
159	0.004302	1.67	5.86	0.08

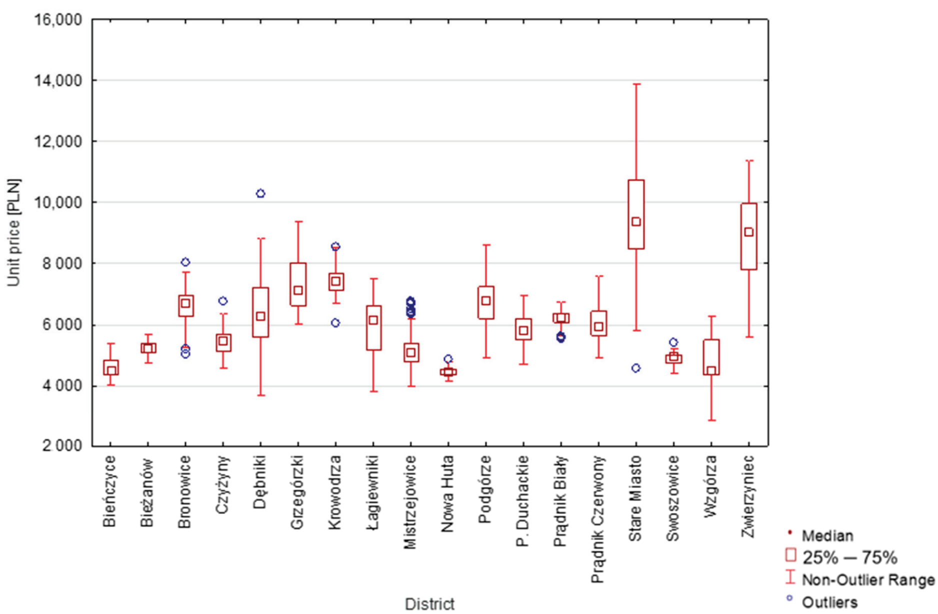

Figure 25. Box plot of unit price grouped by District—8290 properties.

3.2. Multidimensional Regression Models for Kraków Databases

In the case of six districts where the value of R^2 is statistically insignificant: Bieńczyce, Podgórze D., Prądnik Biały, Prądnik Czerwony, Swoszowice, Zwierzyniec (Table 4), the regression model is not suitable for predicting the market value of the property. In these cases, subsequent iterations should eliminate subsequent outliers resulting from the change in the regression model, or another predictive solution should be used.

Table 4. Regression model parameters—database after removal of outlier observations.

Object	R^2	σ	Distance	Usable Area	Storey	Rooms	Transaction Date
Bieńczyce	0.47	317	-	−0.100	−0.550	0.914	−0.330
Bieżanów	0.82	350	−0.583	−0.110	0153	−0.280	0.210
Bronowice	0.76	493	−0.440	−0.080	0.026	−0.390	0.135
Czyżyny	0.79	162	0.026	0.911	−0.010	−1.300	0.003
Dębniki	0.92	286	−0.960	0.497	0.084	−0.320	0.017
Grzegórzki	0.92	226	−0.880	0.063	0.028	−0.250	0.030
Krowodrza	0.78	220	0.056	0.818	−0.070	−0.140	−0.040
Łagiewniki	0.72	445	0.127	0.203	−0.260	−0.800	−0.050
Mistrzejowice	0.78	238	−0.480	−0.050	0.191	−0.230	0.270
Nowa Huta	0.74	353	−0.390	0.006	−0.024	0.310	−0.040
Podgórze	0.84	297	−0.740	−0.300	0.206	−0.350	0.011
Podgórze D.	0.47	337	−0.510	−0.580	0.169	0.244	0.120
Prądnik Biały	0.56	144	−0.130	−0.440	0.298	−0.230	0.010
Prądnik Cz.	0.49	393	−0.540	0.336	0.330	−0.380	0.065
Stare Miasto	0.79	781	−0.780	0.175	0.318	−0.250	0.020
Swoszowice	0.18	228	−0.270	−0.550	0.160	0.622	0.184
Wzgórza K.	0.79	492	−0.580	−0.250	0.057	−0.590	0.211
Zwierzyniec	0.43	969	−0.470	−0.410	0.081	0.397	0.123

3.3. C&RT Trees

When the C&RT tree schema is created, the following parameters are assumed [38,39]:

- variable dependent—unit price,
- quality predictors—district,
- quantitative predictors—distance, area, floor, transaction date,
- minimum number in the end node: 20.

For the above parameters, considering the original database (8812 properties), more than 250 trees can be created. The characteristics of the selected sample tree are shown in Figure 26.

The average unit price at the first node is PLN 6625/m^2 ± 1795 PLN/m^2. Its number is equal to the number of the base, i.e., 8812 properties. The division of the first node was made based on the distance attribute, dividing the entire base into two subsets, above and below a distance of 3.5 km from the city centre. In the case of base analysis, after eliminating outliers by Cook's distance, the corresponding tree is presented Figure 27.

In this case, it is worth noting a significant decrease in the value of variance. However, one of the most important factors determining the value of the property is still the distance from the city centre.

3.4. Chi-Square Automatic Interaction Detector (CHAID) Trees

Figures 28 and 29 show the CHAID decision tree model, which confirms the conclusions. The designated decision tree is a statistical classification procedure in this case. The nodes correspond to the statistical tests carried out on the values of property attributes, the branches are the potential results of the tests carried out and the leaves of these trees present the decision-making, that is, the dependent variable—in this case, the market value of the residential property in Kraków. Decision trees are straightforward to interpret and allow, among other things, estimation of the value of the property.

Division on nodes is most often done by a variable district, then by distance. It should be noted that these two predictors are interdependent. The relationship, based on the correlation of Spearman's and Kendall's ranks, is 0.70 and is statistically significant. The division only occurs twice because of the area of the apartment. The minimum unit prices of the property can be found in the end nodes. The maximum unit price is characterized by properties from the Old Town.

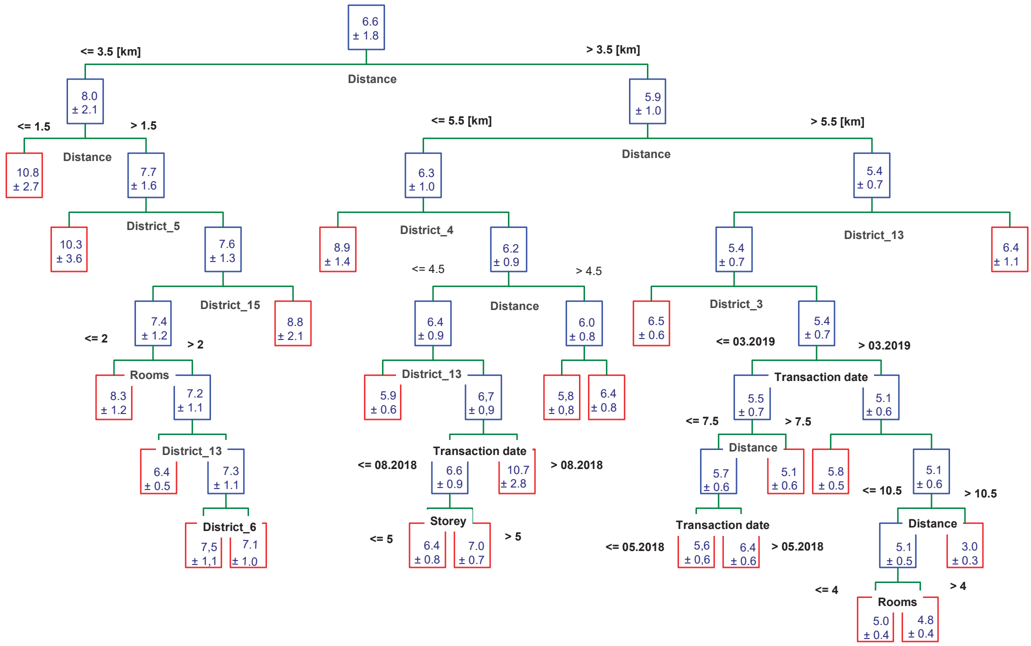

Figure 26. C&RT tree model, 20 end nodes. Database before elimination of outliers: 8812 properties.

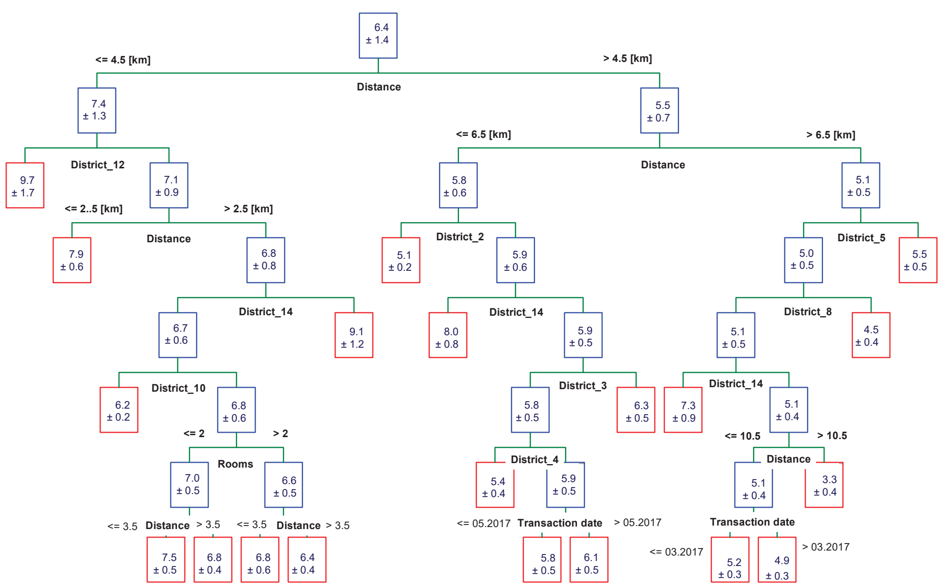

Figure 27. C&RT tree model, 17 end nodes. Database after elimination of outliers: 8290 properties.

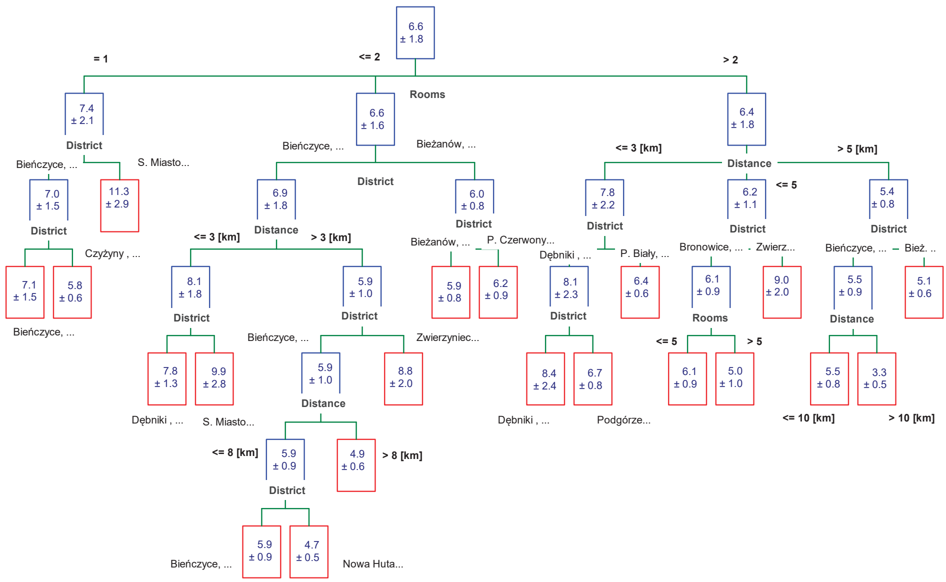

Figure 28. CHAID tree model, 20 end nodes. Database before elimination of outliers: 8812 properties.

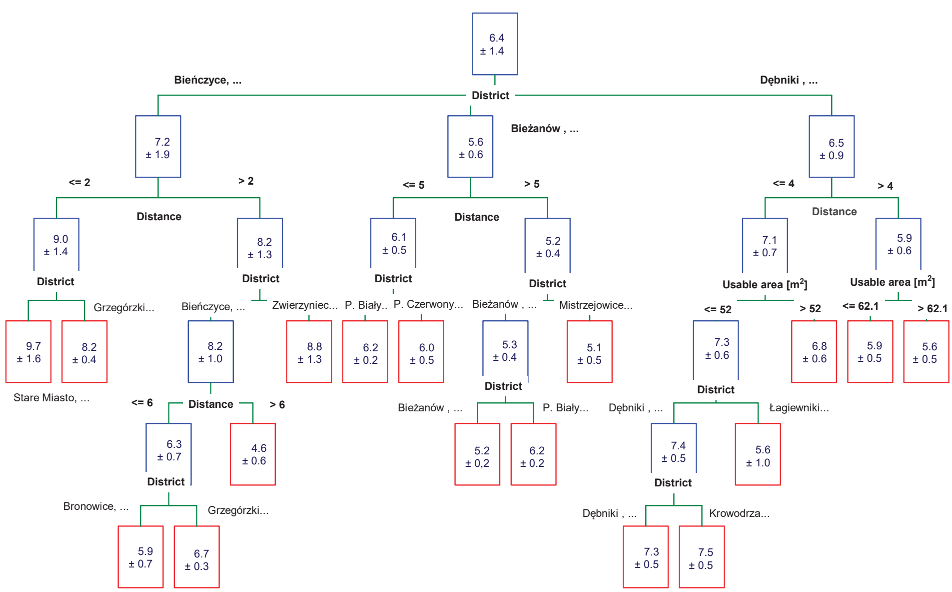

Figure 29. CHAID tree model, 17 end nodes. Database after elimination of outliers: 8290 properties.

4. Conclusions

This study analysed a database of 8812 dwellings that were traded on the primary market in Kraków. The basic characteristics that shaped property prices were established, while at the same time providing variables explaining the regression model. Beta (bi) weights were designated for these variables. Regression models for individual districts of the city were determined by the least-squares method. The results show that it is not possible to use a multi regression model based on a raw database. The coefficients of determination R^2 are unsatisfactory for each of the analysed districts of Kraków.

To detect outliers, the following indicators were set: projection matrix, Mahalanobis distances, standardized chi test, and Cook's distances. Critical values were calculated based on the proposed Formulas (7), (9) and (13). The probability level of P = 0.95 was assumed. Mahalanobis distances only consider explanatory variables, so for the present issue, in which prices are the most common cause of outliers, they only provide information on influential observations. Similar regression models were obtained by eliminating outliers by standardized residuals and the Cook's distance method. In the case of 12 districts of Kraków, the regression model can be considered satisfactory, while in six cases it cannot be used to predict the market value of the property because of the very low coefficient of determination. For these six districts, it is advisable to supplement the database with new observations and then re-eliminate outliers. Analysis of the results compiled in Table 2 shows that in most districts a negative correlation with the price per m^2 has the attributes of distance from the centre and the number of rooms. The usable area affects property prices differently in different districts. On the other hand, a higher floor generally shows a positive correlation with the unit price.

The second part of the research was aimed at determining the suitability of C&RT trees to determine the effect of property attributes on their prices. Trees created using C&RT and CHAID have shown that the district attribute has a key influence on the unit price. The study was conducted for the entire database (8812 properties) and the database created after the outliers were eliminated by the Cook's distance method. Regression and classification studies confirmed the results of analyses carried out by multiple regression. The market for residential real estate in Kraków is not uniform. The individual districts create separate price zones. The apartments with the highest unit price are located in the Old Town and Zwierzyniec districts, located at a distance of up to 1.5 km from the city centre and located on higher floors.

From all tables we present in the publication two of them show how useful the presented solution is: Tables 2 and 4. Automating deleting outstanding data, based on clearly defined principles, significantly improves the accuracy parameters of the model describing the local real estate market. This relationship is especially beneficial when working on large data sets (several thousand). The lack of a precise definition of the criteria allowing for the recognition of real estate as an outlier is a significant obstacle here. This is especially true of Cook's distance in real estate analysis. Based on the Fisher–Snedecor distribution, the authors precisely defined the Cook distance criterion for the analyzed data set. Further studies will include the separation of sub-zones in individual districts. The number of attributes will be expanded with features such as street, noise, distance from green areas, window exposure, bathroom area, balcony area and window view. Preliminary analyses carried out for individual districts of Kraków showed that these are important factors influencing the market value of the residential real estate.

Author Contributions: Conceptualization, E.J. and E.P.; methodology, E.J. and E.P.; software, E.P.; validation, E.J.; formal analysis, E.P. and E.J.; investigation, E.P. and E.J.; resources, E.P. and E.J.; data curation, E.J. and E.P.; writing—original draft preparation, E.P.; writing—review and editing, E.J.; visualization, E.P.; supervision, E.P.; project administration, E.P.; funding acquisition, E.J. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: This paper was created as part of statutory research 16.16.150.545. The authors express sincere gratitude to the Journal Editor and the anonymous reviewers who spent their valued time to provide constructive comments and assistance to improve the quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Dimensions of Urban Blight in Emerging Southern Cities: A Case Study of Accra-Ghana

Sally Adofowaa Mireku [1,2,*], Zaid Abubakari [3] and Javier Martinez [2]

1 AnL Valuation and Property Consult, Kanda, Accra P.O. Box YK 627, Ghana
2 Department of Urban Planning and Management, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands; j.a.martinez@utwente.nl
3 Faculty of Planning and Land Management, SDD University of Business and Integrated Development Studies, Wa P.O. Box WA64, Ghana; abubakari.zaid@gmail.com
* Correspondence: sallimireku@gmail.com

Abstract: Urban blight functions inversely to city development and often leads to cities' deterioration in terms of physical beauty and functionality. While the underlying causes of urban blight in the context of the global north are mainly known in the literature to be population loss, economic decline, deindustrialisation and suburbanisation, there is a research gap regarding the root causes of urban blight in the global south, specifically in prime areas. Given the differences in the property rights regimes and economic growth trajectories between the global north and south, the underlying reasons for urban blight cannot be assumed to be the same. This study, thus, employed a qualitative method and case study approach to ascertain in-depth contextual reasons and effects for urban blight in a prime area, East Legon, Accra-Ghana. Beyond economic reasons, the study found that socio-cultural practices of landholding and land transfer in Ghana play an essential role in how blighted properties emerge. In the quest to preserve cultural heritage/identity, successors of old family houses (the ancestral roots) do their best to stay in them without selling or redeveloping them. The findings highlight the less obvious but relevant functions that blighted properties play in the city core at the micro level of individual families in fostering social cohesion and alleviating the need to pay higher rents. Thus, in the global south, we conclude that there is a need to pay attention to the less obvious roles that so-called blighted properties perform and to move beyond the default negative perception that blighted properties are entirely problematic.

Keywords: urban blight; prime area; customary land tenure; socio-cultural values; Sub-Saharan Africa; Ghana

Citation: Mireku, S.A.; Abubakari, Z.; Martinez, J. Dimensions of Urban Blight in Emerging Southern Cities: A Case Study of Accra-Ghana. *Sustainability* **2021**, *13*, 8399. https://doi.org/10.3390/su13158399

Academic Editor: Pierfrancesco De Paola

Received: 4 June 2021
Accepted: 16 July 2021
Published: 28 July 2021

1. Introduction

In recent decades, due to the increasing urbanisation and economic development, the demand for urban properties for various purposes, such as residential, commercial and industrial, has increased steadily. However, this increasing demand is hardly uniform across the city [1]. Prime urban areas are characterised by high property values, quality neighbourhoods and modernised developments. Nevertheless, some prime areas simultaneously experience urban blight in the form of vacant plots of land, abandoned structures, littered sites and degraded buildings, leading to the deterioration of cities in terms of physical beauty and functionality [2,3]. Urban blight is described by Weaver [4] as underinvestment in real property. This incidence of blight in the city presents an interesting dilemma where properties in prime areas, despite having great potential that can support useful developments, lie underused.

The phenomenon of urban blight dates back from cities in the global north, especially the United States of America (USA), United Kingdom (UK), and Germany, among others, after the industrial revolution era in the 19th–20th centuries. The incidence of the industrial revolution in the 19th century caused an urban population boom where people migrated to the urban cities due to employment in manufacturing industries [5,6]. The subsequent economic decline resulted in urban cities becoming economically vulnerable, with industries collapsing, businesses decreasing and people losing their jobs [6]. Ultimately, these cities experienced physical and functional stagnation as real property, mainly of a residential and commercial type, became obsolete, with high vacancy ratios and a decline in maintenance [3]. Although several studies have investigated the main causes of urban blight in the global north to be population loss, deindustrialisation, economic decline and sub-urbanisation, few of such studies exist in the global south, predominantly in Sub-Saharan Africa (SSA). In SSA, land holdings and use practices are not separate entities from people and their belief systems but are constitutive and embedded in customary land tenure systems [7,8].

Different terminologies are used in describing cities' deterioration. For this study, the nuances of urban blight; urban decline, shrinkage and decay have been fostered into a mutual communication notion, "urban blight". This is because urban blight is a known concept in Ghana's urban land use policy. The current Land Use and Spatial Planning Act 2016 (Act 925) provides detailed descriptions of the criteria and the roles of the District Assemblies in tackling urban blight [9].

Specifically in Accra, Ghana's capital city, Appiahene-Gyamfi [10] argues that the city is knotted with cultural values; familistic, social lifestyles; and modernisation. While some stakeholders/actors attribute economic value to prime areas, others perceive urban spaces/properties differently, which do not match the modernised area [11,12]. Apparently, these unmatched properties, viewed as blight, are unevenly distributed within prime areas. While there is the possibility to leverage these blighted properties for the provision of modern housing or commercial development, some remain in the same conditions for many years for unknown reasons. Thus, the main question posed by this study is "*how can the existence of distributed pockets of urban blight in a prime area in Accra-Ghana be explained?*". The specific objectives are to determine the distribution of blighted properties in East Legon and ascertain the reasons from key stakeholders. This paper is structured as follows: Section 2 delves into the theoretical underpinnings and nuances of urban blight, as well as the perception of values attached to urban spaces. Section 3 describes the methodology. The results are presented in Section 4 and discussed in Section 5. Conclusions are drawn in Section 6.

2. Urban Blight and Value Systems

2.1. The Phenomenon of Urban Blight

The genesis of urban blight can be traced to the United States of America (USA). According to Gordon [3], use of the term occurred as early as 1918 in Philadelphia, where a planner described blight as an unbefitting district. This notwithstanding, different states in the USA fashioned their urban blight description based on peculiarities or uniqueness in their jurisdiction. For instance, Missouri state pronounced urban blight as overcrowding, inadequate light, ventilation and lack of sanitary facilities in an area, whereas New Jersey described urban blight to be abandoned industrial use; substandard, unsafe properties; and vacant lots. Additionally, California state added defective designs, either interior or exterior, to their urban blight description [3].

In the United Kingdom (UK), it was revealed by Haase et al. [13] that urban blight occurred in major commercial and industrial hub cities, such as Newcastle, Manchester, Liverpool, Birmingham and Glasgow. These cities experienced a population decrease and economic decline caused by the collapse of well-patronised commercial activities and auxiliary industries. Subsequently, there was suburbanisation, leading to the abandonment of industrialised cities. Additionally, Germany's case was likened to that of the United Kingdom (UK), which also evolved in the 1980s [14,15]. There was out-migration and deindustrialisation, resulting in population changes in cities. Nevertheless, in other parts of Europe such as Poland and Romania, the cause of urban blight was quite different.

According to Haase et al [13], urban blight in Poland and Romania resulted from a decline in the natural population change, high death rates and ageing of the population in the country.

From the global south perspective, however, existing literature reveals that in Latin American cities—Sao Paulo in Brazil and Guadalajara in Mexico—the causes of urban blight were similar to the global north. It was reported by Audirac et al. [16] that the causes of urban blight in these areas result from suburbanisation, deindustrialisation, and population loss. Similarly, in Africa, the most prominent cause of urban blight was the suburbanisation in South Africa in 1994. This was caused by a complex racial structure where a formerly white neighbourhood, Hillbrow, experienced an abandonment of houses by white people. Subsequently, the area was occupied by immigrants with low-income status who could not maintain the high standard of the area [17,18]. Furthermore, a study conducted by Reckien and Martinez-Fernandez [14] presented social factors to be the driving force for cities' blight in the Sub-Saharan African (SSA) region. The social factors given were hunger and epidemics like Human Immunodeficiency Virus Infection and Acquired Immunodeficiency Syndrome (HIV/AIDS). Nevertheless, no thorough explanations of the social factors were classified in their study. Many urban cities have issues relating to land use and development in Sub-Saharan Africa [19], yet little knowledge exists regarding the emergence of urban blight. Urban blight is likened to the accelerated growth of urbanisation, which is primarily caused by a high birth rate in urban cities and rural-urban migration. Notably, most of these urban cities were previously indigenous settlements [20]. Although urbanisation is good and has resulted in modern land use and development in African cities, rapid urbanisation, on the other hand, has resulted in unsustainable development where high population growth is not matching the existing urban infrastructure, especially housing [21,22]. Subsequently, the inadequate housing infrastructure has triggered the development of illegal settlements, leading to poor neighbourhoods that lack social amenities like water, toilet facilities and garbage bins, among others [22]. Neighbourhoods that lack basic infrastructure and are in disorder are also regarded as urban blight [3,23,24].

In Ghana, the enforcement of land use policies and laws is tackled by the local government. However, according to Cobbinah and Aboagye [20], the local governments do not have complete control over the enforcement due to the role played by traditional authorities in regulating and managing customary lands. They further explained that there is an inadequate collaboration between local governments and traditional authorities. Additionally, the current Land Use and Spatial Planning Act 2016 (Act 925) specifies the criteria for District Assemblies determining blighted properties, irrespective of the land tenure system, as either customary or statutory. Therefore, these criteria, stipulated in Section 103 of Act 925, set the basis and measures for identifying blighted properties in this study. They include:

a. "Irregularity of plots or parcels,
b. Inadequacy of street in the vicinity,
c. Lack of access to plots or habitable dwelling within the area,
d. Diversity of existing use which makes development control difficult or impossible,
e. Incompatibility with:
    i. The existing or proposed use
    ii. The spatial development framework and
    iii. The structure or local plan,
f. Adverse impact on the environment,
g. Overcrowding leading to unhealthy population density,
h. Lack of sanitation, drainage or appropriate service,
i. High incidence of crime which has been confirmed to be attributable to the type of development and
j. Safety or restriction to other authorised users"

As characterised by Act 925 [9], several commentators have also categorised urban blight from different perspectives. Such characterisation efforts enable a more global understanding of what urban blight could be, as well as the dynamics of its manifestation and nature. These are presented in the following section.

2.2. The Nuances of Urban Blight

There is a large body of literature on the deterioration of urban cities with diverse terminologies. The terminologies used in describing cities' deterioration differ from place to place, including the descriptions used by urban scholars such as city shrinkage, urban decay, urban decline, brownfields, or urban blight. However, whilst, on the one hand, Reckien and Martinez-Fernandez [14] assert that these terminologies may mean the same thing with regards to cities' physical characteristics and functioning, Haase et al. [25], on the other hand, argue that the emphasis and concepts of these terminologies are developed in diverse contexts, times, theoretical frameworks, and empirical backgrounds. Often, deterioration is studied at different geographical levels, either at the city or neighbourhood level. Urban blight is described in terms of real properties and/or urban spaces. Specifically, real properties consider the land and the buildings, while urban spaces are related to entire neighbourhood or city levels. According to Albers [26] in the history of urban planning, the changing attitudes of the population, which usually means the perspectives and priorities ranging between neglect and attention, affect the urban fabric, its beauty and landscape. Notably, this manifests in both the global north and south. In the global north, after the industrial revolution era, businesses declined and people lost their jobs. Subsequently, neighbourhoods became less attractive, experiencing physical and functional stagnation. Residences and commercial buildings have become obsolete, with high vacancy ratios and less maintenance culture by landlords due to low profits [1]. Livingston et al. [27] argue that there is a lack of inadequate effectiveness from local governments in satisfying the needs of such deteriorated neighbourhoods. Despite the level of deterioration, some residents may remain in the area as a result of low income. In the global south, on the other hand, Getis [21] argues that the deterioration of cities is partly due to rapid urbanisation. Inadequate housing infrastructure has triggered the development of unauthorised and illegal structures leading to poor neighbourhoods that lack basic social amenities such as water and toilet facilities [28]. Consequently, urban blight deteriorates cities' beauty and landscape [29,30]. The nuances of blight regarding different conditions, physical states, and uses and developments in urban settings, which are deemed contextual, are illustrated in Table 1.

Table 1. A summary of the nuances of urban blight.

The Nuances of Urban Blight	Description & Sources from Literature
An idea with regards to the use of real property	Urban blight is described as an idea in the minds of various stakeholders concerning the condition, use and function of real property [21,22].
The lack of basic urban infrastructure	Urban blight is an element that is caused by a lack of infrastructure [3,22].
Neighbourhood disorder/lack of physical beauty	Many abandoned and deteriorated buildings in the area [23–25].
Results in physical stagnation	The attributes of urban blight are visually demeaning and aesthetically depressing. This could lead to stagnation of land use and development in an area [30].
A contributing factor to slum	Urban blight is an element that results in a slum [3]. Additionally, Breger [2] emphasises that historically, slums were regarded as blighted areas.

Table 1. *Cont.*

The Nuances of Urban Blight	Description & Sources from Literature
Comparable to urban decline/shrinkage	Weaver and Bagchi-Sen [31], Miekley [32] and Hoekveld [33] believe that the leading causes of urban blight from the global north perspective, such as poverty, unemployment, and vacancy, align with urban factors for decline/shrinkage.
The initial stage of urban decay	The severe phase of urban blight is used to describe urban decay's commencement [2]. Urban decay as explained by Fabiyi [34] is the neglect of the built environment symbolised by poor urban dwellers unable to repair their old structures.

Authors' construct (2019).

Urban transformation programmes such as urban renewal and regeneration have been developed to reduce urban blight [3]. In the 21st century, however, the Sustainable Development Goals (SDG) framework has been established by the United Nations to guide developmental efforts between the years 2015 to 2030 [35]. According to De Vries and Voß [36], a greater percentage of the Sustainable Development Goals (SDG) is related to urban land, yet contemporary land management practices are fraught with issues of varied value systems. The level of utilisation of urban spaces thus differs regarding values, perceptions, priorities and reasoning [12]. The next section tackles the perception of values (economic, social and cultural) attached to urban spaces. While economic and social values are common in both the global north and south, in the global south, especially Sub-Saharan Africa (SSA), socio-cultural values are embedded in the land tenure systems, which makes the property rights regime unique and different from that of the global north.

2.3. The Perception of Values Attached to Urban Spaces

Values attached to urban spaces are discussed in this study because the issues of urban blight may be influenced by varying priorities and perceptions by stakeholders/actors. According to Galster [37], the four main actors who make use of an area are households, property owners, business holders and the local government. The households use the neighbourhood through the occupation of residential units. Additionally, the surrounding environments, like recreational facilities, add some form of residential satisfaction and quality to the use of the neighbourhood. Business holders, on the other hand, occupy non-residential facilities yet obtain some monetary value in the form of profit. As well as this, property owners occupy residential properties themselves or rent real property. Lastly, local governments mainly consume areas through tax revenues and provision of social amenities.

The explanations of the diverse values of the global north and south are described as follows: predominantly in the global north, the primary values attached to real properties are economic and social. Economic value is mainly associated with urban investment, where three of the aforementioned stakeholders of an area—business holders, local government and some of the property owners—make certain financial gains from the area. Somerville et al [38] emphasise that the economic structure of a country, real estate market, policies, and the level and nature of public goods and services determine the economic fabric of an area. Additionally, Galster [37] highlights that most of the residential neighbourhoods in the global north are established through large-scale construction. Nonetheless, the changes that occur afterwards are a result of how stakeholders attach value to the area. Hidalgo and Bernardo [39] therefore argue that the type and level of attachment placed on neighbourhoods and real properties differ in degrees and dimensions. When the level of social values exceed that of economic values, then the attractiveness of the neighbourhood and needs satisfaction are relatively assessed in comparison with other neighbourhoods by financially inclined stakeholders [40]. Ultimately, the decisions taken by wealthy actors affect the economic growth and development of the area, as well as the provision of public resources and services like recreational facilities by the local government. Others who normally remain in deteriorated areas are those who attach social values to their urban spaces [41]. According to Scannell and Gifford [42], there are varied explanations for place and social attachment due to the cross-cutting nature of the notion in the fields of psychology, urban studies and environmental studies. In urban studies, however, place attachments are regarded as a strong emotional bond and sense of place that a group or an individual may have concerning a neighbourhood or a real property [41,42]. The social values, as inferred by researchers, are emotional bonds and affections developed over time in an area that results in strong networks and cohesion [42–44]. Additionally, Livingston et al. [41] and Johnston [44] agree that social value is a collective attachment to a place by homogenous people with common backgrounds. Instances of community attachment to places in the global north are native settlements such as Maori in New Zealand, Aboriginals in Australia, and Canadian and American Indians. These people believe their spaces are imbued with the spirit of their ancestors (spiritual identity), thus the need for heritage conservation. While the aforementioned assertion is not different for the global south, specifically in Sub-Saharan Africa (SSA), customary land tenure systems play a significant role, making up about ninety percent (90%) of landholdings in the region. As already mentioned, land holdings and use practices are not a separate entity from people and their belief systems but are constitutive and embedded in customary land tenure systems [7,8].

The conception of land in Sub-Saharan Africa (SSA) is nuanced and transcends the physical land per se. As described by Elias [45], land in Africa belongs to the living, the dead and the unborn. Sometimes, land is seen as a deity and entity from which people derive spiritual identity. A study by Abubakari et al. [8] in the Upper East region of Ghana explicates such spiritual connections with land where the earth priest (Tendaana) pacifies and sanctifies land allocations and transfers. Under customary tenure, the right to use land in a particular manner is contingent on one's gender, birth order and position within the social group [8]. Essentially, land is not disconnected from people, but the two are conflated and hardly separable. The transcendence in the conception of land makes customary law and practices reflect the exigencies of specific communities, although there are commonalities as well [30,31]. Thus, customary practices are not a coherent set of stable rules that apply uniformly across communities but evolve within and vary across communities [7]. From a system perspective, the embodiment of customary rules can be likened to a complex adaptive system whereby the actors (members) and the system (customary system) itself evolve, adapt and shape each other in a constantly evolving manner [46–48]. Customary lands are not only characterised by a communality in the manner they are held, but they are also characterised by an evolved set of norms and practices. Such norms and practices define membership and associated rights of land use, restrictions and responsibilities. Members usually have usufructuary interests (superior rights) and are given portions for their usage and livelihoods such as farming but sometimes without rights of disposition [49]. Although urbanisation, modernisation and economic development have resulted in increasing demand for properties in urban areas, such trends are still somewhat influenced by the resilient customary rules and belief systems. Landowners within cities still hold on to their beliefs and practices because of the continuity and preservation of their culture. According to Arko-Adjei [46], customary land tenure systems are usually unwritten, yet they are passed from one generation to another. In sum, the relationship between people with respect to land is governed by a continuously evolving set of rules, which are known within the social groups in which they are practiced. Distinct from statutory rules of tenure, customary rules of tenure are neither written nor consciously formulated at one point in time and are normally enforced within local circles. In the case of Ghana, where the constitution recognises customary law, this provides room for forum shopping and strategic choice making on the part of members [50].

3. Methodology

This study uses a qualitative research strategy coupled with a case study approach because the study aims to understand the contextual reasons for urban blight in Sub-Saharan Africa (SSA) in the case of Ghana (see Appendix A for analytical framework). According to Yin [51], the niche of a case study approach is to investigate a contemporary phenomenon that is labelled as "the case" in the real world. This research approach enables in-depth understanding of the pertinent contextual circumstances associated with the case. The choice of Ghana makes the study an interesting one to be investigated in SSA. This is because Ghana is the first SSA country to ascertain independence from colonisation in 1957 and thus the premier country to gain full control of urban planning and land management by an aboriginal government [52]. Additionally, the concept of urban blight is known in Ghana's urban policy, Land Use and Spatial Planning Act 2016 (Act 925), as previously mentioned. The research will provide a contextual understanding of urban blight to assist city planners and government agencies in operationalising urban policies.

3.1. The Study Area

This study is conducted in East Legon, a first-class suburb of Accra. The area measures approximately 4.95 square kilometres and falls under the Ayawaso West Municipal Assembly (AWMA), as shown in Figure 1. It is classified as a first-class area by the Assembly mainly due to good infrastructural facilities, such as roads, water, and electricity, inclusive of modern developments and major commercial activities. Additionally, it is recognised as one of Accra's most expensive areas, with an influx of international businesses and expatriates [53]. Despite being noted as an affluent area with a high demand for urban space, the area is experiencing blight, and some areas have been in the same condition for many years [54]. To understand the nature of urban blight in East Legon, the study was conducted in phases. These are described in the next section.

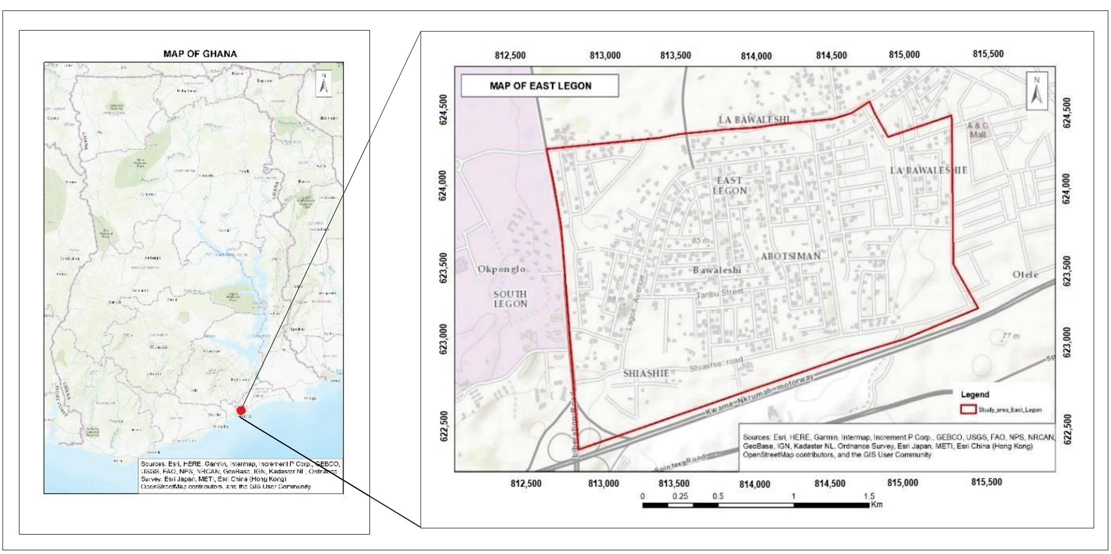

Figure 1. Map of East Legon, Accra-Ghana. Source: Esri Topographical Map and Land Use and Spatial Planning Authority.

3.2. Criteria for Identifying Blighted Properties

To identify blighted properties within East Legon, we used a two-stage criteria. The first stage entails definition and characterisation of urban blight, which paves a way for the second stage, a visual selection process based on the outcomes of the first stage.

In the first stage, we traced the characteristics of urban blight from the existing local law: Land Use and Spatial Planning Act 2016 (Act 925), as cited earlier in Section 2.1. Characterising urban blight according to the laws of Ghana is necessary to understand the case of Accra as a typical emerging southern city. A global characterisation would otherwise not match the local characteristics and thus have the tendency to blur or misrepresent the local reality/context of how urban blight is understood. We, however, acknowledge that a comparison between local and global perspectives is imperative to position our study within the discourse on urban blight. Thus, based on the characteristics of urban blight stipulated in Section 103 of the Land Use and Spatial Planning Act 2016 (Act 925), we categorised the characteristics into four forms of urban blight according to common descriptions found in literature [23,32,55]. These categorised forms of blight are shown in Table 2.

Table 2. A summary of the criteria for selecting blighted properties in this study.

No.	Categorised Forms of Blight	Criteria According to the Land Use and Spatial Planning Act 2016 (Act 925)
(a)	Cluster of disordered settlements	"Irregularity of plots or parcels"
		"Lack of access to plots or habitable dwelling within the area"
		"Safety or restriction to the other authorised users"
		"Overcrowding leading to unhealthy population density"
		"Lack of sanitation, drainage or appropriate service"
(b)	Vacant plot/undeveloped land	"Safety or restriction to the other authorised users"
		"Adverse impact on the environment"
(c)	Single dilapidated (degraded) property	"Incompatibility with the existing or proposed use; the spatial development framework; and the structure or local plan"
		"Diversity of existing use which makes development control difficult or impossible"
		"Safety or restriction to the other authorised users"
		"High incidence of crime which has been confirmed to be attributable to the type of development"
(d)	Uncompleted buildings	"Adverse impact on the environment"
		"High incidence of crime which has been confirmed to be attributable to the type of development"

In the second stage, we used the categorised forms of blight to identify blighted properties within East Legon using a virtual neighbourhood audit technique on the Google Earth aerial image. Neighbourhood audit on the general land use of an area could be reliably conducted with Google street view since the viewer is given a virtual feeling of about 15 m resolution [56]. However, the limitations of this remote observation were the fact that it could only provide the spatial perspective of the blighted properties, which was significantly dependent on the spatial resolution. Furthermore, the coverage was constrained because not all the streets and landed properties in the area could be viewed in the aerial images in 3D. Additionally, Pratomo et al. [57] argue that there are uncertainties regarding the spatial analysis of blighted areas because of non-observable indicators such as land tenure. Additionally, Kohli, Sliuzas, and Stein [58] acknowledge that the accuracy of remote sensing techniques for city deterioration requires some level of tacit knowledge. Thus, we augmented the Google Street view with tacit knowledge of the study area and physical inspections (field investigations).

First, different spots of each category of blight were visually detected on the Google image of the study area using visual image interpretation elements such as pattern, shape, and location/association. According to Bakx et al. [59], pattern depicts the spatial arrangements of the buildings where there is repetition of form, style, or relationships; shape takes into consideration the two or three-dimensional projection of the property with Google Street view; association takes into account the relationship between recognisable features and other structures. In this study, we used the element of shape to identify uncompleted structures within the study area; we also used the association of the blighted property with regards to its surroundings to determine single dilapidated/degraded and uncompleted buildings. Finally, we used pattern and location to determine clusters of disordered settlements and vacant plots, respectively. The four categorised forms of blight are illustrated in Figures 2–5 in the subsequent segment. However, during the field visits, some of the properties initially identified as blight were being developed into ultra-modern structures. This enabled us to further narrow our selection to properties that truly match the different forms of blight, as categorised in Table 2.

3.2.1. The Aerial Views of the Four Forms of Urban Blight

Cluster of Disordered Settlements

Figure 2 illustrates an aerial view of clusters of disordered settlements with blue dots. The selection of this form of urban blight is based on irregularity of plots, overcrowding and lack of access to habitable dwellings.

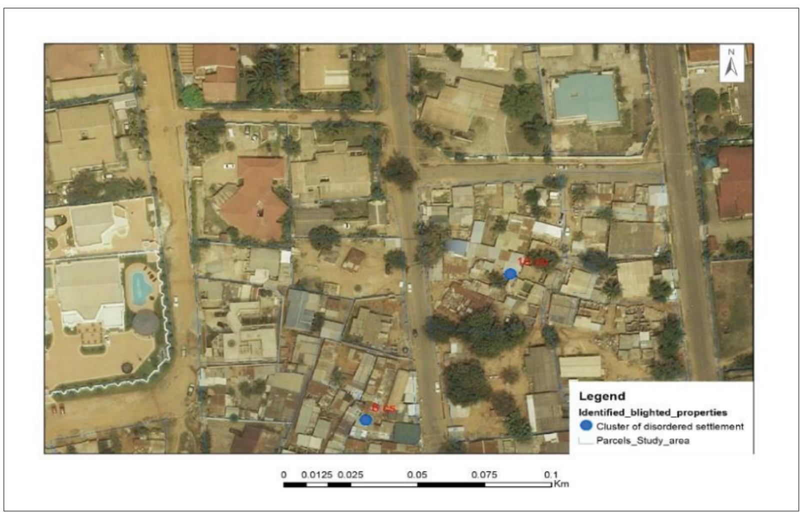

Figure 2. Aerial view of cluster of disordered settlements. Source: Google Earth 2018 and parcel plan from Land Use and Spatial Planning Authority.

Vacant Plot of Land

The aerial view of a vacant plot of land surrounded by well-developed properties is shown in Figure 3 with a green dot. The criterion for the selection of vacant plots of land is their undeveloped nature.

Figure 3. Aerial view of a vacant plot of land. Source: Google Earth 2018 and parcel plan from Land Use and Spatial Planning Authority.

Single Dilapidated Property

The selection of dilapidated properties is based on identification as old, obsolete buildings that are degraded or fallen into disrepair. This is shown by the two red dots in Figure 4 below.

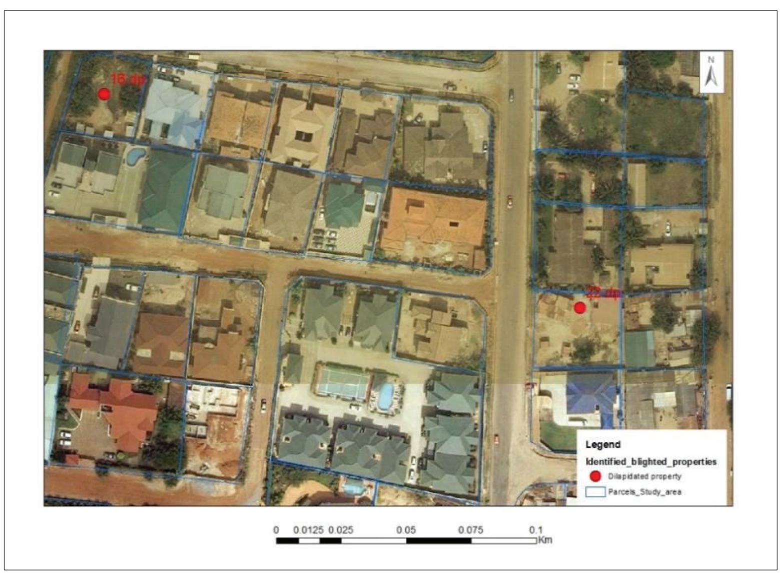

Figure 4. Aerial view of dilapidated properties. Source: Google Earth 2018 and parcel plan from Land Use and Spatial Planning Authority.

Uncompleted Structures

Figure 5 shows an aerial view of an uncompleted structure. Aerial selection is based on the foundations of building constructions on site, as shown by the orange dot.

Figure 5. Aerial view of an uncompleted structure. Source: Google Earth 2018 and parcel plan from Land Use and Spatial Planning Authority.

3.3. Data Collection

Both primary and secondary data were collected for the study. For the primary data, a field investigation was carried out in December 2019/January 2020. This involved purposeful identification of the current distribution of blighted properties. To visually engage and stimulate interest and understanding of urban blight in the respondents, as well as evoke deep reflections, a photograph showing the general description of the mixture of well-developed properties and blighted properties in the study area was used in the interviews (see Appendix B). According to Bryman [60], the photo-elicitation method in qualitative interviews serves as an anchor to trigger, excite and evoke the thoughts, views and perceptions of the respondents to provide a meaningful context for the subject matter of discussion. Furthermore, electronic devices—a digital camera and an audio recorder—were used to capture photographs of blighted properties and conversations with the respondents, respectively. Alternatively, there were narrative recordings and jotting down of notes when respondents were uncomfortable with audio recordings.

Secondary data, on the other hand, were information gathered from scientific articles, journals and aerial images: Google Earth 2018, orthophoto 2016 and the land use plan of the study area obtained from Land Use and Spatial Planning Authority (LUSPA) and Accra Metropolitan Assembly (AMA). The Google Earth aerial image was selected based on spatial resolution to help with the visual image interpretation of the blighted properties. Additionally, the orthophoto gave a better spatial resolution of 0.2 m, as well as spatial data from LUSPA. Furthermore, the boundary of the study area (shape file) was acquired from LUSPA, which was used to locate the study area on the aerial images. The Google Earth image was then exported as a kmz file and subsequently converted to kml files in ArcGIS software and geo-referenced accordingly. Finally, the land use plan assisted with the boundaries of the parcels, which was very helpful to the visual interpretation of the Google Earth image, as shown in Figures 2–5.

3.4. Sampling Technique

A study conducted by Galster [37] described the four main actors of neighbourhoods: households, businesses, property owners and local government. In this study, the four key stakeholders considered are experts from statutory agencies, residents/households, property owners and real estate developers. We used non-probability sampling techniques (purposive and convenience sampling) for the selection of respondents. A purposive sampling technique was used to obtain information from the experts. Purposive sampling is the judgment a researcher uses regarding who can provide the needed and required data for a study [61]. In order to understand the dimensions of land tenure and administration, as well as how they feed into the emergence of urban blight, we interviewed four (4) divisional heads of the Greater Accra Regional Lands Commission. Additionally, given that local authorities in conjunction with the Land Use and Spatial Planning Authority (LUSPA) in Ghana have the prerogative of spatial and land use planning, we interviewed four (4) experts from these authorities to determine their perspectives on urban blight, as well as the root causes, characteristics and implementation dynamics that have featured so far in the regulation of property development in East Legon. In this category, we interviewed eight (8) experts for this study.

Additionally, it is important to recognise that urban blight is perceptive in nature and thus may vary across stakeholders/actors. Therefore, we needed to get a clear understanding of how other actors perceive and define urban blight, the socio-cultural practices that surround property holdings, and how such dynamics influence the overall attitude of property management and development within the study context. To find respondents for this category, we used convenience sampling, also known as accidental sampling, which is based on the researcher's ease of accessing, contacting and reaching respondents. Kumar [61] describes convenience sampling as a technique based on suitability and ease of accessing the respondents for a study. Additionally, response saturation (repetition) was used as a guide for our sample size. As explained by Bryman [60], the saturation point is reached by a researcher when either there are no new discoveries of information or any new information is negligible regarding the objective of the study. For this category, we interviewed 22 respondents, which included residents, property owners and real estate developers in the study area. Overall, a total of 30 respondents were interviewed using the two sampling techniques, as presented in Table 3.

Table 3. Summary of respondents and sampling strategies.

No.	Description of Respondents	Sampling Strategy	Total Number
1	Residents	Convenience sampling	12
2	Property owners		8
3	Real estate developers		2
	Experts		
4	Lands Commission		
i.	Public and Vested Lands Management Division	Purposive sampling	2
ii.	Land Valuation Division		1
iii.	Survey and Mapping Division		1
5	Land Use and Spatial Planning Authority		1
6	Local Government Authorities		
i.	Accra Metropolitan Assembly		1
ii.	Ayawaso West Municipal Assembly		2
	Total number		30

3.5. Data Analysis

The primary data collected via audio recordings were first transcribed into text using Microsoft Word documents. Subsequently, the transcribed documents were uploaded into Atlas.ti software for thematic analysis via open coding in order to identify emerging perceptions and reasons for urban blight. Bryman [60] describes open coding as the process of analysing qualitative data where the researcher remains open-minded to generate as many ideas as possible as well as make meaning out of the data collected by breaking down, comparing and categorising the data into themes. Additionally, the secondary data obtained from the land-use plan (local plan) and the aerial images were used to generate maps using ArcGIS software, as illustrated in Figures 2–6.

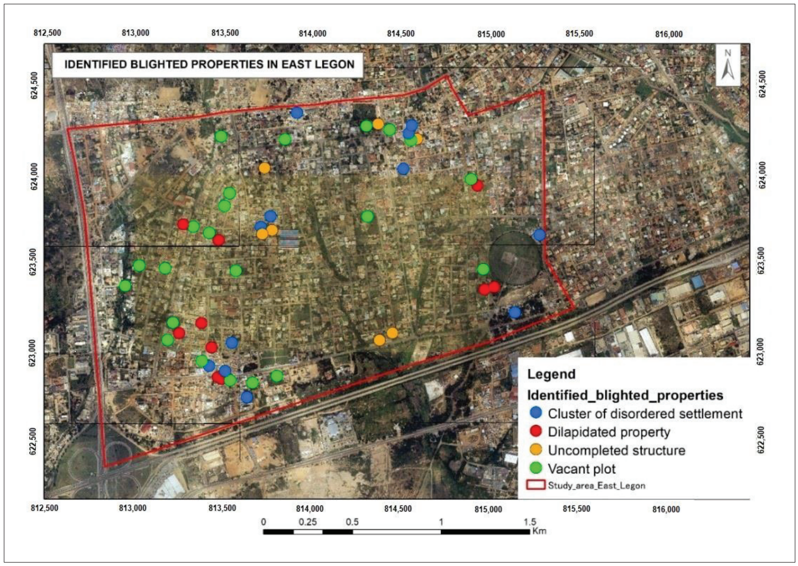

Figure 6. Distribution of blighted properties in East Legon. Source: Land Use and Spatial Planning Authority, Orthophoto 2016 and Google image 2018.

4. Results

In this section, we present the findings of the study. We begin by illustrating the distribution of urban blight in the study area. In order to ascertain the reasons for blight, we described the perceptions of urban blight across different stakeholders/respondent groups. Next, we present how East Legon became urbanised and subsequently the underlying causes for blight in the area, highlighting how socio-cultural values play a significant role. Finally, we describe the effects of urban blight on the development of the area.

4.1. Current Distribution of Urban Blight in East Legon

From the four categorised forms of blight for the study, it was observed that the clusters of disordered settlements are predominantly located at the outer edges of the study area. This confirms the statement made by one of the interviewed experts that planning with infrastructure was carried out in the inner cities whilst the native settlements were left on the outskirts. In terms of frequency (rate of occurrence), vacant/undeveloped plots were most frequent, followed by the clusters of disordered settlements, then dilapidated properties. Uncompleted properties were the least frequent. The observations gathered indicate that some identified uncompleted structures and dilapidated properties were completed or redeveloped into ultra-modern buildings as a result of gentrification. Furthermore, property owners of vacant plots were mostly spectators who were looking for an opportune time to invest in their property. Yet, the cluster of disordered settlements (indigenous and squatter settlements) often stayed in the same condition for many years. The indigenes perceive themselves as natives who must preserve their heritage (customary land rights/properties), whereas squatters (illegal settlers) are mostly immigrants. Figure 6 illustrates the distribution of the forms of blight in the study area.

4.2. Local Perception of Urban Blight

Urban blight is a relative concept that is perceived differently by various stakeholders, as demonstrated in Table 4. Generally, urban blight may be regarded as an unsatisfactory use of urban space or real property. Yet, the unsatisfactory manner is usually determined by other stakeholders, while the person using the property may have other values that may be hidden from the other actors. Although urban blight is generally regarded as a negative phenomenon, different respondent groups highlight different perceptions influenced by their relative backgrounds. For instance, drawing from professional standards and intuition, urban planners use non-adherence to land use plans as a reference to establish blight in areas such as squatter settlements. Similarly, residents and property owners in the neighbourhood perceive urban blight from an aesthetic point of view (level of beauty), material culture (the material for construction) and the degree of permanence (squatter settlements). Apparently, most of the respondents perceived squatter (illegal) settlements to be blight, attributing them to the rapid urbanisation. Consequently, there are unauthorised structures portraying non-compliance to city plans and policies. For real estate developers, urban blight is regarded as the non-exploitation of the economic potential of property. The succeeding section provides the background of how East Legon became urbanised.

Table 4. Local perception of urban blight.

	Local Perception	Respondents			
		Experts	**Property Owners**	**Residents**	**Real Estate Developers**
1	Aesthetics			✓	
2	Indigenous buildings—"*atakpami*" (*local term for mud houses*)	✓		✓	
3	Squatter settlements—"*kiosks*" (*local term for wooden structures built by illegal settlers*)	✓	✓	✓	
4	Untapped economic potential				✓

4.3. Urbanisation in East Legon

Historically, East Legon was a Ga traditional area with four main settlements: Shiashie, Okponglo, Abotsiman, and La Bawaleshie. In 1944, the area was compulsorily acquired by the colonial government as an extension of the International Airport zone. Subsequently, the government carved a portion of the acquired land and created a residential estate for senior civil servants. To all appearances, East Legon became a first-class residential area from the onset after the government established the estate and provided infrastructure such as roads, electricity and water. Information gathered indicates that the indigenes were compensated for the loss of their land inclusive of farmlands. Despite the compensation, they still remained there based on humanitarian grounds. This was articulated by the Land Administrator as "*when the acquisition was done, there was a committee that was set up to look at this particular acquisition. They called it the Alomatu committee. So they were the ones that interacted with the chiefs and the people and they recommended that once they are living there and it is also residential, what is the point in driving them out? They should allow them to be there because, with time, they will grow out of it*". Another expert, Planner, mentioned that urbanisation has caught up with indigenous settlements that were previously at the outskirts of the planned area. He explained, "*unfortunately, developments have sprung up and have made these indigenous buildings to be in the centre of the city but the initial plan had them on the outskirts of the planned area. In order words, the area was planned around them*". Yet, the natives are still glued to their indigenous properties despite being in a first-class area.

4.4. The Underlying Reasons for Urban Blight in East Legon

4.4.1. Socio-Cultural Values Attached to Real Property

Socio-cultural values are expressed with deep emotions and intense feelings. They concern traditional and emotional attachments that are not monetary based. It was also established that some properties were named after their ancestors, which had to be preserved for future generations. As it was aptly put by one respondent, "*We have stayed in what our great grandparents built for us. We are also supposed to leave a legacy for generations to come*". Another indigene explained, "*When the property is there, it is immovable . . . anyone who knows the family and wants to trace the family can easily do that because of the property such as somebody who has travelled overseas, he can easily locate the family*". Traditionally, it is believed that real property provides the family lineage and ancestral background of a person. Additionally, people hold on to property as a result of the lasting memories established there. One respondent said, "*This building was put up by our grandmother . . . So we have to preserve her memory for now*". Furthermore, it was recognised that some properties serve as a bolster for life where family members could live, work and go about their daily activities with less stress and traffic than living in the outskirts. As expressed by one respondent; "*they can be in town and transact their activities and businesses, have a place to lay their heads and start life before they go and find their own places . . . development is good but money came to meet human beings. We value human beings and their livelihood, where they will lay their heads, go to work rather than somebody giving you money to take your property*".

4.4.2. Customary Land Control Versus Weak Enforcement of Urban Policies

The spontaneous growth of urban areas without guiding layouts and land use plans has resulted in urban blight. Experts have expressed concerns that not much can be achieved by enforcing urban policies in native settlements termed as "city villages". These indigenes were the customary land owners and first occupants before the formal planning of areas. Invariably, their settlements are often considered as spontaneous growth, although traditional authorities play a critical role in the land use of their jurisdictions. Thus, land use and developments are ahead of planning in most parts of Ghana. Additionally, the study discovered that there are no strict measures for the implementation of urban policies, only eviction and clearing of squatters (illegal settlers). Rapid urbanisation has caused a massive influx of immigrants into the capital city, Accra. Whenever these squatters are evicted from their unplanned dwellings and the cleared space is left undeveloped, the squatters always go back to settle there. According to the expert, there was one such experience in early 2018: "*You know there are recalcitrant people. Even when we cleared them, two (2) to three (3) days later we realized some of them were putting up table tops, containers and kiosks that we had broken down. So whoever is there now, no one has permitted them*". Apparently, after clearing the place in 2018, as at the time of the data collection in December 2019/January 2020, the squatters were still there.

4.4.3. Land Disputes

The land disputes were mainly associated with inadequate transparency regarding land ownerships. Ghana is characterised by a dual system of land tenure: statutory and customary land tenure systems. Most often, conflicting land ownership rights arise among individuals, family members, traditional authorities and government institutions, either between people in the same group or through the involvement of different parties in different groups. Eventually, these conflicts result in litigation, creating a huge backlog of land cases in court, some of which have remained unsettled for many years. The Land Administrator gave an example where the Shiashie family in East Legon instituted a legal case against the Lands Commission for granting leasehold titles to their land. In April 1999, the High Court ruled the case and granted ownership in favour of the Shiashie family. Subsequently, an appeal was made by the Lands Commission in June 2013, and the case was overturned and ruled in favour of the Lands Commission. The latter judgment was based on evidence provided by the Lands Commission regarding the Certificate of Title for compulsory land acquisition under the Public Lands Ordinance (CAP 34) in 1944. Apparently, for fourteen (14) years of litigation, court orders such as injunctions were placed on land use and development in the areas under contention. Ultimately, blighted properties were left in their blighted conditions, especially the vacant/undeveloped plots and uncompleted structures.

4.4.4. Hybrid Land Tenure and Administration

The process and structures involved in managing and disseminating information about the rights and use of land in Ghana are seen to be ineffective by most respondents. Land administration functions cut across both state and non-state (customary) actors. There is a binary distinction in the levels of recording across state and customary land. While customary land tenure system covers about seventy eight percent (78%) of the total land in Ghana, they vary regarding their practices and are mostly undocumented [46,62]. The landholding types under customary land tenure systems in Ghana are family, stool and skin. For the study area, the land ownership is both statutory and customary (family landholding). Due to the inadequate land records, it is difficult to establish certainty of ownership that allows room for fraud and also hinders land transfer. A resident expressed her experience where, in the process of purchasing a blighted property in East Legon, she had to conduct a search at the Lands Commission to ascertain true ownership but never reached an outcome, so she abandoned it, and to date, the property is still in a blighted condition. She stated, "*Land ownership and proof of ownership is difficult in Ghana … obtaining information on the ownership alone can take years … the whole process is so cumbersome*". Additionally, customary land owners in East Legon (families) are discouraged from regularsing their interest in the land. Explanations for this unwillingness lie in the mechanisms of land rights translation by the Lands Commission. In these processes, the usufructuary rights (superior rights) of families are truncated to leasehold rights, which requires them to pay ground rents (periodic payment of money as a tenant) to the Government.

4.4.5. Economic Reasons

Finance is a requisite for property development. While some property owners need capital for the development of their properties, others, such as speculators, are expecting an opportune time to make financial gains from their properties. In the period of waiting, some do not keep their properties in a good state, and they end up becoming blight. Others, on the other hand, choose caretakers or squatters for safety. However, for the indigenous buildings, the question that was asked was, whose responsibility is it to provide capital to develop family property? The indigenous buildings in East Legon are predominantly family properties managed by a family head. By virtue of being a family member, each person has the opportunity to use the property. Nevertheless, regarding development and maintenance, as was stated by one expert, "*The tragedy of the commons happens. Who should connect his resources into redeveloping the family property?*". It was found that some family members with financial capabilities act independently and prefer acquiring personal properties for their nuclear family since any investment made on family land automatically becomes family property per the laws of Ghana.

4.5. Effects of Urban Blight on Land Use and Development in the Study Area

4.5.1. Positive Effects

Instituting the Historical and Cultural Background of the Area

For the customary landowners, preserving their culture is the main focus. As mentioned earlier, East Legon was hitherto a Ga traditional area. It is believed that most urbanised areas in Accra have indigenous settlements as part of the urban setting. An expert explained, "*When we take every urban settlement, you see the indigenous settlements as part of it … you know these villages have always existed*". To all appearances, the indigenous people have settled to maintain their way of living. One resident responded, "*They see* *themselves as they are the owners of the land and they have been there for this long time. It is their property so they take it to be a normal phenomenon so even if you want to develop the place, they won't contribute or participate to make it fruitful. They will just say, after all, we have been here already and we are okay*". Consequently, there is a clear purpose to the present generation holding the land as stewards and leaving a legacy for future generations.

Establishment of Security

For the indigenes and some squatters, the properties, despite their condition, provide security. Security was expressed as a state of well-being and safety. It was discovered that blighted areas are comfortable with less competition. Additionally, the blighted properties keep a low profile and do not expose wealth. Some property owners mentioned that one way to safeguard properties is to keep the exterior of the residence very simple. He stated, "*People look at the exterior of your house to see if there is something valuable. If you look at this building, you will think that there is nothing valuable inside*". Furthermore, some squatters live in blighted properties to save money for future investments. One of them revealed, "*Most of us, not to say we cannot hire a house. For instance, I cannot hire a house but take money say two years advance, Two Thousand, Four Hundred Ghana Cedis (GHC2, 400.00). How much will I use to purchase land? I can use part of the money to buy my own land . . . So it is more like we are also building so we don't want to make more expenses*".

Companionship

Residents in blighted areas feel friendliness among themselves. Some of the respondents expressed that the well-developed properties have fence walls, secured gates with barbed wires, and dogs to deter strangers. Others have security guards and watchmen who would question you whenever you get close to their properties. A resident lamented, "*But what we see is they only think of themselves and fence their property leaving the others*". However, with the blighted areas, there are no such hindrances. They could visit friends without any impediments establishing attachments. An expert explained, "*So in terms of people in these settlements, there is some connection, some attachment and it is difficult to be broken*".

4.5.2. Negative Effects

Aesthetics

Aesthetics concerns the attractiveness of a building. Most of the respondents described well-developed properties and gated communities as pleasant, whereas blighted ones were regarded as being in a poor state. A resident mentioned, "*They don't make the area beautiful . . . but when you get to the gated communities, the buildings alone and the uniformity speak for themselves that it is a beautiful area . . . it makes the area nice and attractive*". Therefore, blighted properties deface the brightness and stunning design of the entire area.

Underutilisation of Properties

Underutilisation was described in terms of the economic potential of a property. This negative effect affects some experts, residents, and real estate developers. The experts mentioned that area classification forms the foundation for property rate. Property rate is described by Asiama [63] as an assessed value of tax levied on real estate properties by the local government authorities. Although East Legon is classified as a first-class residential area, not all properties qualify as such. Thus, it was reported by the experts that the revenue generated from blighted properties is low, which means that the properties are being underutilised despite having high economic potential. Additionally, it was discovered that blighted properties could reduce the value of adjoining properties in a good state. An example given was the sale of a residential property, which, although in a good state, did not command the actual market price as a result of an adjoining blighted property.

Social Inequality and Tension

Inequalities create tension between two groups: those in well-established developments and others. This affects residents and property owners. It was discovered that there is lack of cordial relationships between the two groups. One respondent stated, "*There is no uniformity because you see the clear demarcations between the rich and the poor*". Notably, a master–servant relationship is established between the two groups. Another person responded, "*You realise that most of these people serve as servants for the rich people*". Furthermore, experts and property owners explained the tendency of privacy intrusion; when a well-developed property, like a high-rise structure, adjoins a blighted one which is a single storey, there could be privacy invasion. An expert explained, "*You have done your three bedrooms residential property which is like 30 years old and the next one close to you is a high-rise structure. They are looking into your house and whatever you are doing, they can see*".

Pollution

Air and noise pollution were relatively higher in blighted areas which affects the residents and property owners. This leads to improper waste disposal which contaminates the environment and affects the residents' health. One respondent explained; "*these squatters create a lot of mess around*". Additionally, some vacant plots were considered unkempt with filth where people dump refuse. Furthermore, some residents and property owners complained of the squatters causing noise pollution through loud music and dance in the evenings. A property owner gave an articulate account of his experience; "*where there are squatters* . . . . *they can really disturb when they play their music. The others come around and dance and have fun. You cannot complain because of democracy and they are also the majority. At times you will be in the room and feel the vibration. This has a negative effect on us*".

Insecurity

Some of the respondents stated that there was some level of insecurity in the area, whereas others compared East Legon to other areas. In comparison, East Legon is more secured. Nevertheless, it was observed that the well-established areas within East Legon are secured. The information gathered indicates that some blighted properties could serve as hotspots for criminal activities. Again, a resident shared his experience: "*In this stretch, there are thieves around. Personally, we experienced theft of African clothes that were put in a locker. Security in this area is low. They can jump from that spot to my place. The rich only secure their places with security men and guards*".

5. Discussion

This section reflects and juxtaposes the results of the study with the reviewed literature. Substantial comparison is made between the global north and south. Additionally, the implications of the results of the study on urban land use and policies are considered.

5.1. Urbanisation and Distribution of Blight

Urban blight is generally regarded as a negative phenomenon. However, careful reflection on the evolution of urban blight in the global north and south, particularly in the study area, shows an inverse correlation. In the north, a vibrant area was transformed into a deteriorated one [3,5,20,21], whereas in the south, urbanisation transformed an indigenous area and caused the native settlements to be regarded as blight because they do not fit the contemporary setting. Again, rapid urbanisation has resulted in squatter (illegal/unauthorised) settlements due to inadequate housing infrastructure, coupled with lack of social amenities [21]. These relationships are not limited to Ghana but more broadly reflect the character of urban development in Sub-Saharan Africa (SSA) [20,64]. The study found that in the history of urban development in SSA, urban cities were once native settlements, which concurs with the assertions made by Cobbinah and Aboagye [20] and Clarke [65]. Yet, the cities are planned in an ad hoc manner, where infrastructure is provided in certain areas only by neglecting the native settlements. Additionally, the distribution of blight, as illustrated in Figure 6, confirms this, where clusters of disordered settlements (indigenous and squatter settlements) are predominantly at the outer edges of the study area. Again, in terms of frequency, vacant/undeveloped plots were the most prominent, indicating a high degree of land speculation in the area. Furthermore, uncompleted buildings were the least prominent, and it was observed that some identified blighted properties were being redeveloped. Consequently, the ideas of urban renewal and gentrification have heightened the transformation of existing developments and so-called blighted properties into ultra-modern facilities. These ultra-modern facilities have become the standard of development for existing buildings to be regarded as blight. Careful examination plays an important role in policy development and implementation, with the intention of providing a cosmopolitan community with infrastructure, especially in native settlements. However, there should be strict measures to deter the formation of illegal settlements.

5.2. Reasons for Urban Blight

The primary similarity between the cause of blight in both the global north and south is economic factors. However, economic reasons manifest differently. While in the north, economic factors normally manifest on a macro scale, such as the collapse of industries and businesses transforming vibrant cities into abandoned ones, in the south, as in the current study, economic factors largely manifest at the micro level of individual property holders, where, due to lack of finances, properties are not upgraded or left to deteriorate relative to their surroundings. This agrees with the observations made by Crankshaw et al. [17] and Weaver et al. [31] in their studies in South Africa and North England, respectively, suggesting that low-income residents do not maintain a good neighbourhood, which leads to physical stagnation. Another dimension of blight influenced by economic factor is the deterioration of the city landscape resulting from land speculation. Weak land administration coupled with land disputes have caused the property market to be poorly regulated, with some speculators waiting for an opportune time to invest in their property and therefore not keeping their properties in good condition. Instead, they prefer to occupy their land with squatters as a form of security against adverse claim and encroachment. This therefore confirms the argument made by De Soto [66] that property owners in the south are more engrossed in securing their properties by relying on local arrangements.

Additionally, property ownership and/or holdings in the global south are predominantly shrouded in socio-cultural values. As explained by researchers such as Chimhowu [7], Abubakari et al. [8] and Arko-Adjei [46], socio-cultural values have deep roots that not only regulate the interactions between people but also between people and land. The conception of property in many parts of Sub-Saharan Africa (SSA) as a communal entity makes property inseparable from people and also highlights its relevance in establishing one's identity. This resonates with the study of Abubakari et al. [8], which indicates that people trace their identity over time through land. The north, however, is predominantly branded with social values, especially in low-income neighbourhoods where place attachment is established with mutual dependencies on other residents. Additionally, the global north is characterised by few native settlements such as Maori in New Zealand, Aboriginals in Australia, and American and Canadian Indians [42,43]. These northern native settlements are typically concerned with heritage conservation regarding the spirit of their ancestors rather than embedded socio-cultural values in land ownership and use. Apparently, landholdings are predominantly statutory based.

Furthermore, the global south is characterised by fragmented and complex tenure systems. Woven layers of subsisting land rights enable different people or parties (for example, traditional authorities versus government) to lay conflicting claims to land concurrently. The pluralistic land tenure systems provide avenues for encroachment given the weak capacity on the part of planning authorities [20]. A greater percentage of land, specifically in the Sub-Saharan Africa (SSA) area, is under the customary land tenure system, which is largely undocumented, creating forums for fraud and inefficiency of the property market [7,66]. Additionally, customary landholders are deterred from registering or regularising their interests because of the conversion from freehold to leasehold by the state land agencies. This confirms the claim made by Abubakari et al. [67] that the formal Land Administration System does not recognise the customary freehold, and hence a greater percentage of the property owners are not documented, leading to land disputes. However, in the global north, Zevenbergen [68] highlights that security of tenure is guaranteed either through deeds or land title registration.

5.3. Effects of Urban Blight

The main positive effect for both the north and south is place attachment where community bonds and social networks are established [42–44]. Yet, in the south, cultural values are mainly attached to properties [46,49]. Properties are inseparable from people where there is an intended purpose of leaving a legacy for future generations [46]. The intention behind this is that the people (future generations) will not lose their identity [8], thus preserving the cultural background of the area. Additionally, the study found that some squatters rented kiosks in order to save and establish their own residences. This, however, assigns a positive attribute to squatters, which is not frequently found in literature. On the other hand, the predominant negative effect of blight in the north is high criminal activities [14,23], whereas in the south, a dent on aesthetics is the main concern. This confirms the arguments made by Kleinhans et al. [43] and Galster [37] that blighted properties are usually stigmatised when the occupants of blighted properties are less recognised in terms of social status, causing tensions and social imbalances between residents/households.

6. Conclusions

Urban blight is a relative concept that is perceived differently by various actors. While urban blight in the global north has been discussed largely from the point of view of its negativity in the broader scheme of city planning and infrastructure development [2,3], the case of East Legon and the global south depict a mixed scenario where urban blight serves a dual function. Whereas urban blight deteriorates the city landscape on a broader level, it also serves the function of promoting cultural heritage for families. More importantly, urban blight in the global south is more nuanced and demonstrates high relativity in what might be considered a blighted property, depending on perspective and purpose. As an emerging trend in developing countries, urban planners and city authorities, in pursuit of city gentrification, promote the development of ultra-modern edifices in native neighbourhoods, which often renders the existing buildings unfit by emerging and contemporary standards. Such induced urban blight not only redefines a criterion for development but, in so doing, opens up cultural homogeneity to heterogeneity and cosmopolitanism. Therefore, in the global south, maintaining a balance between the way of life of a people and emerging global trends of gentrification is essential as the majority of the population are economically vulnerable. It is thus important to identify the significant functions that so-called blighted properties perform within the city core and how such functions strengthen general standards of living and social cohesion. Recognising subtle positive functions in the context of southern cities is crucial in shaping the overall discourse on southern urbanism. The limitation to this study is that the customary land tenure for this study (family landholding type) may not apply to all areas. Customary practices are not a coherent set of stable rules that can be applied uniformly across communities but evolve within and vary across communities [7]. Thus, the influence of land tenure systems on blight may differ because of the pluralistic and varied land tenure systems and practices in the global south. For further studies, the results of this study can be extrapolated to other areas (either within Sub-Saharan Africa or any southern city) with different characteristics, since land tenure systems vary from place to place. Additionally, a study on the role of urban blight and neighbourhood governance in achieving a balance of value systems should be conducted.

Author Contributions: Conceptualization, S.A.M., Z.A. and J.M.; methodology, S.A.M.; formal analysis, S.A.M.; investigations, S.A.M.; writing—original draft, S.A.M.; writing—review and editing, S.A.M., Z.A. and J.M.; supervision, Z.A. and J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data was archived in University of Twente students database. This is private. However can be accessed with the link:\\UT152200\StudentData/mireku_s6039510.

Acknowledgments: To the respondents during fieldwork: the experts for their time and sharing their in-depth knowledge, property owners and residents in East Legon.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Analytical Framework

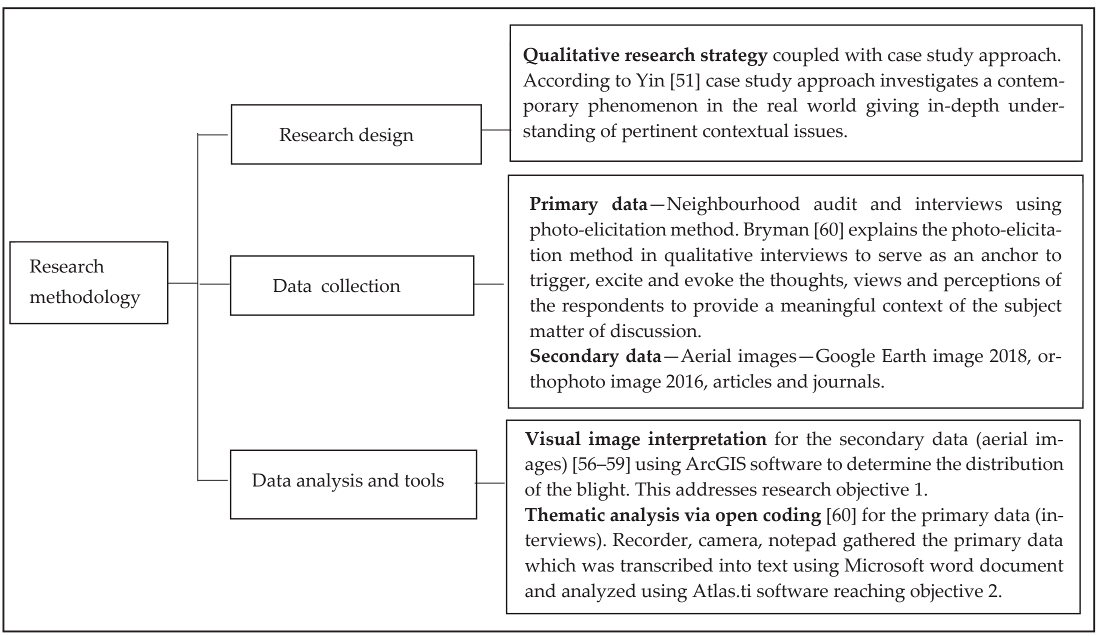

Figure A1. Analytical framework showing the research steps for the study.

Appendix B Photograph Used for Photo-Elicitation during Fieldwork

Figure A2. Views of both blighted and well-developed properties.

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Perceptions about Tourism and Tourists in Historic Neighborhoods: The Case of Alfama

Arlindo Madeira [1], Teresa Palrão [2,3], Alexandra Sofia Mendes [4,*] and Ernesto López-Morales [5]

1 TRIE—Centro de Investigação Transdisciplinar para o Empreendedorismo & Inovação Ecossistémica, ESCAD, School of Science and Administration, 1950-396 Lisbon, Portugal; arlindo.nmadeira@gmail.com
2 Tourism Department, Universidade Lusófona de Humanidades e Tecnologias, 1749-024 Lisbon, Portugal; teresa.palrao@ulusofona.pt
3 CiTUR, Estoril Higher Institute for Tourism and Hotel Studies, 2769-510 Estoril, Portugal
4 CiTUR, Polytechnic of Leiria, 2520–614 Peniche, Portugal
5 Centro de Estudio del Conflicto y la Cohesión Social (COES), Departamento de Urbanismo, Universidad de Chile, 8320000 Santiago de Chile, Chile; elopez@uchilefau.cl
* Correspondence: alexandra.mendes@ipleiria.pt

Abstract: Tourism makes destinations adapt to receive those who visit them, with a great impact among traditional residents. Overtourism affects picturesque places, and these areas end up losing their authenticity, submitting themselves to the consumption needs of tourists. Neighborhoods' traditional residents also see their routine completely changed due to the different habits of tourists, and displacement rates rise. This study aims to understand how local people perceive tourism in Alfama, one of the most unique and tourist-oriented neighborhoods of Lisbon. Our study involves a questionnaire to old long-term residents and content analysis of their responses. We used Leximancer software to create categories of analysis depending on frequency of mentions and the way themes are related. Our interviewees testified that overtourism in Alfama generates perceptions that range from a generalized acceptance for the benefits that an improved safety associated to an increased street-life and a cleaner neighborhood generate, and on the other hand the grievance for the loss of a pre-existing community. We also conclude that the benefits of tourist-led gentrification are relevant for the gentrification analysis because they show the contradictions that the remaining residential community experience as tourist-led gentrification unfolds.

Keywords: gentrification; historic neighborhoods residents; social sustainability; tourism benefits; tourism impacts

Citation: Madeira, A.; Palrão, T.; Mendes, A.S.; López-Morales, E. Perceptions about Tourism and Tourists in Historic Neighborhoods: The Case of Alfama. *Sustainability* **2021**, *13*, 8357. https://doi.org/10.3390/su13158357

Academic Editor: Pierfrancesco De Paola

Received: 25 June 2021
Accepted: 22 July 2021
Published: 27 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Tourism in historical cities often leads to gentrification processes [1]—a phenomenon that affects places and the life of local low-income inhabitants due to the valorization of space and the consequent increase in their costs of life, leading to dissatisfaction with their places [2] and ultimately their displacement (Lees et al., 2016). Tourism-related gentrification, or tourist-led gentrification, refers to the socio-spatial transformations that occur due to the intense appropriation of a place for tourism purposes, in which there is a physical and socioeconomic restructuring of the urban environment [3].

In Lisbon, Portugal, tourism has deeply changed the city's age distribution. Between 2001 and 2011, Lisbon experienced an average of population rejuvenation, with an increase of the group between 25 and 39 years of +5% in contrast with the total population decrease of −3% and further population decrease in Alfama, during the same period, of −21%, except for the group between 25 and 39 years, whose share rose 12% [4].

Although it is not certain that by 2011 Alfama had already undergone a gentrification process, its population was quite elderly by then. In 2001, the Ageing Index—namely, the number of people aged 65 and over per 100 people under 15 years old—in Alfama was

315. Additionally, in the parish of Santa Maria Maior, where Alfama is located, the Ageing Index was 286, above Lisbon's index of 186. By 2001, low-income and low-educational levels were predominant in Alfama, as the neighborhood's houses and buildings were also degraded [5]. For the following two decades, there was a progressive de-population in Alfama, explained by the natural death of the senior residents, the outmigration of residents, and the general decrease of immigrations experienced in Portugal, different to the strong population growth due to immigration during the first half of the 20th century in other countries.

However, recently, Alfama, the so-called 'oldest neighborhood in Europe', has been rediscovered not only as a place to visit, but also as a place where accommodation can be found for tourists. This new context has drastically changed the social panorama of Alfama [6]. For most authors, the main problem in Alfama is the growing supply of short-term rental accommodation [4,7,8]. The second related problem is the extended presence of tourists that seemingly undermines the sense of community based on social relationships, which long-term residents consider essential to reproduce their quality of life and which may lead them to leave the neighborhood, even if not for purely economic reasons [9], there is a cultural nerve that somehow aggressive tourist development hurts, a comparable nostalgia found by Fullilove [10] in black neighborhoods in the US threatened by state-led urban renewal.

The aim of this article is to describe and analyze the perception of a sample of Alfama's long-term residents regarding the positive and negative impacts of tourism in their everyday experience in the neighborhood and compare these two apparently opposed perspectives. We observe the contradiction people have between acknowledging the material benefits gentrification has brought to their neighborhood and grieving for the loss of the community. We conducted structured interviews and collected data that helps us to increase the understanding of the perceived changes that have been occurring due to the growth in tourism demand in this area, and the contradictive narratives these changes generate. Finally, as an empirical contribution to theoretical debates on gentrification, we not only concur with Atkinson and Bridge's [11] idea that contrasting both the acceptance- and rejection-sides of gentrification is theoretically valid, but also, we conjecture whether the temporalities of gentrification affect the residents who remain, particularly after intensive processes of outmigration have already occurred and vacuumed a neighborhood. We therefore claim that gentrification needs to be understood in a temporal evolutionary way, as the perceptions of Alfama's original residents seem otherwise inexplicable. The research questions are: What do Alfama residents think about the increase in tourist activity in this neighborhood? Can gentrification have a positive side?

2. Literature Review

Glass [12] introduced the idea of gentrification based on her observations of the mass middle-class incursion in London's neighborhoods, which led to the displacement of the working class and original inhabitants, altering the whole social character of the neighborhood. More than half a century later, we attempt to understand if this negative perception of gentrification is unanimous among contemporary scholars; however, it can be stated that gentrification is both a process of spatial change and a process of social change [7].

Short-term residents have the power to impose spatial changes in a neighborhood, in a current, more travelling global society than the 1960s', as affluent European, North American and Asian middle-classes massively consume new places and experiences, so this activity reflects residents' values and norms and induces residents' pride in their neighborhoods [13].

A rapid tourist development can sometimes mean a non-sustained growth lacking measures and regulations and originating dissatisfaction in destination local inhabitants. The touristification of historic neighborhoods in cities of Central America and the Caribbean, Middle East, Southern Europe, as in many other places, has a determining factor: the approval of a broad legal framework for the conversion of these neighborhoods into urban theme parks of a touristic nature and the rapid purchase of many properties for short-term renting purposes [14]. Short-term rentals through Airbnb have accelerated the growth of low-priced real estate sets and, as a consequence, European and American global cities have undergone a long-term process of replacing the working and lower-middle classes, thus depriving them of the opportunities and amenities that these cities offer [15–17].

Gentrification can be understood as a process where a population of lower socio-economic status is replaced by a population of higher socio-economic status. The process is invariably accompanied by speculation, but also by reinvestment and improvements in the built environment, always because of the logic inherent to the way the market operates in a capitalist city [18]. Gentrification cannot be reduced to a concept based on capitalist development, being a process that results from substantially different urban dynamics that incorporate distinct ideological and ontological assumptions in a socio-spatial way [19].

This connection makes sense within the framework of theories of planetary gentrification because the social injustices it spawns have a global pattern [18]. According to López-Morales [20–22] the increasing number of cases of state-led gentrification in the world shows how the phenomenon is growing in scale and scope under state power and gentrification is also a much richer narrative than simply discussing it locally as if it was detached from global economic and cultural flows and waves. Already in the early 2000s, Hackworth and Smith [23], claimed that gentrification changed due to economic and political restructuring and made state intervention over gentrification quite decisive. We concur with Smith [24] that gentrification has gone global by the hand of the blueprints of neoliberal urban governance [25] that nevertheless not always end up the same way.

Aalbers [26] calls a fifth-wave gentrification as the urban materialization of finance-led capitalism as a complement to the also leading role of the state and comprises corporate landlords and real estate as an asset class. However, a salient feature of fifth-wave gentrification is investment by transnational wealth elites and middle classes, platform capitalism and touristification, global mortgage debt, lack of housing affordability, the role of the state and the subsumption of alternatives.

Global tourist-led gentrification transforms popular neighborhoods into places of consumption and tourism, and expanding the recreational and leisure function to tourist accommodation or short-term rental can exacerbate tendencies of displacement and residential segregation. Neighborhoods can be drained of their original population, blocking lower socio-economic level people to access habitation, and putting at risk the social sustainability of the historic center [27]. A place is considered sociocultural sustainable, in sociocultural terms, taking into account the level of support and satisfaction of local needs, namely: meaningful sets, sense of belonging, sense of place, and memories, as well as the feeling of a physical environment [28].

However, gentrification should have a plural sense. Local places' trajectories or socio-spatial relations are reflected in the debates on gentrification, but the shape of gentrification may differ from one place to another [29]. In a few words, neoliberal gentrification reflects the variegated complexity and somehow unexpected outcomes of actually existing neoliberalism [30], as local gentrification is the global economy's spatial form [31]. Policy-led gentrification processes can result from land valuation policies, projects designed to promote the opening of economic opportunities to produce higher-income housing, or even the direct application of social relocation policies in originally low-income residential areas or public spaces [22]. The real meaning of sustainable growth comes from the fact that most residents should benefit from the anticipated prosperity and the improved environment [32]. Sustainable development must consider strategic planning for heritage protection, the definition of community building structures and tools that respect urban memory and the social needs of the inhabitants [33]. As we see, the majority of Alfama's residents did not enjoyed the areas' improved as they earlier moved away.

In Portugal, by 2012, a New Urban Rental Regime policy was incepted, negatively affecting the rental market and boosting residential displacement rates and given rise to other forms of tourist accommodation and to new luxury real estate projects [16]. In 2019, Alfama was Lisbon's neighborhood with the highest number of Airbnb apartments working. At the time, Alfama had around 3300 permanent inhabitants and 35% of the existing properties were exclusively for tourist accommodation [4]. Tourist accommodation units coexisting with long-term or permanent residents is considered among the main cause of gentrification and involuntary displacement [34]. International investments and tourism have redefined the urban culture of the city, promoting a gentrification process that has resulted, in the past, in the relegation of old residents to the suburbs or other cities [33].

Holgersen [35] states that the middle class has become both the cause and the result of gentrification by being its storyline, its main actor, its beneficiary, and the end point. We believe that fifth-wave gentrification now might be fracturing the middle-class concept in two halves; one is the low and lower-local middle class old time residents, the other are the travelling middle class mainly from the richest regions of the world representing short-time rental platform capitalism's users and investors [4]. Gentrification in a geography like Alfama, brings the class-dispute on local space into a global level.

Gago and Cocola-Gant [7] argue that the development and success of platforms such as Airbnb, as well as tourism promotion carried out by public institutions, have created additional incentives to the financing process, with a special focus on short-term accommodation. Sequera and Nofre [4] have analyzed the transformations and negative impacts affected by gentrification and the quality of life of the community, mentioning that Alfama, has been transformed by tourism, both by local and transnational real estate investors, through touristification and airbnbization processes, transforming the whole neighborhood into an open-air hotel.

Few authors advocate some positive impacts of tourism on the perception of communities' residents. Although cultural tourism plays an important role in economic development, tourism's success can be a double-edged sword, because it causes a strong impact exposing the quality of life of residents to both benefits and costs [36]. For this study, current resident's responses in Alfama shows they constantly evaluate the positive and negative sides of neighborhood change, and consider its economic, symbolic, and psychological components [10,37,38]. Many studies confirm that residents who can benefit from a tourism activity tend to support its development [39–41]. The liberalization of the rental law, the incentives for the expansion of cultural facilities in the center of Lisbon, municipal investments in mobility, and the rehabilitation projects for specific areas, in combination with the growing number of tourists, have created the necessary conditions for the area to be considered attractive to private investors, overcoming the gap caused by years of abandonment [42]. The urban regeneration of these cultural neighborhoods has also brought social benefits, since the space used by tourists is the center of life for remaining residents, and improvement in their quality of life help solve several problems of the local community [43]. On the other hand, many grieve for the diminished sense of community among neighbors.

3. Materials and Methods

3.1. Data and Single Case Study-Approach

Our information was obtained from 50 informal interviews not allowing conclusions based on statistical representativeness, being an exploratory study, whose results should be interpreted with caution and related to Alfama exclusively. The interviews were conducted from February to April 2020, and the sociodemographic characterization of the sample was made according to age, nationality, occupation, and educational qualification, among residents living inside Alfama's boundaries (Figure 1). The interviews were conducted by one of the authors on residents approached in the neighborhood, and in addition to the socio-demographic characteristics, the questions asked are described in the results analysis.

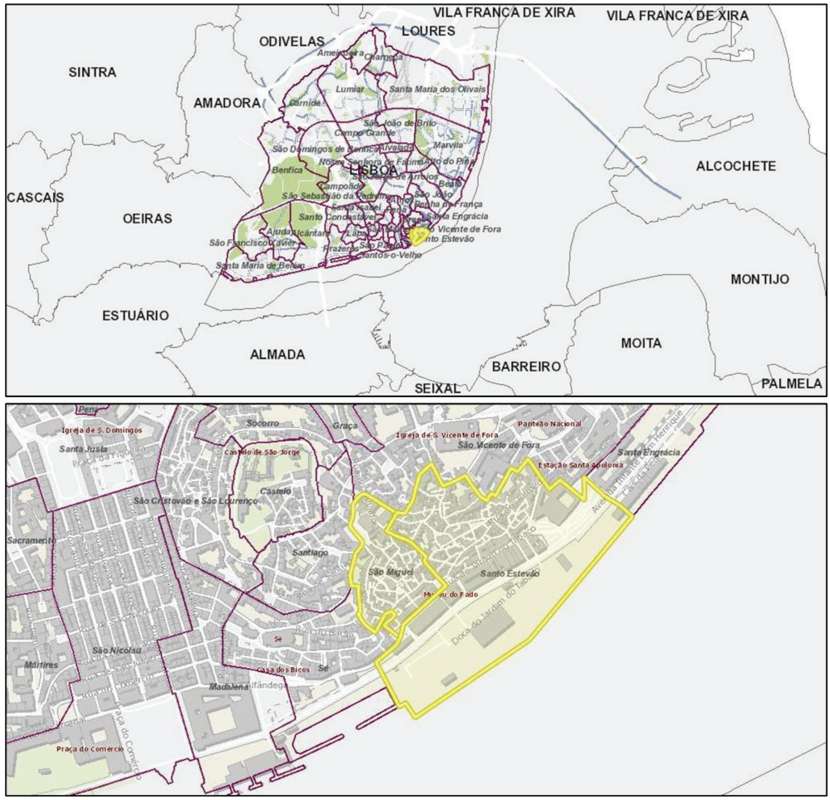

Figure 1. Lisbon and Alfama. Source: Lisboa interativa. Available online https://bityli.com/S4fvz (accessed on 24 April 2021).

This research uses a qualitative descriptive, non-comparative, single case study design under recommendation by Harding et al. [44] and Yin [45]. We define the neighborhood area and its inhabitants as our 'rare case' [44] and we do not claim statistical representativeness, as we accept a low degree of freedom. In order to triangulate the information, additionally, we made four in-depth interviews with representatives of the most relevant stakeholders in Alfama, including a representative of the Parish Council of Santa Maria Maior, a representative of the Heritage and People's Association of Alfama, a representative of the Alfama Merchants' Association and a representative of the Cultural Centre Magalhães Lima. The interviews with these local organizations included the same non-demographic questions applied to residents.

3.2. Concept Analysis

We conducted content analysis following Bardin's [46] consecutive steps of: pre-analysis of the interviews, exploration of the answers, processing of results and, finally, inferences and interpretation of findings. The summative approach to qualitative content analysis should begin with an analysis of word frequencies to identify patterns, complemented by an analysis of their use in the context of the responses [47].

We mapped concepts of information through a simultaneously quantitative and qualitative analysis that allowed us to transform large amounts of information according to semantic patterns, and group them via related concepts [48,49].

The identification of key concepts was performed using Leximancer software, version LexiPortal V4.5. This software automatically develops concept-maps representing the main concepts within the text and how the themes are related, using an approach named summarized content analysis. This analysis considers the frequencies that precede the interpretation [50,51]. Leximancer was used to analyze all respondents' answers to each of the four questions, separately. It is a lexical software that maps conceptual information from large amounts of text by grouping themes according to the relationships between them [49,52]. This software starts by generating a thesaurus that, after an iterative process through a machine learning algorithm, allows reaching the optimal thesaurus that will result in a collection of themes based on the examination of these words in the context of the text and on their frequency in the text blocks. Leximancer has shown several important advantages for text data analysis, since large amounts of text can be analyzed quickly in a quantitative way, generating well-defined themes, and the machine learning eliminates much of the need to revise thesauri as the domain vocabulary evolves [53,54].

Themes are mapped in descending order of color temperature according to their importance: the most important theme appears in red, followed by orange, successively to more cold colors such as blue and green according to the color wheel. The concept map shows the themes covering the concepts that are most frequent in the text and those that are connected to more concepts on the map [54]. Concepts are formed based on the most frequently occurring words. Concepts that occur frequently concurrently in the same coding blocks are closer together on the map. The circles gather clusters of concepts and are named by the most prominent concept in the group (we chose to represent only these concepts that name the themes). Thus, the map visually represents the strength of association between concepts and a conceptual view of the semantic structure of data.

3.3. Local Population and Neighborhood

From the socio-demographic point of view we find that the ages of the interviewees vary between 18 and 85, with the average age being 50 and 50% of the interviewees being 50 or under. It is a bimodal sample with one of the modes in the 25 to 35 year old class and the other mode situated in the 55 to 65 year old class clearly showing two different social groups of residents, but that currently coexist in Alfama. Only 2% of respondents are foreigners (Brazilian and Spanish), and the sample is evenly distributed between the two genders (48% of respondents are female; 52% are male). Regarding occupation, 32% of the sample are public employees, 20% are retired, 18% are traders and 8% have jobs related to catering. Other reported occupations include dressmakers, musicians, actresses, barbers, economists, security guards and students. As for academic qualifications, 48% have only basic education, 40 have secondary education and 12% have higher education.

Alfama, in terms of territorial units for statistical purposes is included in LAU1 (Local Administrative Unit) Lisbon (Figure 1) and in two LAU2, namely, Santa Maria Maior and São Vicente, concentrating its largest area in Santa Maria Maior. According to the Communication and Image Office of the Parish Council of Santa Maria Maior, in 2020, it was estimated that the resident population of Alfama was, approximately 2500 inhabitants and about 1965 registered voters. Our interviewees are residents of Alfama's case-study area, namely, within the yellow area shown in Figure 1.

Lisbon experienced a severe population decrease fundamentally between 1981 and 1991 (−18%) and between 1991 and 2001 (−15%) [5]. However, from the 2000s onwards, Lisbon has seen a repopulation of some of its neighborhoods due to the arrival of young adults (liberal professionals, intellectuals, and scientists), tourists, travelers, and university students, in the revitalization processes of the historic neighborhoods in the center of the capital, such as Alfama, Baixa, Bairro Alto, Mouraria and Cais do Sodré being part of a process of population replacement and urban land revalorization known as gentrification [12–16].

4. Results

One of the questions in the structured interview intended to find out if the existing residents of Alfama consider that tourism brings benefits to the neighborhood. Only 16%

of the interviewees referred that tourism does not really bring them benefits. The answers obtained about the benefits that result from the existence of tourists in Alfama (What are the main benefits that tourists have contributed to the Alfama neighborhood?), were semantically analyzed through Leximancer, and the result can be found in Figure 2.

Figure 2. Concept map for benefits.

The main benefits indicated are related to the fact that tourists (one of the most relevant themes) contribute to an increase (relevant theme) in the safety (relevant theme) of the neighborhood, contributing to a better quality of life, also associated with more street life and a cleaner neighborhood. They also state that tourism (one of the most relevant themes) has brought benefits to retail (emerging theme) and to the local accommodation business (relevant themes). Some respondents consider the local accommodation business has rehabilitated many buildings that were becoming uninhabitable, and many residents left the neighborhood because houses were too small for large families. Benefits related to local retailers and restaurants are emerging themes as they are the least relevant of the 50% most relevant (Leximancer concept maps are built on the 50% most relevant concepts). Local retail has been rehabilitated, while restaurants continue to bring many tourists to the neighborhood looking for traditional cuisine and fado music. As two interviewees stated,

> *Tourism helps a lot to rehabilitate the commerce and to raise prices without interfering with the typical dishes because they like our gastronomy. More security, more police, cleaner areas.*(Source: female resident, Age: 61 years)

> *The property owners started to do improvements, giving the people of the neighborhood good sales, which allowed them to inflate the prices and make more profit.*(Source: female resident, Age: 77)

Of all respondents only 12% stated that tourism does not bring any problems to the Alfama neighborhood. This indicates that 74% of the interviewees consider that tourism brings both benefits and problems. All problems (What are the main problems that tourists have brought to Alfama neighborhood?) described by 88% of respondents were semantically analyzed, and the results obtained are shown in Figure 3.

For the interviewees who indicated that the increase in tourism in Alfama neighborhood (the most relevant theme) is associated with problems, the most frequent ones are robberies and noise (both emergent problems represented with a cold color). Noise is associated above all with local accommodation (relevant theme). The problems for inhabitants (low relevant theme) are related to the fact that tourism (low relevant theme) has brought an increase in prices (low relevant theme). The interviewees also identified problems related to the use of space (relevant theme), on the one hand related to prices (low relevant theme) and, on the other hand, to real estate speculation, which is an emerging problem. As two interviewees said, *With the increase in tourism, everything is bad for the residents: rents, rubbish, noise.*(Source: female resident, Age: 78)

Real estate sales estate has driven away the residents, the neighborhood now has nothing, even the neighborhood commerce is dead. Tourists also like to see the typical and less tourists.(Source: male resident, Age: 65)

Figure 3. Concept map for problems.

The first testimony is an example of the few interviewees who hold a completely negative approach to touristification. The second one regrets the loss of authenticity and recalls a lost past. Concerning the question related to the preference for old Alfama or Alfama nowadays, 70% of the interviewees affirmed that they prefer old Alfama, 14% said they prefer Alfama in the present and 16% could not decide. Although it was a more direct question (Do you prefer the Alfama of nowadays or the old Alfama?) the interviewees engaged in a conversation about this duality. The results of the semantic analysis of their answers are represented Figure 4.

Figure 4. Concept map for the duality between old Alfama and Alfama nowadays.

For Figures 3–5, we enabled in the software the neighborhood theme (one of the most relevant themes) to remain as a possible output of the semantic analysis, to better understand how the different reasons were linked to the neighborhood concept. People's testimonies addressed the older (relevant theme) quarter as a place where neighbors used to talk (relevant theme), where children used to play (relevant theme) and that it was a place more traditional (relevant theme). The neighborhood is linked to tourism (one of the most relevant themes), which has brought a renewed (relevant theme) neighborhood. An emerging trend that is linked to the older Alfama is parishioner (low relevant theme) that is a spirit that is being lost. The concept of parishioner is related to the sense of belonging and unity. Residents feel that their past neighbors and friends are no longer part of the community, which reinforces the duality they feel when they agree with the changes but regret what they have lost. As two interviewees pointed out:

> *I miss the old Alfama, I miss people, I miss listening to them yelling in Portuguese, I miss the traditional commerce, the children playing football, I miss knowing the news of the neighborhood in everyday conversation.*(Source: female resident, Age: 60)

> *Either of the two, previously more parishioner and now with more nationalities and cultures.*(Source: female resident, Age: 46)

Figure 5. Concept map for contributions from tourism to quality of life.

When semantically analyzing how respondents think tourism can contribute to an improvement in their quality of life (How can tourism improve the quality of life of Alfama's residents and what measures should be taken to make tourism more of a positive impact on the neighborhood?), the results can be seen in Figure 5.

The two most relevant themes resulting from the semantic analysis of the answers are tourism and the neighborhood, as expected. We choose to keep these themes to analyze the connection between the solutions and the interpretations given for this last question. It can thus be seen that the quality of life in the neighborhood has improved regarding safety (emerging theme) and that the businesses (emerging theme) in the neighborhood can contribute to a neighborhood with more life for the inhabitants (relevant theme) as well. Tourism adds life to the area, which promotes interculturality. Residents who work or own businesses in the quarter also benefit financially, but more rules should be established to protect inhabitants' interests.

The results obtained through the interviews with the residents can be compared with the answers given by the representatives of four organizations in Alfama we contacted;

these organizations are: Santa Maria Maior Parish Council, Alfama Heritage and People's Association, Alfama Merchant's Association and Cultural Centre Magalhães Lima.

All the representatives of the organizations affirm that tourists bring benefits to commerce and to the local accommodation businesses. The changes for the neighborhood include job creation, business valorization, urban requalification, increased security, and the valorization of cultural expressions, from the point of view of the Parish Council. The fact that there are an increasing number of tourists has also increased municipal support for some cultural activities according to the representative of the Cultural Centre. For the Merchants' Association and for Heritage and People's Association there should be policies to protect the rights of residents. A representative of the last one also states that tour operators should involve the community and know more about the history.

Almost all organizations, through their representatives, indicate that noise is one of the main problems of the increase in the number of tourists in Alfama. The representative of the Parish Council also mentions the lack of parking and traffic problems and the increase of domestic waste production. Real estate speculation is mentioned by the representatives of two of the four organizations. Exploitation of tourism-related activities, greed, rising prices, and excess of local accommodation are other problems identified. Heritage and People's Association representative indicates that there is an increase in problems related to drugs and prostitution and a disinvestment at social level, while there is a degradation of the public space, facts that were not mentioned by the residents. The loss of identity of Alfama is mentioned by two of the organizations (Merchant's Association and Cultural Centre).

For the Parish Council representative, a balance between the local resident population and long-term rentals should be promoted in Alfama nowadays, making essential services available for families to settle in the neighborhood. Urban regeneration and an increase in the dynamism of the neighborhood are positive factors in the current Alfama. On the other hand, the representative of the Heritage and People's Association does not like current Alfama, stating that after an initial boost, the neighborhood has declined again. For the representative of the Merchant's Association, tourism should involve residents, and public spaces should be rehabilitated, since tourists are welcome. The Cultural Centre also prefers old Alfama and states that nowadays residents have many bad habits.

For the representative of the Heritage and People's Association, tourism does not contribute in any way to the quality of life of residents. For the other organizations, through their representatives, tourism can contribute to their quality of life if it is regulated and does not push residents away. It creates jobs, boosts the economy, and can result in greater investment in public space. It brings a lot of life to the neighborhood.

5. Discussion and Conclusions

For the limitations of the single case-study approach we used, we claim the data and knowledge obtained in this project is highly relevant to this local territory (Alfama neighborhood, in Lisbon, Portugal), not necessarily leading to generalized conclusions. Aspects as specific as residents' feelings on increased security, greater liveliness and liveliness in the streets depend on government policies that vary in different touristic cities. Although in Alfama, tourism brought more noise at night, the streets are cleaner now and there has been an improvement in the quality of life. We learned that many residents left the neighborhood because houses were too small for families, which could be related to increasing housing costs and minimized affordable places. The neighborhood has lost population and the neighborhood historical social attachments have faded away, with noticeable grievance by those who remained in the area. Previous studies [55] also reported residents' complaints about noise, which is in line with our results, but complaints related to a more general feeling of insecurity do not coincide with the testimonies of Alfama residents we collected here.

Awareness of the threats of overtourism has led the local governments of some destinations to agree to promote and share best practices in dealing with this ubiquitous phenomenon, where the central role of tourism in the development pathways of destinations was recognized and the need to address the challenges posed by the ongoing growth of tourism on urban livability was underlined [56]. There is general agreement on the increasing material benefits for local businesses. Local commerce has been rehabilitated and traditional cuisine restaurants are attracting more tourists; however, residents report that it has increased prices in general and, particularly, estate prices due to local accommodation and commerce alike. The local business network may have the capacity to link residents to the revitalization process, sharing the benefits of economic development, for example by creating new culture-based employment opportunities for residents by participating, after on-going training, in the tourism industry as tour guides in the historic neighborhood [57]. These results are considerably related to generalized narratives of gentrification [25].

As immaterial or symbolic aspects of gentrification seen [10,37,38], in a great deal, our interviewees miss the old quarter because of the neighborhood spirit, childhood friends and community experiences, which was the basis of a sense of belonging. This nostalgia is expressed through the memories, the sound of children playing, the conversations between neighbors, the festivities of the popular saints, the games at the weekend, the festivities, knowing each other as if they were one big family. Resident participation and involvement are essential to the success of any regeneration program, and their roles and activities must be compatible with the historic neighborhood's distinctiveness [58]; a remaining question is how to achieve this goal. Local tourist policies seem not addressing these people's feelings, it seems that economic development has been greatly prioritized. The valorization of cultural expressions should be made involving the community and leading it to know better its history.

Most of answers indicated by our respondents are confirmed by the organization representatives we further interviewed, as a form of triangulation. Still, organization representatives hold perceptions which are different to residents', as they not only perceive but also defend political or commercial agendas, and we consider this could be a bias and a pitfall in our results. Anyway, the idea of creating a sense of belonging and pride in the local community seems to generate consensus among almost all our respondents to counteract the negative effects of gentrification and a strategy to democratize the neighborhood governance [59].

The fact that elderly inhabitants feel nostalgia while they also recognize that Alfama is now more secure, cleaner and has a lot of liveliness, and also reflects a sense of belonging and connection recognized by older people in previous studies [60] that they still wish to contribute to the community as a whole, which plays a holistic experience that is intended to be transmitted to future generations and conveys a sense of affiliation and connection to the place, which can only benefit this type of neighborhood.

This study has sought contributing to ongoing discussions on the complexities on tourist-led gentrification. While most studies on the theme focus strongly on the negative aspects of Alfama's gentrification, we believe that studying the contradictions between positive and negative experiences by the residents shed lights on a still apparently unrecognized aspect of the matter: those who remain living in the neighborhood, after gentrification has displaced population in great deal, prove being more economically resilient and struggled by the changes. The way overtourism manifests itself depends critically on the city context, and solutions must be adjusted to the local environment, involving all stakeholders to reach inclusive solutions [55]. We realize that our sample is biased towards those who remained living in Alfama for having higher economic capital, as this sample does not include those who have already left the area and might have a divergent approach towards economic benefits, as they lost the strong social capital that once existed in this area [10,37], a capital that was not strong enough to counteract people's direct displacement. We understand this bias as a limitation of our methodological approach.

Our results concur with other studies [61] regarding how tourist-led gentrification can have positive aspects and not only negative ones. Building rehabilitation, increased security, job creation and neighborhood life are all factors that have been identified in our research. As an earlier work by Gago [3] mentioned Alfama's displacement of former residents as its central point, this issue was not mentioned by our respondents. According to Benis [6] a socially sustainable revitalization includes both a conservation and development dimension and takes the form of strategies and actions that improve the lives of residents and their perception of the neighborhood, attract tourists, new residents and investors. The interviewees have some perception about their lives' improvement related to tourism, so we believe that a process of revitalization of Alfama is in progress that can approach a sustainable development in the future. According to Hall [62], to address the challenges of overtourism, local interventions of attractiveness, destinations and tourism travel stages have to go hand in hand with multilateral initiatives on a global scale.

Author Contributions: Conceptualization, A.M., T.P. and E.L.-M.; methods, A.S.M.; software, A.S.M.; validation, A.M., T.P. and E.L.-M.; formal analysis, A.M., T.P. and E.L.-M.; resources, A.M. and T.P.; writing—original draft preparation, A.S.M.; writing—review and editing, A.S.M. and E.L.-M.; funding acquisition, A.M. and A.S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TRIE—Centro de Investigação Transdisciplinar para o Empreendedorismo & Inovação Ecossistémica; FCT—Foundation for Science and Technology, IP, within the scope of the reference project UIDB/04470/2020; Chile's Research Agency—Fondap Project Number #15130009.

Institutional Review Board Statement: Ethical review and approval of this study was waived due to the fact that the participants were informed of the study objectives and freely consented to participate.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Theft Prediction Model Based on Spatial Clustering to Reflect Spatial Characteristics of Adjacent Lands

Dongyoung Kim, Sungwon Jung * and Yongwook Jeong

Department of Architecture, Sejong University, Seoul 05006, Korea; yosi91@naver.com (D.K.); yjeong@sejong.ac.kr (Y.J.)
* Correspondence: swjung@sejong.ac.kr; Tel.: +82-02-3408-3289

Abstract: Previous studies have shown that when a crime occurs, the risk of crime in adjacent areas increases. To reflect this, previous grid-based crime prediction studies combined all the cells surrounding the event location to be predicted for use in model training. However, the actual land is continuous rather than a set of independent cells as in a geographic information system. Because the patterns that occur according to the detailed method of crime vary, it is necessary to reflect the spatial characteristics of the adjacent land in crime prediction. In this study, cells with similar spatial characteristics were classified using the Max-p region model (a spatial clustering technique), and the performance was compared to the existing method using random forest (a tree-based machine learning model). According to the results, the F1 score of the model using spatial clustering increased by approximately 2%. Accordingly, there are differences in the physical environmental factors influenced by the detailed method of crime. The findings reveal that crime involving the same offender is likely to occur around the area of the original crime, indicating that a repeated crime is likely in areas with similar spatial features to the area where the crime occurred.

Keywords: crime prediction; machine learning; spatial clustering; smart city; GIS

Citation: Kim, D.; Jung, S.; Jeong, Y. Theft Prediction Model Based on Spatial Clustering to Reflect Spatial Characteristics of Adjacent Lands. *Sustainability* **2021**, *13*, 7715. https://doi.org/10.3390/su13147715

Academic Editors: Pierfrancesco De Paola, Francesco Tajani, Marco Locurcio and Felicia Di Liddo

Received: 17 June 2021
Accepted: 8 July 2021
Published: 10 July 2021

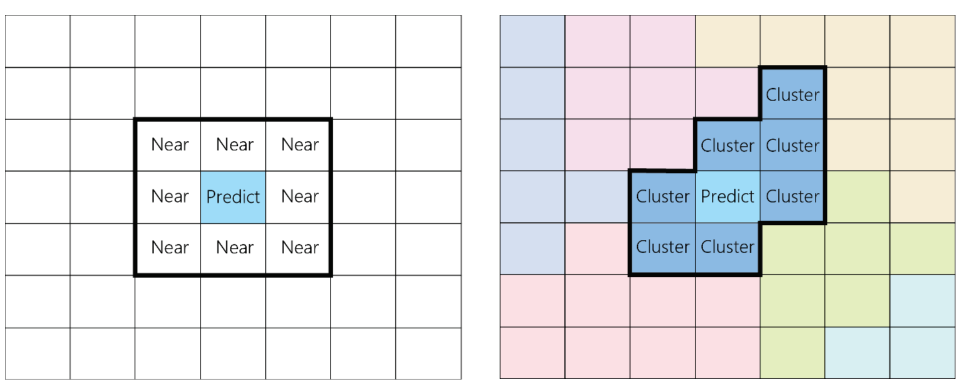
1. Introduction

Today, with the enhancement of computer performance and data analysis techniques, it has become possible to process large amounts of data with ease. Pre-processed big data is used for prediction and analysis in various fields, such as stock price predictions [1,2] and financial analysis [3,4], using machine learning or artificial neural networks. In the field of crime prediction, various studies related to online crime detection [5] and the identification of crime hotspots [6] are being actively conducted.

Many government authorities across the world are already making efforts to prevent crime by applying crime prediction systems. In the case of PredPol, a crime prediction system for the Santa Cruz Police Department in the United States, the number of breaking and entering cases dropped by 27% from July 2010 to July 2011, when the system was in place, and fell by 25–29% in June and July 2013 compared to the same months of the previous year, which demonstrated the consistency in its effect. In Korea, GeoPros and CLUE are being used as part of the Smart City initiative. As a result of the GeoPros pilot run in 2013, robbery cases declined by 44.4%, while rape and theft decreased by 22.1% and 13.1%, respectively. Meanwhile, CLUE provides similar cases and investigation clues based on police investigation records, as well as crime prediction. Other crime prediction systems such as HunchLab and COMPStat, used in the Miami and New York Police Departments, are also contributing meaningfully to crime reduction, with reliable results.

In order to effectively carry out crime prevention activities through crime prediction, it is important to accurately set the prediction range, as well as making precise predictions, so that crime prevention resources such as CCTVs and police personnel can be properly allocated. Recently, researchers have actively studied machine learning-based crime prediction using grids as the units of analysis. In this regard, because grids have a uniform shape and size compared to administrative districts or census output areas, statistical information can be objectively examined. Moreover, because grids can be flexibly applied to changes in map scale, microscopic analysis is also possible. Yu et al. [7] predicted residential burglaries by training an algorithm using the crime records of each cell, based on the crime's spatiotemporal concentration characteristics. To reflect the effects of crimes in an adjacent land and the physical environment during training, Lin et al. [8] predicted vehicle theft crimes by using 84 types of landmark data through Google API, along with crime information from adjacent cells for learning. Here, in the landmark data of Google API, the purposes and addresses of establishments such as schools, pubs, and restaurants are indicated, and these were used to reflect the geographical characteristics of the study site. As an extension of earlier research, the purpose of this study is to develop a crime prediction model that reflects the influence of surrounding areas and geographic characteristics on crime.

An actual land is continuous, rather than independently divided like a grid, in a geographic information system (GIS), and when a crime occurs, the risk of crime in the adjacent areas increases [9–11]. According to studies analyzing the relationship between spatial characteristics and crime, environmental factors such as patterns, establishments, and land use were found to be different, depending on the detailed modus operandi of crimes [12–15]. Even in the case of the same type of crime, the related factors were shown to be different depending on the detailed modus operandi [16]. Therefore, in micro-scale studies using a grid, there is concern regarding how to reflect the characteristics of the adjacent land. When training with crime information, this issue can be solved by combining all the cells adjacent to the point to be predicted and using it in the training. However, this solution requires a focus on a specific method of crime, and if the cell to be predicted and its adjacent cells vary greatly in spatial characteristics, the training may be negatively affected. Accordingly, to distinguish cells with similar spatial characteristics for use in training, this study proposes a crime prediction method that applies spatial clustering as shown in Figure 1. To perform spatial clustering, high weights are assigned between geographically adjacent cells, according to the distance between each instance in the vector space. Thus, cells adjacent to the cell to be analyzed and with similar attributes are included in the same cluster and, rather than training all the adjacent cells, only the cells with similar spatial characteristics can be used for training.



(**a**) Crime prediction combining adjacent cells (**b**) Crime prediction reflecting spatial similarity

Figure 1. Proposed crime prediction using spatial clustering.

The flow of this study is shown in Figure 2. Dongjak District, Seoul, the target analysis area, is divided into grids of 100 m $\times$ 100 m on GIS. After inserting data on the physical environment in each cell, such as crimes, facilities, and land use that occurred previously, the target sites are clustered according to spatial similarity, based on the physical environment data. Cells in which no crime occurred during the analysis period are removed because they might negatively impact training. The remaining cells are then used for training. Crime data are imbalanced because there is less data on where a crime occurred than where it did not. Accordingly, resampling is used to solve the problems caused by the data imbalance. The preprocessed data are trained using a random forest, a tree-based machine learning algorithm, and the differences between the model with spatial clustering and the general model are compared.

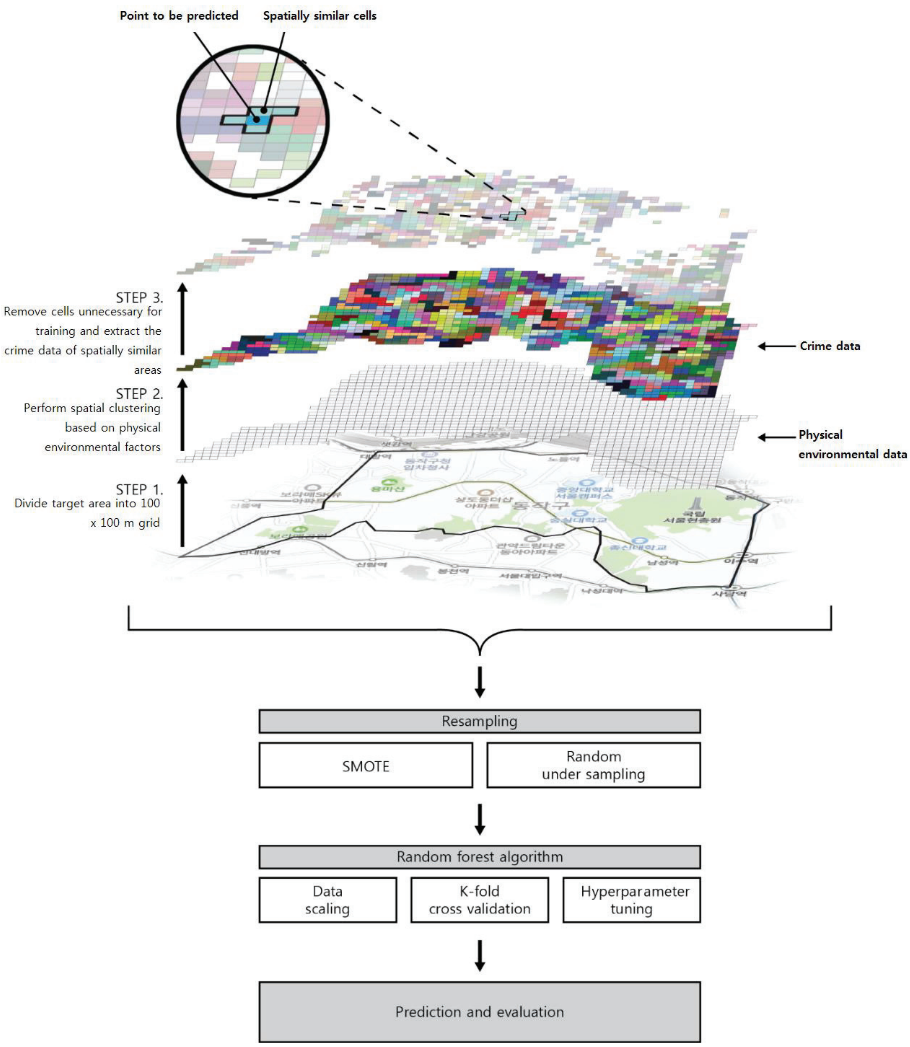


Figure 2. Research flow.

2. Theoretical Review

Efforts have been made to prevent crime by identifying and mitigating its causes. Environmental criminology seeks to explain the causes of crime using the surrounding environment. The main theories employed are routine activity theory (RAT) [17] and crime pattern theory (CPT) [18]. RAT states that a crime occurs when a motivated offender (a suitable target) and the absence of a capable guardian simultaneously intersect in time and space. According to RAT, it is important to view individuals as motivated offenders and minimize their opportunities to commit the crime. The CPT states that people move in certain patterns because of their physical or social environment, such as their occupation. During their routine activities, motivated offenders identify the characteristics of these areas and suitable targets for crime, choose a suitable time and place, and then carry out the crime. Hence, crimes do not occur randomly; however, they are concentrated in certain locations, owing to specific factors, and are influenced by the surrounding environment and living patterns of individuals and their neighbors.

Wolfgang, Figlio, and Sellin [19], and Sherman, Gartin, and Buerger [20] found that approximately 50% of all crimes every year occur within 4% to 5% of the total street and explained that crime is spatially concentrated. Studies have also shown that the areas surrounding the place where a crime occurs are at risk of identical crimes, and the more recent the crime, the greater its influence [9–11]. Notably, Bernasco [10] reported that, among the crimes that occurred within 100 m of an earlier crime, 90% that occurred within seven days involved the same offender. Moreover, the same offender was involved in 64% of the crimes that occurred within 90 days, and 13% within nine years. This indicates that offenders familiar with the surrounding area are more likely to commit other crimes in neighboring locations.

Facilities and land use play a key role in the relationship between crime and the physical environment. These factors provide the purpose of people's movements and have a close relationship with individuals' living patterns. Brantingham and Brantingham [11] analyzed the correlation between commercial theft and facilities. In their results, blocks with supermarkets and department stores showed similar crime rates to blocks without these landmarks, whereas blocks with fast-food restaurants, traditional restaurants, and pubs had 2- to 2.5-times more commercial theft than blocks without these landmarks. Lee, Yoon, and Kim [13] analyzed the causes of crime according to crime type in specific cities in Korea. Visitor accommodation, restaurants, financial institutions, and homes in non-residential buildings were highly correlated with theft crimes. In the case of CCTV, it was found that the related factors were different depending on the type of crime, such as showing a significant correlation only with rape and violence. Studies analyzing the impact of land use on crime are also underway. As in the case of facilities, there were differences in the factors affected by crime and, in the case of commercial areas, it was discovered to be related to most crimes [14–16]. Stucky and Ottensmann [15] analyzed the relationship between land use and crimes such as violent crime, homicide, robbery, aggravated assault, and rape. The correlation between land use and crime type was shown to be different, showing a significance in crime, homicide, and aggravated assault. Kwon, Kwon, and Jung [16] examined the correlation between each crime type and land use by clustering the theft crimes into detailed types according to the victim's gender, the time of the occurrence, and the place of the occurrence. It was shown that the associated physical environment was different. As such, crimes do not occur randomly, but have factors influencing them; in environments where crimes can occur with ease, it is important to identify these related factors.

3. Data and Methodology

3.1. Research Area and Analysis Unit

Dongjak-gu, the research area, is one of the administrative districts of Seoul, the capital of South Korea. Its population density is 24,190/km^2, which is similar to that of Manhattan in the United States. Residential areas are high-density areas comprising 84% of the total population, and there are 8.5 cases of violent crime per 1000 people. Although this rate is ranked 17 out of the 25 administrative districts, it is rather high because most of the areas with high crime rates have a developed entertainment industry.

To effectively perform crime prevention activities using crime prediction, it is important to precisely set the analysis unit so that crime prevention resources can be allocated to the appropriate locations. Accordingly, this study attempts to predict crime in the microscopic range through grid-level analysis. Compared to the administrative districts and census output areas, which are statistically spatial units used in existing statistical map services, grids have a uniform shape and size, allowing statistical information to be objectively examined. Moreover, the grids can be flexibly applied to changes in the map scale. This study used GIS to divide the target area into a grid of 100 × 100 m cells, then time- and space-related data were added to each cell to perform the analysis.

3.2. Crime Data

In the case of crime prediction, it is generally known that theft crimes are easier to predict than other types of crimes. Crimes such as murder and assault are highly influenced by ill feelings between the offender and the victim because the target is a specific individual. In contrast, since the target of theft is a specific building or object, it is influenced more by the surrounding environment and the behavioral characteristics of the criminal than by personal feelings [21]. The analysis of this study focuses on theft. With the cooperation of the police department with the relevant jurisdiction, data on incidents of theft in Dongjak-gu from 2013 to 2017 were used in the analysis. Figure 3 shows the monthly distribution of theft in Dongjak-gu. During this period, an average of 95 thefts occurred per month; the most occurred in March 2013 (199), and the fewest occurred in November 2016 (31). The theft data include the date, time, method, and exact location of the crime. Inaccurate data (such as cases with incorrect addresses and duplicate reports on the same date) were excluded. A total of 8023 theft cases were used for the analysis. Based on prior studies showing that the more recent the crime, the greater its influence on future crimes, in order to train the influence over time in a predictive model, this study calculated the average number of crimes that occurred in each cell over the periods of two weeks, one month, three months, six months, and one year, and used these values for the training. In the grid-level analysis, cells in which crime never occurred were mainly those areas (such as mountains or water) in which it was difficult for crime to occur. These data can easily lead the model to predict that no crime incidents occur in areas with no previous record of crime, which may negatively impact the predictions [7,8]. Therefore, before training, the cells in which no crime occurred from 2013 to 2016 were removed. The 2017 crime record was excluded, as it was used as the test set.

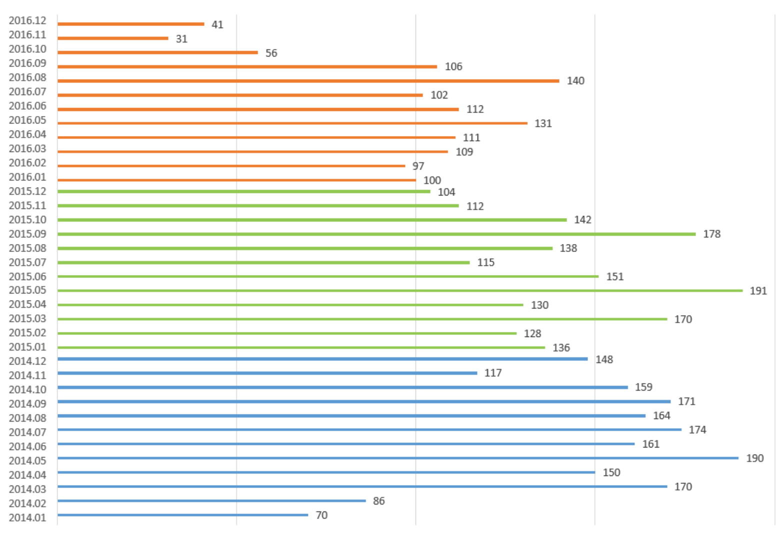


Figure 3. Distribution of theft, sorted by month, in Dongjak-gu.

3.3. Physical Environment Data

The data used in this study were provided by the National Spatial Data Infrastructure Portal (http://www.nsdi.go.kr, 15 January 2020) and the Open Data Plaza (https://data.seoul.go.kr/, 15 January 2020). The data on building usage comprise basic information on location, size, etc., and are categorized into 152 types according to building use. However, using data on all buildings for the training may degrade the model's performance while consuming extensive computing resources because the model would be trained on data with an insufficient correlation with crime. Consequently, considering the training, this study applied data on building use related to restaurants, pubs, accommodations, banks, and residences, which have been demonstrated by previous studies as being related to crime. Restaurants were categorized into general restaurants, where patrons stay for a long time to eat, and rest-area restaurants, which sell simple meals such as fast food. Residential buildings were categorized into single-family housing, multi-family housing, and apartments, depending on the type of residence. Additionally, CCTV and streetlights, which are factors influencing natural surveillance, and bus stops, known to induce crime because of crowding, were added to the facility variables for the training.

Regarding the information on land characteristics, data on land usage and officially assessed land prices (OALP) were used for the training. In South Korea, land use is divided into eight categories: general commercial areas, neighboring commercial areas, circulating commercial areas, first-class residential districts, second-class residential districts, third-class residential districts, semi-residential areas, and natural green belt zones. The facilities and allowable sizes that can be built according to each usage area have different legal regulations. To apply the land usage data for the training, the area occupied by the usage category in each cell of the grid was converted to a percentage. In addition to land use, the average OALP of each cell was calculated and used as a variable. This is used as an indicator to identify the geographic continuity in the spatial clustering analysis. Table 1 lists the variables used in the study. Finally, applying crime data from 2014 to that of 2016, with the training set and crime data from 2017 as the test set, the data were used in training, and the model's performance was evaluated.

Table 1. Feature selection.

Feature	Precision
Crime	Average number of crimes in each cell over the previous 1, 3, 6, 9, and 12 months
Adjacent crime	Average number of crimes within the same cluster over the previous 1, 3, 6, 9, and 12 months
Factors related to crime	CCTV, streetlight, bus stop
Facility-related variables	General restaurants, rest-area restaurants, pubs, accommodation, banks, multi-family housing, single-family housing, apartments
Land-related variables	General commercial area, neighboring commercial area, circulating commercial area, first-class residential district, second-class residential district, third-class residential district, semi-residential area, natural green belt zone, officially assessed land price (OALP)

3.4. Spatially Constrained Clustering Methods

Clustering is a data-mining technique that classifies the given data into multiple clusters, based on the similarity of their attributes. Because it is difficult for general clustering techniques to reflect the spatial continuity of data in a vector space such as GIS, researchers have been studying spatially constrained clustering methods [21,22] to solve this issue. One of them is the max-p regions model [23,24]; unlike the general clustering techniques that classify data into a limited number of clusters, this model aims to maximize the number of clusters that satisfy the minimum threshold of the constraint, while minimizing spatial heterogeneity in each cluster. This constraint is the minimum value of the variables (population size, number of houses, etc.) included in each instance, or the minimum number of instances that must be included in each cluster. To cluster the cells that are spatially similar and adjacent in distance, this study sets the number of cells that can be included in each cluster as the constraint. As a feature of the max-p regions model, a specific cluster can be prevented from growing excessively larger than the other clusters, and the land can be uniformly clustered while maintaining spatial continuity. Thus, the model can be effectively used for microscale analysis.

The equation of the max-p regions model is as follows: first, $A = \{A_1, A_2, \cdots, A_n\}$, $(n = |A|)$ is defined as the set for the entire land area, and A is defined as the set divided into p regions, $P_p = \{R_1, R_2, \cdots, R_p\}$, $(1 \le p \le n)$. In this study, l_i is the attribute that must at least reach the minimum threshold in area A_i.

$$\begin{cases} |R_k| > 0 \; for \; k = 1, 2, \cdots, p \\ R_k \cap R_{k'} = \theta \; for \; k, k' = 1, 2, \cdots, p \wedge k \neq k' \\ \cup_{k=1}^{p} R_k = A \\ \sum_{A_i \in R_k} l_i \ge thershold > 0 \; for \; i = 1, 2, \cdots, n \; and \; k = 1, 2, \cdots, p \end{cases} \tag{1}$$

Here, all the divisible sets of A are defined as Π. Thereafter, the max-p algorithm can be defined as in Equation (2). $H(P_p)$ is the sum of the heterogeneity of space over all of $P_p \in \Pi$.

$$\begin{cases} P_p^* = max\left(\left|P_p^*\right| : P_p \in \Pi\right) \\ \nexists P_p \in \Pi : |P_p| = \left|P_p^*\right| \text{ AND } H(P_p) < H\left(P_p^*\right) \end{cases} \tag{2}$$

In this study, facility and land data were inserted into the grid-divided area and used as variables for the max-p regions model, through which cells with geographically similar characteristics were clustered. Based on this, in the machine learning step, crimes that occurred in the same cluster were used as a prediction variable to reflect the influence of crimes that occurred in the adjacent land during the training. Figure 4 shows an example of the max-p regions model, and Table 2 shows an example of average attributes for each cluster. To ensure that the cell to be predicted and cells that are physically far away do not belong to the same cluster, the number of cells n belonging to each cluster was set between 2 and 10.

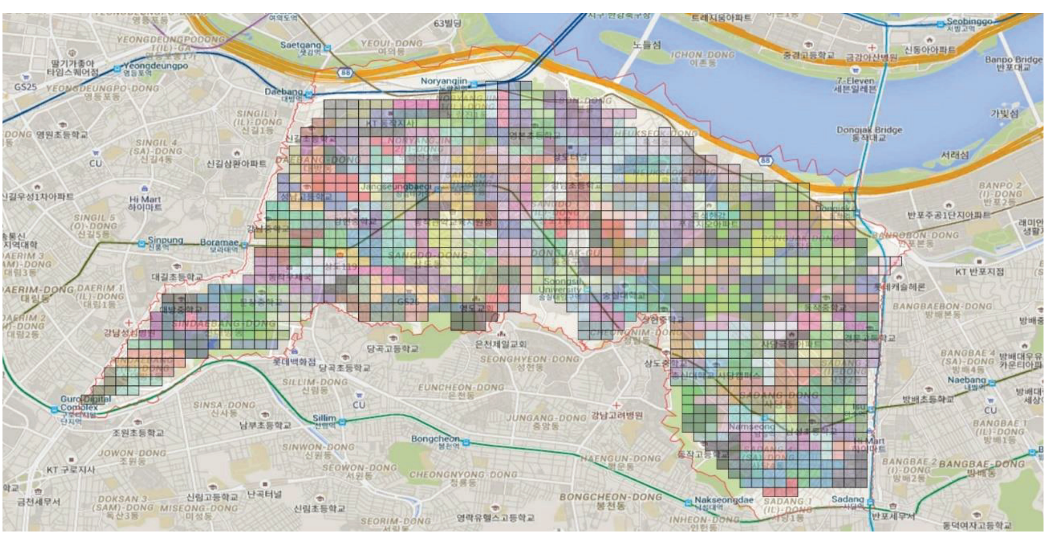


Figure 4. Example of a max-p regions model (*n* = 4).

Table 2. Example of average attributes for each cluster in the max-p regions model.

Cluster Number	General Restaurant	Alcohol	Multiple Housing	Single Housing	…	Type 2 Residential Area	Type 3 Residential Area	Natural Green Area
1	0	0	4.91	5.33	…	14.5	0.01	0
2	1.09	0.27	25.90	10.81		91.4	8.03	0
3	0	0	0	0		0	0	100
304	6.5	2	3.75	4.5		29.04	70.94	0
305	0	0	28.5	12.5		95.2	0.02	0
306	10.5	2.75	14.75	25.25		45.04	53.67	0

3.5. Resampling

Imbalanced data are those in which the distribution is overconcentrated in a specific class. In imbalanced data, the minority classes are recognized as noise in the training process, and the classification does not proceed correctly, which may adversely affect performance [25]. The theft data used in this study are also imbalanced; only approximately 10% of the total data correspond to the theft class. Accordingly, this study used random undersampling and the synthetic minority oversampling technique (SMOTE) to solve the problems due to data imbalance.

Random undersampling is a resampling technique that randomly deletes instances from the majority class to balance distribution with the minority class. When there are many training sets, it is possible to increase the learning speed and reduce the data capacity by decreasing the number of samples. However, because this technique involves deleting data, there is a risk of information loss. The SMOTE is an oversampling technique that interpolates data in the minority class to create new instances to balance the data. Whereas this results in a slower training speed than undersampling, there is no risk of data loss, and overfitting is less likely to occur than random oversampling, which randomly replicates the minority data.

3.6. Model Training and Evaluation

3.6.1. Model Training

The data preprocessed via the above procedure were trained using a random forest, a tree-based machine learning algorithm. Random forest, an ensemble technique widely used in general classification problems, creates multiple decision trees and combines the output of each decision tree. This study used the random forest technique to build a crime prediction model and then compared each model.

First, as the range of values for each variable differed, the values of the data were normalized using min-max scaling. The ratio between the training set and test set is generally set to between 7:3 and 8:2; nevertheless, this is flexible, depending on the amount of data and the research method. The purpose of crime prediction is to predict future crimes based on those crimes that occurred in the past. As such, the data from 2014 to 2016 were used as the training set, and those from 2017 were used as the test set. K-fold cross-validation was applied to each model in the training process to prevent the bias and overfitting that might occur when repeatedly performing the training using only the training and test sets [26,27]. In the k-fold cross-validation, the test set was divided into k-folds, and training and validation were performed sequentially. The K value typically ranges from five to ten. In this study, it was set to five. After the cross-validation, the parameters of each model were adjusted to obtain the optimal performance. In this study, the grid search CV of the Python scikit-learn library was used to adjust the parameters and found those parameters with optimal performance for each model.

3.6.2. Model Evaluation

Because the crime data used in the training were imbalanced, it was difficult to determine how well the minority class was predicted by evaluating the model with any accuracy, and this was a classification indicator for the entire dataset [28]. Therefore, suitable methods for evaluating imbalanced data must be considered. This study evaluated the performance of each model using a confusion matrix [29,30], which is primarily used when evaluating the performance of general algorithms and imbalanced data. The confusion matrix compares the results predicted by the model with the actual class in the data, and classifies them as TN, TP, FP, or FN. Using this, the precision and recall values were obtained and harmonized in order to calculate the F1 score. The accuracy and F1 score of each model were compared to evaluate prediction performance (Figure 5).

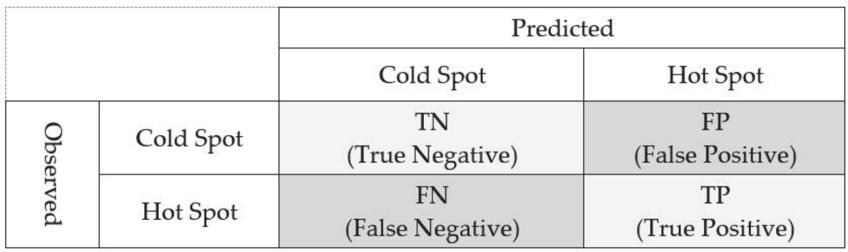


Figure 5. Example of a confusion matrix.

4. Results

4.1. Model Prediction Results

Table 3 lists the model prediction results based on the difference between the clustering and resampling methods. The model using spatial clustering showed higher F1 scores than the calculation method that combined the adjacent cells. Accordingly, there are differences in the physical environmental factors influenced by the detailed method of crime. Based on the findings of previous studies, a crime involving the same offender is likely to occur around the area of the original crime, indicating that a repeat of the crime is more likely in areas with similar spatial features to the area where the crime occurred. For both the SMOTE and random undersampling techniques, when the minimum threshold for a cell was $n = 6$, the F1 score was the highest, at 33.85% and 34.90%, respectively, and the F1 score increased by approximately 2% compared to the method combining the adjacent cells. In the models using the max-p method, the SMOTE-based model showed a regular pattern in which the F1 score gradually decreased as the distance from $n = 6$ increased, whereas the F1 score in the random undersampling-based model showed an irregular pattern according to the *p*-value. The results show low stability because the random undersampling method randomly deletes the instances. The pattern of the F1 score in the SMOTE-based model indicates that the model's performance may decrease if the *p*-value is too small or too large, and that there is a value yielding the optimal performance.

Table 3. Model performance according to resampling method and minimum threshold.

Resampling	Threshold Value	Precision	Recall	Accuracy	F1 Score
SMOTE	Surrounding grid	33.5727	30.1127	87.074	31.7487
	$n = 2$	31.8462	33.3333	86.2279	32.5728
	$n = 4$	35.8736	31.0789	87.5723	33.3046
	$n = 6$	34.9315	32.8502	87.1865	33.8589
	$n = 8$	32.4734	34.4605	86.3023	33.4375
	$n = 10$	32.6466	33.1723	86.4952	32.9073

Table 3. *Cont.*

Resampling	Threshold Value	Precision	Recall	Accuracy	F1 Score
Random Undersampling	Surrounding grid	22.81	57.48	76.33	32.66
	$n = 2$	24.13	56.33	78.02	33.73
	$n = 4$	22.35	59.09	75.41	32.43
	$n = 6$	24.26	62.15	76.84	34.90
	$n = 8$	24.15	56.52	77.94	33.84
	$n = 10$	24.25	55.23	78.31	33.71

Comparing the average accuracy and F1 scores of the models according to the resampling method, the SMOTE and random undersampling methods showed accuracies of 86.81% and 77.14% and F1 scores of 32.97% and 33.54%, respectively. Therefore, the SMOTE method had a 10% higher accuracy and a 0.5% lower F1 score than the random undersampling method. The random undersampling-based model showed a recall of approximately 55% to 62%, predicting many crime classes out of the total data. However, the precision and accuracy values were generally lower than those of the SMOTE, showing that its ability to accurately predict crime was inadequate. Figure 6 shows the models' prediction results according to the resampling method using a confusion matrix ($n = 6$). The value in the second quadrant is the number of data that correctly predicted cold spots (i.e., where no crime occurred), and the value in the fourth quadrant is the number of data that correctly predicted hot spots (i.e., where the crime occurred). The value in the first quadrant is the number of data points that incorrectly predicted a hot spot where the actual data were cold spots. The value in the third quadrant is the reverse (i.e., points that incorrectly predicted a cold spot where the actual data were hot spots). Considering the SMOTE method, 204 of the 584 data predicted as crime classes were correctly predicted, and for the random undersampling method, 386 of the 1591 data were correctly predicted. Because random undersampling deletes data from the majority class among all the data, precise prediction is difficult because of information loss.

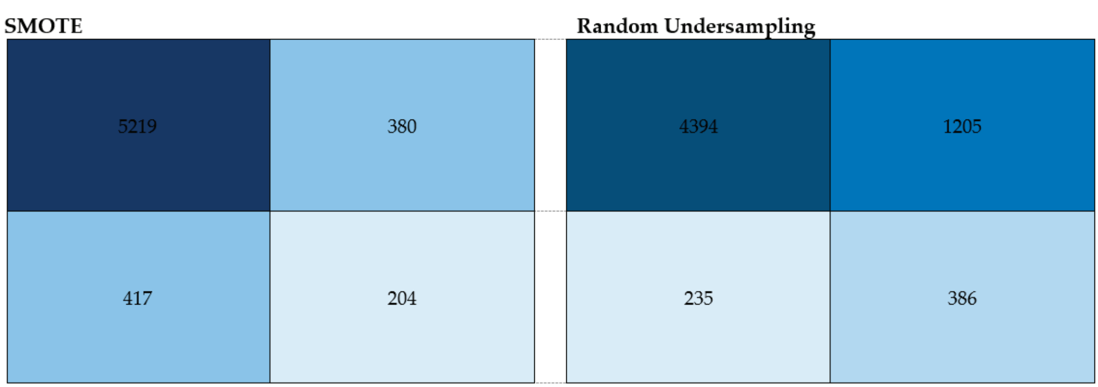
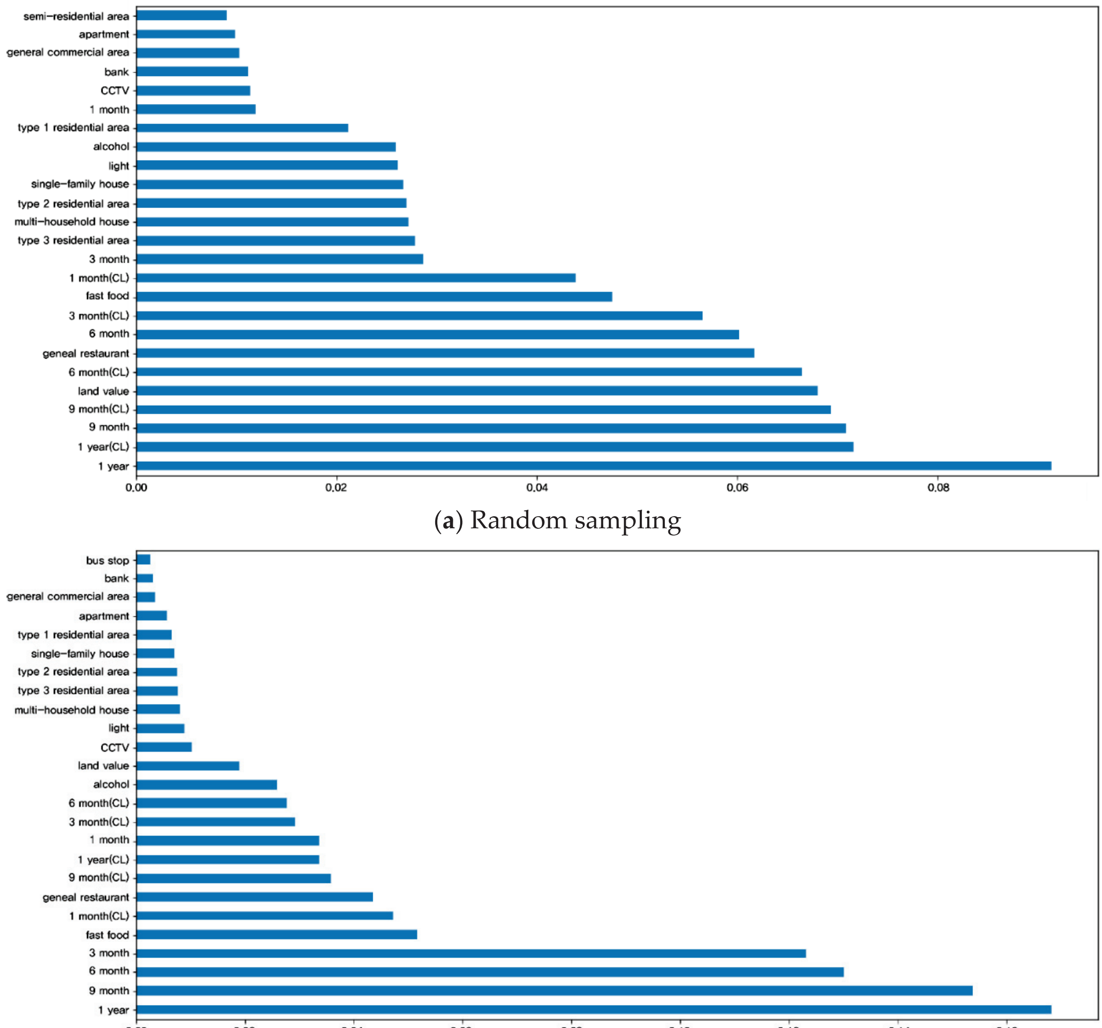


Figure 6. Confusion matrix results according to the resampling method ($n = 6$).

4.2. Feature Importance

In the case of the random forest algorithm, the feature importance function can be used to numerically express the influence of each variable for the prediction. Accordingly, this study analyzed the relative importance of each variable using this function. According to the analysis, the distribution of the feature importance varied with the resampling method (Figure 7). The feature importance was more evenly distributed under the random undersampling method than the SMOTE method. Because the random undersampling method reduces the size of the entire dataset for training, the model is more sensitive to the features of the data with fewer samples.



(**a**) Random sampling

(**b**) SMOTE

Figure 7. Feature importance chart, following the resampling methods.

For both the random undersampling and SMOTE, time-related variables were the highest. Among these, the variable related to the average number of crimes that occurred in the cell over the previous year was the most important. In this regard, because crimes generally do not occur frequently, when the analysis period is shorter, less information can be learned from the variable. In contrast, crimes that occurred within the cluster showed different patterns according to the resampling method. Considering the random undersampling, the variables related to the average number of crimes during a particular period showed a higher importance as the period increased to six months, nine months, and 1 year, respectively. However, with regard to the SMOTE method, the influence of recent crimes was high at three, six, and nine months. Because the SMOTE method generates new instances by interpolating the data, a large amount of data can be trained. Moreover, because the crime data created in the clustered instances are used together for the training, sufficient crime-related information can be obtained, even for short periods. While more recent crimes are known to generally have a greater influence on future crimes, in crime prediction research using machine learning it is important to appropriately configure the time-related variables, considering the training of the algorithm. Considering the physical environment-related variables, when using random undersampling, general restaurants showed the highest importance, followed by rest-area restaurants and pubs. When using the SMOTE method, the order of importance was rest-area restaurants, general restaurants, and pubs. However, the importance of residential buildings, banks, and CCTV-related facilities is relatively low. As is similar to the findings of previous studies on the influence of the surrounding environment, the likelihood of becoming a target of repeated crime is high when there are insufficient factors that can deter crime in places where people frequently engage in routine activities. Therefore, it is necessary to identify places where crime is spatiotemporally concentrated based on crowded spaces, predict where crime is likely to occur, and strengthen crime prevention activities in those places.

5. Conclusions

In previous grid-based crime prediction studies, information from all cells was combined and used for training the data on crimes in adjacent land. However, the actual land has a continuous flow, and the patterns and affected environmental factors vary with the method of crime. This study proposes a spatial clustering technique to solve this problem. The results showed that using reflecting spatial continuity to predict crime was effective in enhancing the model's performance. Moreover, by identifying the importance of each variable, it was found that there were places where crimes were spatiotemporally concentrated. With regard to the time-related variables, more recent crimes are known to have a greater influence on future crimes. However, it was difficult to significantly influence the model training if the period set as a variable was too short. Considering the physical environment-related variables, the feature importance of restaurants and pubs was high, suggesting that spaces frequented by people in their daily lives are more related to crime. Therefore, further in-depth analysis is required.

As part of the existing machine learning-based crime prediction research, this study is important because it provides guidelines for future related studies to apply spatial clustering in the crime prediction process and compare the results according to the cluster's configuration. Furthermore, this study attempted to predict the location of crimes more microscopically, using a grid unit in the analysis. Once this study is supplemented and practically applied in the future, it can help to improve the effectiveness of crime prevention by distributing crime prevention resources more efficiently.

Regarding this study's limitations, first, while the physical and environmental factors described in environmental criminology are highly diverse, this study used only some of them as variables. Second, because machine learning algorithms focus on prediction and classification using the given data rather than identifying the correlation between each variable, it is difficult to describe the correlation between each variable and the prediction result in detail. This study performed spatial clustering based on the entire target area; however, future studies can consider a method to derive cells with high similarity that is based on each cell. Finally, this study is expected to serve as a basis for further studies that use various variables and conduct both regression and statistical analyses.

Author Contributions: Conceptualization, D.K. and S.J.; methodology, D.K. and Y.J.; software, D.K.; validation, S.J.; formal analysis, D.K., Y.J. and S.J.; investigation, D.K. and Y.J.; resources, Y.J. and S.J.; data curation, D.K. and Y.J.; writing—review and editing, D.K and S.J.; visualization, D.K.; supervision, Y.J. and S.J.; project administration, S.J.; funding acquisition, S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (No. NRF-2018R1A2B2005528).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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From TOD to TAC: Why and How Transport and Urban Policy Needs to Shift to Regenerating Main Road Corridors with New Transit Systems

Peter Newman [1,*], Sebastian Davies-Slate [1], Daniel Conley [2,3], Karlson Hargroves [1] and Mike Mouritz [1]

1 Curtin University Sustainability Policy Institute (CUSP), Curtin University, Perth, WA 6102, Australia; sebastian.davies-slate@curtin.edu.au (S.D.-S.); charlie.hargroves@curtin.edu.au (K.H.); mike.mouritz@curtin.edu.au (M.M.)
2 School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, SA 5005, Australia; daniel.conley@adelaide.edu.au
3 Entrepreneurship, Commercialisation and Innovation Centre, University of Adelaide, Adelaide, SA 5005, Australia
* Correspondence: p.newman@curtin.edu.au; Tel.: +61-8-9266-9032

Abstract: The need for transit oriented development (TOD) around railway stations has been well accepted and continues to be needed in cities looking to regenerate both transit and urban development. Large parts of suburban areas remain without quality transit down main roads that are usually filled with traffic resulting in reduced urban value. The need to regenerate both the mobility and land development along such roads will likely be the next big agenda in transport and urban policy. This paper learns from century-old experiences in public–private approaches to railway-based urban development from around the world, along with innovative insights from the novel integration of historical perspectives, entrepreneurship theory and urban planning to create the notion of a "Transit Activated Corridor" (TAC). TACs prioritize fast transit and a string of station precincts along urban main roads. The core policy processes for a TAC are outlined with some early case studies. Five design principles for delivering a TAC are presented in this paper, three principles from entrepreneurship theory and two from urban planning. The potential for new mid-tier transit like trackless trams to enable TACs is used to illustrate how these design processes can be an effective approach for designing, financing and delivering a "Transit Activated Corridor".

Keywords: transit; entrepreneurship; rail; effectuation; entrepreneur rail model; finance; PPP; transit-activated corridor; corridor transit; urban planning

Citation: Newman, P.; Davies-Slate, S.; Conley, D.; Hargroves, K.; Mouritz, M. From TOD to TAC: Why and How Transport and Urban Policy Needs to Shift to Regenerating Main Road Corridors with New Transit Systems. *Urban Sci.* **2021**, *5*, 52. https://doi.org/10.3390/urbansci5030052

Academic Editor: Pierfrancesco De Paola

Received: 7 June 2021
Accepted: 2 July 2021
Published: 7 July 2021

1. Introduction

Transit oriented development (TOD) [1,2] and transit adjacent development (TAD) [2,3] are current terminology in transport and land use planning with TAD being called "TOD gone bad" by Reconnecting America [4]. Others have suggested transit and joint development (TJD) as a concept needed to bring together the necessary public and private sector development opportunities [5]. All of this literature and practice is based on single entity developments around individual stations. This paper introduces the concept of a "Transit Activated Corridor" (TAC), which emphasizes the role of transit in enabling denser development along a whole corridor with a series of station precincts, or TODs. It seeks to help define how the concept of a TAC can be done through a novel integration of three theoretical approaches: from historical analysis of how transport creates land value; how entrepreneurship theory can enable the approaches to tapping that value; and how urban planning tools can enable it to be designed, financed and delivered providing both effective corridor transit and high-quality station precincts.

2. Theoretical Basis 1: Historical Analysis of Transport and Land Value

Effective and efficient corridor transit infrastructure is a key part of a growing city, with numerous cities across the world rediscovering transit's economic value after decades of automobile dependence [6]. The effects of the COVID-19 pandemic on transport intensity, and, therefore, emissions and traffic fatalities, has reinforced the potential of moving away from automobile-dominated transport planning. This new market is being driven by the fact that transit is becoming faster than traffic in most cities and thus providing cities with the option to deliver transit services that are less welfare oriented [7]. In many cases this is a return to the past when railway projects around the world were used to unlock new development opportunities, such as the privately-operated trams and trains of the 19th and early 20th century that were used by most major cities to create real estate opportunities [8]. These were typically entrepreneurial projects funded by the private sector and this approach can be traced as far back as the horse-drawn carriages that ran from the 17th century, through to the tram era and omnibus projects in New York city in the 1820s [9].

Britain's railway expansion in the 19th century and early 20th century was almost entirely led by private entrepreneurs, which resulted in an extensive rail network. Both rail and tram corridors were built primarily as private real estate ventures based on the land value unlocked by the new transit technology. This approach was replicated in many cities around the world as the basis for expanding mobility and settlements for the next 100 years. Some countries took a more public-led approach that lagged behind the British success, such as the French who relied on state-led planning of routes and facilities before engaging the private sector [10].

In many cities the legacy of the entrepreneurial rail era is a medium density urban fabric that follows corridors out from the traditional walking fabric town center; despite many of the railway lines since being taken up these corridors are still quite distinct and given the levels of accessibility that were created often represent higher than average real estate prices with a substantial proportion of the city's knowledge economy jobs [11]. The benefits of transit and walking urban fabric are now one of the driving forces as to why cities are seeking to build more transit down corridors and are wanting more TODs instead of outer area urban sprawl. Hence there is a growing demand for Transit Activated Corridors that deliver both effective transit and cost-effective dense urbanism.

The problem in the recent decades of building railway infrastructure is that it has been built much like freeways, as transport engineering projects only. This is understandable as transport engineering from the 1940s was built around the notion of freeing up congestion by building extra road capacity for automobiles. The new era of cars and buses saw cities spread outwards from the old tram and train lines which were either closed or made part of a welfare-oriented "public" transport system [7]. Thus, the previous approach to transport as being transit integrated with private land development was largely abandoned in favor of government funded freeways and then government funded rail projects. Their value was measured mostly in time savings.

The freeway approach has dominated urban growth until more recent times when sprawling outer suburbs could no longer be effectively serviced by roads and automobiles as congestion levels and average trip times were rising to a level that called for an alternative solution [7]. Whilst many planners like Calthorpe (1993) [1], Newman and Kenworthy [7], Dittmar and Ohland [12], with the Congress of New Urbanism, called for transit oriented developments (TODs) as a solution to this problem, there was little that could happen until rail transit began to be refurbished and new lines installed. Building new rail lines, both heavy rail and light rail, accelerated in the early part of the 21st century, especially in China and India, along with virtually all major developed cities; this has become known as the "Second Rail Revolution" [7].

However, delivery of contemporary transit did not always involve TODs as the mind set and institutional setting of these transport projects was often focused on only the transit solution to time savings and not on land use outcomes, similar to the way of building a freeway. Planning and delivery of TODs was often seen as an optional extra and usually only associated with one or two station precincts while the rest was TAD or park and ride [13]. Thus, urban sprawl was not always reduced as dense urban regeneration around new rail stations often remained marginalized in favor of parking. Thus, the goal of achieving more urban fabric in transit corridors and more walkable urban fabric in TODs has not been as successful as hoped when the rail revival happened. It is possible to make a case for such "freeway-like" rail projects for fast trains servicing outer suburbs without proper transit options [14], but there remain real challenges in stimulating urban regeneration in inner and middle suburbs.

Such transit adjacent development, or isolated TODs, is inevitable if funded entirely by governments as they are typically not able to leverage the land development being implemented around stations as a primary funding source. This suggests a re-invention of the historic approach to building transit as a partnership with the private sector through land development.

With a growing market for fast, high quality transit the idea of bringing in private funding has become more obvious for cities that are growing rapidly [15]. The obvious mechanism is through land development rather than just fare box returns which often do not cover the cost of operation. In Chinese cities, land value capture to fund transit is commonplace [16].

Integrating TODs, or station precincts, into a transit system from the start to enable funding of the transit, as well as urban regeneration along a corridor is therefore of growing interest. This approach we have called the Entrepreneur Rail Model [13] and the core principles are outlined below. Hong Kong and Japan use this approach and more recently interest in using private investment has grown with new mid-tier transit technologies like the trackless tram showing the potential for a low-cost urban regeneration catalyst [17]. The success of the Brightline private rail project in Florida has shown that the approach can work in more car dependent cities and regions; this is funded and financed through land development and fare box returns and has begun an extension, and a new, unconnected line, with plans to extend into 20 other cities. Although not an urban TAC but a regional rail corridor the same approach has been used to generate funding and financing from the associated land value around stations.

This paper seeks to show how the Entrepreneur Rail Model approach could be mainstreamed and extended into planning systems to design, finance and deliver Transit Activated Corridors (TACs). The paper suggests how insights can be gained from entrepreneurship practice-based theory and urban planning tools that favor the combination of transit that is designed to deliver reasonable speed along the corridor and walkable station precincts.

In the current approach to building transit (Figure 1) government transport agencies forecast transit numbers based on current and forecast development in the corridor, then set the route and station locations based on the least resistance and least costs, and then finally seek funding from government. In this approach, under-developed land in the corridor can be over-looked as these areas do not currently generate transit demand and the potential to merge the transit and land development interest can be largely lost. If funding is achieved using this approach, new land use opportunities are considered last when the value of the land has already increased following the construction of the transit infrastructure and there is less profit margin for land developers, and no incentive to invest in the transit infrastructure.

Instead, an ERM-based approach (Figure 2) would suggest that rather than beginning with a pre-determined route and station configuration, governments could harness available means by drawing on the private sector to develop a number of proposals for transit service configurations within a broader corridor based on the uplift potential of available land and development sites—or a private proponent could make an unsolicited bid to government to harness such potential. This way partnerships can be formed that include local governments that can often foresee development opportunities and with private developers who make their living out of recognizing good value urban development opportunities. The goal is to harness the available means, both the expertise of the municipality and the private sector and the physical assets themselves in the corridor, to propose transit configurations that create sufficient development opportunities to allow investment in transit infrastructure, while also satisfying the corridor's transport needs. This process can also make use of under-developed public land. Hence in this approach the first step is to identify uplift potential from transit services along the corridor, to then leverage this to secure financing, finally followed by design of the most appropriate transit configuration.

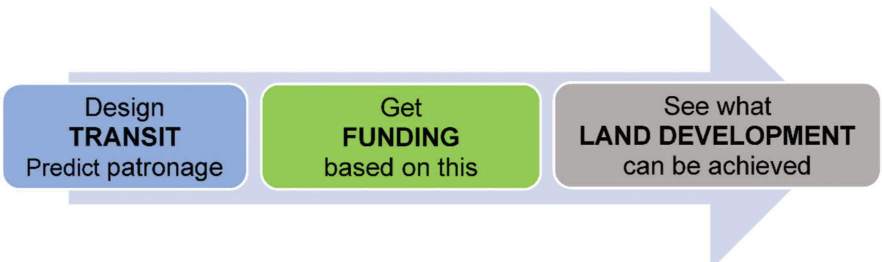

Figure 1. A schematic representation of a typical corridor transit planning process. Source: [13].

Figure 2. A schematic representation of an entrepreneurial approach to the corridor transit planning process. Source: adapted from [13].

The synergy created through such an entrepreneurial approach where the new land development is made viable because the new transit station makes it accessible, is one which aggregates both commuters and customers. In turn new developments attract more people to use the transit system, a mutually reinforcing relationship that sees more people opt for shared transit rather than private vehicles—forming a strong business case for greater development (rather than land-based charges that make it more expensive to be located near a station whether it delivers value or not). When developers are given the opportunity to co-locate stations with office complexes or choose land parcels in areas with greater need for more office space, there are compounding benefits across many financial and livability measures when compared to development "added" after transit is provided [18]. This approach to building transit down a whole corridor of TODs used to fund and finance it, is the approach adopted by Hong Kong in its MTR, and by Japan in projects such as the new Tsukuba Express Line and more recently in China.

3. Theoretical Basis 2: Entrepreneurship Theory for Transit Activated Corridor Development

The historical analysis shows that the transit-oriented, dense urbanism developed from the mid-19th to mid-20th century was created by entrepreneurs along corridors. Thus, it would appear sensible if this urban fabric is again on the agenda for 21st century cities to understand the role of entrepreneurs in creating TACs.

The study of entrepreneurship is a growing discipline, mostly focused on individual start-up approaches for new businesses, with a lack of consensus on the definition and practice of the knowledge in the field [19,20]. There is general agreement however that a core feature of the practice of entrepreneurship is creating value, often under conditions of uncertainty, and typically to obtain private wealth [19] though not without seeing its public benefits. Thinking of entrepreneurship as a process of value creation has led to its broadening beyond just start-up individuals, and towards the traits and approaches sometimes displayed by government and civil society, termed "Entrepreneurial Governance" [21–23]. Similarly, Harvey [24] presented "urban entrepreneurialism" as urban governance that increasingly focuses on "new ways in which to foster and encourage local development and employment growth".

Rather than thinking of "entrepreneurial approaches" as purely strategies that are applied by individuals or start-ups seeking to grow profitable companies, these approaches can also be used to create value in the form of jobs and wealth, improved use of public space, reduced environmental pollution, alleviating congestion, and delivering cleaner and more efficient cities [25]. In the same way, this paper refers to principles of entrepreneurship to outline the process of entrepreneurially activating corridors using new transit lines—given the entrepreneurial legacy of this process throughout history.

The entrepreneurship literature that seems to provide the greatest guidance on how to achieve the entrepreneurial approaches required for TACs and to provide the most potential to further enhance its application, is called "Effectuation" [26]. According to Sarasvathy, effectuation is a logic used by entrepreneurs during new venture creation under conditions of uncertainty and involves a number of key principles with three particularly relevant to TACs and the Entrepreneur Rail Model: create partnerships from the start; value creation rather than prediction; and begin with available means rather than pre-determined ends [26].

3.1. Principle 1: Create Partnerships from the Start

The first principle drawn from effectuation is to build a group of partners and stakeholders from the beginning, reducing uncertainty and risk as a co-created vision is developed between all parties and is realized through collaboration [26]. Just as expert entrepreneurs build partnerships from the start, an ERM or TAC project would begin with a partnership between land interests, communities, local authorities and financiers, and then reaches agreement with government. Effectuation suggests that "self-selecting stakeholders" tend to have more commitment to the project; and in the case of private funding and financing of urban rail projects, self-selecting stakeholders are often able to reach agreements around the distribution of benefits and costs more easily [27].

These partnership-first approaches have been growing rapidly around the world in recent years, taking the place of siloed professional practice [28]. For cities and infrastructure, this partnership approach has sometimes been called a "City Deal", and enables a more bottom-up approach to infrastructure planning and provision. These new approaches will be important for involving private funding to help fund the capital costs involved in quality transit projects [13]. The Australian Federal Government has followed the success of the UK City Deal policy and has created a program based on this concept to encourage urban renewal, that includes a focus on urban rail [29]. The program offers financial risk guarantees rather than contributing direct funding, reducing the risk for private sector involvement. The City Deal program includes requirements to enable [30]:

- An agreement between the three tiers of government, setting out a plan for the City Deal,
- Greater community involvement and support for any projects, and

- Involvement of the private sector, including innovative financing that integrates transit and land development, and with supporting funds from local and state government, with the federal government providing a risk guarantee.

The United Kingdom's City Deal approach began as part of an agenda to devolve power from the national government to city governments, with the aim of boosting economic growth. This began with a first wave of the eight largest city economies in England, outside of London. The Manchester City Deal was notable for its "earn back" feature, which allowed the local authority to retain part of additional tax revenue gained from investments connected with the City Deal [31]. This is akin to tax increment financing, combined with central government funding, and does not involve the entrepreneurial approaches as outlined in this paper. Since then, the City Deals have become more entrepreneurial.

The approach to the City Deal program in Australia was analyzed by Clark and Moonen [32] and involves an integration of policies related to providing infrastructure and urban planning with private sector land development in order to create "great cities". It requires governments at all levels to set up partnerships with private financing, especially superannuation companies looking for long term investments, developers who understand markets and innovation in urban development, as well as communities who know what they prefer in their precincts and neighborhoods for the long term [28,30]. The partnerships enable the best economic value creation by facilitating social capital, financial capital and political capital as explained in Newman and Kenworthy [7]—see Figure 3.

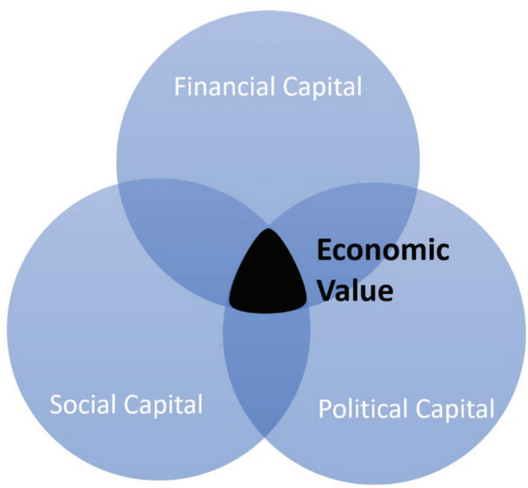

Figure 3. Economic value creation through integration of financial, social and political capital—the intention of a "City Deal". Source: [7].

Another key feature of the City Deal approach is it provides an effective mechanism to align the policy intent of the different tiers of government. This provides greater clarity to the private partner, reducing risk, and facilitates co-ordination with other government programs, see Figure 4.

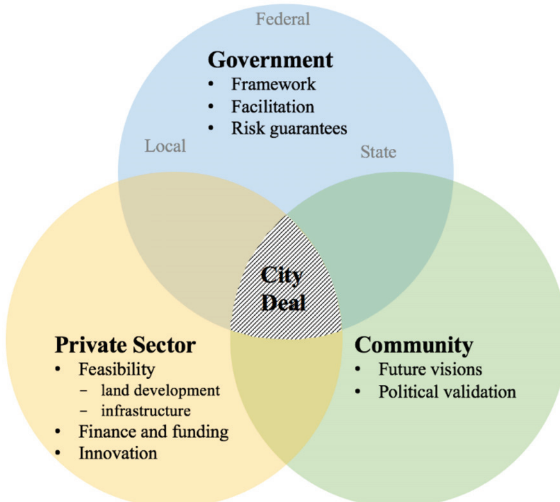

Figure 4. The City Deal partnership model. Source: [7].

This key feature of a City Deal, the alignment of multiple tiers of government, community and the private sector, can be seen to various degrees in existing rail projects around the world, including:

- The Tsukuba Express project in Japan, which came about as a result of long-term government strategic planning. It was delivered on commercial terms by a specially constituted company with ownership shared between city, prefectural and metropolitan governments along the route, and the private sector. The central government provided concessional financing to support the project, but it was delivered by a private company [8].
- The Indian Government's Metro Rail Policy, which sets as a requirement of central government support of a project that it includes private participation, and also must consider the potential for private funding contributions and transit-oriented development. The implementing agencies are also encouraged to maximize project revenue from commercial real estate development at the stations and other non-fare box revenue. Metro rail is seen as a means to achieving sustainable development and a more compact urban form and the mechanism for delivery includes the Urban Mass Transit Company which is a 50:50 government and private agency that has flexibility in raising finance as well as enabling assessments of Metros [33].
- London Crossrail—a project jointly funded by private interests, the Greater London Authority and the national Department for Transport with partnerships developed through the Infrastructure and Projects Authority which is a national government advisory group establishing PPP to enable the funding and financing of infrastructure [8].

City Deals are well-suited to facilitating Transit Activated Corridors, as they can provide increased regulatory certainty or guidance along the corridor, by aligning the objectives of the different tiers of government and can enable the private sector to obtain their finance. In Australia this involves an Infrastructure and Projects Finance Authority that operates in parallel to the assessment process through Infrastructure Australia. At state and local level where detailed planning is done, this would include environmental approvals, land use planning changes, reduced parking requirements and appropriate regulatory approvals in transport, including rail safety regulation. Agreements can also be reached with multiple levels of government to provide associated public infrastructure work such as recharge services for stations where electric battery recharging is needed.

3.2. Principle 2: Value Creation Rather Than Prediction

The second principle drawn from effectuation is to focus on what can be controlled to "create value" rather than to act based upon "predicted outcomes". In practice, according to Sarasvathy [26], this means expert entrepreneurs focus on the controllable aspects of an unpredictable future rather than acting based on predictions of an uncertain future. Some of the mechanisms for capturing value created by the transit system are set out in Newman et al. [7], including the highest value-producing mechanism of a fully private entrepreneurial approach through to the lowest value-producing fully public approach with various levels in between.

Currently, transit corridors are assessed based on predicting the number of people who would potentially use a new mass transit system based on present land use and travel patterns and seek to finance this through public funds or additional rents and land-based charges imposed on surrounding landowners. Traditional government funded value capture approaches rely on a "predicted return", whether this be a predicted number of passengers, a predicted reduction in congestion, or a predicted amount of development and thus value capture can be managed; however, most of the value leaks as soon as a route and set of station locations with density zoning is made public by government, unless partnerships with entrepreneurs are made at the planning stage. There is also an issue with prediction. Transport planners have struggled with prediction, particularly for road networks, due to the principle of induced demand which causes unexpected behavior from commuters when new travel options become available [34]. A prime example of this is that despite providing additional vehicle lanes to relieve congestion, the new lanes are unable to provide lasting congestion relief, due to travelers shifting travel times, routes and modes when networks are changed, even slightly. This is referred to by Downs [35] as the theory of triple convergence and it leads to ineffective prediction-based interventions. This effect can also occur when forecast-based transit interventions deployed in isolation of land development are undertaken and can result in less-than-expected reduction in traffic congestion [36]. Means of overcoming this in Europe are set out in Principle 4 using Sustainable Urban Mobility Plans.

The Entrepreneur Rail Model however creates Transit Activated Corridors through a focus on creating complimentary opportunities for both new land use investment and increased transit ridership, resulting in greater urban densification and less urban sprawl—which is not possible through current transit planning. This is made viable through integration of private land development with transit services to create station precincts which creates two increased sources of value: one is due to the land value increases of between 20% and 50% usually associated with transit (summarized in [13] which enables higher density development, and second, a reduced need for expensive car parking infrastructure of around 20% which enables better urbanism [7]. The result of greater value increase is that it can also mean investment to construct the transit infrastructure, so the value is created. It is in this way that the entrepreneurial approach "creates new markets" that government planners cannot achieve on their own. This value increase can only be achieved in partnership with governments that manage the common good outcomes necessary but are freed from the need to raise all the funds.

This entrepreneurial approach was used by Hong Kong in its metro and in the development of the private suburban railways in Japan, primarily in the first half of the Twentieth Century. Railway companies augmented their transport revenue through real estate development and management, but also proactively managed land uses around their stations to influence passenger demand. Land was provided to institutional users such as hospitals or universities at concessional rates at the outer terminal stations, creating demand for travel in the reverse direction from central business district commuting patterns [37]. The private railways had to diversify in this way to survive, as the Japanese Government had partially nationalized the industry to create the Japan National Railway. Private companies were forbidden from building railways which interfered with the national railway's operations and were mostly restricted to areas with low population. This forced them to build their own catchment population around their railways [38], making the best use of the assets at their disposal. This is a good example of a TAC that was privately created but had significant benefits to the wider community. Similar results, albeit with less striking development histories, have taken place in Hong Kong, and more recently, has begun to take place in mainland China.

Thus, value creation can be applied to the TAC model using value uplift in land development to create value for the transit funding, rather than the value capture or value leakage that occurs under the present approach to "predict and provide" transit, leading to limited interest in transit projects.

In cities that do not have such attractive land development potential as does Hong Kong and Japan, this approach can be taken a step further to attract private investment in transit infrastructure. Rather than just buying pre-rail land and selling it at post-rail prices, the partnerships with landowners and developers can be expanded to capture even greater value around stations. This can be done by incorporating developer preferences for the location of the transit line and associated stations to allow for fully private transit lines to be constructed and operated in unison with new developments [8]. Coupled with this, there are technological innovations occurring in the transport technology sector that are providing rail-like solutions at a much cheaper cost, discussed below.

Such an approach stands to provide cities and nations with a way to break out of the gridlock of automobile dependence and under-financed transit by harnessing private investment to deliver integrated transit and land development along corridors. This way enables value creation from the transit that can be used to contribute to the costs associated with delivering the transit without driving away investors and developers.

3.3. Principle 3: Begin with Available Means Rather Than Pre-Determined Ends

The third key principle drawn from effectuation is to "begin with a set of available means, rather than pre-determined ends" [26]. This requires thinking differently about what constitutes a cornerstone for action, innovation and finance. During new venture creation, expert entrepreneurs tend not to decide upon a "final product" and then seek to assemble the required resources, but instead begin with what is available, giving preference to actions which harness available resources or networks and which appear to help with their perceived journey.

Unlike the current approach to transit which seeks to predict and build transit infrastructure based on current conditions and reliant on government funding, this principle suggests that instead of using a pre-determined route and trying to "add on" land value creation at the end, the "available means" or available land opportunities are in fact the basis for the viability of the entire project and need to be considered right from the start.

Despite entrepreneurs often being considered "risk takers", expert entrepreneurs seek to minimize risk by "controlling the downside scenarios and finding ways to reach the market with a minimum expenditure of such resources as time, effort and money" [26]. This means entrepreneurs seek to creatively leverage underutilized or "slack" resources, such as land development sites that can be made viable through transit accessibility. Such development opportunities can then provide a powerful dynamic in the process to design and deliver transit infrastructure. Hence, rather than having a fixed route and set of station locations in mind, the process can begin with a configuration that best leverages investment in the early stages. As station precincts then begin to be built and create more value, the investment in the transit can continue to grow to provide greater services and station precinct locations. Organic growth of a TAC project can be based on stages that depend on what the land development market can achieve.

Examples of this organic process of beginning with what is available can be seen in the United States in the development of new corridor rail lines based on a series of TODs built-in stages. Organic stepwise approaches to US transit and land development are usually based on entrepreneurial land developers linked in partnership through mechanisms like Tax Increment Financing or Business Improvement Districts. TIF projects raise bonds based on estimated future tax revenue developed from successful urban development. Business Improvement Districts (BIDs) are more directly involving contributions from business and have mostly been used to regenerate urban areas though they are now being extended along a corridor. While BIDs do involve new levies, they are either initiated by, or negotiated with, local businesses who will benefit from the infrastructure.

Four examples of such organic TAC-like delivery are outlined.

3.3.1. San Francisco

A BID in the Bay Area established a local committee of the district's residents, business owners, tenants, schools and developers, creating a strong base in social capital. The committee prepared a local development proposal including a financial plan and sought approval from local government authorities thus generating the political capital. In this case however, the district residents were charged with elevated property taxes to fund the infrastructure to help regenerate their area. This consensual charge generated the financial capital, rather than leveraging land value uplift to attract new investment [39].

3.3.2. Pearl District Streetcar

The Portland MAX Light Rail, or Metropolitan Area Express, was a fully government funded project from the 1980′s and was so successful that various other communities wanted to have a similar urban renewal process in their area. The Pearl District of Portland was an old industrial area—creating "available means" for urban regeneration, with businesses and residents wanting a modern transit service to link them to the city center. An organic process was begun in the 1990′s to generate a variety of funding sources including a Tax Increment Financing (TIF) set up through the local council (providing 13% of funding) and a BID-style "Local Improvement District Levy" on local business (providing 17% of funding) in partnership with state and federal funds. The first two stages of the Portland Streetcar opened in 2001. One further stage was extended in 2007 using 21% TIF funding and 31% BID funding as the success of the first two stages had raised land values.

When the Pearl District was legally formed in 1998 the value of property was estimated at $446 million and in 2014 at $2.2 billion. The tram system for the Pearl District is owned by the City of Portland and managed by Portland Streetcar Incorporated, a non-profit public benefit corporation whose board of directors report to the city's Bureau of Transportation. The Pearl District corridor that is serviced by this light rail is an outstanding success story of urban regeneration with multiple sustainability out-comes [40–43].

3.3.3. South Lake Union Streetcar, Seattle

The South Lake Union Streetcar project was initiated by community and business interests working together over several years. The prospect of urban renewal opportunities being generated by a light rail service was embraced by a range of businesses and residents who lobbied for the return of the historic tram car service. The South Lake Union Streetcar project was able to attract the interest of local, state and federal governments who worked out how to fund the project with the local business community. A fee from 760 land parcels was estimated to provide 52 percent of the total project cost. The City of Seattle issued government bonds to raise capital and linked them with the private funds. The city assessed a fee in 2004 and landowners in the precinct approved it in 2005. The street car project became operational in 2007. The assessed fee was based on estimated land value uplift for various land uses. The land owners were provided an option to pay a fee up front or in 18 years at a 4.4% interest rate. In this case the project was considered a low-risk as it was applied in an established urban area with a strong real estate market [44]. Only 12 of the affected property owners formally objected to the proposed Local Improvement District tax. The South Lake Union Streetcar is owned by the City of Seattle and operated and maintained by a transit agency with representation from the local community.

The last two examples show how a range of procurement and financing models can be organically leveraged through partnerships, based on what is available, to support projects focused on urban regeneration using transit infrastructure—and to further expand as the area grows. By starting with available means, further entrepreneurial opportunities are created as the initial segments succeed. From the perspective of the private sector, the benefits from the urban regeneration opportunities are greatest when they are in-volved early, which makes early partnerships and inclusive planning crucial.

3.3.4. Brightline

A larger development known as Brightline, Florida has been set up as a purely private rail project using a TAC approach. The project began by leveraging funding from a New York hedge fund based on private sector opportunities around new stations as well as potential fare box returns.

The first stage of the Brightline was developed in partnership with the local and county governments and the local community [7,45]. It opened in late 2017, initially running from Miami to Fort Lauderdale, but with an extension to Orlando International Airport under construction, and further extensions to Disney World and Tampa in planning [46]. There are also plans to build a new line from Los Angeles to Las Vegas.

The latter project includes purchasing 38 acres of land adjacent to the Las Vegas strip for the station and a mixed-use development. It came about via the acquisition of Xpress-West, which had secured federal approvals for the rail corridor [47]. The company plans to expand further and describes its business model as "a scalable model for twenty-first century passenger travel in North America" and identifies eight new potential corridors within the United States and Canada [48]. Thus, by taking an organic approach the corridor was eventually completed and the model is now being replicated.

In practice Transit Activated Corridors raise investment for transit through partnerships that grow organically as the land development opportunities are realized and expanded. This minimizes risk for participating private parties and increasingly shifts towards private funding to complete projects. Hence this can reduce government's role especially in terms of having to raise the full capital (often difficult and compared with the ERM/TAC model less value creating) allowing a focus on roles more aligned to the purview of government such as being critical in the delivery partnerships. Government needs to provide creative leadership on zoning, planning integration, and facilitating connections to the wider transit network. Government can also assist with land assembly and risk management in procurement [7], easing the process for private parties to participate and creating new value. Similarly, for the public sector, project-based implementation risk is reduced through sharing with the private sector in this organic stepwise process.

The application of these three principles of effectuation will be a key determinant of the success of the application of the ERM model to deliver Transit Activated Corridors. There are also a range of government tools in urban planning that can be delivered in partnership with developers and investors, and which can help create Transit Activated Corridors.

4. Theoretical Basis 3: Urban Planning Tools for Fast Transit Corridors and Walkable Station Precincts

Urban development and infrastructure are best developed when they are part of both a strategic and a statutory framework. The majority of these planning systems, especially in Australia and America, still enable urban sprawl and associated car-based communities and have a lesser focus on enabling transit and urban regeneration. There is however a growing movement to find new ways that urban planning can produce effective corridor transit and TODs. These approaches will be examined in terms of tools for corridor design that facilitate transit and dense urbanism as in a TAC, as well as tools for walkable urban design in the associated TODs. Thus, two more principles have been selected from urban planning tools to help design, finance and deliver Transit Activated Corridors.

4.1. Principle 4: Define Transit Activated Corridors

The first planning tool for creating a high-quality transit system down a corridor is to declare it or zone it in strategic and statutory plans as primarily for transit and dense urbanism. A series of such plans are being developed around the world since Transport for London declared their policy called "Street Families" [49] which sets out the streets that give priority to transit and where density will be given special encouragement. In Melbourne the Victorian Government has a policy called the "Movement and Place" framework which recognizes that streets are not only about moving people from A to B, but in many contexts also act as places for people and public life. Similar policies have been developed for Auckland, New Zealand, and Western Australia. The movement and place framework enables the "place" prioritization of streets to create walkable, livable centers. In Perth the approach has been proposed to create a "Green Route" in the Metropolitan Region Scheme that requires transit priority and density to be the joint focus along the road. Such routes could be specified as potential Transit Activated Corridors with associated zoning along the corridor.

This approach is increasingly being used in the UK and Europe more generally as part of Sustainable Urban Mobility Plans [50]. The approach is outlined in Table 1 below.

Table 1. Summary of guidelines for sustainable urban mobility plans compared to traditional planning. Source [50].

Traditional Transport Planning	**>**	**Sustainable Urban Mobility Planning**
Focus on traffic	>	Focus on people
Primary objectives: Traffic flow capacity and speed	>	Primary objectives: Accessibility and quality of life, as well as sustainability, economic viability, social equity, health and environmental quality
Modal-focussed	>	Balanced development of all relevant transport modes and shift towards cleaner and more sustainable transport modes
Infrastructure focus	>	Integrated set of actions to achieve cost-effective solutions
Sectorial planning document	>	Sectorial planning document that is consistent and complementary to related policy areas (such as land use and spatial planning; social services; health; enforcement and policing; etc.)
Short- and medium-term delivery plan	>	Short- and medium-term delivery plan embedded in a long-term vision and strategy
Related to an administrative area	>	Related to a functioning area based on travel-to-work patterns
Domain of traffic engineers	>	Interdisciplinary planning teams
Planning by experts	>	Planning with the involvement of stakeholders using a transparent and participatory approach
Limited impact assessment	>	Regular monitoring and evaluation of impacts to inform a structured learning and improvement process

A core part of designing TACs would be a set of detailed design options for how a mid-tier transit service like light rail or a trackless tram (see below) could travel at speed down a clearway where road space is available, and then slow down when it enters a station precinct where the design and place focus would be to facilitate walkability and pedestrian activity. The latter part of the road works could be the responsibility of the private sector partners. This would send the signal that dense urban development would be favored as it would have a high-quality transit system linking it to the rest of the city and would have a highly attractive urban design quality for attracting people-based activities in and around the stations.

The responsibility to enable TACs would be given to an agency, or cross-agency group, that has both responsibility for delivering transit and delivering urban regeneration. Thus, roads chosen for this category would shift their priority for providing mobility services for through traffic, to a focus on how they could enable quality transit and urban design along the corridor that delivers value to both developers and the community. This would mean more of a focus on accessibility, sustainability and equity as set out in Table 1. Compared with car only lanes such routes could carry the equivalent of six lanes of traffic [51], easing congestion issues while increasing activity along the corridor through transit and urbanism.

4.2. Principle 5: Walkable and Sustainable Station Precinct Design

Station precincts must be allowed to be dense and mixed use in the strategic and statutory zoning systems used to enable TACs. There are a large number of design tools created to make station precincts or TODs into "inclusive, safe, resilient and sustainable" places including walkable urban design, solar design, water sensitive design, biophilic design, affordable housing design and most of all integrated design. For instance, there are a number of detailed manuals from the Congress of New Urbanism that set out best practice in these areas [52–55]. Such guidance now needs to be reflected in statutory requirements for station precinct developments along transit corridors. Such requirements also need to consider how new technologies for smart and sustainable systems can enhance various design outcomes. This may include how driverless electric shuttle buses can carry people to the station precincts (providing first and last kilometer solutions) without ruining the walkability qualities of the area [30]. Evidence is showing that Uber (and potentially driverless vehicles) are increasing the vehicle kilometers travelled (VKT) rather than decreasing it as many had anticipated, causing greater congestion and accessibility issues [56]. To counter this trend will require a different approach to mobility and TACs are likely to be part of this.

5. Applying Transit Activated Corridor Development with Mid-Tier Transit

A research project as part of the Sustainable Built Environment National Research Centre (SBEnrc) has been developed with a series of partners seeking to deliver a mid-tier transit-based TAC using the ERM approach. It was given a significant boost when a new transit technology was discovered that we have called a "Trackless Tram". The trackless tram systems (TTS) have taken six innovations from high-speed rail, put them in a carriage bus—or tram like vehicle—with stabilization through bogeys and optical guidance systems, that not only mean it is largely autonomous (though not completely driverless), but it is also enabled to move at speed down a road with the ride quality of a light rail. Being electric through batteries and with no need for steel tracks, it is significantly cheaper and easier to implement than a light rail and significantly better than BRT at creating urban land value uplift. Research was conducted on assessing this technology [51] and the conclusions are presented in Table 2.

Table 2. Indicative comparison of characteristics of corridor based urban rapid transit systems.

Characteristic	Bus Rapid Transit (BRT)	Light Rail Transit (LRT)	Trackless Tram System (TTS)
Speed and Capacity	✓	✓✓	✓✓
Ride Quality	✗	✓✓	✓✓
Land Development Potential	✗	✓✓	✓✓
Cost	✓	✗	✓
Disruption during construction period	✓	✗	✓✓
Implementation Time	✓	✗	✓
Overall	✓	✓✓	✓✓✓

The assessment provided above highlights that TTS has the potential to stimulate urban redevelopment potential just as well as good light rail and hence can enable the delivery of TACs. This will require assessment in different cities, but an approach is suggested using the five principles developed from the three entrepreneurial principles and the two urban planning tools. This enables a high-level approach to assess the potential to deliver very efficient and effective Transit Activated Corridors using a mid-tier transit as the catalyst. The core requirements from the five principles for TAC are applied to the three options of BRT, LRT and TTS and are set out in Table 3. This enables us to see how well the new technology of TTS promises to facilitate a TAC.

Table 3. Comparison of TAC characteristics for corridor based urban rapid transit systems of BRT, LRT and TTS.

Characteristic 1: Ability to facilitate partnership-driven planning		
BRT	BRT is able to achieve partnership driven planning, however partnerships are generally transport-centric given the lesser urban regeneration ability achieved by traditional bus-based schemes.	✓
LRT	LRT is able to bring transit, land development and community interests to the table and this has been demonstrated around the world, including in the case studies above.	✓✓
TTS	TTS are able to bring the same interests together as LRT to plan a transit project financed by urban regeneration, however TTS can enable the inclusion of far more parties than under the recent welfare finance model of most light rail. Projects do not need to be "Tokyo" in scale to get started, and have less risk. An inclusive, bottom-up, community-engaged planning approach can be achieved with the less expensive trackless trams, rather than only being considered by the top-down stakeholders.	✓✓✓
Characteristic 2: Ability for value creation through urban regeneration		
BRT	Bus-based systems have had less urban regeneration success in most cases.	✗
LRT	Light rail has been successful in attracting investment and urban regeneration around its lines, especially given its fixed nature, however urban regeneration is best achieved if land development is used as the cornerstone of transit finance such as proposed here.	✓✓
TTS	Ability to be used like light rail, particularly through an entrepreneurial financing process to ensure urban regeneration is undertaken, but at lower cost to the entrepreneurs and thus is more likely.	✓✓
Characteristic 3: Ability for organic resourcing through staged financing		
BRT	The lack of strong urban regeneration attraction created by BRT systems creates a lack of investor incentive for the finance of new lines.	✗
LRT	Has been achieved in a number of cities, highlighted in case studies above.	✓✓
TTS	Organic resourcing through staged financing would be similar to the LRT as in the case studies outlined above. At each stage of financing the two parts of the TAC, the trackless tram and the chain of TODs could be financed with steps assessed for land value uplift, patronage and other benefits and costs, before proceeding to the next stages.	✓✓

Table 3. *Cont.*

Characteristic 4: Ability to service strategic plans (TAC route)		
BRT	If strategic plans are developed mode agnostically, BRT is competitive on infrastructure cost and speed if given priority. However, it will not achieve urban regeneration outcomes.	✓
LRT	If strategic plans are developed mode agnostically, LRT is competitive on capacity per vehicle, speed and ability to attract regenerative investment.	✓
TTS	If strategic plans are developed mode agnostically, TTS can enable the capacity and speed of LRT but cost much less. This is likely to open up the potential for many more strategic routes and help create an overall network with far greater overall benefits.	✓✓
Characteristic 5: Ability for integrated application of TOD design tools		
BRT	The same TOD principles can be applied but without private investment they rarely happen.	✗
LRT	Able to utilize best-practice integrated TOD design from light rail projects to achieve walkable, people-centric transit precincts.	✓
TTS	Design tools for TODs would be just as effective in station precincts around trackless trams as around LRT except the cost of the infrastructure is much less (no overhead catenary and no steel tracks).	✓✓

The high-level assessment would suggest there is a very high capability of a trackless tram system and a light rail to enable a TAC to be created with a quality transit corridor and a chain of high-quality station precincts linked to it. These results are summarized in Table 4.

Table 4. Indicative comparison of characteristics of corridor based urban rapid transit systems in terms of entrepreneurship and urban planning factors supporting a Transit Activated Corridor.

Characteristics in Terms of Ability to Use	Bus Rapid Transit (BRT)	Light Rail Transit (LRT)	Trackless Tram System (TTS)
Partnerships	✓	✓✓	✓✓✓
Value Creation in Urban Regeneration Potential	✗	✓✓	✓✓
Organic Resourcing through Staged Financing	✗	✓✓	✓✓
Strategic TAC Route	✓	✓	✓✓
Design Tools for TODs	✗	✓	✓✓
Overall	✓	✓✓	✓✓✓

6. Conclusions

Growing cities around the world are looking for new ways to deliver transit and urban redevelopment. This paper suggests a new option called a Transit Activated Corridor (TAC) and sets out how best to achieve them using five principles drawn from entrepreneurship theory and urban planning:

1. *Create partnerships from the start*, that suggests for TAC the need for partnerships between government, community and the private sector which can leverage such entrepreneurial approaches similar to the historic role of entrepreneurs in creating train and tram corridors, and the emerging models for involving the private sector in rail developments, especially involving City Deals;
2. *Value creation rather than prediction*, which suggests for TAC taking value creation opportunities through involvement of private sector financing of land development rather than predicting transit outcomes as in current transit planning;
3. *Begin with available means rather than pre-determined ends*, suggesting that TAC could use available resourcing from land development in organic steps to stage the financing;

4. *Define Transit Activated Corridors*, that suggests a high-level strategic plan to develop Transit Activated Corridors (like the European Sustainable Urban Mobility Plans) with statutory mechanisms that require the delivery of transit priority as well as dense, urban regeneration, and providing a delivery agency focussed on this task; and
5. *Walkable and sustainable station precinct design*, that would mean a series of statutory design requirements for the station precincts to be high quality designed TODs for walkability, affordability and sustainability.

All these require the private sector to be actively involved from the beginning of the planning process, providing the opportunity to collaboratively shape and capture benefits from transit activation along the corridor, creating the basis for the private sector to contribute financing given the attractive development opportunities that exist.

When the five principles were applied to a high-level assessment of new mid-tier transit technology, it showed that these lower cost new technology options are likely to help with the design, financing and delivery of a Transit Activated Corridor down urban streets.

Author Contributions: Author contributions were as follows: S.D.-S. (30%), P.N. (25%), D.C. (20%), K.H. (20%), M.M. (5%). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Sustainable Built Environment National Research Centre, Project 1.74. In addition, Sebastian Davies-Slate received PhD scholarship funding from the CRC for Low Carbon Living.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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ISBN 978-3-0365-5832-5