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Sustainability, Challenges and Opportunities to Optimize Building Performance

Edited by
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About the Editors

Igor Martek

Igor Martek is currently an academic at Deakin University, Australia. He earned his PhD in "Enterprise Strategies in International Construction" from the University of Melbourne. He also has an MBA from the Australian Graduate School of Management, University of NSW, and an MA in International Relations from the Australian National University, Canberra. His first degree is a Bachelor of Architecture (Honours) from the University of Melbourne.

He has extensive professional experience in evaluating, generating, managing, and turning around large capital projects in various locations around the world. He has worked in Europe, including Eastern Europe, the Middle East, China, Korea, and Singapore. In Kuwait, he was second to the Ministry of Finance, assessing and developing projects financed by the Kuwait Fund. He worked in Japan for over ten years as the Managing Director of Far-East Operations for a British Consultancy, advising major global enterprises on strategy and competitiveness.

Igor is a visiting scholar at places as far as China, Poland, and Indonesia. Most recently, he was a guest of "Konstruksi Indonesia" where he spoke at numerous forums on sustainable infrastructure and international project partnerships. He has authored over 170 peer-reviewed articles, and his latest book is titled "International Construction Management".

Mehdi Amirkhani

Mehdi Amirkhani is an Educator at UniSA Online, STEM, leveraging his extensive experience across five Australian universities to create engaging learning environments. With twelve years of experience as an architect, in addition to being a nationally Accredited Home Energy Efficiency Assessor, he has enriched over 120 construction projects, bridging theory with practice.

Mehdi's expertise lies in sustainable design and building retrofitting, aiming to enhance occupants' health and wellbeing. As a researcher, he focuses on building environmental technologies, net-zero energy buildings, and indoor environmental quality. His PhD introduced an innovative approach to lighting design in office buildings, optimizing visual comfort and energy efficiency. He has edited prominent academic collections, producing over 50 papers across five Q1 journals. A recognized thought leader, Mehdi has delivered technical talks and served as an invited panelist at esteemed national events and industry summits; moreover, he has lectured at universities globally. With over AUD 79,000 in external research funding secured as the Chief Investigator and an additional AUD 41,700 secured in non-research funding from various sources, Mehdi continues to champion sustainability, bridging academia and industry to advance the construction sector.

Mehdi's dedication to education is reflected in his leadership roles and curriculum development efforts, including increasing student satisfaction ratings and integrating industry standards into teaching. He has served as a guest lecturer at various universities and as a judge for prestigious industry awards. An Associate Fellow of the UK Higher Education Academy, Mehdi is also the Co-Director of the Zero Energy Mass Custom Home (ZEMCH) Network Australia and a Full Member of Design Matters National.

sustainability

Editorial

Latest Research on the Theme of "Sustainability, Challenges, and Opportunities to Optimize Building Performance"

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1. Introduction

In the face of escalating climate change, rapid urbanization, and dwindling natural resources, the imperative for sustainable practices within the construction and architectural sectors has never been more critical. Buildings are not only fundamental to human habitation and economic activity but also significant contributors to global energy consumption and carbon emissions. "Sustainability: Challenges and Opportunities to Optimize Building Performance" offers a comprehensive exploration of the multifaceted strategies and innovations essential for enhancing building performance while minimizing environmental impact. This collection of 21 meticulously curated articles delves into the various dimensions of sustainable building design, construction, and operation, presenting both the theoretical frameworks and practical applications that address contemporary challenges and pave the way for a resilient, efficient, and sustainable built environment.

The book is organized into five sub-themes, each addressing a core aspect of sustainability in building performance. This structured approach facilitates logical and scientific progression, enabling readers to grasp the foundational concepts before delving into advanced applications and specialized topics. Each article within these sections contributes uniquely to the overarching theme, creating a cohesive narrative that underscores the interconnectedness of sustainable practices in the construction industry.

The following editorial sequence facilitates the reader's understanding of sustainability in the built environment, from overarching theoretical concepts to practical application.

1. Foundational Concepts in Sustainable Building Design;
2. Advanced Applications and Modular Design Solutions;
3. Structural Innovations and Energy Efficiency;
4. Energy Optimization in Extreme Climates;
5. Retrofit Strategies and Energy Efficiency in Urban Housing.

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2. Thematic Content

This collection showcases 21 studies and is structured to provide logical and scientific progression, beginning with fundamental research on energy optimization in building design and advancing towards more specific, innovative solutions that address the myriad challenges of sustainable construction. Each article contributes to a holistic understanding of sustainable building performance, highlighting the current research, innovative methodologies, and practical applications that push the boundaries of conventional design practices.

It should be noted that the researchers contributing to this collection are drawn from every continent, truly representing the concerns and priorities of those around the world working at making our built environment truly sustainable. Represented here are the cutting-edge work of experts from the USA and Brazil in the Americas; the UK, Portugal, Spain, Italy, and France in Europe; Egypt, Saudi Arabia, and Turkey in the Middle East; South Africa, Namibia, and Zambia in Africa; China, Hong Kong, South Korea, Japan, and Thailand in Asia; and researchers from Australia.

2.1. Foundational Concepts in Sustainable Building Design

This initial section establishes the essential principles and methodologies that underpin sustainable building performance. It lays the groundwork for understanding how strategic design and early-stage planning can significantly influence a building's energy efficiency and environmental footprint.

Thus, in this section, the bigger picture is presented. Simulations have long been understood as potential aids in the optimization of building design, and, in particular, with regard to energy use. Yet to date, the standardization of simulation models has remained elusive. Our first study offers a solution by way of a framework. Similarly, we would expect the efficiencies inherent in modular construction to leverage the affordability of housing. Yet, modular construction continues to suffer from a lack of traction. If this is to be addressed, a clearer understanding of the impediments must be had, and this insight is offered in our second paper. The decision-making process, so necessary to be attuned with sustainable design principles, also remains underexplored. Thus, offered in this collection is a comparison of the current systems which wrestle with the competing criteria of economic, social, and environmental considerations, with a validated multi-criteria model proposed. Finally, this section also examines BIM. Much has been said on the topic and in regard to the potential of BIM to lift construction productivity. However, here we present a paper that reveals BIM's capacity to integrate the digital technologies on which leverage of productivity is predicated.

A precis of the four papers comprising this first section is presented as follows:

The first paper "The Use of Energy Simulations in Residential Design: A Systematic Literature Review" underscores the importance of energy efficiency, examining how early-stage simulations can help optimize residential building design. By identifying critical design parameters and proposing a standardized nine-step framework, it aligns residential energy optimization with the United Nations' Sustainable Development Goal 11 for sustainable cities. The paper emphasizes how energy simulations can optimize designs early on, reducing energy consumption and enhancing environmental performance. The systematic review identifies gaps in standardized approaches, establishing a nine-step framework for integrating energy simulations into early design phases. These simulations are critical for sustainable urban densification, where efficient energy use can mitigate the environmental impact of growing cities.

The second paper "Overcoming Deterrents to Modular Construction in Affordable Housing: A Systematic Review" explores the deterrents to adopting modular construction in affordable housing, identifying key barriers, and proposing strategies for overcoming them. Modular construction holds great potential to reduce material waste, minimize environmental impact, and streamline construction processes, but as this study reveals, significant economic, regulatory, and technical barriers prevent widespread adoption. By highlighting the interconnections among various challenges, this study provides a strategic blueprint for promoting sustainable and cost-effective housing solutions.

Ma and Siddhpura [1] introduces a decision-making framework that evaluates structural systems based on economic, social, and environmental criteria using the Fuzzy Analytic Hierarchy Process (FAHP). The comparison of the innovative and traditional structural systems offers a guideline for selecting sustainable designs that balance multiple sustainability dimensions.

Finally, the fourth paper "Building Information Modeling Technology Capabilities: Operationalizing the Multidimensional Construct" of this section focuses on the digital transformation of the construction industry; this study operationalizes Building Information Modeling (BIM) capabilities as a multidimensional construct. It provides a robust framework for measuring and enhancing BIM's role in integrating sustainability across a building's lifecycle, facilitating informed decision making and efficient project management.

2.2. Advanced Applications and Modular Design Solutions

Building upon the foundational concepts, this section explores the advanced applications of sustainable practices with a particular emphasis on modular design and disaster resilience. It showcases innovative solutions that integrate sustainability with practicality and resilience.

Moving from the necessary theoretical abstractions to application is the focus of this second group of research. The theme of modular design is revisited, but this time in regard to the manufacture of inflatable cabins to be used in flood scenarios. The first paper in this section explores the added layer of 'green' considerations in the design of such life-saving innovations. Similarly, while Japanese construction expertise is widely recognized with respect to earthquake resilience, soil subsidence, and wind resistance, such as in typhoons, transferring such expertise to less capable nations represents a significant step in globalizing sustainability capacity. The second paper explores the transference of Japanese technologies to needy communities in impoverished Northern Vietnam. The third paper explores a more controversial problem; the suppression of vernacular construction practices at the behest of far-off governments, whose policies seek to homogenize national values. Here, the interests of minority voices are championed in alignment with the UN's Sustainable Development Goals that seek for 'inclusion.' The final paper in this section is a somewhat personal case study of single-house construction, which may easily be extrapolated to indicate the fundamental problem underlying building construction everywhere. That problem is the pervasive limited knowledge building designers, tradesmen, and regulators have that are ultimately essential to the success of the sustainable built environment mission.

A summary of the four papers comprising this second section is provided in the following:

Wang, Pan, and Liu [2] present a green, inflatable cabin for flood prevention utilizing a combined Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) analysis. By prioritizing design elements and developing spatial strategies, it offers a scalable solution for enhancing disaster resilience in urban environments prone to natural disasters.

Zhang, Li, and Komai [3] integrate Japanese construction techniques with the local conditions in Northern Vietnam. This empirical study enhances structural safety and disaster resistance. It demonstrates how tailored design approaches can optimize building performance in challenging geographical and climatic contexts, promoting sustainable and resilient construction practices.

The paper "Sustainable Construction through the Lens of Neoliberal Governance: The Case of Vernacular Building Systems in Catalonia, Spain" examines the impact of neoliberal governance on vernacular construction methods in Catalonia. It highlights the tension between expert-driven systems and traditional sustainable practices, emphasizing the need to preserve diverse building techniques that contribute to sustainable construction.

Finally, Wehbi and Messadi [4] delve into the pre-construction challenges and modular sustainable design solutions of a multi-generational Passive House. The paper provides insights into the gaps and barriers encountered, aligning with the advanced and innovative applications of the sustainable design principles explored in this section.

2.3. Structural Innovations and Energy Efficiency

Focusing on structural advancements and energy-efficient technologies, this section delves into the innovations that enhance the sustainability and performance of buildings. It explores how cutting-edge materials and structural designs can reduce environmental impacts and improve energy efficiency.

Improving the sustainable usage of concrete, which is both ubiquitous and at the same time environmentally costly, is a worthy research pursuit. Two papers in this section cover this theme. In the first study, the authors investigated a substitute for the declining availability of fly ash, which is used in processes such as cement manufacture. Here, the emphasis is on finding materials that might be recycled, one of which is waste clay brick powder. Though it is still environmentally impactful, if it is used in the right proportions, efficient results are obtained. The second study also investigates concrete optimization. Again, concrete and its negative impact on the environment is tackled. This time, the study reveals how concrete volumes in foundation members may be reduced with the use of suggested optimal retrofit detailing.

An overview of the two papers that comprise this third section is given as follows:

Sharmin, Biswas, and Sarker [5] explore the use of waste clay brick powder in geopolymer binders. This study assesses the economic and environmental benefits of recycling construction materials. The lifecycle analysis highlights the potential of waste clay brick powder (WCBP) to reduce environmental impact while maintaining mechanical strength, advocating for sustainable material reuse.

Finally, the paper "Investigation of Load-Bearing Capacity for Reinforced Concrete Foundation Retrofitted Using Steel Strut–Tie Retrofit System" presents an optimized steel strut–tie retrofit system for reinforced concrete foundations, significantly reducing foundation thickness and material usage. Through finite element simulations, it demonstrates how structural innovations can enhance load-bearing capacity while minimizing environmental and economic costs.

2.4. Energy Optimization in Extreme Climates

Addressing the unique challenges of energy optimization in extreme climatic conditions, this section presents solutions that balance thermal comfort, energy efficiency, and aesthetic considerations. It emphasizes the importance of adaptive strategies in regions with harsh weather patterns.

Often understood as the most pressing aspect of sustainable construction, energy usage remains a key research concern, and with that, heating and cooling. In this section, we present studies that address how energy use in buildings may be mitigated. The first study looks at redressing the poor thermal performance of office buildings in the remote city of Turpan, China. The researchers demonstrate that the three measures of energy consumption, carbon emissions, and lifecycle costs can all be reduced with the judicious use of intelligent systems. Similarly, in the second study, the author shows that the optimal use of adjustable blinds in the hot environment in Saudi allows architects to continue to favor glazed facades for aesthetic purposes while reducing ingress heat flow from 7.1 W/m^2K to as little as 4.2 W/m^2K. Overheating also proves to be a problem in the UK, especially in post-2012 terraces and flats. Reducing window area along with triple glazing reduces solar gains by 85%. The final contribution to this section explores the superior predictive quality in regard to the energy consumption of the author's predictive multi-head transformer model.

A synopsis of the four papers comprising this fourth section is offered as follows:

The first paper of this section "Prediction and Optimization Analysis of the Performance of an Office Building in an Extremely Hot and Cold Region" utilizes a Convolutional Neural Network (CNN) model to optimize energy use and reduce carbon emissions in an office building located in Turpan, China. Through multi-objective optimization and decision analysis, it provides a framework for enhancing building performance in regions with extreme seasonal temperatures.

The paper "Aesthetic and Thermal Suitability of Highly Glazed Spaces with Interior Roller Blinds in Najran University Buildings, Saudi Arabia" evaluates the thermal performance of highly glazed spaces equipped with dark-tinted double low-E glass and interior roller blinds in hot arid climates. It balances aesthetic appeal with thermal efficiency, offering insights into how architectural elements can mitigate heat gain while maintaining visual attractiveness.

Jariwala and Taki [6] address the rising risks of overheating in UK housing stock by employing Dynamic Thermal Simulations (DTS) to evaluate passive cooling mitigation strategies in modern flats. The findings highlight effective design modifications that significantly reduce solar gains and energy consumption, guiding policymakers to develop resilient housing strategies.

Zhao and Zhang [7] explores energy efficiency in photovoltaic-integrated buildings. Utilizing a hybrid optimization approach combining Particle Swarm Optimization (PSO), Support Vector Machine (SVM), and Non-dominated Sorting Genetic Algorithm II (NSGA-II), the author aims to reduce energy consumption, carbon emissions, and operating costs by optimizing building envelope and photovoltaic components. The results demonstrate a 41% reduction in energy consumption, 34% in carbon emissions, and 20% in retrofit costs over 25 years. Sensitivity analysis highlights the significant roles of window–wall ratios and photovoltaic elements in maximizing building efficiency, suggesting a sustainable model for energy optimization in building retrofits.

Finally, Oliveira and Oliveira [8] introduce a modified multi-head transformer model; this study enhances energy consumption forecasting accuracy, enabling more effective energy optimization in building operations. By outperforming traditional neural network models, it underscores the potential of advanced machine learning techniques in promoting sustainable and energy-efficient building practices.

2.5. Retrofit Strategies and Energy Efficiency in Urban Housing

The final section focuses on retrofitting the existing structures to improve energy efficiency and sustainability. It explores innovative tools and methodologies that facilitate the transition from traditional to sustainable building practices in urban settings.

This portion of the collection is the largest, with seven submissions. The first paper looks at retrofitting from a health perspective. While the economic benefits and energy consumption reduction benefits are well known, here the health benefits of retrofitting are examined. Second, in the section is a study on how the shadows cast by buildings impact the environment. However, computing the geometry of shadow movements to be cast by a proposed building has remained difficult to predict. Here, an adaptation of BIM is presented which can accomplish this. A third aspect of human comfort is that of indoor environmental quality as experienced in mass transit. The study presented here looks at aspects of the thermal, acoustic, and visual environment offered by Nigerian train cabins. The results, while revealing the sub-optimal quality of the tested trains, offer a framework for assessing similar environments in an effort to responsibly inform retrofits. The retrofitting of domestic houses is also examined, this time with the homeowners' limited budgets for doing so in mind. The authors explore a simulation tool that advises users of the cost–benefits and payback periods for any retrofitting option that may be considered. The fifth study also attempts to make complex applications available to novice users. This time, BIM modeling and simulation data are shown to be accessible to non-digital experts charged with improving the performance of the existing building stock.

A feature of a sustainable built environment that should not be neglected is its economic contribution, noting of course that this should not be achieved at the expense of the environment. The pursuit of economic development and environmental preservation often appears contradictory. Finding the optimal balance of one against the other is the subject of the sixth study presented in this section, where the commercial attractiveness of a three-star hotel was measured against the personal preferences of consumers. Finally, we have the most eclectic paper of the mix. Our final contribution examines food security, and specifically the fisheries of the Kavango-Zambezi, Africa. As might be expected, the findings reveal government policy, regulations, and enforcement to be far from adequate. However, again, the revelations of this one case hold lessons that may be extracted more broadly. Indeed, the take-away from each paper presented in this mix can be extrapolated far and wide to good effect; and this is their ultimate value.

An outline of the seven papers comprising this final section is provided as follows:

Benites-Aguilar and Marmolejo-Duarte [9] examine how residents' perceptions of health benefits influence their willingness to undertake energy retrofits. The findings reveal a low awareness of health co-benefits among less educated households, highlighting the need for policy interventions that promote both energy efficiency and public health.

Voivret, Bigot, and Rivière [10] introduce a novel solid clipping method by automating shadow geometry computations in BIM tools, facilitating the verification of solar protection measures. This innovation streamlines the integration of thermal regulations into the design process, enhancing energy conservation efforts in hot climates.

The third paper "Indoor Environmental Quality Assessment of Train Cabins and Passenger Waiting Areas: A Case Study of Nigeria" of this section focuses on indoor environmental quality (IEQ) in mass transit environments; this study assesses the air quality, thermal comfort, noise levels, and lighting in Nigerian train cabins. The results highlight significant IEQ deficiencies, emphasizing the need for sustainable design interventions in public transportation to ensure commuter well-being.

Algohary, Mahmoud, and Yehya [11] present a decision-making tool designed to help homeowners select optimal energy retrofit measures for gated communities. By prioritizing budgets, payback periods, and energy savings, the tool promotes informed and strategic retrofitting decisions that enhance energy efficiency and sustainability in urban housing.

The fifth paper "Building Information Modeling and Building Performance Simulation-Based Decision Support Systems for Improved Built Heritage Operation" of this section explores the integration of BIM and performance simulation technologies into decision support systems (DSSs). This study enhances the management and operation of built heritage. Making building data accessible to non-experts supports sustainable preservation efforts and informed decision making for energy performance improvements.

Sirirat and Thampanichwat [12] analyzes how architectural design and service factors influence consumer choices in the hospitality sector. By aligning aesthetic and comfort elements with sustainable design principles, it demonstrates how hotels can enhance customer satisfaction while promoting sustainability.

Finally, the last paper "Transboundary Fisheries Management in Kavango–Zambezi Transfrontier Conservation Area (KAZA-TFCA): Prospects and Dilemmas" underscores the broader implications of sustainable resource management on community well-being and environmental conservation. It connects to the book's overarching theme by highlighting the interdependence of sustainable practices across different sectors, including those beyond the built environment.

3. Conclusions

"Sustainability: Challenges and Opportunities to Optimize Building Performance" is a timely and essential resource for professionals, researchers, and policymakers in the fields of architecture, engineering, urban planning, and environmental management. As the world strives to meet ambitious sustainability targets, the insights and methodologies presented in this book offer valuable guidance for optimizing building performance across diverse contexts and challenges.

The relevance of this compilation lies in its comprehensive coverage of both foundational concepts and cutting-edge innovations in sustainable building practices. By addressing a wide array of topics—from energy simulations and modular construction to advanced forecasting models and retrofit strategies—the book provides a holistic perspective on the multifaceted nature of sustainability in the built environment. Moreover, the inclusion of case studies from different geographical regions emphasizes the global applicability of the research, fostering a cross-cultural understanding of sustainable practices.

In the current context, where sustainable architecture and building optimization are pivotal in mitigating climate change and enhancing urban livability, this book stands out as a critical tool for fostering informed decision making and promoting innovative solutions. It not only highlights the existing challenges but also illuminates pathways for overcoming them, empowering stakeholders to contribute to a more sustainable and resilient future for our built environment.

By weaving together theoretical insights, empirical research, and practical applications, "Sustainability: Challenges and Opportunities to Optimize Building Performance" serves as a cornerstone for advancing sustainable construction and architectural practices, ultimately contributing to the creation of healthier, more efficient, and environmentally responsible buildings worldwide.

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List of Contributions:

1. Sağdıçoğlu, M.S.; Yenice, M.S.; Tel, M.Z. The Use of Energy Simulations in Residential Design: A Systematic Literature Review. *Sustainability* **2024**, *16*, 8138.
2. Khan, A.A.; Amirkhani, M.; Martek, I. Overcoming Deterrents to Modular Construction in Affordable Housing: A Systematic Review. *Sustainability* **2024**, *16*, 7611.
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Systematic Review

The Use of Energy Simulations in Residential Design: A Systematic Literature Review

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Abstract: The Industrial Revolution and technological advancements have led to the densification and expansion of cities. In urban environments, residential buildings are common, and optimizing energy use in these structures is achieved by focusing on key parameters during the early design phases. These parameters can be tested through simulations. This study aims to define the scope of energy simulations in residential design to contribute to design optimization and reduce energy consumption. A systematic literature review and qualitative analysis were employed, using the PRISMA protocol for data collection and Vosviewer and Bibliometrix tools for bibliometric analysis. The keywords obtained were subjected to qualitative analysis. The research revealed the absence of a standardized approach in simulation studies. To address this, a nine-step framework has been proposed. A discrepancy between the objectives of certain studies and the keywords used was identified. Themes were created based on the studies' objectives, and keywords were recommended accordingly. Several studies have determined the energy potential of buildings during the occupancy phase. Simulations should be integrated into the early design phase to facilitate pre-design optimization. A framework for residential simulation methodology was developed, believed to enhance the validity of studies and facilitate result comparisons. Minimizing energy consumption is a primary objective in residential buildings. The recommendations developed align with the United Nations' Sustainable Development Goal 11: Sustainable Cities and Communities.

Keywords: energy simulation; EnergyPlus; DesignBuilder; sustainable development goals; energy efficient; thermal performance; HVAC; systematic review

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1. Introduction

Energy consumption in residential buildings represents a significant portion of daily energy demand. Energy efficiency is a critical concern across all sectors. Research and strategies intended to reduce energy consumption in residential buildings are crucial for sustainable development. This paper investigates the use of simulation techniques for energy management in residential buildings. The data indicate that energy consumption in residential buildings has reached substantial levels on an urban scale. It is anticipated that energy simulations based on the approach outlined in the study will contribute to reducing energy consumption in residential buildings, underscoring the paper's significance.

The Industrial Revolution has created a significant energy demand and environmental threats [1]. Since then, various concepts have emerged, and awareness of these issues has increased. Consequently, sustainability has become a part of national and international policies [2]. Globalization accelerated as the Industrial Revolution spread geographically and socially. The growth of the population has also increased societal needs [3]. Improved standards, a growing population, and an increasing number of dwellings have raised demands for energy [4]. All these developments have led to a rise in the urban population worldwide. The urbanization movement has impacted energy consumption, industrial processes, and waste management in cities [5–7]. Cities are essential for global sustainability [8,9]. Worldwide, cities are energy-intensive regions. Buildings currently account for 50% of total energy consumption, which is expected to increase to 60% in the near future [10,11]. Further, the building sector accounts for 19% of total greenhouse gas emissions [12,13]. Analyzing the morphology of cities reveals that residential buildings are the most critical and common building types [14].

The increase in the rate of urbanization worldwide and the advancement of technology have affected energy consumption behaviors in housing. Under changing circumstances, the occupancy phase generates the most carbon emissions in the building sector [15]. During the use phase, indoor environmental quality and user comfort have become prominent factors affecting energy consumption. As the comfort needs of users increase, maintaining the energy balance in residential buildings becomes more complex [16]. This comfort is provided through various equipment. The most energy-consuming installations are primarily HVAC equipment [17]. Therefore, heating and cooling are the most energy- and carbon-intensive operations during the use phase [18].

With the increasing number of housing units and urban populations, it is crucial to develop new approaches for sustainable development [19]. Energy-related decisions are key to the approach to be developed. The transition to renewable energy is inevitable [20]. Dealing with large-scale issues requires holistic approaches. Global energy challenges have promoted interdisciplinary studies [21]. Balocco et al. [22] indicated that the construction sector is critical in achieving sustainable, low-carbon energy in Europe [23]. Considering developing countries, this statement may also be applicable on a global scale.

Energy management in buildings is accomplished through a range of design strategies. These strategies can be validated through energy simulations. Energy simulations dynamically calculate the energy consumption of buildings [24]. From this perspective, energy simulations in residential buildings have been investigated. A common framework needs to be identified among the simulation studies reviewed. These differences in approach are explained further in the discussion section. In studies employing simulation in housing design, several discrepancies were observed based on parameters such as building status, zoning regulations, study objectives, and the type of simulation. This situation highlights the existing research gap. At the outset of the research, the rationale is determined: "The lack of systematic use of energy simulations in housing design." The research question was then defined:

RQ: "What is the range of applications for energy simulations in residential design?"

This study aims to define the scope of energy simulations in residential design to improve energy efficiency. In this context, the study targets identification of the role and application of energy simulations in architectural design. The hypothesis of this study is as follows:

Defining the scope of energy simulations in residential design will contribute to optimizing architectural design. Consequently, this can lead to a reduction in energy consumption in residential buildings.

This study applied a systematic literature review (SLR) method. SLRs are based on researching, collecting, evaluating, and processing current literature information [25]. The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) protocol was employed for data collection. Following the screening process, 97 studies were analyzed using Bibliometrix and VOSviewer for bibliometric data. Subsequently, a qualitative analysis was conducted on the keywords, and the studies were interpreted. Recommendations were made based on the identified deficiencies.

A roadmap for researchers in the field was provided based on bibliometric data and insights from the qualitative analysis. The fundamental concepts and emerging trends in the field are presented herein. The methodological deficiencies in the existing literature were examined using qualitative analysis. No comparable study on using simulation tools in residential buildings was identified. Thus, the original value of the study is demonstrated. The approach developed in this study stands out as a novel contribution to the field.

The introduction outlines the significance of the study, formulates the research question and hypothesis, and presents the aim, objective, contributions, and overall research flow. The methodology section of the study describes the methods and tools employed. In the findings section, the quantitative bibliometric data are presented. In the discussion section, the contents of the clusters obtained from the keyword co-occurrence analysis are analyzed, and two themes are formed. These themes are examined, and the deficiencies are identified. The results are provided in the conclusion section.

As a result of the study, an approach has been developed to determine the simulation parameters based on the building and the purpose of the research. This approach also provides a framework for data sharing within simulation methodology. Also, a suggestion has been developed regarding the methodology of the studies and the keywords used to increase their accessibility.

2. Materials and Methods

The method of this research is a systematic literature review (SLR). SLRs are based on researching, collecting, evaluating, and processing current literature information [25,26]. A research question was first determined at the beginning of the systematic literature review. Then, articles, papers, and book chapters written on the subject were collected within specific frameworks. Sources compiled from selected databases were analyzed in depth. Inferences drawn from the analyses were interpreted, and the results reported. As a result, existing knowledge is revealed, deficiencies are identified, and suggestions are provided for future research. The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) protocol was used for data selection in this paper (Figure 1). PRISMA ensures data uniformity and decreases bias in SLRs and meta-analysis studies [27]. This study, with ID number 586782, is registered in the PROSPERO (International Prospective Register of Systematic Reviews) database.

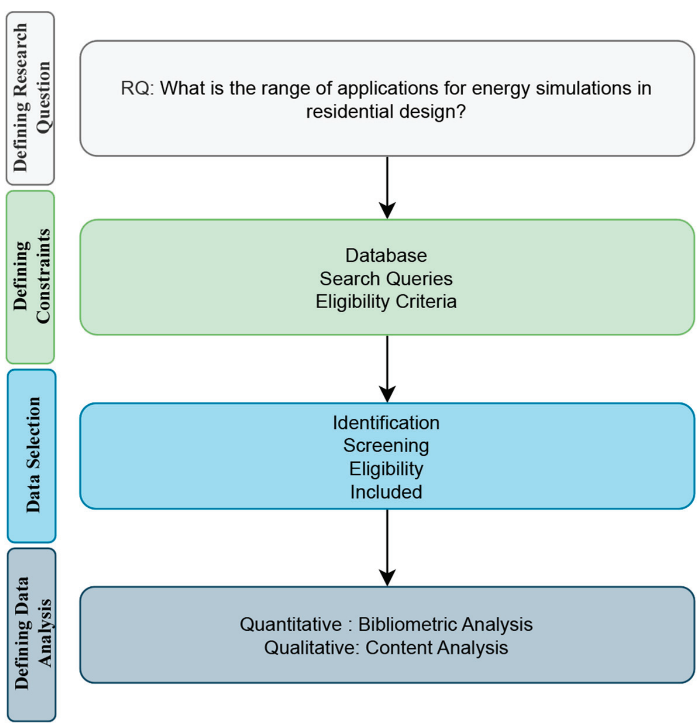

Figure 1. Study Workflow.

The study covers only the Web of Science database. As a consequence of the searches, it was observed that the database contains a sufficient number of studies in the field of architecture in terms of quantity and quality. Two separate search queries were conducted for data collection. These searches are as follows: In the first search, the terms “energy analysis” and “hous*” were used in the topic parameter. The second search was performed on the topic parameter and with the keywords “energy simulation” and “hous*”. The queries employed broad keywords. Two extensive searches were conducted to compile all simulation-related studies. All results are limited to the “Architecture” field from the” Web of Science Categories”, and no further limiting parameters were applied (Table 1).

Table 1. Literature Search Criteria.

Database	Web of Science (April 2024)
Search	-energy analysis (Topic) AND hous* (Topic) AND Architecture (Web of Science Categories) -energy simulation (Topic) AND hous* (Topic) AND Architecture (Web of Science Categories)
Time Period	No Restriction
Search Categories	Architecture
Document Type	Proceeding Paper, Article, Book Chapters, Review Article
Language	English

In the search for ‘energy analysis’, 168 proceeding papers, 158 articles, and seven book chapters were identified. For the ‘energy simulation’ search query, 145 proceeding papers, 105 articles, and two book chapters were retrieved. After eliminating duplicate entries, 492 studies were listed. Then, the abstracts, titles, and keywords of the studies were reviewed for eligibility based on the following criteria:

- Studies conducted in the field of architectural design;
- Studies on residential buildings;
- Studies that used computer simulation in energy analysis;
- Studies published in the Web of Science database and written in English.

After eliminating 395 entries, 97 studies were listed for review (Figure 2).

The issue addressed in the study is that energy simulations of residential buildings are not systematically employed. The Biblioshiny interface of the Bibliometrix application (R-tool 4.3.3) and VOSviewer 1.6.20 were utilized for quantitative analysis and visualization [28–30]. Bibliometrix (4.3.0) is an open-source software package designed for bibliometric analysis. It functions as a free plugin for R, a statistical programming language. VOSviewer is a free software tool for analyzing and visualizing bibliometric data. Bibliometric analyses were included in the quantitative findings section of the study. In the discussion section, clusters obtained from the co-occurrence keyword analysis were utilized. VOSviewer was used for the ‘co-occurrence of keyword analysis’, while the ‘most used simulation software’ and ‘annual scientific production’ were conducted manually. Bibliometrix was employed for the remaining bibliometric analyses. Figure 3 addresses the workflow of data analysis.

The content, methodology, and results of all of the studies were examined in the entire record, and clusters were analyzed. The clusters obtained with Vosviewer were validated by referencing the reviewed studies. Studies with common purposes, objectives, and results were classified under two themes at synthesis. The occurrence of clusters and the outcomes of studies within the same cluster were examined. Then, the studies were evaluated under two categories based on their shared and contrasting aspects in terms of content. In the content analysis, the current status and deficiencies of the themes were examined. The results are included in the discussion and conclusion sections to guide future research. The themes in the discussion section were built with clusters validated by references from the reviewed studies. The keywords of the 97 studies align with their themes and clusters. However, the contents of some studies are similar to each other. Some keywords refer to the same concept, leading to heterogeneity in keyword analysis. This challenge is analyzed in the following sections of the study, and solutions are presented in the conclusion.

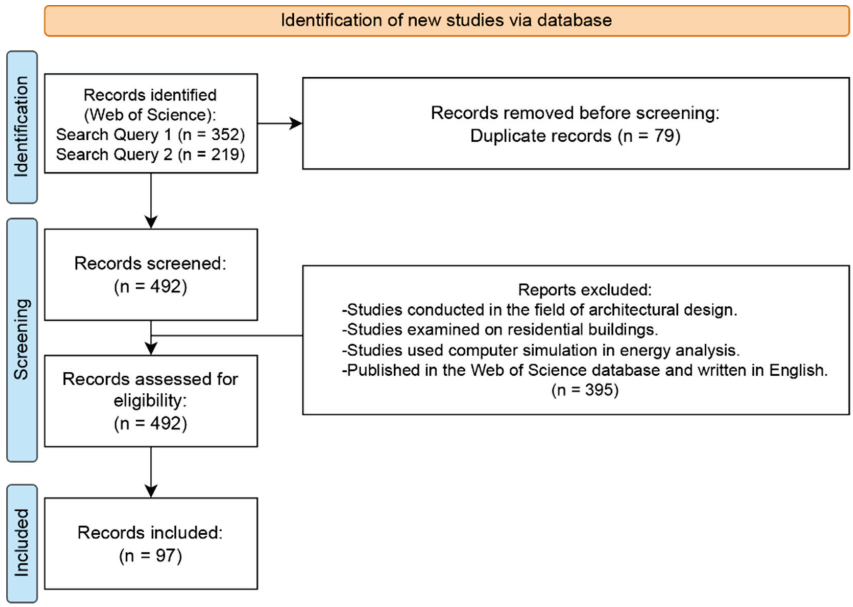

Figure 2. Data Selection Workflow (PRISMA).

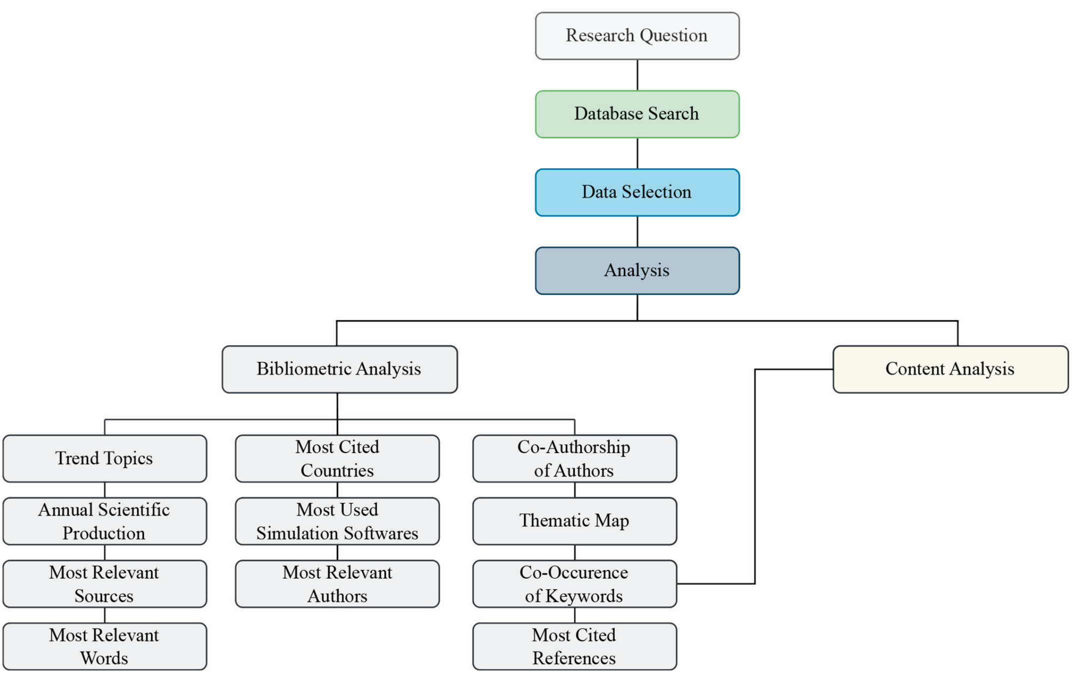

Figure 3. Data Analysis Workflow.

A further risk of SLR is the crossover between themes. The results of a study on one theme can become a research topic for another. While this may seem like a risk for bibliometrics, it does not pose a problem for energy simulations. While one study may focus solely on energy performance, another study may analyze the planning decisions that led to it in the same building. Simulation tools in architectural design are used in both directions.

All the studies examined in this SLR conducted quantitative measurements with simulation tools. The results were calculated using publicly available software packages. Researchers interpreted the results of these calculations. However, the simulation results do not introduce bias or uncertainty. This paper investigates the use of energy simulation tools. The contents and interpretation of the results are not included in the SLR. The themes, clusters, and types of energy analysis in all of the studies are combined and presented in a table.

The studies included in the review had no restrictions for the regions selected for field research. The authors in the studies detail the parameters such as climate data, local conditions, floor plans, and the software used. The information provided by the authors can be used to develop 3D models of buildings, execute simulations, and validate results when necessary. However, there is a lack of unity in data sharing regarding the energy consumption period and the unit of energy. Shared data have a unit conversion problem.

3. Findings

The bibliometric data collected in the study are presented in this section. The first study on the use of energy simulations in residential design was published in 2002. Then, 12 studies were conducted until the end of 2013, and the number increased in 2014 and thereafter. Between the beginning of 2014 and the end of 2020, 69 studies were published, and then interest began to decline. Although the number of studies conducted has decreased, the subject remains relevant. Studies on this subject can be divided into three phases. The first phase is 2002–2013, the second is 2014–2020, and the third is 2021 and later. The most productive period in these studies is the second phase (Figure 4).

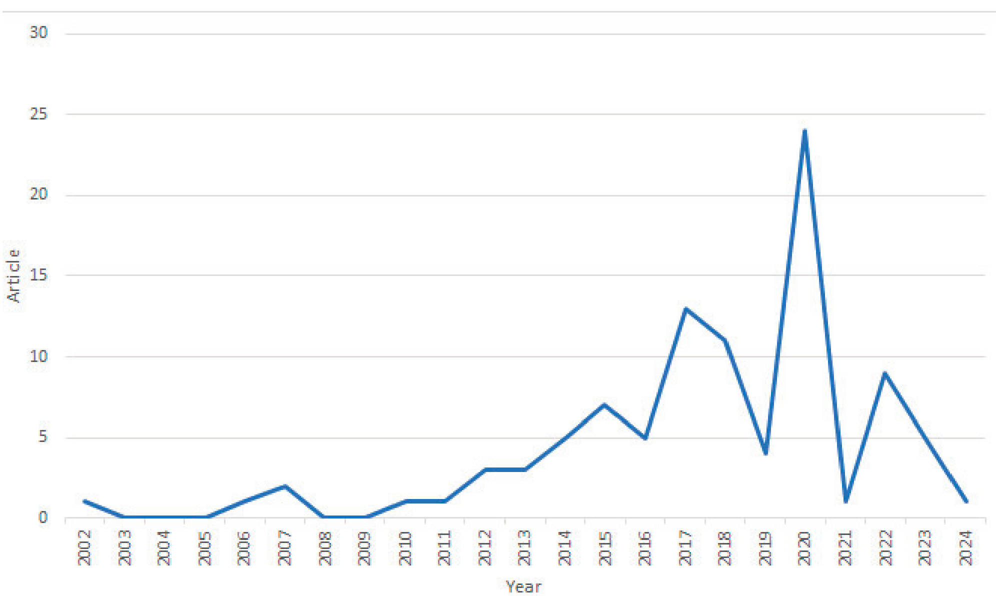

Figure 4. Annual Scientific Production Analysis.

Among the conferences containing the most studies, NSB 2017 (Nordic Symposium on Building Physics), 2020, and PLEA 2018 (Passive and Low Energy Architecture, Smart and Healthy Within the Two-Degree Limit vol1 and vol3) come first. *Architectural Science Review*, *Open House International*, *Journal of Green Building*, and *Frontiers of Architectural Research* are the journals where most of the articles were published (Figure 5).

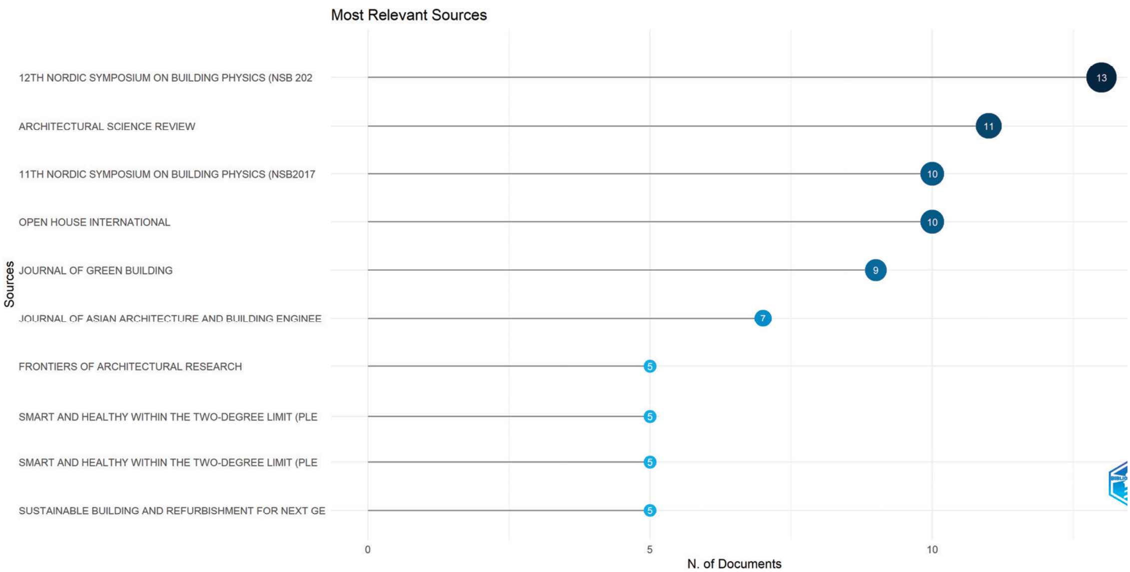

Figure 5. Most Relevant Sources of the Literature Review.

The authors focused on three main keywords: thermal comfort, energy efficiency, and thermal mass. These keywords were followed by words such as thermal performance and building energy. There is no severe decoupling between these keywords (Figure 6).

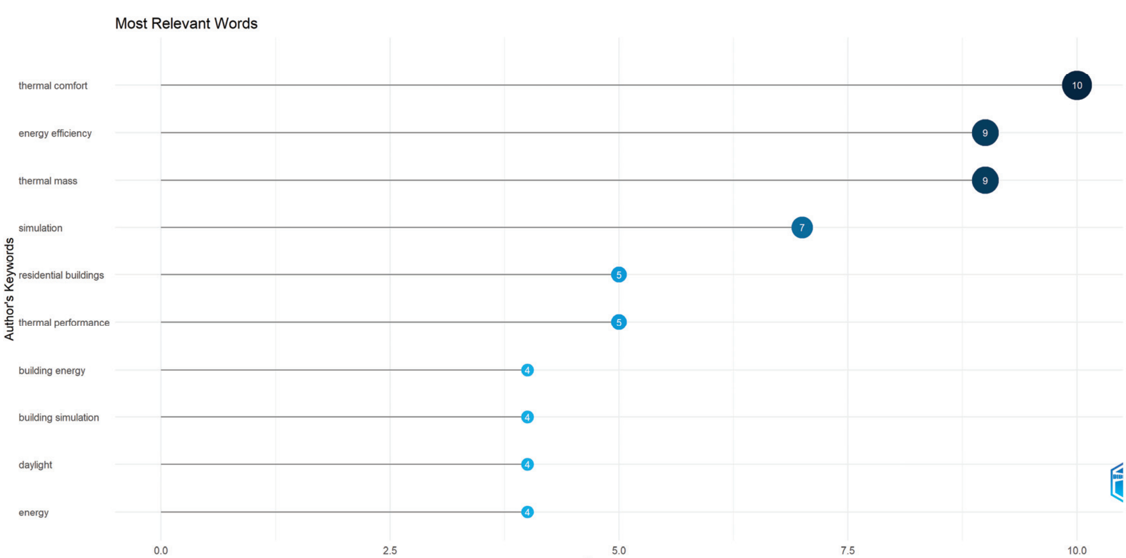

Figure 6. Most Relevant Words of the Literature Review.

For studies published in 2022 and later, the trending words are "CFD, data analysis, courtyard, and orientation". Beginning in the 2010s, "energy" has become one of the most widely used words over the long term. Trending terms such as "thermal performance" and "energy efficiency" have been replaced by keywords like "sustainability," "simulation," and "consumption." The analysis included the three most frequently used words for each year (Figure 7). "Energy," "sustainability," and "consumption" are three keywords that remained on the list for an extended period.

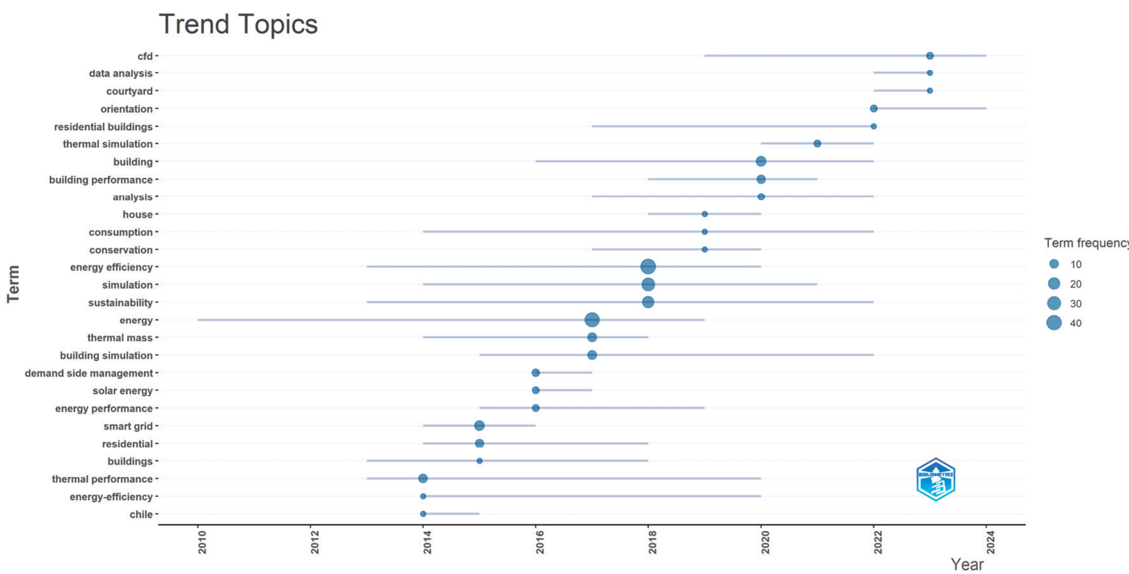

Figure 7. Trend Topic Analysis.

The figure highlights the countries with the highest number of studies. The image's bolded symbols represent countries with many scientific studies (Figure 8). The USA, China, the UK, Australia, and India are the leading five countries, respectively.

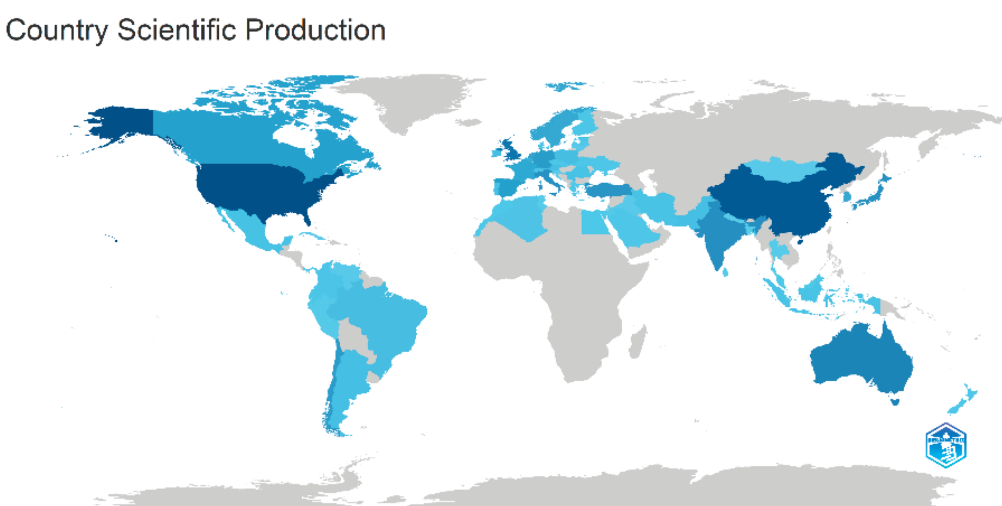

Figure 8. Scientific Production by Country in the Literature Review.

Table 2 lists the countries that received the most total citations among the studies analyzed in full record in the searches. Germany comes first with 592 citations. Four of the ten countries identified are located in Europe. Citations exhibit a global distribution pattern through their presence across various continents.

Table 2. Most Total Citations by Country.

	Country	Citation
1	Germany	592
2	USA	525
3	Peoples R. China	355
4	U. Arab Emirates	250
5	Australia	164
6	England	117
7	Canada	112
8	Switzerland	96
9	Japan	82
10	Turkiye	65

The simulation software that the authors used most is shown in Figure 9. Among the studies examined, the most used simulation software in architectural design is DesignBuilder. DesignBuilder serves as an interface to the EnergyPlus simulation engine. EnergyPlus is an open-source simulation tool capable of collaborating with other programs. They can perform simulations such as HVAC, lighting, and carbon calculations. DesignBuilder and EnergyPlus are followed by Ida-Ice (11), Ies Ve (8), Trnsys (5), Grasshopper (5), and various other programs.

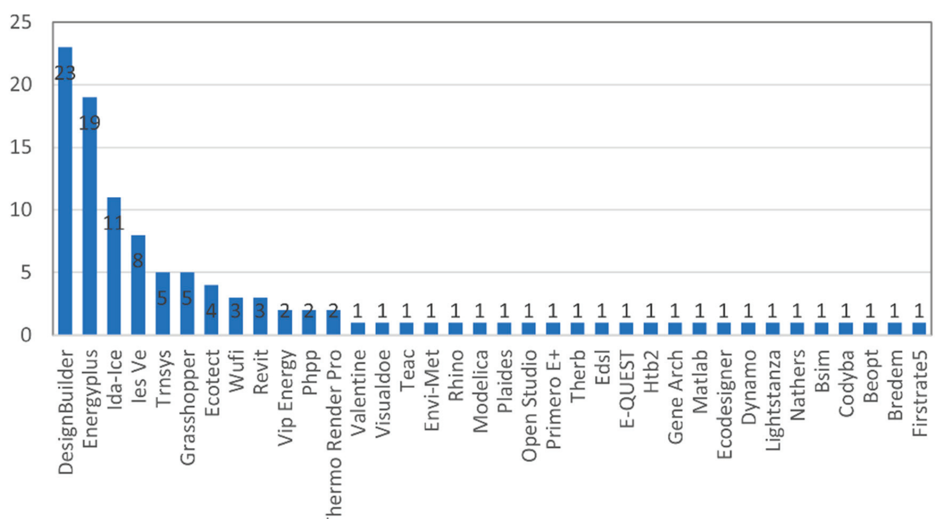

Figure 9. Most Used Simulation Software.

Among the 97 studies, the authors with the most publications were Kurnitski, J. (4) and Thalfeldt, M. (3). These authors are followed by people who have two works each (Figure 10).

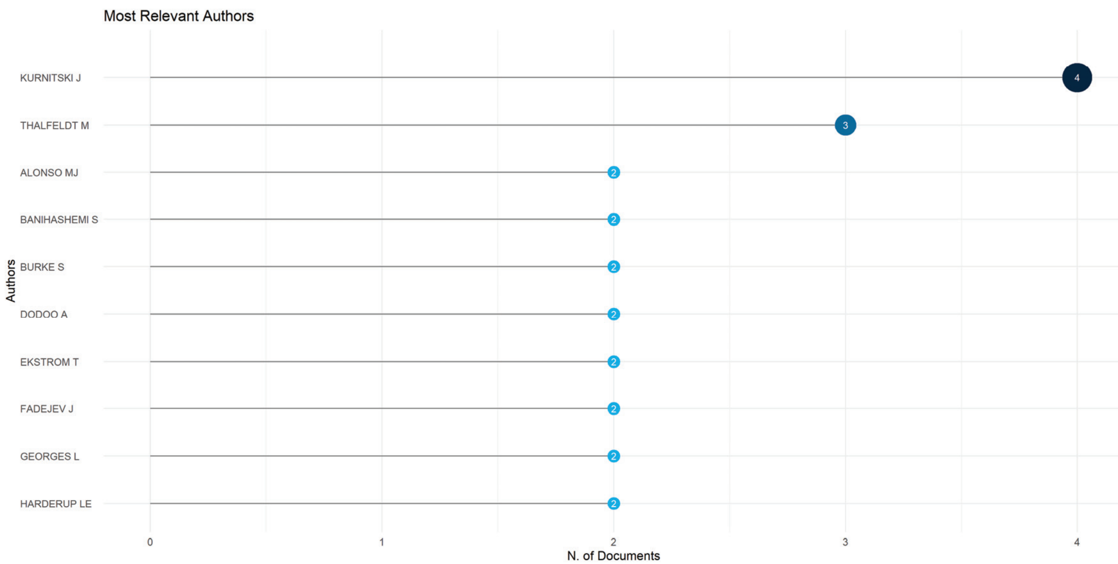

Figure 10. Most Relevant Author Analysis.

Kurnitski, Thalfeldt, Burke, Ekstrom, Fadejev, Harderup, and Simson collaborated the most. Figure 11 shows a network analysis of the authors.

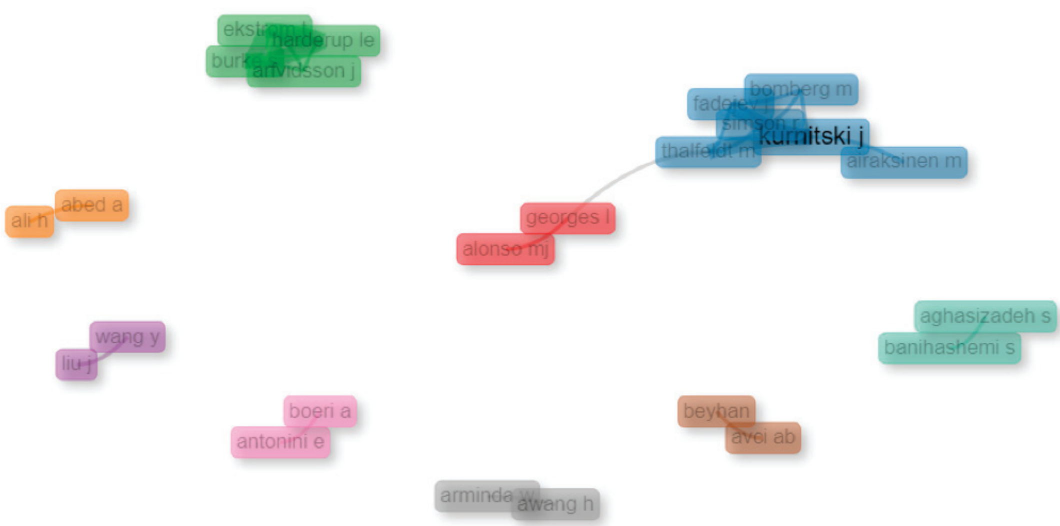

Figure 11. Author Collaboration Analysis.

Table 3 shows the most cited studies based on a complete record analysis of the listed sources. Nguyen [31] comes first with ten citations (Table 3).

The thematic map created from the analysis of the searches is provided in Figure 12. This analysis, conducted using Bibliometrix, examines studies by keywords and years and identifies the frequently used concepts. Concepts that show an emerging or declining trend appear as “monitoring” and “energy consumption”. The vertical development axis indicates popularity in the lower left area, where the keyword “monitoring” appears to rise, while "energy consumption" shows a downward trend. The concepts of "sustainability", "simulation" and "thermal performance" are the main study areas of this topic. All studies are theoretically grounded in these concepts. Motor concepts are the driving forces behind contemporary research. The current literature focuses on "Orientation" and "energy efficiency". Niche work areas include the "passive house", "natural ventilation", and "smart grid" keywords. Researchers conducting new research on this subject should focus on niche themes and know the basic themes.

Table 3. Most Local Cited Authors.

	Cited Reference	Number of Citations
1	Nguyen At, 2014 [31]	10
2	Crawley Db, 2008 [32]	8
3	De Wılde P, 2014 [33]	8
4	Pérez-Lombard L, 2008 [34]	8
5	Anna-Marıa V, 2009 [35]	7
6	Grıego D, 2012 [36]	7
7	Roudsarı Ms, 2013 [37]	7
8	Bustamante W., 2009 [38]	6
9	Caetano I, 2020 [39]	6
10	Coakley D, 2014 [40]	6

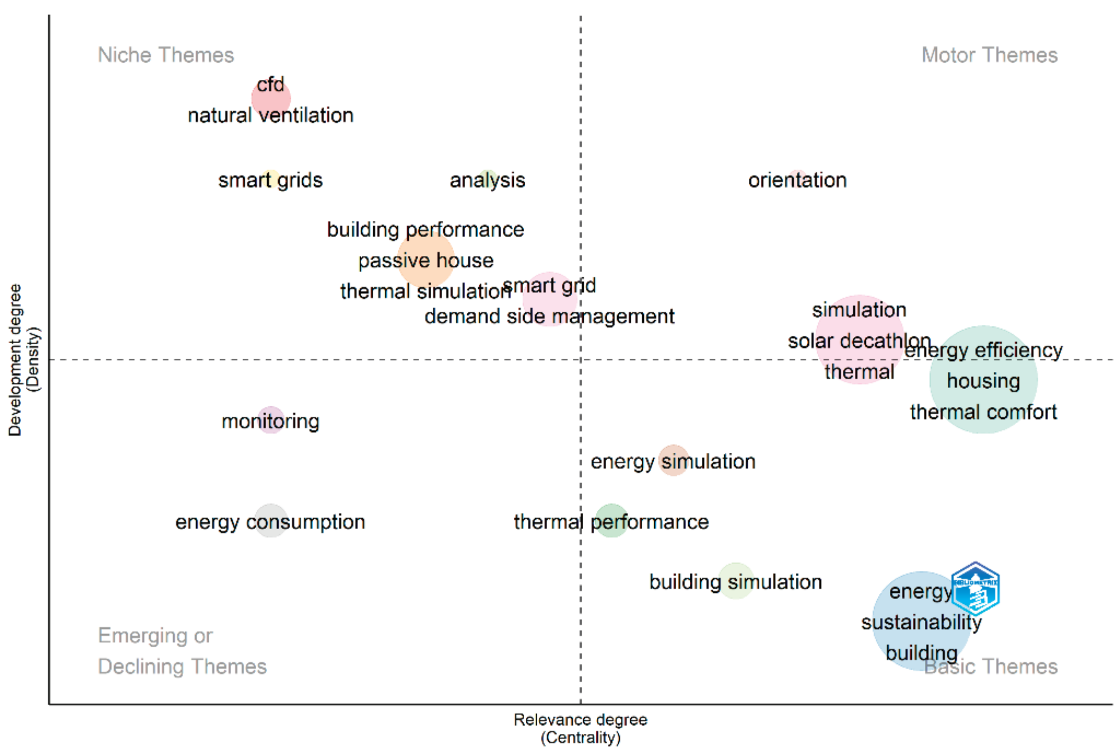

Figure 12. Thematic Map Analysis.

Figure 13 shows the co-occurrence analysis of the keywords used in the studies. This analysis shows which sub-areas of energy simulation the studies are concentrated on. The clusters formed from the analysis reveal which research methods were used in the studies.

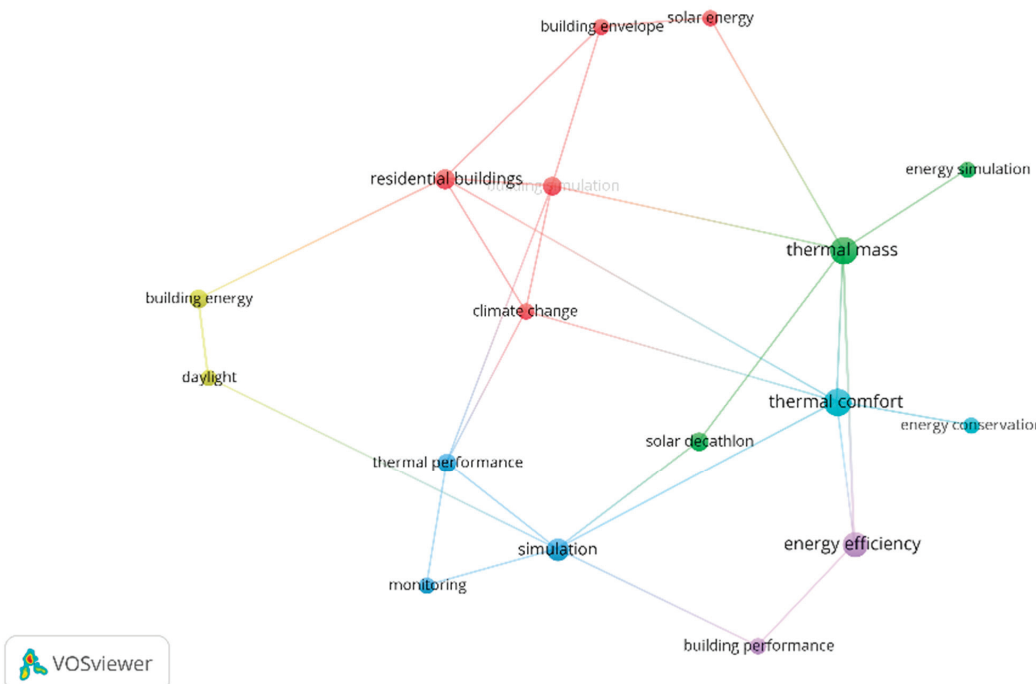

Figure 13. Co-Occurrence of Keyword Analysis.

Table 4 indicates clusters formed by keywords used together. The minimum occurrence threshold of a keyword was set to three.

Table 4. Cluster from Keyword Analysis.

Cluster	Keywords
1	Building Envelope Building Simulation Climate Change Residential Buildings Solar Energy
2	Energy Simulation Solar Decathlon Thermal Mass
3	Monitoring Simulation Thermal Performance
4	Building Energy Daylight
5	Building Performance Energy Efficiency
6	Energy Conservation Thermal Comfort

4. Discussion

The quantitative data of the research are interpreted in this section. Clusters and sub-themes from the keywords in Table 4 were defined. Studies conducted within these thematic frameworks are examined below.

4.1. Cluster I

The keywords in the first cluster are "building envelope", "building simulation", "climate change", "residential buildings", and "solar energy". Studies focused on building envelopes are interpreted as studies on materials science in architecture. These studies investigate the impact of construction material selection on energy efficiency. Different materials and different detail design phases are compared with computer simulations. These comparisons may include renovation or usage phases of existing residences, as well as newly designed residences [41–45].

The building simulation keyword primarily focuses on the functions of buildings and their overall energy consumption. Climate change studies make predictions based on best- and worst-case scenarios. The significance of these studies is to make designs according to the predictions of climate conditions. Forecasted climate conditions are determined with climate data on previous years and mathematical equations [46,47].

The solar energy keyword represents the utilization of renewable energy in architecture. Renewable energy sources that impact the designs of residential buildings are defined as solar and wind energy. These studies aim to assess the effects of parameters such as daylight, sunshine duration, shading elements, prevailing wind, and natural ventilation on the design. The optimal utilization of these variables is intended to increase energy efficiency [48].

4.2. Cluster II

Studies with the "Energy simulation" and "thermal mass" keywords concentrate on the heat transfer between indoor and outdoor environments. In this context, "Energy simulation" includes calculating heat transfer. While the concept of "thermal mass" seems closely related to building material science. The primary studies in this cluster concentrate on the energy difference between indoor and outdoor spaces. The definition of energy simulation includes all simulation types, such as heating, cooling, ventilation, and lighting. The concept of thermal mass explains the relationship between all the energy in the building and its surrounding outdoor space. These studies are generally the subject of building physics. The objective of simulations is to compare design alternatives and provide optimization. While the selection of building materials remains a parameter in these simulations, factors such as form design, courtyards, and atriums are among the basic parameters in the design process [49–52].

The Solar Decathlon is an annual student design competition focused on clean energy. Teams participating in competitions turn their research into scientific studies and publish them in various journals. The works submitted to the competition appear to focus on "energy simulation" and "thermal mass" [52,53].

4.3. Cluster III

The keywords in this cluster are used in studies primarily focused on measurements and calculations. These studies are categorized into two groups. Simulation measurements are sufficient in cases where all the building materials are known [54,55]. The thermal conductivity coefficients of materials are defined using software, and the measurements are then verified. Simulation measurements must be verified in the field in cases such as those of historical buildings. Temperature measurements are employed in cases where building materials cannot be precisely determined. These measurements are conducted periodically, and the results are compared [56]. Studies in this cluster focus on the use of information technologies in architecture. As a result of these measurements, the thermal performance of the buildings can be evaluated. Studies in this field are usually based on thermal performance comparisons [57–61].

4.4. Cluster IV

Daylight is one of the critical parameters affecting architectural design [62]. A holistic approach is necessary for "building energy" and "daylight" in the design process. Space and façade orientations, façade width, window-to-wall ratios, lighting design, heating and cooling energy, and shading elements are design inputs affected by daylight. Daylight impacts building energy in various ways [63,64]. The sun is a renewable energy source, and using natural light enhances the energy efficiency of buildings. Lighting design influences both visual comfort and electrical energy usage [65–67]. "Building energy" refers to all the energy usage of buildings. The building energy model is used to analyze energy consumption in buildings. Studies in this cluster concentrate on building energy consumption and daylight analysis [68].

4.5. Cluster V

The terms 'building performance' and 'energy efficiency' have been employed in studies comparing the energy usage of buildings or design alternatives. In this context, the keyword "building performance" refers to energy performance. A building's energy usage is intended to be reduced according to sustainability targets. To assess whether these targets have been met, specific indicators are necessary, and design criteria are required to make comparisons with these indicators [69–71]. The most common comparison method involves sustainability assessment systems utilizing the LCA model (BREEAM, LEED, DGNB, etc.). In these comparisons, indicators of certain sub-criteria can be accessed with simulation tools. For example, if annual heating data in a residence is considered an indicator, the simulations provide a quantitative comparison for two design scenarios [72]. Building performance and energy efficiency comparisons can be made through simulations and indicators such as daylight, heating, cooling, lighting, carbon emissions, and zero-energy targets. However, while carrying out these studies, it is essential to define targets, criteria, and indicators [73–75].

4.6. Cluster VI

The studies with the keywords "Energy conservation" and "thermal comfort" focus on protecting energy in indoor spaces. These studies involve comparative strategies on energy in architectural design. These comparisons focus on energy losses and gains [76]. Loss and gain data are calculated through simulations. Additionally, simulations can provide data on perceived temperature, relative humidity, and airflow as inputs for thermal comfort analysis. Energy costs directly affect thermal comfort [77,78]. High energy costs can reduce indoor environmental quality. Therefore, comfort achieved at less cost is essential for users. Improving the quality of indoor environments is also beneficial for users' health. However, user habits are a crucial parameter for thermal comfort [79]. Various methods are used to collect user data. These methods include analyzing invoiced energy consumption or collecting user data through questionnaires. Defining the variables to be compared is crucial for the validity of the studies [80].

Table 5 summarizes all the reviewed studies. The themes and clusters shown in Table 5 are explained in the discussion section. Theme 1 refers to "energy efficiency", and Theme 2 refers to "architectural design strategies".

Studies included in the SLR are only from the Web of Science database. Upon analyzing the clusters and themes, it was observed that the database contains sufficient studies for meaningful results. The study focuses only on residential buildings. Therefore, the conclusions and recommendations apply only to housing structures. The findings presented in this paper are solely based on the study of architecture. The results are primarily related to architectural design but apply to interdisciplinary studies. The clusters and themes of the review are shown in Figure 14.

Table 5. Summary Information from Included Studies.

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[81]						•		•	Designbuilder	Heating, Cooling, CO_2
[82]				•				•	Designbuilder	Daylight
[72]					•		•		Ecodesigner, Firstrate5	Thermal Load
[83]		•		•				•	Designbuilder	-
[75]					•		•		Energy+	Heating, Cooling
[66]				•				•	Beopt	Heating, Cooling
[84]					•		•		Ies Ve	CO_2
[67]					•			•	Revit	Daylight
[85]						•		•	Designbuilder	Thermal Comfort
[69]					•		•		Designbuilder	Thermal Load
[43]	•						•		Valentine	Heating, Cooling
[53]		•						•	Pleiades	Thermal Load
[44]	•						•		Ida-Ice	CO_2
[86]	•						•		Designbuilder	Heating, Cooling
[50]		•						•	Gene Arch	Heating, Cooling, Lighting
[87]		•						•	Grasshopper, Dynamo	Daylight, Thermal Load
[88]	•						•		Trnsys	Thermal Load
[58]			•		•		•		Energy+, Heliodon, Analysis Bio	Thermal Comfort
[59]			•				•		Codyba	Thermal Comfort
[89]	•						•		Nathers	Thermal Comfort
[51]		•				•		•	Rhino, Envi-met	Thermal Comfort
[90]						•		•	Energy+	Heating
[70]	•				•		•		Ida-Ice	Thermal Load
[74]	•				•		•		Ida-Ice	Heating, Cooling
[60]			•		•		•		Ida-Ice	Heating, Cooling
[91]					•		•		Designbuilder	Thermal Load
[92]			•				•		Ecotect	Heating
[56]			•				•		Designbuilder, Energy+, Revit	Thermal Load
[93]			•				•		Ida-Ice	Thermal Comfort
[42]	•						•		Designbuilder	CO_2
[49]					•		•		Ies Ve	Thermal Load
[65]				•				•	Vip Energy	Daylight
[62]				•				•	Revit	Thermal Comfort
[94]	•		•				•		Energy+	Thermal Load
[63]		•		•				•	Trnsys, Energy+	Heating, Cooling
[76]				•				•	Energy+	Thermal Load
[80]						•		•	Primero, Energy+	GHG
[95]					•		•		Phpp	Thermal Comfort
[79]						•		•	Ies Ve	Thermal Comfort
[41]	•						•		Open Studio, Energy+	Thermal Load
[96]						•		•	Htb2	Thermal Load
[97]					•		•		Energy+	Heating, CO_2
[45]	•						•		Ies Ve	Heating, Cooling, CO_2
[78]						•		•	Ecotect	Thermal Comfort

Table 5. *Cont.*

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[98]					•		•		Matlab	Thermal Comfort
[99]	•				•		•		Designbuilder	Thermal Comfort
[100]		•						•	Phpp	Heating
[101]					•		•		Therb	Heating, Cooling
[102]			•				•		Thermo Render Pro	Heating, Cooling
[103]					•		•		Bredem	Thermal Load
[104]	•				•		•		Designbuilder	Thermal Load
[105]	•						•		Designbuilder	Thermal Load
[68]				•				•	Grasshopper	Heating, Cooling
[55]			•				•		Visualdoe	Heating, Cooling
[106]	•				•		•		Designbuilder	Heating
[107]	•						•		Designbuilder	Thermal Load, CO_2
[108]	•						•		Wufi	Heating, Cooling
[109]	•				•		•		Trnsys	Heating, Cooling
[110]					•		•		Ida-Ice	CO_2
[111]	•						•		Energy+	Heating, Cooling
[112]	•						•		Bsim	Thermal Comfort
[113]	•						•		Wufi	Thermal Comfort
[114]		•				•		•	Energy+	Thermal Load
[115]					•		•		Trnsys	Thermal Load
[116]	•						•		Ida-Ice	-
[64]		•		•				•	Energy+	Thermal Comfort
[61]			•		•		•		Designbuilder	Heating
[52]		•						•	Energy+	Thermal Load
[47]	•		•				•		Ecotect	Thermal Comfort
[71]					•		•		Ida-Ice	Heating
[117]	•						•		Ies Ve	Heating, Cooling
[118]	•						•		Designbuilder	Daylight
[119]				•				•	Designbuilder	Heating, Cooling
[120]				•				•	E-quest	Thermal Load
[48]	•						•		Lightstanza	Daylight
[121]						•		•	Grasshopper	Thermal Comfort
[122]					•		•		Energy+	-
[123]			•				•		Ies Ve	Cooling
[124]			•				•		Vip Energy	Heating
[54]			•				•		Ida-Ice	Heating
[125]	•						•		Designbuilder	Thermal Comfort
[126]				•				•	Designbuilder	Thermal Load
[77]						•		•	Trnsys	Thermal Comfort, Cooling
[127]					•		•		Designbuilder	-
[57]	•		•				•		Modelica	Heating, Cooling
[128]	•						•		Ies Ve	Thermal Load
[129]			•				•		Designbuilder	Thermal Comfort
[130]	•						•		Thermo Render Pro	-

Table 5. *Cont.*

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[131]					•		•		Wufi	Thermal Load
[132]					•		•		Ecotect	Lighting, Ventilation
[46]	•				•		•		Ida-Ice	Heating, Cooling
[133]					•		•		Energy+	Thermal Load, Daylight
[134]	•				•		•		Grasshopper	Thermal Load
[135]					•		•		Designbuilder	Heating
[136]					•		•		Energy+	Thermal Load
[73]					•		•		Teac, Energy+	GHG

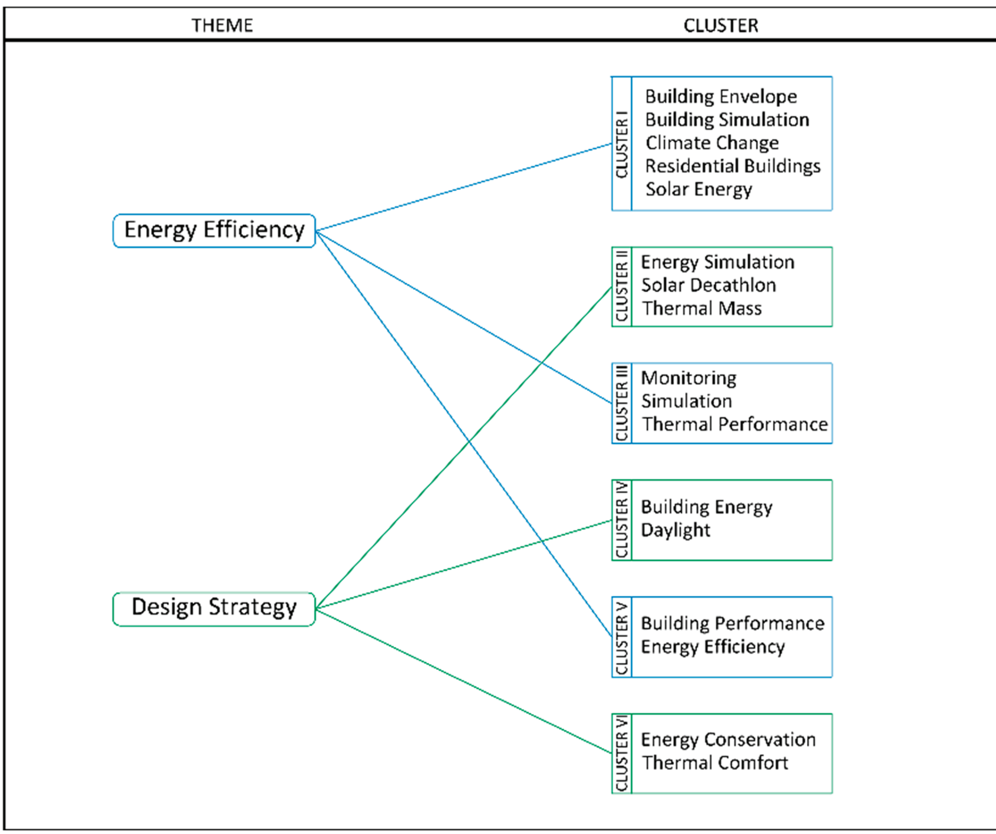

Figure 14. Themes and Clusters of SLR.

4.7. Theme 1 Energy Efficiency

Studies on this theme focus on energy performance. Keywords such as building envelope, building simulation, climate change, residential buildings, solar energy, monitoring, simulation, thermal performance, building performance, and energy efficiency constitute this theme. The studies in this theme center on comparing buildings based on specific indicators. Research questions relate to whether building energy efficiency targets are being met.

Energy efficiency is one of the critical criteria of sustainability goals in architecture. Once these goals are set, measuring the results becomes crucial. At this stage, energy analysis plays a critical role. Energy simulations allow the determined parameters to be calculated in a digital model. Calculating energy consumption data before construction provides a significant advantage for measuring targets and comparing the performances of buildings. The primary objective of studies on energy efficiency theme is to measure and compare the energy performances of buildings using simulation analyses [94,98,104]. These analyses are performed with various criteria.

Building materials and insulation details significantly impact building energy performance. Building materials can be modified without changing the design of the buildings. Monitoring the energy consumption of buildings with different materials is possible through energy simulations [111,113]. These simulations can ensure that the most suitable materials are selected before the construction process begins.

Another advantage of energy simulation is the ability to change environmental data. This enables the prediction of the energy performance of buildings under various climatic conditions [46,86,121]. Energy simulations can determine the effects of factors such as climate, daylight, and materials on building energy performance. Energy simulations are a crucial tool for setting targets and policies in the construction sector. Utilizing simulations for energy performance assessment is essential. Optimization of energy consumption should be achieved through simulations before the construction phase.

4.8. Theme 2 Architectural Design Strategies

This theme investigates the inputs affecting architectural design. It attempts to identify the elements that reduce energy consumption and shape the architectural design. Methods that provide energy efficiency in architecture are categorized into active and passive strategies. In passive strategies, natural resources are utilized without energy consumption [137]. In active strategies, energy efficiency is achieved through specific equipment. An initial investment and energy are required to install these systems. Examples of active methods include heat pumps, solar panels, and HVAC systems.

Passive methods are highly suitable for urban-scale applications. Energy simulations offer the opportunity to compare these design strategies [62,105]. This optimizes buildings for energy consumption before the design phase and increases user comfort and indoor environmental quality. This positively impacts user health and provides economic benefits. Achieving comfort with fewer resources contributes to sustainable development and economic sustainability. The widespread implementation of passive strategies, tested with energy simulations, in residential areas is crucial for the national and global economy.

The total energy within a building is directly related to the design of its components. The space syntax shapes terms such as thermal mass, thermal comfort, and energy conservation. Parameters such as atriums, courtyards, balconies, terraces, circulation areas, and building form affect energy conservation [78,109,118]. Environmental factors such as daylight and wind influence these parameters. Design inputs, including building orientation, wall-to-window ratio, space orientations, and setbacks, are directly related to energy conservation [83,121,126]. All these components should be designed with an integrated approach, in which simulation is essential.

Many countries have legal obligations or classifications regarding consumption related to energy savings targets. However, in most cases, these regulations concern the usage phases of buildings. The potential for energy savings in operational buildings has been identified in the reviewed studies [42,51,109]. Energy simulations must be integrated into the early stages of architectural design. This approach optimizes the inputs affecting energy consumption during the architectural design phase. However, specific workflows must be established to ensure this integration. These workflows are the subject of future work. Steps should be determined according to architectural design stages. To illustrate, specific limits can be set for annual energy consumption or carbon emission values. Compliance with these limits can be verified through energy simulations before construction begins.

New buildings that comply with energy policies can obtain construction permits in this way. This system could lead to a significant reduction in energy consumption, especially in developing countries.

4.9. Section Summary

The research and analysis have revealed a need for a standardized approach in studies that employ simulation software for residential design. The decision-making processes in the studies are correct and adequate; however, the decision procedures are not explained in sufficient detail, resulting in uncertainties. The authors' approaches in this regard were analyzed.

Studies [57,62,71,123,128] examine parameters such as daylight, wind, and shadow, which must be simulated at the inter-building scale. However, the authors did not identify this as a limitation or disclose their simulation models. Modeling the buildings and their immediate surroundings is essential to achieving accurate results concerning these factors. This does not imply that the studies discussed here overlooked the issue; however, not sharing this information introduces uncertainty for readers.

Gado and Games [92] measured 24 days during the hottest period of the year to verify their simulation results. They conducted an annual simulation to assess the overall energy performance in the study. This raises question of why the design day method was not used. The authors must have determined that 24 days of monitoring were sufficient. However, a specific explanation must be provided for the discrepancy between the monitoring and simulation periods. Yao and Zang [133] conducted annual simulations of energy performance, thermal load, and glare for a hot summer and cold winter climate zone. The scope of the study is also consistent with the design day method. However, the authors did not explain their choice of annual simulation.

Eikemeier et al. [90] examined the optimization parameters of heating, shading, natural ventilation, and daylighting through two scenarios. The study includes conceptual designs rather than an analysis of an existing building. However, it needs to be specified why only two scenarios were considered, or why specific scenarios were not developed for each parameter. The scope of the simulation was probably sufficient for the authors' aims and objectives; however, the adequacy of using only two scenarios for multiple factors should be demonstrated with evidence in the study.

Bustamante [86] evaluated the energy performance of retrofit proposals across nine scenarios. They proposed changes to the floor plans, provided that the main features of the houses remained intact. However, the rationale for not utilizing parametric design tools still must be explored. The likely rationale for this is that the genetic algorithm generates many scenarios, and the authors sought to limit the scope. However, the authors should provide more comprehensive details on the selection of simulation type and software.

Ibiyeye et al. [79] evaluated natural ventilation using annual simulations in their study. They simulated the periods during which the windows were left open using only two scenarios: 06:00–22:00 and continuously throughout the day. The decision process for this duration and the number of scenarios should be clearly explained. This will help address how varying weather conditions influence ventilation during the night and across different seasons.

In their study, Taki and Alabid [122] assessed energy performance during the summer months. However, details regarding the building materials utilized in the simulation were not provided. Details regarding the building envelope are crucial for assessing energy performance, and this information needs to be shared clearly with the readers. Mousa et al. [109] specified the simulation inputs in their study, but they still needed to provide the thermal conductivity coefficients of the building materials.

To address these uncertainties, structured workflows should be established. The simulation methodology, along with the aims and objectives of the studies, should be clearly explained. This approach should encompass the entire process, from selecting the study area to attaining the simulation results. The proposed process comprises nine steps, with decision stages arranged from general to specific (Table 6).

Table 6. Proposal for a Methodological Framework for Simulation-Based Research.

1	Location	Determination of the study area.
	Environmental data Climate data	The study area determines the environmental data at this stage.
2	Typology	Analyzing the typology of the building.
	Block layout Detached layout Apartment	Typology affects parameters such as the form of buildings and their relationship with each other. The variations exemplified here can be further multiplied.
3	Scale	Determining the scope in which the building will be approached.
	Housing scale Scale between housing units Neighborhood scale	The accurate determination of the analysis scale is crucial for selecting the appropriate simulation type and ensuring the reliability of the results. The simulation to be employed will be selected based on the building form, environmental data, and typology.
4	Phase	Defining the stage of intervention in the building.
	Use Early design Retrofit	Properly defining the phase to be analyzed is essential for choosing the simulation type and ensuring reliable results.
5	Materials-Equipment	Defining the systems and materials used in the building.
	Building envelope HVAC Shading Domestic hot water	The structural elements have a direct impact on the simulation outcomes. To achieve an effective result, these systems must be accurately defined. The examples provided here can be expanded.
6	Target	Determining the target of the obtained data for the result of the analysis.
	Energy savings Design optimization Comfort	Determining the study's objective is essential for selecting the type of analysis to be performed. Selecting the appropriate type of analysis and providing justification will enhance the accuracy of the results.
7	Simulation Scope	Determining the scope of the simulation.
	Existing situation analysis Generate scenarios Genetic algorithm	Determining the simulation method according to the study content will enhance the reliability of the study.
8	Analysis Period	Determining the simulation period.
	Annual/monthly Daily/hourly Design day	The determination of the analysis period narrows the scope of the results, enables clear outcomes, and also plays a role in the selection of the software to be used.
9	Software and Analysis	Determination of the software and simulation type.
	DesignBuilder EnergyPlus IES VE	Sufficient data have been collected to select the most appropriate software and analysis for the study's context and objectives. The energy unit in which the results will be presented should be clearly specified at this stage.

At the end of each stage, decisions are systematically made to ensure the selection of a simulation that aligns with the study's objectives and intended outcomes. Presenting this process transparently, along with its underlying rationale, is essential to highlight the similarities and differences with other studies in the literature. This will enhance the accuracy of the results and facilitate researchers' access to and comparison of results.

The lack of data sharing methodology in simulation studies can lead to misclassification of studies. The inappropriate use of keywords may mislead readers when previewing the work. Due to the complexity of the content, clearly distinguishing study topics can be very difficult. Keywords often have very similar definitions, and it is possible for multiple keywords to express the same concept. For this reason, it is crucial to determine and distinguish titles and keywords according to the content of the study. For instance, keywords such as daylight and solar energy, as well as thermal comfort and thermal performance, belong to different clusters and themes. But the content of the studies with these keywords is very similar. The studies can be classified under one theme in terms of content, but under another theme in terms of keywords. References [55,118,136] use the keyword "daylight," which is associated with theme 1; however, the studies themselves are related to design strategy and are categorized under theme 2. References [69,99,105,109] have selected the keyword "thermal comfort," belonging to theme 2, but the research content aligns with theme 1. The keywords and themes suggested in Figure 14 can be utilized to mitigate this confusion.

5. Conclusions

The study's findings indicate that energy simulations should be integrated into the early phases of architectural design. This will prevent the loss of energy-saving potential, as observed in buildings already in use. Incorporating this process into the building permitting procedures will enable better control to achieve regional energy targets. The establishment of this integration process will be the focus of future studies.

The absence of a common approach to the methodological knowledge of simulation studies has been identified. The decisions and limitations of simulations need to be clearly articulated. A nine-step approach has been proposed to eliminate ambiguities (Table 6). The lack of such a methodology results in the inconsistent use of keywords in studies. Keywords were categorized according to the objectives of the studies to address this issue (Figure 14).

The recommendations proposed in this study will contribute to the establishment of a methodology for using simulation for residential buildings. The spread of simulation applications will indirectly reduce energy consumption. In addition, the bibliometric data presented is expected to help the people who conduct new research on this subject.

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sustainability

Systematic Review

Overcoming Deterrents to Modular Construction in Affordable Housing: A Systematic Review

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Abstract: The study aims to identify and categorise the deterrents to adopting modular construction (MC) in affordable housing (AH), revealing their interconnections, and proposing strategies to overcome them. A systematic literature review (SLR) was conducted, followed by Pareto analysis and total interpretive structural modelling (TISM). A total of 75 deterrents were identified from 46 studies, spanning 7 categories: environmental, social and cultural, technical and construction, industry and market, administrative and bureaucratic, economic, and regulatory and policy. The top deterrent category was found to be economic, specifically high initial investment costs and financing challenges. Significant deterrents, particularly economic ones, that impede the adoption of MC in AH are revealed. The interconnectedness of these deterrents highlights the need for comprehensive strategies addressing multiple categories simultaneously. Mitigation strategies and countermeasures are proposed to facilitate the adoption of MC. The study is based on the existing literature, which may have limitations in terms of capturing all possible deterrents. Further empirical research is needed to validate and expand upon these findings. A critical gap is filled by this study, which systematically categorises and analyses deterrents to MC in AH and proposes actionable strategies to mitigate them, thereby contributing to more effective and widespread adoption of MC. The findings are valuable to both global audiences and Australian stakeholders and provide insights that allow the barriers to MC in AH to be overcome.

Keywords: modular construction; affordable housing; Pareto analysis; total interpretive structural modelling

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1. Introduction

The global housing crisis is a complex issue that is worsened by various factors, such as urbanisation, population growth, socioeconomic disparities, and inadequate infrastructure [1]. According to a report from the United Nations, approximately 1.6 billion people around the world do not have access to adequate housing, a number that is projected to increase to 3 billion by the year 2030 [2]. This means that 96,000 affordable homes must be built every day to meet the demand. However, the rising costs of land, materials, and insufficient government policies are hindering the provision of affordable housing (AH) [3]. The significance of AH cannot be overstated, as it is vital for social stability and economic growth [4]. The United Nations defines AH as housing that is accessible to individuals or families earning a median income or below, where they do not have to spend more than 30% of their income on housing-related expenses [1,5].

The utilisation of contemporary construction techniques, such as modular construction (MC), offers a promising remedy for the AH crisis [6,7]. MC includes the prefabrication of building components in a factory setting; these are subsequently transported to the construction site for assembly [8]. This approach notably diminishes construction time and expenses, thereby supporting affordability concerns [9,10]. Several countries, including the United States [11], the United Kingdom [12], and Australia [13], have embraced MC to expedite housing development. For example, in Australia, numerous modular housing projects have been initiated to provide swift and cost-effective solutions to the escalating housing demand [14].

The MC approach incorporates various methodologies, including prefabrication, offsite construction, modular integrated construction, and industrialised construction, among others [15]. Though these methodologies share the fundamental principle of offsite manufacturing, they have subtle differences in terms of the extent of the prefabrication, integration, and assembly processes. Elaborating on each type and their minute dissimilarities is beyond the scope of this study; however, a thorough overview can be obtained from [16].

Despite the advantages of MC, such as reduced construction time, cost savings, improved quality control, and minimised environmental impact [15], its adoption in the AH sector remains limited, embryonic, and in its early stages [17]. Several deterrents impede its widespread use and application in the construction domain. For instance, in Australia, the slow uptake of MC for AH is primarily due to factors such as high initial costs, regulatory hurdles, and cultural resistance to new construction methods [18]. It is crucial to understand the specific factors that deter the adoption of this modern construction method to reduce the pressing housing issues.

The adoption of MC in AH is hindered by numerous deterrents that fall under various categories, including environmental, social and cultural, technical and construction, industry and market, administrative and bureaucratic, economic, and regulatory and policy factors. While recent studies have brought to light certain deterrents, such as the high expenses associated with meeting energy efficiency standards [19] and the scarcity of skilled labour [20], there is still a lack of a comprehensive understanding of these deterrents. Additionally, the existing research often neglects to systematically categorise these deterrents, identify their relative importance, and develop causal relationships and mitigation strategies to overcome them.

This research aims to bridge the gap by offering a comprehensive examination of the factors that deter the adoption of MC in the AH sector. The objectives of this study are as follows: (i) to identify the deterrents to MC in AH sector, (ii) to categorise these deterrents in a systematic manner for better comprehension, (iii) to develop a causal relationship and interdependency map for these deterrents, and (iv) to propose strategies and countermeasures to mitigate these deterrents.

The timely delivery of this study is of paramount importance, given the pressing necessity for AH solutions on a global scale. By identifying and addressing the particular deterrents to MC, this research seeks to make a meaningful contribution to the more efficient and extensive application of this innovative construction method; ultimately, the goal is to mitigate the ongoing global housing crisis and enhance the living conditions of millions of individuals.

2. Materials and Methods

2.1. Research Strategy

This research employs a systematic literature review (SLR) as its primary method to comprehensively identify, classify, and analyse the factors that deter the adoption of MC in the AH sector [6,13]. The SLR is a well-established and systematic approach that synthesises and compares findings from relevant studies to achieve research objectives [21]. Its wide application across various disciplines, including construction-related studies, is a testament to its precise, clear, and comprehensive methodology [22]. This method allows the consolidation of existing knowledge, critique of current understanding, revelation of patterns, and formation of new theories. In this study, the SLR method is implemented following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol [23], which is essential in minimising bias and enhancing the scientific validity of the findings. The PRISMA protocol includes several stages, such as developing research questions, selecting keywords, choosing a database, conducting a literature search, screening, applying inclusion and exclusion criteria, extracting metadata, and data analysis. These steps are thoroughly explained in the following sub-sections.

2.2. Data Collection

For this study, the Scopus database was chosen as the primary source for the retrieval of the relevant studies. Scopus is renowned for its extensive coverage, advanced search capabilities, and comprehensive indexing of peer-reviewed literature, making it an ideal choice for an SLR process [24]. Its strength lies in its indexing of a wide variety of journals, conference proceedings, and other scholarly sources, ensuring a thorough and inclusive search of the literature. The keywords used in the search were categorised into three groups: modular construction, affordable housing, and deterrents. To ensure a comprehensive retrieval of relevant studies, synonyms and related terms were also included. The search strategy keywords for each term are presented in Table 1. The search was conducted in the title, abstract, and keywords fields of Scopus, and the initial search yielded 87 documents.

Table 1. Keywords search strategy used in Scopus.

Primary Keyword	Search Strategy
Modular construction	"modular construction" OR "modular integrated construction" OR "mic" OR "osc" OR "ppvc" OR "prefabrication" OR "prefabricated" OR "offsite construction" OR "offsite manufacturing" OR "osm" OR "offsite production" OR "modern method of construction" OR "industrialised construction" OR "industrialised building systems" OR "systems building" OR "prefabricated prefinished volumetric construction"
Affordable housing	"affordable housing" OR "low-income housing" OR "social housing" OR "public housing" OR "housing affordability" OR "sustainable housing" OR "community housing" OR "green affordable housing" OR "sustainable affordable housing" OR "energy-efficient housing" OR "eco-friendly housing"
Deterrents	deterrents OR barriers OR obstacles OR hurdles OR challenges OR impediments OR constraints OR limitations OR blockages OR roadblocks OR restrictions OR difficulties OR hindrances OR bottlenecks OR inhibitions OR inhibitors

Next, the articles were screened using the PRISMA protocol (Supplementary Materials), which involved applying filters based on publication year (2010–present), document type (articles and conference papers), source type (journals and conference proceedings), and language (English). In contrast to most literature searches that typically exclude conference papers, this study included them in order to capture the most current and emergent research, which is often presented at conferences before being published in journals [25]. Conference papers can provide valuable early insights and innovative approaches that may not yet be fully explored in journal articles. As a result, 63 papers remained after applying these filters. The next step was to evaluate the eligibility of these papers. The research team read the abstracts of all 63 papers to determine their relevance to the integration of MC and AH. The papers that did not directly address this integration were excluded, resulting in 46 papers being retained for further analysis. Figure 1 illustrates the PRISMA protocol steps for this study. All the studies are specifically related to residential construction, with certain additional attention given to technologies that advance construction techniques within this field. A list of the studies, including their respective titles, types, and sources, can be found in Appendix A.

The study incorporated viewpoints from various jurisdictions, enhancing its scope by emphasising the worldwide nature of AH challenges. In both developed and developing jurisdictions, the deterrents to MC in AH are universally significant. By examining a wide array of geographical contexts, the study gains a more comprehensive understanding of how different environments, economies, and cultural factors affect the implementation and effectiveness of MC techniques. This diversity of perspectives boosts the relevance and applicability of the study's results across a variety of global settings.

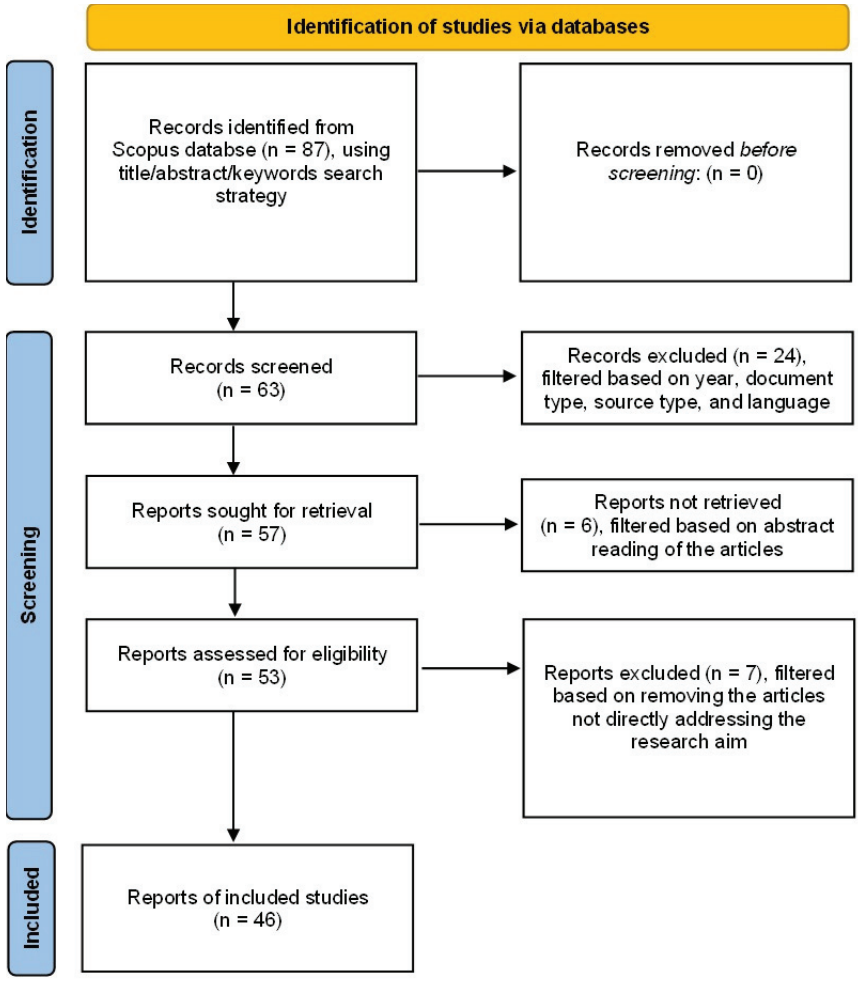

Figure 1. PRISMA protocol for the study.

2.3. Metadata Extraction and Data Analysis

The 46 selected articles were thoroughly assessed to extract crucial metadata, with a focus on the year of publication, the type of source, the recognised deterrents, and the documented connections between various deterrents. To address the varying terms for similar deterrents, the study identified implicit or synonymous mentions and calculated the overall deterrent frequency based on these combined mentions, ensuring accurate representation of all the relevant deterrents. A deterrent was considered only if it was referenced by at least two articles, ensuring the reliability and coherence of the data. The frequency of each deterrent's mention was recorded in an Excel summary sheet. The deterrents were categorised based on their relevance to the adoption of MC in the AH domain. The mean citation scores for these categories were calculated using the following equation:

$$\text{Mean Index } (\mu_i) = \frac{\sum_{j=1}^{n} D_j}{n} \quad (1)$$

Here, the mean citation score, denoted by μ_i, represents the average number of citations for each category, while D_j indicates the citation frequency for each individual deterrent within that category. Furthermore, *n* represents the total number of deterrents in the category. By utilising these mean citation scores, the deterrents can be ranked quantitatively, providing a basis for comparison and evaluation.

Furthermore, a Pareto analysis was performed to prioritise the most significant deterrents, utilising the "80/20" principle [26]. This approach posits that a small number of deterrents (20%) typically account for a large portion of the impact (80%) [27]. This study used Pareto analysis as the primary data consisted of citation frequencies, thus limiting the available analytical methods. With the objective of prioritising deterrents within each category in order to guide mitigation strategies, Pareto analysis was deemed appropriate. In this analysis, the cumulative frequency was set at 100%, whereby the "vital few" deterrents accounted for roughly 80% of the overall citation frequencies, while the "trivial many" represented the remaining 20%. To identify the most critical deterrents within each category, Pareto charts, including histograms and curves, were utilised, focusing on those that contributed to 80% of the cumulative citation frequencies. By ranking deterrents based on their citation frequencies, the Pareto analysis pinpointed those that, if addressed, could significantly mitigate the overall challenges. This technique is especially beneficial for directing resources towards the most influential deterrents, resulting in efficient and strategic intervention [28].

Additionally, the study investigated the relationships between the identified deterrents in order to construct a theoretical framework explaining their interdependencies. The study documented, where empirically verified, the established relationships among the deterrents reported in the eligible studies. Although not explicitly stated, the literature provides significant support for the theoretical foundations regarding the interdependencies among deterrents and their categories in the adoption of MC for AH. Recognising these interconnections enables the development of theories that explain the macro- and micro-level relationships between these deterrents in the context of MC adoption in AH projects. This was achieved through the use of total interpretive structural modelling (TISM), a systemic approach that deconstructs complex problems by delineating the interconnections among different components and elements [29]. TISM captures causal interactions, relationships, and transitive links, providing a hierarchical model of the system based on driving forces and dependencies [6].

The development of a TISM model involves several key steps, including the identification and verification of deterrents, the establishment of their relationships, the creation of interpretive logic through pairwise comparisons, the construction of an agency matrix, the formation of a reachability matrix, the generation of a binary interaction matrix, the hierarchical partitioning of the reachability matrix, the creation of a directed graph (digraph), and the interpretation of the TISM model [30]. The most significant challenge in constructing a TISM model is identifying and establishing the contextual relationships between the deterrents, which have already been outlined in the reviewed literature. A similar method was applied in a few previous review articles [31,32]. This concluding model provides a comprehensive understanding of the hierarchies and interactions among the deterrent categories, offering valuable insights into their interdependencies.

Overall, this rigorous approach to metadata extraction and analysis, combined with Pareto analysis and TISM, ensures a robust and nuanced understanding of the deterrents to MC methods in the AH sector. The next section presents the results and discussion of the study followed by the implications and conclusion of the study.

3. Results

3.1. Categorisation of Deterrents of MC in AH

The study identified a comprehensive set of 75 deterrents impacting the integration of MC in AH, spread across 7 distinct categories. These categories are as follows: environmental, social and cultural, technical and construction, industry and market, administrative and bureaucratic, economic, and regulatory and policy deterrents. Each category includes various factors, as shown in Table 2, that deter the adoption and successful implementation of MC methods in the housing sector.

Table 2. Categorisation of deterrents along with cited frequency, mean index, and overall rank.

ID	Deterrents	Total Frequency	Mean Index	Overall Rank
ED	Environmental deterrents	90	7.50	5
ED1	Strict waste disposal regulations and project timelines	8		31
ED2	Designing for resilience against natural disasters	11		10
ED3	Incorporation of renewable energy systems in design	4		62
ED4	Compliance with energy efficiency standards and costs	12		7
ED5	Limited availability of sustainable materials	9		23
ED6	Carbon footprint reduction strategies and feasibility	6		47
ED7	Environmental impact on local flora and fauna	4		62
ED8	Challenges in climate adaptation and resilience planning	6		47
ED9	High environmental impact assessments delaying projects	9		23
ED10	Biodiversity protection requirements impacting site selection	3		69
ED11	Environmental regulations affecting project feasibility	8		31
ED12	Stringent sustainability standards increasing costs	10		18
SCD	Social and Cultural deterrents	61	7.63	4
SCD1	Social equity concerns in housing distribution	6		47
SCD2	Lack of awareness and misinformation about modular benefits	9		23
SCD3	Resistance to change in construction methods	3		69
SCD4	Public scepticism about quality and durability	7		39
SCD5	Community resistance and stigma against modular housing	13		5
SCD6	Cultural biases and traditional housing perceptions	8		31
SCD7	Tenant acceptance and satisfaction challenges	4		62
SCD8	Cultural preferences and aesthetic concerns	11		10
TCD	Technical and Construction deterrents	77	7.00	7
TCD1	Challenges in achieving uniformity in construction	5		55
TCD2	Material compatibility issues and supply chain disruptions	4		62
TCD3	Construction delays during modular assembly	5		55
TCD4	Limited technical expertise and skills in modular construction	15		2
TCD5	Quality control issues and manufacturing standards	6		47
TCD6	Foundation problems and installation precision	3		69
TCD7	Safety concerns and regulatory compliance	8		31
TCD8	Integration challenges with existing infrastructure	6		47
TCD9	Site preparation complexities for modular projects	5		55
TCD10	Design limitations impacting architectural flexibility	11		10
TCD11	Logistics of transporting modular components	9		23
IMD	Industry and Market deterrents	71	7.89	3
IMD1	Skilled labour shortages and workforce challenges	10		18
IMD2	Lack of standardised practices and regulatory compliance	7		39
IMD3	Fragmentation and lack of collaboration in the industry	14		3
IMD4	Slow market acceptance and scalability of modular housing	11		10
IMD5	Perception of modular housing as lower quality	6		47
IMD6	Supply chain disruptions and logistical inefficiencies	5		55
IMD7	Resistance to innovation and traditional construction bias	9		23
IMD8	Reliability issues with modular suppliers and partners	5		55
IMD9	Competitive disadvantages compared to traditional methods	4		62
EcD	Economic deterrents	106	10.60	1
EcD1	Funding limitations and stakeholder financing	12		7
EcD2	Uncertainties in project cost estimates	7		39
EcD3	High initial investment costs and financing challenges	16		1
EcD4	Market conditions and affordability constraints	14		3
EcD5	Transportation expenses and logistics for modular units	7		39

Table 2. *Cont.*

ID	Deterrents	Total Frequency	Mean Index	Overall Rank
EcD6	Rising construction material costs	8		31
EcD7	Return on investment concerns in modular construction	8		31
EcD8	Elevated insurance premiums for modular projects	11		10
EcD9	Economic feasibility and cost–benefit analysis	13		5
EcD10	High land costs and site acquisition challenges	10		18
RPD	Regulatory and Policy deterrents	72	8.00	2
RPD1	Political resistance and lobbying against modular construction	3		69
RPD2	Building code discrepancies and compliance issues	11		10
RPD3	Stringent zoning laws and land use restrictions	8		31
RPD4	Lack of supportive policies for modular housing	11		10
RPD5	Jurisdictional conflicts over regulatory oversight	4		62
RPD6	Uncertainty in regulatory requirements and interpretations	9		23
RPD7	Environmental regulations impacting project feasibility	7		39
RPD8	Compliance costs and financial implications	12		7
RPD9	Lengthy approval processes and bureaucratic delays	7		39
ABD	Administrative and Bureaucratic deterrents	100	7.14	6
ABD1	Challenges in stakeholder engagement and consultation	11		10
ABD2	Legal disputes and contractual issues	6		47
ABD3	Lengthy permit processes and regulatory hurdles	5		55
ABD4	High administrative costs impacting project budgets	9		23
ABD5	Policy inconsistencies across different jurisdictions	8		31
ABD6	Coordination challenges among multiple agencies	10		18
ABD7	Administrative delays in decision-making processes	7		39
ABD8	Lack of transparency in administrative procedures	7		39
ABD9	Lack of public sector support and funding	10		18
ABD10	Inefficient governance and project oversight	4		62
ABD11	Capacity constraints within regulatory bodies	9		23
ABD12	Bureaucratic red tape and project approval delays	6		47
ABD13	Documentation requirements and legal complexities	3		69
ABD14	Impact of political cycles and leadership changes	5		55

Among these, the top ten overall deterrents based on their total frequency are high initial investment costs and financing challenges (EcD3), limited technical expertise and skills in modular construction (TCD4), fragmentation and lack of collaboration in the industry (IMD3), market conditions and affordability constraints (EcD4), community resistance and stigma against modular housing (SCD5), economic feasibility and cost–benefit analysis (EcD9), compliance with energy efficiency standards and costs (ED4), funding limitations and stakeholder financing (EcD1), elevated insurance premiums for modular projects (EcD8), and lack of supportive policies for modular housing (RPD4). These deterrents represent significant barriers to the broader acceptance and deployment of MC techniques in creating AH solutions.

Despite the nuanced variations that distinguish different methods of MC, the deterrents that have been identified in this study are generally applicable. For instance, technical and construction challenges such as transportation logistics, on-site assembly precision, and quality control are inherent in all MC approaches. Similarly, economic deterrents, like high initial costs and limited financial incentives, apply universally, regardless of the specific modular method that is employed. This consistency highlights the commonality of the identified deterrents within the broader context of the MC method.

3.2. Analysis of Deterrents of MC in AH Based on Mean Index Score

The ranking of the deterrents was determined based on their mean index scores, which provided insight into the overall impact of each category. The mean index score is calculated using Equation (1), and Figure 2 illustrates the outcomes of the mean index score. The analysis indicates that economic deterrents are ranked first with a mean index score of 10.60, suggesting that financial barriers are the most significant deterrents to MC in AH. This category includes high initial investment costs, market conditions, and funding limitations, emphasising the financial challenges faced by stakeholders [33]. Regulatory and policy deterrents are ranked second with a mean index score of 8.00. This category highlights the difficulties imposed by building code inconsistencies, stringent zoning laws, and insufficient supportive policies [34]. These regulatory deterrents can significantly delay or complicate the implementation of MC projects. Industry and market deterrents are ranked third with a mean index score of 7.89, reflecting the industry's resistance to innovation, fragmentation, and slow market acceptance, which hinder the widespread adoption of MC techniques. These rankings imply that economical and regulatory issues are the primary deterrents to incorporating MC in AH. The high mean index scores for these categories suggest a need for targeted interventions and policy reforms to address these crucial deterrent factors.

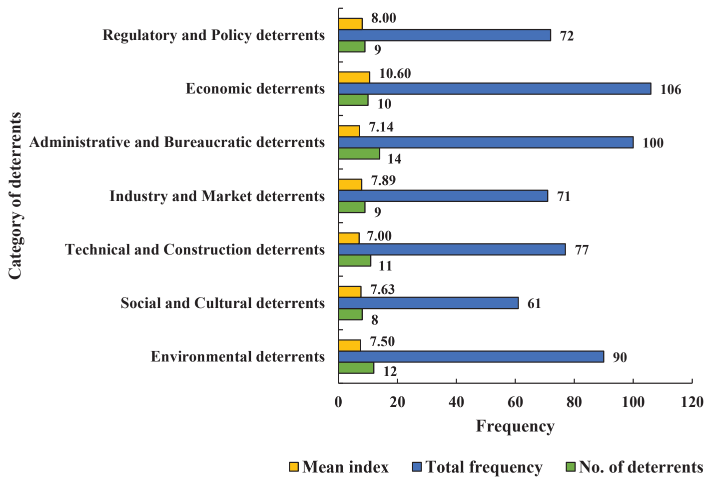

Figure 2. Mean index scores, total frequency, and number of deterrents.

3.3. Content and Pareto Analysis of Deterrents of MC in AH

Content analysis is a systematic process of categorising and interpreting textual information to uncover patterns, themes, and meanings [35]. In this study, it is employed to evaluate the deterrents affecting the adoption of MC in AH by examining the retrieved papers. The subsequent sections explore the specific deterrents within each category, providing comprehensive explanations and illustrative examples. Furthermore, a Pareto chart is included for each category to emphasise the most influential or vital few deterrents that have the greatest impact within the category.

3.3.1. Environmental Deterrents

Environmental deterrents, with a total frequency of 90, a mean index score of 7.50, and an overall rank of 5, include various challenges associated with environmental regulations and sustainability. Table 2 shows the list of environmental deterrents along with the total frequency and rank for each deterrent. The Pareto chart for environmental deterrents in Figure 3A reveals that the vital few deterrents are in compliance with energy efficiency standards and costs (ED4), designing for resilience against natural disasters (ED2), stringent sustainability standards increasing costs (ED12), limited availability of sustainable materials (ED5), high environmental impact assessments delaying projects (ED9), strict waste disposal regulations and project timelines (ED1), and environmental regulations affecting project feasibility (ED11).

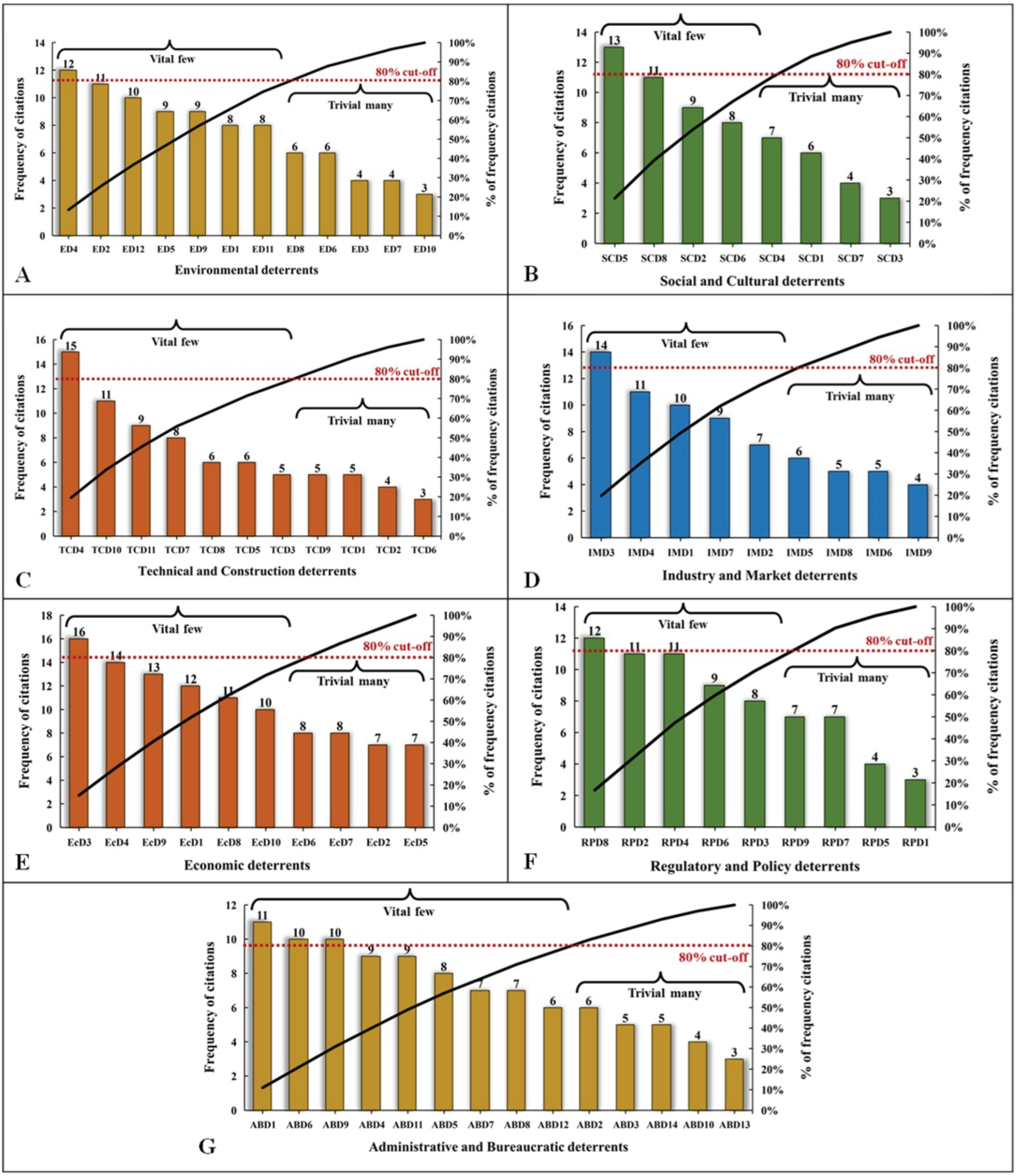

Figure 3. Pareto chart for different category deterrents.

Compliance with energy efficiency standards and associated costs (ED4) serves as a significant barrier, as achieving these standards often necessitates substantial upfront investments [34]. In Australia, for instance, the Nationwide House Energy Rating Scheme (NatHERS) mandates stringent energy efficiency requirements and requires a 7 out of 10 rating for new houses and apartments [36]. Although the rating scheme saves the operational costs of a building, it can increase the initial costs of an MC project. Designing for resilience against natural disasters (ED2) is another crucial deterrent factor [37], especially considering Australia's susceptibility to bushfires and floods. This requires additional design considerations and the use of specific materials, further complicating costs and complexity [38]. The challenge posed by stringent sustainability standards that increase costs (ED12) is also significant and substantial. Although a voluntary system, the Australian Green Star certification process [39], for example, demands high standards of sustainability, which can be cost-prohibitive for AH projects. The limited availability of sustainable materials (ED5) further complicates the adoption of MC [40]. Manufacturing and sourcing environmentally friendly materials that meet sustainability criteria can be difficult and expensive [41].

Environmental assessments and strict waste disposal regulations (ED9), which often necessitate extensive documentation and compliance efforts, can significantly delay projects [42]. In addition to these challenges, climate adaptation and resilience planning (ED8) and carbon footprint reduction strategies and feasibility (ED6) add a layer of complexity to projects, as they require the integration of long-term environmental sustainability goals [38,43]. The incorporation of renewable energy systems in design (ED3) and the environmental impact on local flora and fauna (ED7) are also noteworthy deterrents [38]. Projects must integrate renewable energy sources, like solar panels, which can be expensive and logistically challenging [44]. Moreover, protecting local biodiversity during construction (ED10) and ensuring compliance with environmental regulations affecting project feasibility (ED11) require additional planning and resources [45,46]. As such, addressing environmental deterrents necessitates a balanced approach that considers both regulatory compliance and cost-effectiveness to promote sustainable MC in Australia.

3.3.2. Social and Cultural Deterrents

Social and cultural deterrents, with a total frequency of 61, a mean index score of 7.63, and an overall rank of 4, include various societal and cultural challenges impacting the adoption of MC in AH. Table 2 shows the list of social and cultural deterrents along with the total frequency and rank for each deterrent. The Pareto chart for social and cultural deterrents in Figure 3B highlights that community resistance and stigma against modular housing (SCD5), cultural preferences and aesthetic concerns (SCD8), lack of awareness and misinformation about modular benefits (SCD2), and cultural biases and traditional housing perceptions (SCD6) are the vital few deterrents.

The distribution of AH (SCD1) raises social equity concerns, as it is essential to guarantee equal access to all societal segments [47]. Due to the multicultural population in Australia, addressing social equity is vital to obtain community acceptance and support for modular housing projects [9]. One significant obstacle to the adoption of modular housing is public scepticism about its quality and durability (SCD4). Although advances have been made in MC technology, there is still a perception that modular homes are inferior to traditional buildings, which affects market acceptance [48]. Cultural preferences and aesthetic concerns (SCD8) also play a critical role [49]. Australians often prefer traditional housing designs that reflect their cultural values, which poses a challenge to the acceptance of modular housing.

Resistance to change in construction methods (SCD3) and a lack of awareness and misinformation about modular benefits (SCD2) further hinder the adoption of MC [50]. Additionally, community resistance and stigma against modular housing (SCD5) and cultural biases and traditional housing perceptions (SCD6) add to the complexity of implementing modular construction projects [48]. It is essential to engage the community and address their concerns about modular housing quality, safety, and durability. Tenant acceptance and satisfaction challenges (SCD7) are also significant, as future residents must be convinced of the benefits of modular housing [40]. Addressing social and cultural deterrents requires community outreach and education, highlighting the benefits and quality of modular housing while ensuring that projects are designed to meet local aesthetic and cultural preferences [51,52].

3.3.3. Technical and Construction Deterrents

Technical and construction deterrents, with a total frequency of 77, a mean index score of 7.00, and an overall rank of 7, consist of challenges related to technical expertise, construction processes, and quality control. Table 2 shows the list of technical and construction deterrents along with total frequency and rank for each deterrent. The Pareto chart for technical and construction deterrents in Figure 3C shows that limited technical expertise and skills in MC (TCD4), design limitations impacting architectural flexibility (TCD10), logistics of transporting modular components (TCD11), safety concerns and regulatory compliance (TCD7), integration challenges with existing infrastructure (TCD8), quality control issues and manufacturing standards (TCD5), and construction delays during modular assembly (TCD3) are among the vital few deterrents in this category.

Limited expertise and skills in MC (TCD4) pose a significant challenge. The specialised nature of MC necessitates skilled labour, which is currently in short supply in Australia [53]. This labour gap can result in construction delays and quality issues, hindering the efficiency of modular projects. Design limitations impacting architectural flexibility (TCD10) also present a challenge, as modular designs often need to adhere to strict dimensional constraints, restricting creative architectural expressions [54]. The logistics of transporting modular components (TCD11) is another critical issue [55]. Given Australia's vast geographical expanse, transporting large modular units to remote sites can be costly and logistically complex [13]. Safety concerns and regulatory compliance (TCD7) are also notable deterrents, as ensuring the safety and compliance of modular units involves strict adherence to regulations [55].

Material compatibility issues and supply chain disruptions (TCD2), construction delays during modular assembly (TCD3), and quality control issues and manufacturing standards (TCD5) further complicate MC [34,55]. Ensuring compatibility between different construction materials and maintaining a smooth supply chain are essential for timely project completion. Foundation problems and installation precision (TCD6) and integration challenges with existing infrastructure (TCD8) also require careful planning and execution to avoid delays and additional costs [34]. Site preparation complexities for modular projects (TCD9) and challenges in achieving uniformity in construction (TCD1) add to the technical deterrents. Proper site preparation and achieving uniform construction quality are critical for the success of MC projects [54]. Addressing these technical and construction deterrents requires investment in training and upskilling the workforce, improving design flexibility, and optimising logistics and supply chain management to enhance the efficiency and appeal of MC.

3.3.4. Industry and Market Deterrents

Industry and market deterrents, with a total frequency of 71, a mean index score of 7.89, and an overall rank of 3, include challenges related to market acceptance, industry practices, and supply chain management. Table 2 shows the list of industry and market deterrents along with the total frequency and rank for each deterrent. The Pareto chart for industry and market deterrents in Figure 3D identifies skilled labour shortages and workforce challenges (IMD1), fragmentation and lack of collaboration in the industry (IMD3), slow market acceptance and scalability of modular housing (IMD4), resistance to innovation and traditional construction bias (IMD7), and lack of standardised practices and regulatory compliance (IMD2) as the vital few deterrents.

Skilled labour shortages and workforce challenges (IMD1) constitute a significant deterrent in the construction industry in Australia, particularly in the specialised field of MC [56]. Fragmentation and lack of collaboration in the industry (IMD3) exacerbate this issue by hindering the cohesive collaboration among various stakeholders, including designers, manufacturers, and builders [55]. Slow market acceptance and scalability of modular housing (IMD4) is another major impediment, despite its benefits [51]. MC is still viewed with scepticism by some market players, which slows its adoption and scalability [57]. The perception of modular housing as being of lower quality (IMD5) and resistance to innovation and traditional construction bias (IMD7) also impede the industry's growth [58].

Supply chain disruptions and logistical inefficiencies (IMD6) and reliability issues with modular suppliers and partners (IMD8) further complicate the challenges faced by the industry [55,59]. Ensuring a smooth supply chain and reliable partnerships is crucial for the timely and cost-effective completion of modular projects [59]. Additionally, competitive disadvantages compared to traditional methods (IMD9) and the lack of standardised practices and regulatory compliance (IMD2) further complicate the market dynamics. In order to overcome the deterrents in the industry and market, it is essential to improve the skills of the workforce, encourage collaboration between industries, and emphasise the advantages of MC to gain broader acceptance from the market.

3.3.5. Economic Deterrents

Economic deterrents, with a total frequency of 106, a mean index score of 10.60, and an overall rank of 1, involve financial challenges impacting the feasibility and affordability of modular construction projects. Table 2 shows the list of economic deterrents along with the total frequency and rank for each deterrent. The Pareto chart for economic deterrents in Figure 3E identifies high initial investment costs and financing challenges (EcD3), market conditions and affordability constraints (EcD4), economic feasibility and cost–benefit analysis (EcD9), funding limitations and stakeholder financing (EcD1), elevated insurance premiums for modular projects (EcD8), and high land costs and site acquisition challenges (EcD10) as the vital few deterrents.

High initial investment costs and financing challenges (EcD3) can be significant, as the upfront capital required for MC projects can be substantial and can affect their feasibility, particularly for AH projects [41,49]. Market conditions and affordability constraints (EcD4) also pose major challenges, as fluctuations in the housing market and the need to maintain affordability can affect the financial viability of MC projects [60]. Economic feasibility and cost–benefit analysis (EcD9) is another critical factor, as ensuring that MC projects provide a favourable return on investment is essential for attracting investors and stakeholders [18]. Funding limitations and stakeholder financing (EcD1) and high land costs and site acquisition challenges (EcD10) further complicate the economic landscape [51].

Additionally, rising construction material costs (EcD6) and return on investment concerns in MC (EcD7) are notable deterrents, as the cost of construction materials can significantly impact project budgets, and stakeholders need to be assured of a positive return on their investment [42]. Elevated insurance premiums for modular projects (EcD8) and uncertainties in project cost estimates (EcD2) add to the financial risks associated with MC [60]. Transportation expenses and logistics for modular units (EcD5) also pose economic challenges, as the costs associated with transporting large modular units can be substantial, especially in remote areas. Addressing economic deterrents requires innovative financing solutions, cost-effective construction practices, and robust financial planning to enhance the economic viability of MC projects.

3.3.6. Regulatory and Policy Deterrents

Regulatory and policy deterrents, with a total frequency of 72, a mean index score of 8.00, and an overall rank of 2, include challenges associated with regulatory compliance and policy support. Table 2 shows the list of regulatory and policy deterrents along with the total frequency and rank for each deterrent. The Pareto chart for regulatory and policy deterrents in Figure 3F shows building code discrepancies and compliance issues (RPD2), lack of supportive policies for modular housing (RPD4), compliance costs and financial implications (RPD8), uncertainty in regulatory requirements and interpretations (RPD6), and stringent zoning laws and land use restrictions (RPD3) as the vital few deterrents.

Building code discrepancies and compliance issues (RPD2) pose a significant challenge, as MC must comply with various building codes and standards, which can vary across jurisdictions [20]. The absence of specific policies promoting MC in Australia (RPD4) also hinders its growth and adoption [9]. Compliance costs and financial implications (RPD8) further complicate the situation by increasing the costs associated with complying with stringent regulatory requirements [61]. Other notable deterrents include lengthy approval processes and bureaucratic delays (RPD9) and environmental regulations impacting project feasibility (RPD7) [48].

Similarly, political resistance and lobbying against modular construction (RPD1) and jurisdictional conflicts over regulatory oversight (RPD5) also contribute to the complexity of regulatory compliance. Addressing these issues requires harmonising building codes, developing supportive policies, and streamlining approval processes to facilitate the growth of the MC sector [18]. Uncertainty in regulatory requirements and interpretations (RPD6) and stringent zoning laws and land use restrictions (RPD3) further hinder the adoption of MC. Providing clear and consistent regulatory guidelines and easing zoning restrictions can help overcome these barriers.

3.3.7. Administrative and Bureaucratic Deterrents

Administrative and bureaucratic deterrents, with a total frequency of 100, a mean index score of 7.14, and an overall rank of 6, consist of challenges related to regulatory processes, stakeholder engagement, and administrative efficiency. Table 2 shows the list of administrative and bureaucratic deterrents along with the total frequency and rank for each deterrent. The Pareto chart for administrative and bureaucratic deterrents in Figure 3G reflects challenges in stakeholder engagement and consultation (ABD1), lack of public sector support and funding (ABD9), coordination challenges among multiple agencies (ABD6), high administrative costs impacting project budgets (ABD4), capacity constraints within regulatory bodies (ABD11), policy inconsistencies across different jurisdictions (ABD5), administrative delays in decision-making processes (ABD7), lack of transparency in administrative procedures (ABD8), and bureaucratic red tape and project approval delays (ABD12) as the vital few deterrents.

Stakeholder engagement and consultation challenges (ABD1) are particularly crucial, as successful MC projects necessitate the cooperation of a range of stakeholders, including government bodies, local communities, and private entities [55,62]. Prolonged permit processes and regulatory hurdles (ABD3) also represent significant deterrents. Navigating Australia's complex regulatory landscape can lead to delayed project timelines and increased costs [63]. Coordination challenges among multiple agencies (ABD6) exacerbate the administrative processes. High administrative expenses impacting project budgets (ABD4) and policy inconsistencies across different jurisdictions (ABD5) pose substantial challenges as well [20]. Administrative delays in decision-making processes (ABD7) and a lack of transparency in administrative procedures (ABD8) contribute to bureaucratic inefficiencies. These delays and the lack of transparency can erode stakeholder confidence and affect project timelines [64]. Furthermore, the absence of public sector support and funding (ABD9) and inefficient governance and project oversight (ABD10) impede the adoption of the MC method.

Moreover, limitations in capacity within regulatory bodies (ABD11) and bureaucratic red tape and delays in project approval (ABD12) negatively impact the efficiency of MC projects [34]. To address these issues, it is necessary to streamline administrative processes and enhance the capacity of regulatory bodies to handle MC projects in a more efficient manner. Additionally, documentation requirements and legal complexities (ABD13) and the effects of political cycles and leadership changes (ABD14) pose further challenges [48]. To ensure the long-term success of MC projects, simplifying documentation requirements and maintaining stable policy support throughout political cycles are crucial.

3.4. TISM Modelling of the Deterrents of MC in AH

Figure 4 displays the TISM model for deterrents of MC in AH established through the content analysis of the retrieved literature. It has four levels with interdependent categories (shown within rectangular boxes), as indicated by the arrows. The solid arrow lines indicate direct relationships, and the dotted (broken) arrow lines show transitive connections. Each arrow also provides a rational text about how a particular category links or affects another. Level 1 (administrative and bureaucratic deterrents and technical and construction deterrents) categories are dependent variables with high dependence and low driving power. The deterrent factors in these categories influence each other and depend on the other deterrent categories but are less likely to affect them. Level 1 deterrents are likely to manifest in the integration of MC in the AH drive due to other categories.

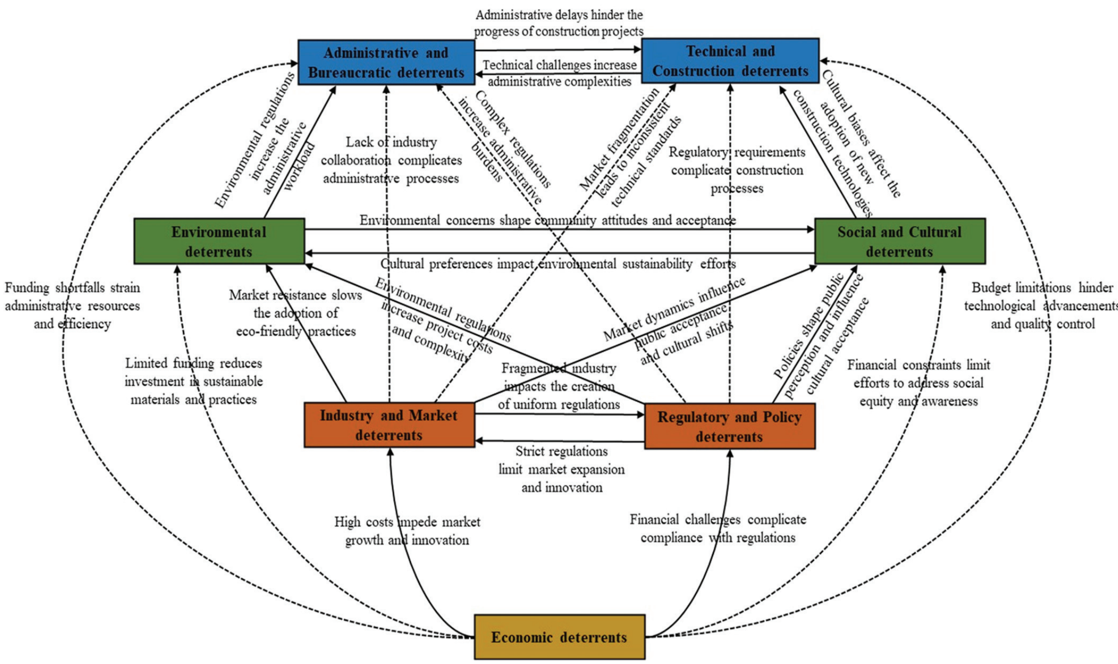

Figure 4. TISM model for deterrents of MC in AH.

Level 2 (environmental deterrents and social and cultural deterrents) and Level 3 (industry and market deterrents and regulatory and policy deterrents) categories are strongly linked and influential. They affect each other, stimulate other categories, and are impacted by other levels. These levels act as a bridge between lower and higher levels in the model. The Level 4 category (economic deterrents) has a profound, delicate impact on the MC–AH integration prospects. This category is usually weakly influenced by other categories and is not dependent on them, however; it has a profound influence on other categories. Controlling and managing these deterrents is essential for feasible MC–AH integration. The thoughtful mitigation of these categories can reduce the impact of other deterrents.

3.5. Mitigating Vital Few Deterrents of MC in AH

The establishment of the categories, paired with their corresponding vital few deterrents, provides a robust foundation for the formulation of strategies and countermeasures and the engagement of pertinent actors and stakeholders to mitigate the consequences of these deterrents. The reviewed studies have tacitly and implicitly delved into approaches for tackling the vital few deterrents in each category, which, when combined, can contribute to an inclusive strategy. Table 3 presents the pertinent strategies, countermeasures, actors, and stakeholders for each of the vital few deterrents in each category.

Table 3. Strategies and countermeasures of the vital few deterrents.

Category	Vital Few Deterrents	Strategies and Countermeasures	Relevant Actors and Stakeholders
Environmental	Compliance with energy efficiency standards and costs	Incentivise adoption through subsidies and grants	Government agencies, environmental organisations, financial institutions
	Designing for resilience against natural disasters	Develop standardised resilient designs	Architects, engineers, urban planners, disaster management agencies
	Stringent sustainability standards increasing costs	Streamline sustainability standards for cost-effectiveness	Standards organisations, policymakers, construction firms
	Limited availability of sustainable materials	Promote research and development of sustainable materials	Research institutions, construction firms, material suppliers
	High environmental impact assessments delaying projects	Streamline environmental assessment processes	Environmental agencies, regulatory bodies, project developers
	Strict waste disposal regulations and project timelines	Implement efficient waste management systems	Waste management companies, construction firms, regulatory bodies
	Environmental regulations affecting project feasibility	Adapt project plans to meet environmental regulations	Environmental consultants, regulatory bodies, project managers
Social and Cultural	Community resistance and stigma against modular housing	Engage communities through awareness programs and showcasing benefits	Community leaders, local governments, NGOs, media
	Cultural preferences and aesthetic concerns	Incorporate local cultural aesthetics in modular designs	Architects, cultural consultants, local communities
	Lack of awareness and misinformation about modular benefits	Launch educational campaigns to inform the public about modular benefits	Media, educational institutions, government agencies
	Cultural biases and traditional housing perceptions	Address cultural biases through targeted communication	Cultural consultants, community leaders, government agencies
Technical and Construction	Limited technical expertise and skills in modular construction	Invest in training programs and certifications for modular construction skills	Educational institutions, vocational training centres, industry associations
	Design limitations impacting architectural flexibility	Enhance design flexibility through modular innovations	Architects, designers, construction firms
	Logistics of transporting modular components	Optimise logistics planning and transportation routes	Logistics companies, transport agencies, construction firms
	Safety concerns and regulatory compliance	Strengthen safety protocols and ensure compliance with regulations	Safety inspectors, construction firms, regulatory bodies
	Integration challenges with existing infrastructure	Develop strategies for seamless integration with existing infrastructure	Infrastructure planners, construction firms, government agencies
	Quality control issues and manufacturing standards	Establish strict quality control measures and standards	Manufacturing firms, quality assurance teams, regulatory bodies
	Construction delays during modular assembly	Improve assembly processes and provide contingency planning	Project managers, construction teams, suppliers

Table 3. *Cont.*

Category	Vital Few Deterrents	Strategies and Countermeasures	Relevant Actors and Stakeholders
Industry and Market	Skilled labour shortages and workforce challenges	Initiate training programs and improve working conditions	Educational institutions, labour unions, construction firms
	Fragmentation and lack of collaboration in the industry	Promote industry-wide collaboration and standardisation	Industry associations, construction firms, regulatory bodies
	Slow market acceptance and scalability of modular housing	Market modular benefits through campaigns and pilot projects	Marketing firms, construction companies, government agencies
	Resistance to innovation and traditional construction bias	Encourage innovation and provide incentives for adopting new technologies	Innovation hubs, industry associations, government agencies
	Lack of standardised practices and regulatory compliance	Develop industry-wide standards and enforce regulatory compliance	Standards organisations, regulatory bodies, industry associations
Administrative and Bureaucratic	Challenges in stakeholder engagement and consultation	Facilitate early stakeholder engagement and continuous communication	Project managers, community leaders, government agencies
	Lack of public sector support and funding	Provide targeted funding and incentives for modular projects	Government agencies, financial institutions, policymakers
	Coordination challenges among multiple agencies	Establish centralised coordination bodies or frameworks	Government agencies, regulatory bodies, project coordinators
	High administrative costs impacting project budgets	Streamline administrative processes to reduce costs	Administrative bodies, project managers, financial auditors
	Capacity constraints within regulatory bodies	Increase staffing and resources within regulatory agencies	Government agencies, regulatory bodies, policymakers
	Policy inconsistencies across different jurisdictions	Harmonise policies across regions to avoid inconsistencies	Policymakers, regulatory bodies, legal experts
	Administrative delays in decision-making processes	Implement time-bound decision-making processes	Government agencies, project managers, legal teams
	Lack of transparency in administrative procedures	Improve transparency and accountability in administrative procedures	Regulatory bodies, project stakeholders
	Bureaucratic red tape and project approval delays	Simplify approval processes and reduce bureaucratic hurdles	Government agencies, regulatory bodies, project coordinators
Economic	High initial investment costs and financing challenges	Offer low-interest loans and financial incentives	Financial institutions, government agencies, private investors
	Market conditions and affordability constraints	Implement policies to stabilise market conditions	Policymakers, economic planners, housing authorities
	Economic feasibility and cost–benefit analysis	Conduct thorough cost–benefit analyses and feasibility studies	Economic analysts, construction firms, government agencies
	Funding limitations and stakeholder financing	Explore alternative financing options and partnerships	Financial institutions, private investors, government agencies
	Elevated insurance premiums for modular projects	Negotiate insurance premiums and provide risk mitigation strategies	Insurance companies, construction firms, risk management experts
	High land costs and site acquisition challenges	Implement land acquisition strategies and provide subsidies	Land authorities, government agencies, developers

Table 3. *Cont.*

Category	Vital Few Deterrents	Strategies and Countermeasures	Relevant Actors and Stakeholders
Regulatory and Policy	Building code discrepancies and compliance issues	Harmonise building codes across regions	Regulatory bodies, policymakers, construction firms
	Lack of supportive policies for modular housing	Develop and implement supportive modular housing policies	Government agencies, policymakers, industry associations
	Compliance costs and financial implications	Reduce compliance costs through streamlined processes	Regulatory bodies, construction firms, policymakers
	Uncertainty in regulatory requirements and interpretations	Clarify and standardise regulatory requirements	Regulatory bodies, legal experts, construction firms
	Stringent zoning laws and land use restrictions	Advocate for flexible zoning laws and land use policies	Urban planners, policymakers, developers

The challenges and potential solutions identified in the context of adopting MC in AH are multifaceted. In Australia, where housing affordability is a pressing issue, modular construction offers promise [14]. However, strategic interventions are necessary to overcome the various obstacles. For instance, environmental deterrents such as energy efficiency compliance can be addressed through financial incentives, such as subsidies and grants, which require the coordination of government agencies, environmental organisations, and financial institutions [20]. Standardised resilient structures can improve natural disaster resilience, necessitating the involvement of architects, engineers, urban planners, and disaster management agencies [65]. Streamlining sustainability standards can help reduce costs and requires collaboration between standards organisations, policymakers, and construction firms.

Social and cultural deterrents, such as community resistance and aesthetic preferences, can be tackled by engaging communities through awareness programs and incorporating local design elements, which involve the participation of community leaders, local governments, NGOs, the media, architects, cultural consultants, and local communities [13]. Technical and construction-related deterrents demand investments in training programs to build technical expertise and innovations to enhance design flexibility, involving educational institutions, vocational training centres, industry associations, architects, designers, and construction firms. Optimising logistics planning can mitigate transportation challenges and make MC more efficient, requiring the coordination of logistics companies, transport agencies, and construction firms [34].

Industry and market deterrents, such as a lack of skilled labour and industry fragmentation, can be mitigated through industry-wide collaboration and standardisation [49]. Overcoming labour shortages requires the development of training programs and improved working conditions, which involve educational institutions, labour unions, construction firms, and industry associations. To enhance market acceptance, marketing campaigns can be implemented by marketing firms, construction companies, and government agencies [51,57]. Addressing administrative challenges, including stakeholder engagement and agency coordination, can be facilitated with early communication and centralised coordination bodies. Project managers, community leaders, government agencies, and regulatory bodies are essential for this process. Targeted funding and incentives can increase public sector support, involving government agencies, financial institutions, and policymakers [58].

Economic deterrents, such as high initial investments, can be reduced with the help of low-interest loans and financial incentives, involving financial institutions, government agencies, and private investors. Stabilising market conditions and conducting cost–benefit analyses can enhance economic feasibility and attract investment, requiring policymakers, economic planners, housing authorities, economic analysts, construction firms, and government agencies [51,58]. Regulatory deterrents, such as building code discrepancies, can be addressed by harmonising codes and developing supportive policies for modular housing.

Streamlining compliance processes can reduce regulatory burdens, involving regulatory bodies, policymakers, construction firms, industry associations, and government agencies.

By implementing targeted countermeasures to address these deterrents, the adoption of MC in AH can be significantly boosted, especially in Australia, where housing affordability is a crucial issue. Coordinated efforts from government, industry, and communities are necessary to foster a supportive environment for modular construction.

4. Discussion and Implications

4.1. Discussions

This study identifies 75 deterrents that hinder the incorporation of MC in the AH sector; these deterrents were categorised into seven distinct categories. Among these categories, economic deterrents, specifically high initial investment costs (EcD3) and financing challenges (EcD1), emerge as the most significant deterrents. These economic deterrents are interconnected, creating a complicated web of challenges that need to be addressed comprehensively. High initial investment costs (EcD3) are exacerbated by funding limitations (EcD1) and market conditions (EcD4), resulting in a cyclical challenge that hampers the adoption of MC. Furthermore, compliance with energy efficiency standards (ED4) and stringent sustainability standards (ED12) increases costs and discourages investment in MC.

Additionally, technical issues, such as limited expertise (TCD4) and quality control (TCD5), are compounded by industry fragmentation (IMD3) and the absence of standardised practices (IMD2). These technical and economic factors often lead to extended project timelines and higher costs, making MC less appealing to developers and investors. The interconnectedness of these deterrents is highlighted by the influence of regulatory and policy barriers, which are often driven by economic deterrents. For example, building code discrepancies (RPD2) and compliance costs (RPD8) add to the financial burden, while the lack of supportive policies (RPD4) and lengthy approval processes prolong project timelines. These regulatory challenges are intertwined with administrative and bureaucratic issues, such as stakeholder engagement (ABD1) and coordination difficulties among multiple agencies (ABD6), further complicating the project implementation process.

Furthermore, the analysis of the TISM model reveals the hierarchical nature of these deterrents, demonstrating that economic and technical factors act as primary drivers that influence the other categories. Social and cultural resistance (SCD5) and community stigma against modular housing (SCD8) are influenced by perceived high costs and regulatory hurdles, which in turn affect public perception and acceptance of MC. As a result, strategies that target economic and technical challenges are likely to have a ripple effect, alleviating deterrents across other categories as well. The proposed mitigation strategies include enhancing financial support for MC projects, improving technical training programs, fostering industry collaboration, streamlining regulatory processes, and promoting public awareness about the benefits of MC. These strategies aim to create a more supportive environment for MC, addressing multiple deterrents simultaneously.

4.2. Theoretical Implications

The categorisation and identification of 75 deterrents have important theoretical implications for the fields of MC and AH. For instance, economic deterrents such as high initial investment costs and financing challenges necessitate more in-depth economic analyses and models to understand and mitigate these deterrents. This study framework enables future researchers to explore the intricate relationships between different deterrents and their cascading effects on MC adoption. By establishing a clear structure of interconnected deterrents, this research lays the foundation for the development of more comprehensive theoretical models that can predict and address deterrents in various contexts related to MC, including AH.

4.3. Practical Implications

The study's practical implications provide actionable insights for industry stakeholders in the areas of MC and AH. Recognising the technical and construction-related deterrents, such as limited expertise and skills in MC, highlights the need for improved training and development programs. Consequently, construction firms and educational institutions can use this information to devise targeted training initiatives that equip the workforce with the required skills to implement MC effectively. Additionally, understanding the impact of logistics challenges in transporting modular components can lead to the development of more efficient supply chain strategies, ultimately reducing costs and improving project timelines. By taking these practical steps, the feasibility and attractiveness of MC projects in various construction projects, including AH, can be significantly enhanced.

4.4. Policy Implications

The implications of this study for regulation and policy are significant. The presence of deterrents such as inconsistencies in building codes and compliance issues highlights a critical area that requires policy intervention. Policymakers can make use of the findings from this research to standardise building codes and regulations across different jurisdictions, thus reducing the compliance burden on MC projects. Furthermore, the absence of supportive policies for modular housing suggests the need for more proactive governmental support. Policies that provide financial incentives, simplify approval processes, and encourage sustainable construction practices can create a more favourable environment for MC. By addressing these regulatory deterrents, policymakers can facilitate the broader adoption of MC in AH, thereby contributing to the resolution of the housing crisis.

4.5. Approach and Results Limitations

This study aims to identify the deterrents to the adoption of modular construction in affordable housing. It does so by way of a systematic literature review, following a well-established procedure, utilising the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol. The outcomes extracted by way of such an approach are widely regarded by the research community as highly robust. Nevertheless, limitations with respect to the findings do exist. Firstly, as a literature review, the results are based on secondary data examined using desktop analysis; that is, no primary research was gathered. The findings are therefore an aggregate of earlier work. Second, the study was limited to the Scopus database. While Scopus self-styles as the largest academic journal database, with over 40,000 indexed titles, it does not fully cover all the research that may be found in other databases, such as the Web of Science. Moreover, as a subsidiary of the publisher Elsevier, Scopus tends to place a strong emphasis on showcasing its own publications. Third, the extracted studies were limited to those identified through the specific keyword search terms used: modular construction, modular housing, and deterrents. While these terms are adequate for the review task at hand, the retrieved studies are directly dependent on the terms used. Other terms would have generated alternate papers. Moreover, the manual vetting process, reducing the initial paper count of 87 down to a final 46 reviewed, involves an element of (albeit expert) subjectivity. An example of this is the rejection of dated papers in favour of more recent studies.

These limitations are ubiquitous to systematic literature reviews, and generally allowed. A more significant limitation, however, is that the ranking of determinants (which make up the major findings) was established on the basis of citation frequency. When a barrier is referenced more often, it drifts up the rankings. This is not the only way to quantify barriers to modular construction in affordable housing. Certain barriers may be more difficult to overcome than others, have greater impact, or be enmeshed in a network of other barriers and therefore resistant to isolated efforts at mitigation. These attributes were not considered, but they invite further investigation in subsequent research efforts.

5. Conclusions

This study presents a comprehensive examination of the deterrents to the adoption of modular construction (MC) in affordable housing (AH), using a systematic literature review (SLR) of 46 scholarly articles. The study identified a total of 75 deterrents across 7 categories: environmental, social and cultural, technical and construction, industry and market, administrative and bureaucratic, economic, and regulatory and policy deterrents. Among these, economic deterrents, particularly high initial investment costs and financing challenges emerged as the most significant deterrent, using Pareto analysis. The interconnected nature of these deterrents, as presented by the total interpretive structure modelling (TISM), underscores the need for a holistic approach to address these deterrents effectively. The findings of this study have substantial implications for theory, practice, and policy. Theoretically, the comprehensive framework of deterrents and their interconnections offers a valuable foundation for future research. Practically, the insights gained from this study can guide stakeholders in the construction industry to develop targeted strategies that address the most significant deterrents. Policymakers can use these findings to create supportive regulatory frameworks and financial incentives that promote the adoption of MC. The proposed mitigation strategies, including enhancing financial support, improving technical training, fostering industry collaboration, streamlining regulatory processes, and promoting public awareness, provide a roadmap for overcoming the deterrents of MC adoption in the AH domain. These strategies aim to create a more supportive environment for MC, addressing multiple impediments simultaneously. As such, this study fills a critical gap in the literature by systematically categorising and analysing the deterrents to MC in AH and proposing actionable strategies to mitigate them. By addressing these deterrents, stakeholders can enhance the adoption of MC, contributing to the resolution of the global AH crisis. The timely delivery of this study is crucial, given the growing need for AH solutions worldwide.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16177611/s1, PRISMA Checklist. Reference [66] is cited in Supplementary Materials.

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

Appendix A

Table A1. List of included studies.

Serial Number	Title of the Paper	Type of Paper	Source	Source Country	Reference
1	Fostering Social Sustainability: Inclusive Communities through Prefabricated Housing	Journal	*Buildings*	Australia	[67]
2	A Review of Prefabricated Housing Evolution, Challenges, and Prospects Towards Sustainable Development in Libya	Journal	*International Journal of Sustainable Development and Planning*	Libya	[68]

Table A1. *Cont.*

Serial Number	Title of the Paper	Type of Paper	Source	Source Country	Reference
3	Nudge or mandate: an exploration into the constraints of volumetric modular construction in Australia	Journal	*Smart and Sustainable Built Environment*	Australia	[69]
4	Prefabrication and Modular Construction—A Potential Solution to Affordable and Temporary Housing in Ontario?	Conference	Lecture Notes in Civil Engineering	Canada	[70]
5	Implementing modular integrated construction in high-rise high-density cities: perspectives in Hong Kong	Journal	*Building Research and Information*	Hong Kong	[34]
6	Analysing value creation in social housing construction in remote communities—application to Nunavik (Canada)	Journal	*Built Environment Project and Asset Management*	Canada	[60]
7	Motivations and market solutions for flexible housing in Finland	Journal	*Journal of Housing and the Built Environment*	Finland	[51]
8	Delivering human-centred housing: understanding the role of post-occupancy evaluation and customer feedback in traditional and innovative social housebuilding in England	Journal	*Construction Management and Economics*	United Kingdom	[71]
9	Assessment of Modular Construction System Made with Low Environmental Impact Construction Materials for Achieving Sustainable Housing Projects	Journal	*Sustainability*	Chile	[72]
10	The Emerging Constraints in the Implementation of Prefabrication for Public Housing in the Philippines using Principal Component Analysis	Conference	International Conference on Construction in the 21st Century	Philippines	[17]
11	Suitability of Modular Technology for House Construction in Sri Lanka: A Survey and a Case Study	Journal	*Buildings*	Sri Lanka	[73]
12	Problems and challenges of the built environment and the potential of prefabricated architecture	Journal	*Archives of Civil Engineering*	Poland	[40]
13	Research on Modularization of Prefabricated Affordable Housing in Zhengzhou Based on the Concept of Sustainable Development	Conference	Advances in Transdisciplinary Engineering	China	[74]
14	Implementation of a novel data-driven approach to optimise UK offsite housing delivery	Conference	IOP Conference Series: Earth and Environmental Science	United Kingdom	[75]
15	Affordable Housing with Prefabricated Construction Technology in India: An Approach to Sustainable Supply	Conference	ECS Transactions	India	[59]
16	Analysis of challenges and opportunities of prefabricated sandwich panel system: A solution for affordable housing in India	Conference	Materials Today: Proceedings	India	[41]

Table A1. *Cont.*

Serial Number	Title of the Paper	Type of Paper	Source	Source Country	Reference
17	Embodied Energy Consumption in the Residential Sector: A Case Study of Affordable Housing	Journal	*Sustainability*	United Kingdom	[19]
18	Prefab micro-units as a strategy for affordable housing	Journal	*Housing Studies*	United States	[47]
19	Prefabricated Houses—A Model to Sustainable Housing Market	Conference	ECS Transactions	India	[57]
20	Customization of on-site assembly services by integrating the internet of things and BIM technologies in modular integrated construction	Journal	*Automation in Construction*	Hong Kong	[55]
21	Application of sustainable prefabricated wall technology for energy efficient social housing	Journal	*Sustainability*	India	[76]
22	Systemized design to deliver leaner mid-rise timber housing	Conference	World Conference on Timber Engineering	Austria	[54]
23	Potentials and Challenges of Accessory Dwelling Units Using Modular Construction	Conference	Computing in Civil Engineering	United States	[52]
24	Analysis of skill shortages in prefabricated residential construction: A case for New Zealand	Conference	Proceedings of the 37th Annual ARCOM Conference	New Zealand	[77]
25	Critical barriers to sustainability attainment in affordable housing: International construction professionals' perspective	Journal	*Journal of Cleaner Production*	Hong Kong	[78]
26	Modeling the Impact of Barriers on Sustainable Housing in Developing Countries	Journal	*Journal of Urban Planning and Development*	Hong Kong	[79]
27	Critical success factors, barriers and challenges for adopting offsite prefabrication: A systematic literature review	Conference	ARCOM 2020—Association of Researchers in Construction Management	United Kingdom	[48]
28	Customer-oriented approaches to housing affordability in industrialised house building	Conference	Joint Asia-Pacific Network for Housing Research and Australasian Housing Researchers Conference, APNHR and AHRC 2018	Australia	[18]
29	Environmental cost-benefit analysis of prefabricated public housing in Beijing	Journal	*Sustainability*	China	[42]
30	Integrated design experiences for energy-efficient housing in Chile	Journal	*Construction Innovation*	Chile	[80]
31	Adoption of Prefabrication in Small Scale Construction Projects	Journal	*Civil Engineering Journal (Iran)*	Saudi Arabia	[81]
32	Assembling an innovative social housing project in Melbourne: mapping the potential for social innovation	Journal	*Housing Studies*	Australia	[82]

Table A1. *Cont.*

Serial Number	Title of the Paper	Type of Paper	Source	Source Country	Reference
33	Awareness level and adoption of modular construction for affordable housing in Nigeria: Architects' perspective	Journal	*International Journal of Innovative Technology and Exploring Engineering*	Nigeria	[83]
34	An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction	Journal	*Automation in Construction*	China	[62]
35	D3 sustainable homes-an alternative design for high-rise affordable housing in tropical climates	Journal	*Malaysian Construction Research Journal*	Malaysia	[43]
36	Research on the application of prefabricated buildings in affordable housing construction in China	Conference	Conference Proceedings of the 6th International Symposium on Project Management	China	[84]
37	Energy and cost efficiency of a prefabricated timber social house in Chile: An interdisciplinary challenge	Conference	World Conference on Timber Engineering	Chile	[85]
38	Major Barriers to Different Kinds of Prefabricated Public Housing in China: The Developers' Perspective	Conference	Proceedings of the International Conference on Construction and Real Estate Management	China	[49]
39	Comparison of Japanese and British off-site housing manufacturers and its relation with low/zero energy/carbon houses	Conference	Proceedings of 33rd PLEA International Conference: Design to Thrive	Japan	[86]
40	Performance and Perception in Prefab Housing: An Exploratory Industry Survey on Sustainability and Affordability	Conference	Procedia Engineering	Australia	[87]
41	Modelling process integration and its management—Case of a public housing delivery organization in United Arab Emirates	Conference	MATEC Web of Conferences	United Arab Emirates	[88]
42	Space standardisation of low-income housing units in India	Journal	*International Journal of Housing Markets and Analysis*	India	[58]
43	Affordable and sustainable housing—Architectural, urban strategies and analysing methodology	Conference	Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future	Germany	[89]
44	Discrete-event simulation model for offsite manufacturing in Australia	Conference	Proceedings of the 31st Annual Association of Researchers in Construction Management Conference, ARCOM	Australia	[56]

Table A1. *Cont.*

Serial Number	Title of the Paper	Type of Paper	Source	Source Country	Reference
45	Technological and functional optimization of a modular construction system for flexible and adaptable multi-family housing	Journal	*International Journal for Housing Science and Its Applications*	Italy	[90]
46	New Chilean building regulations and energy efficient housing in disaster zones: The thermal performance of prefabricated timber-frame dwellings	Conference	Proceedings—28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs—Towards an Environmentally Responsible Architecture	Chile	[37]

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Article

A Multi-Criteria Decision-Making Approach for Assessing the Sustainability of an Innovative Pin-Connected Structural System

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Abstract: Structural design plays a very important role in reducing environmental impacts by reusing resources, recycling materials, and minimizing waste and pollution in the construction sector. Sustainable design becomes more effective than traditional solutions in achieving the transition to sustainability. The decision-making process is not simple due to the different preferences of clients, architects, and engineers. This paper aims to develop a decision framework for assessing sustainability in the early structural design stage. Multi-criteria decision-aiding (MCDA) methods have been implemented to improve the selection of regulations. A technical ranking approach, the Fuzzy Analytic Hierarchy Process (FAHP) method, has been employed to identify the optimal solution. Three alternatives including an innovative and two traditional structural systems have been selected and compared in terms of three criteria—economic, social, and environmental impacts. Nine sub-criteria for ranking the importance level of sustainable design have been determined through a literature review and professional experts. FAHP methods show that the economic impact (58%) is the most important criterion for assessing the sustainability of structural systems, followed by the environment with 31%. The social aspect contributes 11% to this method, and it is ranked as the least important criterion. This research revealed that MCDA methods can be used as a guideline for engineers to improve the selection in the process of sustainable design. The decision model proposed in this study has been verified and, therefore, can be applied for similar projects.

Keywords: structural design; sustainability assessment; Fuzzy Analytic Hierarchy Process (FAHP); multi-criteria decision aiding (MCDA)

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1. Introduction

The construction industry is responsible for 36 percent of global energy demand and 37 percent of energy-related CO_2 emissions in 2020, according to the '2022 Global Status Report for Buildings and Construction' [1]. In order to address climate change, the signing of the Paris Agreement became a crucial moment in global efforts. With rising attributable to materials used in the construction sector (expected to more than double by 2060), the global construction sector shall entirely decarbonize by 2050 to achieve the Paris Agreement. Building sectors play a key role in improving access to decreasing energy, clean fuels, and increasing renewable energy. Architects and allied professionals have advocated sustainable design principles, focusing on frameworks, like the China Green Building Standard, and internationally recognized certification models, such as BREEAM (UK), LEED (US), CASBEE (Japan), NABERS (Australia), and DGNB (Germany). These standards represent benchmarks that many architects and developers aspire to meet, guiding their efforts towards environmentally responsible and resource-efficient building practices [2].

Since building structures make up more than 50% of carbon emissions in terms of the whole construction process, structural engineers become essential players in achieving carbon neutrality. Engineers are inspired to work effectively concerning embodied carbon benchmarks after SE 2050 (The Carbon Leadership Forum's Structural Engineers 2050 Challenge) [3]. Architects and mechanical and electrical engineers are shifting towards embodied carbon with more operationally efficient buildings, while structural engineers are moving much more slowly in this process. To reduce environmental impacts, the most important step for structural engineers is to choose a suitable structural system and use materials efficiently.

However, for structural design, the majority of structural engineers still focus on economic benefits, such as optimizing structural elements and selecting high-strength materials, to meet clients' needs. Other aspects, including social and environmental impacts, have been overlooked entirely. Many countries have launched campaigns and introduced legislation relevant to green building to encourage engineers to control carbon footprints. But, the reality is that one of the important parts of building design, structural design, has been underestimated dramatically by authorities and stakeholders. Additionally, many researchers only emphasize materials selection to reduce environmental effects during the structural design phase. In fact, for some particular buildings, such as long-span industrial buildings, the type of structural system plays a vital role in sustainable structural design [4]. With the increased industrial building development, green industrial buildings have been implemented by more and more professionals; but applicable standards for selecting sustainable building structural systems and materials are notably missing [5]. Therefore, structural engineers are facing unprecedented challenges and difficulties in selecting a sustainable structural system for some specific buildings [6]. There is an urgent need to build a framework or provide some guidelines for selecting feasible building structures [7]. So, structural engineers must act and take responsibility despite the lack of regulatory incentives or guidelines.

This paper gives an extensive review of the process and development of sustainability practices in the construction and structural design area [7,8]. Building a structural system sustainability assessment will help with selecting a reasonable structural system when environmental, social, economic, and other indicators are considered [4]. This study aims to identify the selection criteria to choose, prioritize, and rate different structural systems using a multi-criteria decision-making method. Weightage and pairwise comparison matrixes for the criteria will be developed, and a selection approach will be proposed and recommended. In addition, this study is expected to address the severe shortcomings of current green building assessment in relation to structures and materials. The focus on selecting structural systems will provide deep insight for engineers who hope to perform structural design capturing economic, social, and environmental performance.

2. Literature Reviews

In this section, a comprehensive literature review of the proposed methodologies (Delphi, criteria, MCDA approaches) is provided to introduce the applications in the building literature. The review concentrates on sustainable design or materials selection in building areas, and the review also highlights the use of a multi-criteria decision-making approach in the assessment of building sustainability to support designers in the choice of systems and materials for construction projects. Sustainable assessment should be evaluated and integrated during the preliminary design phases, according to several authors [8–11].

2.1. Structural System Sustainability Assessment

Pin connections are extensively used in the construction of steel structures due to their numerous advantages over other systems, including ease of reuse, retrofitting, and assembly and disassembly [9]. Extensive research on the mechanical properties of pin connections has facilitated their widespread adoption and continuous development in the steel industry. These connections are pivotal for both structural integrity and architectural aesthetics [10,11]. However, despite the ongoing research on various structural systems, there is a significant lack of focus on sustainability within the context of pin connections. Moreover, existing green building regulations do not adequately assess this new system. Currently, there are many green building rating systems, such as the China Green Building Assessment (GB/T 50378), LEED, BREEAM, CASBEE, GBAS, DGNB, Green Star, and SBTOOL [2]. Nevertheless, none of these systems have been evaluated for life cycle indicators specifically in terms of structural design. Green buildings certified by these systems lack the necessary economic, environmental, and social indicators. Moreover, the multiple certifications implemented to date lack clear sustainability goals, resulting in less efficient processes, especially in the area of structural design. According to the current evaluation criteria, systems in almost all countries only evaluate structural materials, material durability, and building structure types.

This gap is particularly concerning given the increasing importance of sustainable design in the face of climate change and resource depletion. To address this sustainability gap, it is essential to reference existing research on sustainable structural design, which encompasses the use of environmentally friendly materials, energy-efficient construction methods, and principles aimed at minimizing environmental impact. Pin-connected structural systems can contribute to more sustainable building solutions by integrating these sustainable practices, thereby promoting environmental responsibility and long-term ecological balance.

As mentioned above, it is important to conduct sustainable analysis for structural engineers to reduce carbon emissions by selecting suitable structures and materials in the design of building structures. Structural design is very important and can reduce its significant environmental impact if specific structural design choices can opt out appropriately. Unfortunately, to achieve a sustainable built environment, there are still no global standards to obtain a balance between the dimensions of sustainability—economy, environment, and society [12–15]. For structural systems, there are different advantages, such as safety, constructability, workability, and durability, which can be seen as attributes of flexible design in terms of sustainability. Additionally, other design aspects including waste generation, energy use, water consumption, and CO_2 emissions can also be affected by structural engineering decisions significantly [16]. On the other hand, the importance of incorporating sustainable development principles in early phases, like feasibility analysis or preliminary design, is not properly understood by stakeholders. Furthermore, sustainable analysis was rarely considered during the design process, and clients, architects, and engineers paid more attention to costs and deadlines. If the structural systems are well planned and sustainable criteria are considered in the design phase, they can help to improve project sustainability magnificently [17].

In addition to structural design, many policies and specifications related to green buildings have been introduced to improve the construction's environmental performance, and some solutions, such as fabricated structures and steel structures, have been prioritized in this area. Regarding structural design to assess sustainability, the use of eco-efficiency materials was compared, and a selection method was proposed for load-bearing structures [18]. A new modular light-gauge steel framed wallboard (structural system) has been presented in the paper [19], and assessment indexes and guidance are proposed to evaluate the performance of the wallboard. Comparisons of different parameters (cost, technology, and environmental impact) have been made to select structures by implementing methodology combining sustainability criteria, BIM (building information modeling), and multi-criteria decision-aiding methods [20]. In order to deliver sustainable structural designs, a systematic approach and database generation for the EE (embodied energy) of building materials has been developed. Overall, EE reductions of up to 40% can be achieved by comparisons of slab construction techniques through environmental performance measures [21]. In the steel manufacturing industry, a case study was conducted to illustrate the proposed framework to determine the cause-and-effect relationships among criteria in terms of four prominent sustainability aspects, including engineering, economic, environmental, and social [22].

However, structural engineers typically prioritize mechanical behaviors and costs in enhancing building performance, with most studies focusing predominantly on economic issues. Although some research includes environmental impacts, social sustainability often remains overlooked [17–21]. When social sustainability is considered, it primarily focuses on the construction and architectural design stages [15–21]. A decision model has been developed to evaluate the sustainability of three types of commercial building structures at the early design stage [23]. This model assesses social benefits such as spatial adaptability, safety, comfort, and maintenance within structural design based on integrated design objectives [20]. Despite the recognized importance of sustainability, there is limited research on optimizing structural systems in this context. Consequently, a significant gap exists in the literature regarding the selection of structural systems that comprehensively address economic, environmental, and social sustainability. Addressing this gap is crucial for advancing the field and ensuring that sustainable design principles are integrated from the earliest stages of building development, ultimately leading to more holistic and resilient built environments.

In this study, the systemic approach for sustainability assessment is proposed in the early stage (feasibility or preliminary design). A criteria system, multi-criteria decision-aiding methods, and a decision model for three different alternative structural solutions in the design phase have been developed to assess sustainability.

2.2. Sustainable Criteria for Structural System Selection

Over the last decades, great numbers of articles, books, and consulting reports offered competing positions on the definition of 'sustainability' and its implications for action. In general, sustainability rests on three (social, ecological, and economic), four (social, ecological, economic, and technological), or five pillars (ecological, economic, social, political/institutional, and cultural) or more [15]. The interactions among pillars will become very hard to distinguish and portray if more than three pillars are implemented. At the same time, sustainable development pillars or indicators should not be oversimplified to warrant a closer examination and better investigation. At present, different indicators have been proposed and used for diverse purposes by different users in many varied contexts. Most of the sustainability indicator frameworks are based on the three most important pillars: environmental, social, and economic [24]. It is revealed that the criteria for structural system selection have not been established according to a comprehensive review of the literature. Based on three different impact categories, a sustainability assessment framework for sustainable material choice has been applied to some construction projects using the BIM and Fuzzy AHP approach [25]. The criteria established for building construction and material selection are shown in Table 1. A variety of technologies distinguish construction processes and require analyzing the technological aspects as separate and important sustainability categories [15]. Technological aspects or other aspects, such as cultures and policies, are all relevant to social, ecological, and economic factors.

In the next sections, the approach for sustainability assessment will be proposed in the early stage (feasibility or preliminary design). A criteria system, multi-criteria decision-aiding methods, and a decision model for three different alternative structural solutions in the design phase will be developed to assess sustainability. Social, economic, and environmental aspects will be included in these sustainability criteria.

Table 1. Criteria established for building construction.

Indicators	Criteria	Source	Main Contributions
Economic	Construction Maintenance Management Investment cost Maintenance and operation Materials cost Energy cost Risk management Life cycle impacts Design changes Constructability	[14,20,26,27]	Financial advantages of designing flexible spaces that can be easily adapted to future needs, extending the building's useful life. Designing structures with reused components; the use of eco-friendly, recycled, and locally sourced materials to reduce environmental impact; analysis of the cost differences between conventional and sustainable materials and the long-term benefits; life cycle assessment methods; and assessing the sustainability of alternative structural solutions.
Environment	CO_2 emissions Energy consumption Waste Recycling and reuse Noise Dust and air pollution Resources, consumption, water, land, and materials Production Transportation Waste management	[28–32]	Site selection and materials to energy efficiency and waste management; sustainable material selection with hybrid MCDA; environmental enhancement via building refurbishment; green building indicators; using materials with low environmental impact; engaging all stakeholders early in the design process to identify and implement sustainable solutions; and incorporating new technologies and approaches.
Social	Noise Aesthetic Safety Health Comfort Functions Reliability/maturity Design life Efficiency Primary energy ratio	[17,22,26,33–35]	Promote well-being, equity, and community engagement; project site selection based on health and well-being; social aspect implementation in sustainable construction; social effects by construction methods; ensuring buildings are structurally sound; engaging the community and stakeholders in the planning and design process; and spaces that support community resilience.
Others	Resource Technology Strategic (political) culture Energy Performance Engineering resource Project management Regulatory	[26,36–40]	Novel sustainability framework; sustainable MCDA in civil engineering through technology, culture, and polices; incorporating advanced building management systems; aligning building projects with government policies and initiatives; involving architects, engineers, policymakers, and other stakeholders from the outset; and adopting a mindset of continuous improvement.

2.3. MCDA Approaches

The MCDA method has been adopted widely in the construction industry to generate effective, sustainable solutions in recent decades [41]. There are a majority of technical methods to carry out MCDA, as shown in Table 2. In the building area, it is necessary to consider different aspects of a project, including cost, quality, time, security, ethics, and resources. During the structural design stage of a project, multiple criteria are often involved with a great number of the decisions undertaken and analyzed to ensure a better solution [42]. Many different technical methods for multi-criteria decision making have been developed to address a variety of issues in the building sector [43]. The FAHP approach, combining the Analytic Hierarchy Process (AHP) with fuzzy logic theory, enriches its precedent [44]. The AHP theory is based on the Cartesian and Newtonian way of thinking, which is composed of making the problem into small parts continually until a precise level is reached. The AHP requires one-to-one comparison judgments among similar criteria to generate the priorities of alternatives using experts [45], while the FAHP employs the fuzzy set theory concepts which use fuzzy numbers instead of real numbers in hierarchical structure analysis [46,47]. In the review of articles regarding the MCDA method (years 2020–2024), the top five most commonly used methods in the construction area are the AHP (878 papers, 24%), Fuzzy AHP (571 papers, 16%), TOPSIS (602 papers, 16.5%), Fuzzy TOPSIS (376 papers, 10%), and ANP (368 papers, 10%). Although the AHP is the most popular method, with 878 papers (24%) from 2021 to 2024, it has several disadvantages, such as subjectivity in judgment, inconsistency in pairwise comparisons, and a lack of handling uncertainty. To address these issues, the use of the Fuzzy AHP (FAHP) is recommended. The FAHP incorporates fuzzy logic to handle the uncertainty and vagueness in human judgment, reducing inconsistencies and improving the overall decision-making quality. Consequently, the FAHP, which accounts for 571 papers (16%) and is a more robust alternative for complex decision-making scenarios in the construction area.

Table 2. MCDA approaches.

Method	Advantage	Limitation	Recommendation
AIRM Aggregated Indices Randomization Method	Ordinal non-numerical information can be translated into a framework.	Time-related biases, especially as sample sizes grow.	Analysis with non-numeric (ordinal), imprecise (interval), and incomplete expert insights.
AHP Analytic Hierarchy Process	Deliberate inclusion of both qualitative and quantitative elements.	This process entails defining the decision problem with precision and crafting accurate pairwise comparison matrices.	Well suited for crafting decisions that encompass a multitude of stakeholders and diverse criteria.
ANP Analytic Network Process	This approach tackles intricate decision challenges involving interconnected criteria and alternatives.	It is more intricate and time intensive compared to the AHP, demanding both expertise and comprehensive data input.	However, it excels in guiding construction decisions where interdependencies among criteria and alternatives are significant.
ARM/ARAS Additive Ratio Assessment Method	Effective for quantitative measurements and allows for flexible adjustment of weights and preference values.	Lacks efficacy in qualitative initial assessments and comparative preference analysis.	It finds extensive use in solving various problems across diverse domains, such as supplier selection and construction issues.
BWM Best Worst Method	Straightforward and user friendly for pinpointing critical factors.	Overlooks interactions between criteria or alternatives.	Conducting pairwise comparisons to ascertain the optimal and least favorable elements within each criterion.
COPRAS Complex Proportional Assessment	Assuming independence between positive and negative ratios.	Subjectivity is involved in assigning weights to criteria.	Particularly useful for structured evaluation processes in construction decisions.
DEMATEL Decision-making Trial and Evaluation Laboratory	Examines the causal connections between criteria and pinpoints pivotal factors.	It prioritizes understanding relationships.	This approach suits decision making in construction, where grasping causal links is vital.
ELECTRE Elimination and Choice Expressing Reality	Tackles the challenge of reconciling diverse criteria through a clear evaluation process.	It takes into account preferences and their respective weights, requiring substantial data.	It is used for construction decisions characterized by conflicting criteria and a is requirement for transparency.

Table 2. *Cont.*

Method	Advantage	Limitation	Recommendation
Fuzzy AHP Fuzzy TOPSIS Fuzzy FMEA and Fuzzy VIKOR	Triangular fuzzy numbers capture the inherent subjectivity of human opinions, while the entropy weighting method efficiently reflects the actual dynamics of decision-making, contingent upon the chosen evaluation criteria.	This method accounts for a decision maker's inclination to allow a single attribute of a candidate or organization to disproportionately influence their overall assessment.	A fuzzy set is well suited for scenarios where precise boundaries or categories are difficult to define, and instead, there exists a degree of ambiguity or uncertainty.
GTA Graph-Theoretic Analysis	Their simplicity and versatility make them applicable across diverse fields.	The permanent function employs qualitative values for different terms.	Widely employed to depict nearly any physical scenario comprising discrete objects and their relationships.
GRA Gray Relational Analysis	This method evaluates the connection between input and output variables.	It is influenced by the choice of reference series and can be challenging to determine input variable weights.	It is valuable for understanding how input variables impact outcomes in construction.
LINMAP Linear Programming Techniques for Multidimensional Analysis of Preference	The LINMAP procedure does not require the decision maker to provide all paired comparison judgments.	However, it is difficult to assess partial orders and obtain reliable weights.	Environmental management, distribution, hydrology, finance, chemistry, logistics, energy management, healthcare, manufacturing, sports, etc.
MAUT Multi-Attribute Utility Theory	MAUT allows decision makers to consider multiple attributes simultaneously.	MAUT can be complex and time consuming.	Involve stakeholders in the decision-making process to ensure that their preferences and concerns are adequately represented.
MIVES Integrated Value Model for Sustainability Assessment	MIVES considers multiple dimensions of sustainability.	Relies on data for various indicators, potentially leading to biases or disagreements.	Transparency and stakeholder engagement.
MOORA Multi-objective Optimization by Ratio Analysis	It can utilize this approach easily to assess different options and choices.	Predicting the weights assigned to different criteria can be challenging.	Performance evaluation in the real estate sector, contractor selection, design selection, and robot selection.
Integrated Methods (Integrated DEMATEL-ANP, Fuzzy FMEA and VIKOR, Gray AHP, Gray TOPSIS, etc.)	It helps alleviate concerns, like human bias and judgment ambiguity.	However, challenges persist in modeling discrete data, particularly when information is lacking, leading to varied outcomes.	In complex projects, it becomes crucial to compare the results generated by diverse methodologies to develop a comprehensive index.
PROMETHEE Preference Ranking Organization Method for Enrichment Evaluations	Ranking alternatives involves comparing them pairwise, taking into account preferences and indifference.	Rankings are more sensitive to normalization methods and weights.	This method is applicable for construction decisions with clearly defined preferences and pairwise comparisons.
SAW/WSM Simple Additive Weightage/Weighted sum method	A proportional linear transformation of raw data.	However, it can be influenced by self-assessment bias.	It is particularly favored for less complex problem environments due to its simplicity.
SWARA Stepwise Weight Assessment RatioAnalysis	This approach establishes priorities based on firms' or nations' set policies and strategies.	Relying on a single ratio might lack comprehensive information and could potentially mislead regarding profits.	It is regarded as the most effective method for evaluating criteria, particularly for determining their relative weights.

Table 2. *Cont.*

Method	Advantage	Limitation	Recommendation
TOPSIS Technique for Order Preference by Similarity to Ideal Solution	Identifies alternatives that closely approximate the ideal solution and accommodates nonlinear relationships.	Rankings are notably influenced by the weights.	It involves defining criteria, standardizing data, and computing Euclidean distances to gauge the proximity of alternatives to the ideal solution, streamlining the ranking process systematically.
VIKOR VIseKriterijumska Optimizacija I Kompromisno Resenje	Offers a compromise solution when faced with conflicting criteria.	Rankings are affected by the weights assigned to criteria and may not be universally applicable.	Particularly beneficial for construction decisions entailing conflicting criteria and a necessity for compromise.
WASPAS Weighted Aggregated Sum Product Assessment	Addressing single-dimensional issues, adept at balancing multiple criteria, and easily understood.	However, it may not always accurately portray real-world scenarios, leading to illogical outcomes.	To overcome this limitation, complex alternative decisions are ranked, and optimal solutions are sought based on multiple, often conflicting criteria.

3. Materials and Methods

3.1. Evaluation Framework

Multi-criteria analyses have been employed for evaluating different options in this case. Steps involve framing the decision problems, such as identifying all possible alternatives through unbiased experts or members; then, evaluation criteria shall be defined to assess technical, environmental, and social aspects of the alternatives; most importantly, the weights of each evaluation criteria should be attributed based on the assessment of experts. The framework is illustrated in Figure 1.

3.2. Fuzzy AHP Method

The Analytic Hierarchy Process (AHP) and Fuzzy AHP are widely implemented to determine the weights of different criteria and priorities of alternatives in multi-criteria decision-making methods. Based on the pairwise comparison, the Fuzzy AHP is a method that fuzzy sets that will be combined with the AHP values [30]. The scale of the relative important factor (1-9, 1/9-1) will be applied to measure comparison values (as illustrated in Table 3). The AHP typically employs precise numerical values (1–9 scale) to indicate the intensity of preferences between two elements. In contrast, decision makers use fuzzy numbers (e.g., triangular or trapezoidal fuzzy numbers) instead of precise numerical values for pairwise comparisons [27]. The fuzzy AHP values will be used in this study.

To calculate the weight factor, the following steps have been depicted:

Step 1: Comparison of factors

Simple Additive Weighting (SAW) is a simple and reliable approach used to find the sum of the weighting for each alternative when conducting multi-attribute decision making to solve the problem. Normalizing the decision matrix (X) is required when comparing all the ratings of the supposed alternatives [29].

$$r_{ij} = \frac{x_{ij}}{Max\left(x_{ij}\right)} \quad (1)$$

$$r_{ij} = \frac{Min\left(x_{ij}\right)}{x_{ij}} \quad (2)$$

$$w = \frac{C1}{C1 + \ldots + Cn} \times 100\% \quad (3)$$

$$V_i = \sum_{j-1}^{n} = 1 w_j r_{ij} \quad (4)$$

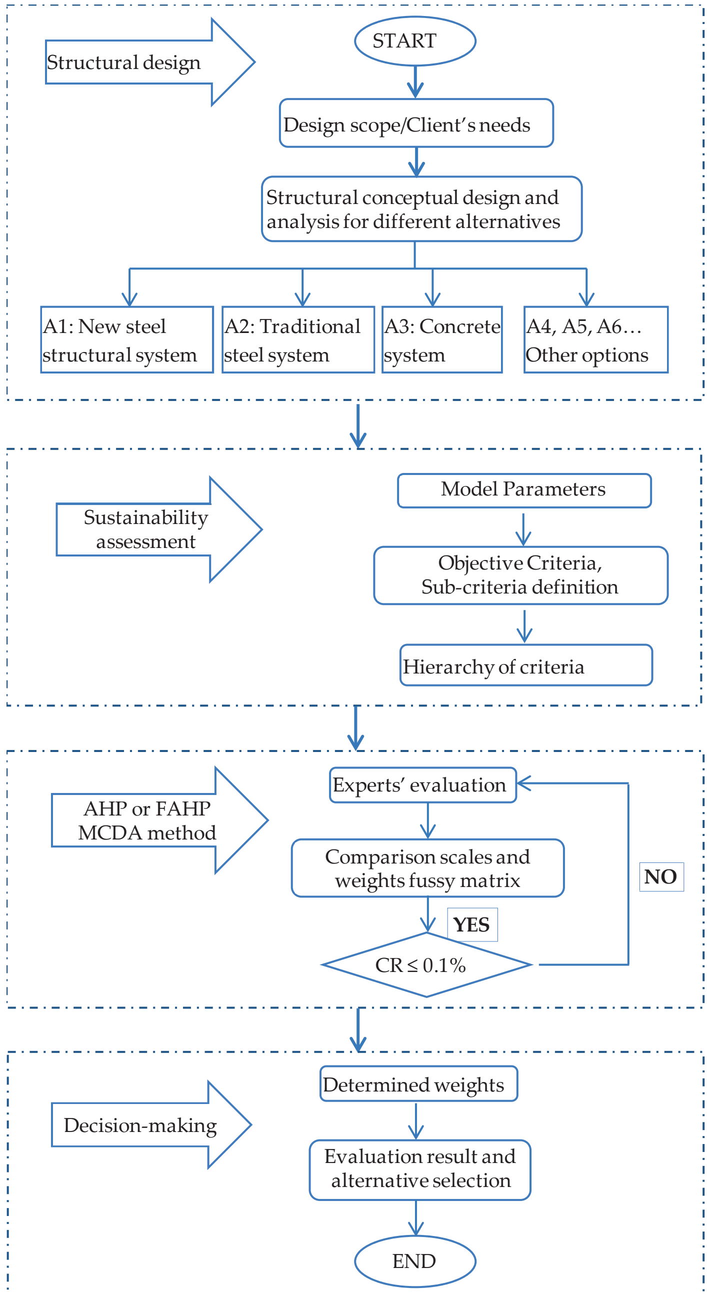

Figure 1. The flowchart of the structural system selection model.

Table 3. Definition of the fuzzy scale.

Importance Assessment	Fuzzy AHP Value	AHP Value
Absolutely strong (AS)	(8,9,9)	9
Very strong (VS)	(6,7,8)	7
Fairly strong (FS)	(4,5,6)	5
Slightly strong (SS)	(2,3,4)	3
Equal (E)	(1,1,1)	1
Slightly weak (SW)	(1/4,1/3,1/2)	1/3
Fairly weak (FW)	(1/6,1/5,1/4)	1/5
Very weak (VW)	(1/8,1/7,1/6)	1/7
Absolutely weak (AW)	(1/9,1/9,1/8)	1/9

The weights of all criteria will be obtained using Formulas (6)–(9). r_{ij} is the normalized performance rating of the alternatives to attribute *Ci*, *Ai*; *i* = 1,2, . . ., n and j = 1,2, . . ., *n*. As shown in Figure 2, $\tilde{n}$ (triangular fuzzy numbers) can be defined by a triplet (*a*, *b*, *c*) with function $\mu_{\tilde{n}}$ as follows:

$$\mu_{\tilde{n}}(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $a < b < c$. *b* is the most likely value of the fuzzy number.

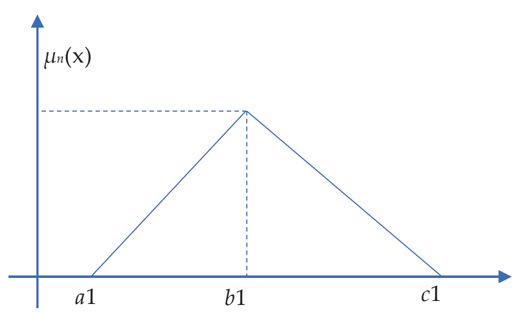

Figure 2. A triangular fuzzy number $\tilde{n}$.

The distance *D* between fuzzy numbers can be defined as follows:

$$D\left(\tilde{n}_1, \tilde{n}_2\right) = \sqrt{\frac{1}{3}\left[(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2\right]} \tag{6}$$

Step 2: Perform consistency

The factor of consistency shall be calculated to control the consistency of subjective opinions and the accuracy of the following weight factors:

$$CF = (\lambda_{\max} - n)/(n - 1) \tag{7}$$

It is acceptable if the consistency factor is less than 0.1, where $\lambda_{\max}$ is the matrix *R* maximum eigenvalue and *n* is the factor number.

The index of consistency for random judgments was defined by Saaty (1980) as the consistency ratio (CR)

$$\text{CR} = \frac{CI}{RI} \tag{8}$$

where *RI* is the average value of *CI* for random matrices using the given scale (as shown in Table 4), according to Saaty (1980) [48].

Table 4. Values of RI.

Matrix Order	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
Matrix Order	9	10	11	12	13	14	15	16
RI	1.45	1.49	1.51	1.48	1.56	1.57	1.59	1.60

Step 3: Converting parameters

Triangular fuzzy numbers follow the conversion rules, and the values of the pairwise comparison matrix shall be converted to these numbers.

$$\tilde{\boldsymbol{R}} = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{r}_{nn} \end{bmatrix} \quad (9)$$

Step 4: Calculation of the factor dimensions

The fuzzy weight factor dimensions can be obtained as follows:

$$\tilde{u}_i = \left(\tilde{r}_{i1} \odot \tilde{r}_{i2} \odot \ldots \odot \tilde{r}_{in}\right)^{1/\mathrm{n}} \quad (10)$$

Step 5: Calculation of the weight factors

The final fuzzy weight factors can be calculated with the following formula:

$$\tilde{w}_i = \tilde{u}_i \odot \left(\tilde{u}_{i1} \oplus \tilde{u}_{i2} \oplus \ldots \oplus \tilde{u}_{in}\right)^{-1} \quad (11)$$

Step 6: Calculation of the true values

The final fuzzy weight factors are as follows:

$$w_{\mathrm{i}} = \left[\left(w_{\mathrm{i}}^{u} - w_{\mathrm{i}}^{\mathrm{l}}\right) + \left(w_{i}^{m} - w_{i}^{l}\right)\right]/3 + w_{i}^{l} \quad (12)$$

where $\tilde{w}_i = \left(w_i^l, w_i^m, w_i^u\right)$.

The normalized weight vector is calculated by applying Equation (13) as follows:

$$w_{ni} = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (13)$$

4. Sustainability Assessment to Select the Structural System

4.1. Structural Systems (Alternatives) Description

In this paper, based on an industrial building, a novel pin-connection joint (shown in Figure 3) was proposed for all truss–column connections to support the floor system subject to heavy loads in the long-span steel structural system. Typical welded and bolted connections were difficult to meet the requirements of stakeholders (such as cost control by clients, esthetics by architects, and constructability by builders). There will be dramatic disadvantages if implementing traditional solutions (as presented in Figure 3), including too many bolts to control the quality, large truss elements, expensive labor and inspection costs, slow construction speeds, and difficulty in reusing. Meanwhile, the critical issue for applying a conventional structure to this project is the safety risk. Bolted connections are assumed to be ideal pinned connections (a semi-rigid assumption is unlikely because of its complexity and software limitations) when carrying out analysis through structural software for normal steel structures [10,11]. But, bolted joints behave as semi-rigid connections rather than ideal pinned connections in the real project. For most normal steel structures, there were minor impacts on the safety of the entire structure and connections if ideal pinned conditions were assumed during the design process. However, for long-span, high floor–floor height, and heavy-loading steel structures, if an ideal pinned connection assumption is used for analysis but is designed as a bolted connection it will put huge risks on columns, especially long columns. A bolted semi-rigid connection will resist the moment and transfer to the column, and then the column capacity will be reduced unpredictably; further, it will damage the entire structural system if under extreme hazards (blasts, earthquakes, and strong winds).

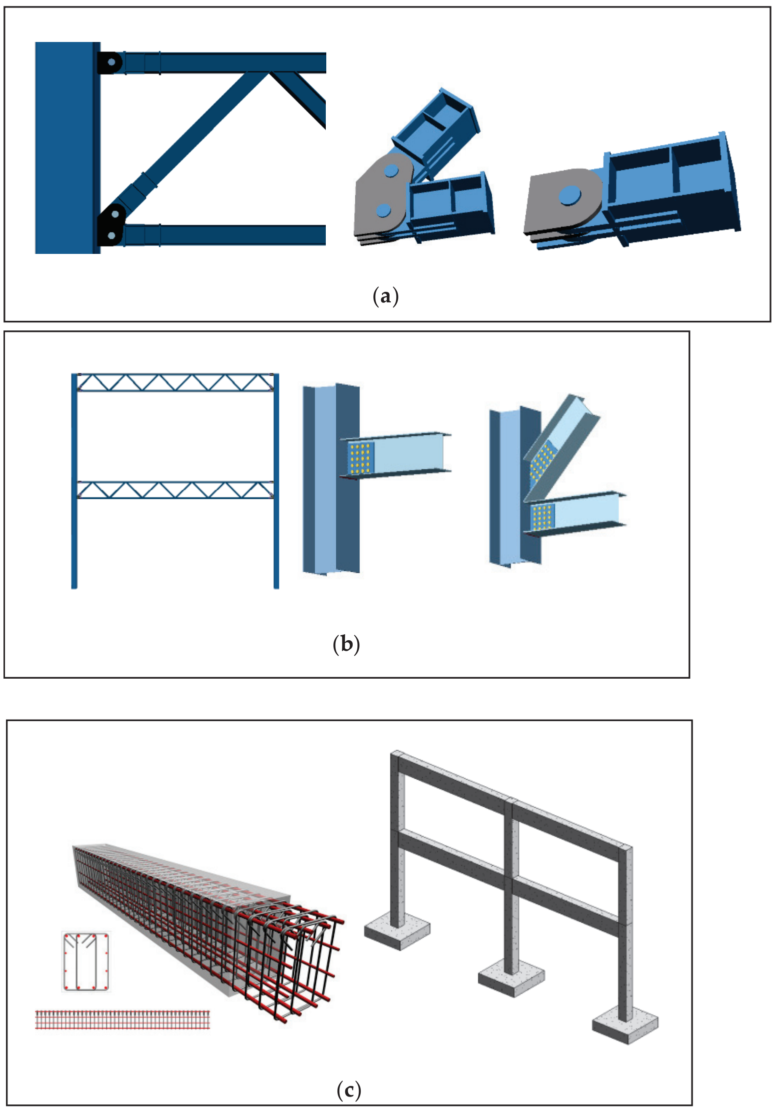

Figure 3. Structural system. (**a**) Pin connection for a long-span steel structure; (**b**) traditional connections for a long-span steel structure; (**c**) a traditional concrete structural system.

4.2. Fuzzy AHP Application

To exemplify the applicability of the proposed sustainable performance evaluation framework to design a structural system, a case study of selecting a suitable structural system is utilized. As detailed in Figure 4, a step-by-step approach to implementing this methodology is developed.

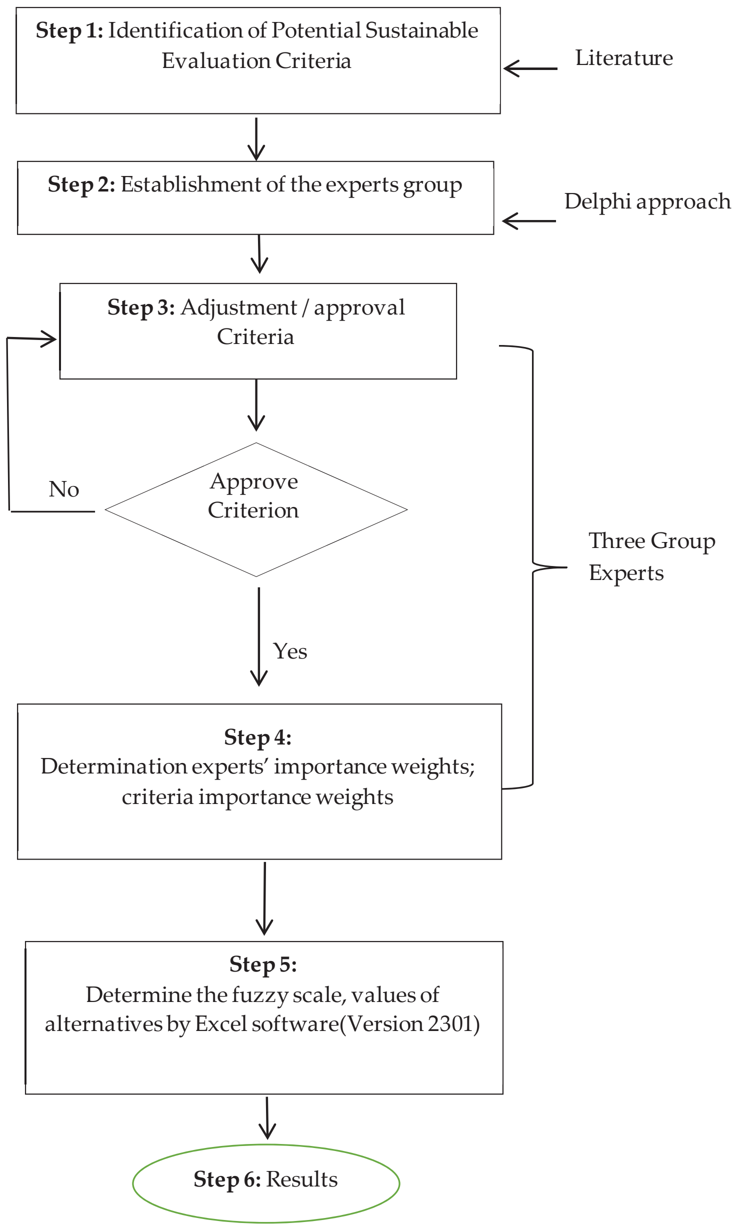

Figure 4. Proposed step-by-step approach.

Step 1. Constructing the hierarchical structure: The main criteria and sub-criteria for the sustainability evaluation of structural systems are identified by considering both the literature review and the expert opinions (Questionnaire refer to Appendix A). to build a framework [27,49,50]. The hierarchical structure is presented in Figure 5.

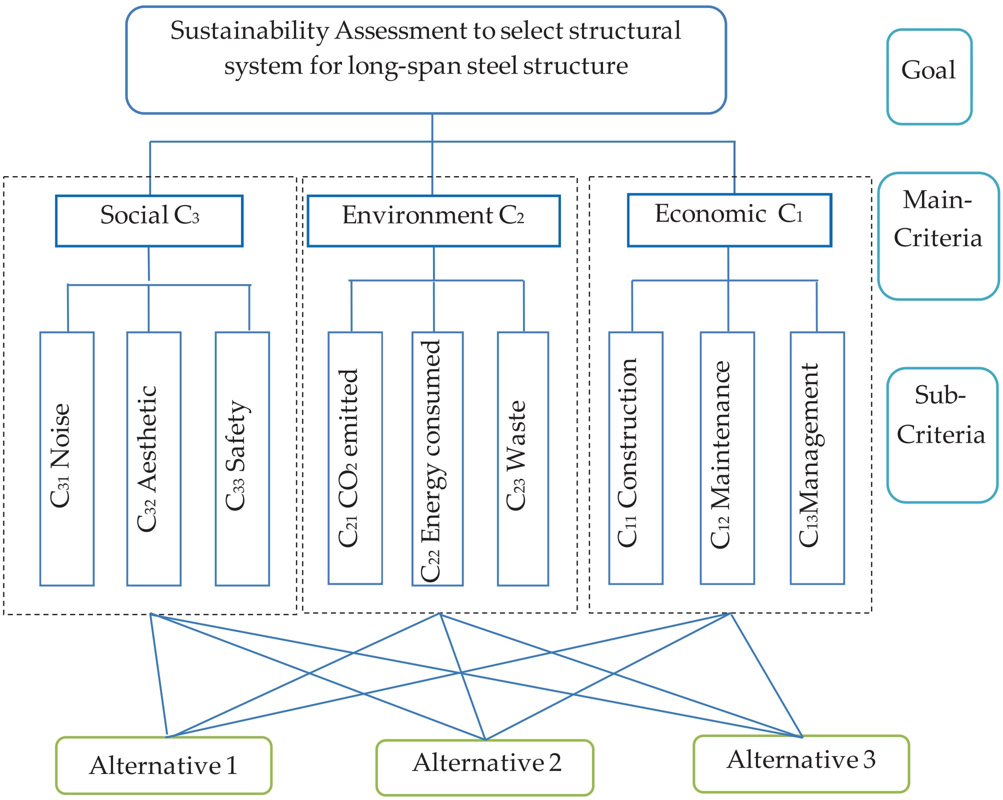

Figure 5. The hierarchical structure of a sustainable design.

Steps 2 and 3. Data collection: In these steps, first, questionnaires are formed as pairwise comparison matrices and evaluated by the 16 experts for the next step (shown in Table 5). In these steps, we outline the criteria used in our FAHP analysis and explain the connection between these criteria and the specific fields of expertise of the professionals interviewed. To ensure the credibility and transparency of the evaluation process, experts are carefully selected based on their qualifications and relevance to this study.

In these steps, the questionnaire (Questionnaire refer to Appendix B). is formed to obtain evaluation data of alternatives. These data are expressed in a matrix format as a fuzzy MCDM problem, with m alternatives and n criteria that are the lowest level criteria of the hierarchy.

Step 4. Determining the weights of the experts and evaluation criteria: Pairwise comparisons are carried out and, thus, fuzzy comparison matrices are obtained, as seen in Table 6. In this scenario, all expert groups are equally important to make decisions. Take the experts in Group 1 as an example; the evaluation matrix built for the evaluation of the sub-criteria with respect to the factors (C1) is provided in Tables 7–10.

Table 5. Characteristics of the experts.

Expert Groups	Experts	Education	Position	Justification for Expert Selection
Group 1	1	PhD	Lecturer	Expert in structural design and construction, extensive knowledge of evaluating Criterion C1 and C2.
	2	Masters	Structural engineer	Professionals in structural design who provide insights into environmental impact; essential for assessing criterion C1/C2/C3.
	3	Bachelors	Building estimator	Professionals in cost estimation for Criterion C1.
	4	TAFE/ University	Builder or supplier	Professionals in construction management; essential for assessing Criterion C1/C3.
Group 2	5	PhD	Prof.	Background in building design and construction and provides critical insights for Criterion C1/C2/C3.
	6	PhD	Assoc. Prof. Dr.	Background in building design and construction and provides critical insights for Criterion C1/C2/C3.
	7	Masters	Structural engineer	Extensive experience in structural design is essential for evaluating Criterion C1/C2/C3.
	8	TAFE/ University	Builder or supplier	Background in building construction and materials.
Group 3	9	Masters	Structural engineer	Professionals in design. Essential for assessing Criterion C1.
	10	Masters	Manager	Professionals from construction management; essential for assessing Criterion C1/C2/C3.
	11	Bachelors	Architect	Professionals in architectural design and green building experts. Essential for assessing Criterion C1/C2/C3.
	12	Bachelors	Building officer	Background in building construction and policy; provides critical insights for C1/C2/C3.

Table 6. Evaluation of the experts.

	Matrix in expert terms		
Experts	G_1	G_2	G_3
G_1	-	E	E
G_2		-	E
G_3			-
	Matrix in fuzzy terms		
G	G_1	G_2	G_3
G_1	1	(1, 1, 1)	(1, 1, 1)
G_2	(1, 1, 1)	1	(1, 1, 1)
G_3	(1, 1, 1)	(1, 1, 1)	1
Note: The weight vector is calculated as W_G = (0.333, 0.333, 0.333)			

Table 7. Evaluation of the main criteria.

Sustainability Assessment	Matrix in expert terms		
	C_1	C_2	C_3
C_1	-	E/SS	FS
C_2		-	SS
C_3			-
	Matrix in fuzzy terms		
C_1	C_1	C_2	C_3
C_1	1	(1, 2, 3)	(4, 5, 6)
C_2	(1/3, 1/2, 1)	1	(2, 3, 4)
C_3	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	1
Note: The weight vector is calculated as W_C = (0.566, 0.324, 0.110)			

Table 8. Evaluation of the sub-criteria with respect to C_1.

	Matrix in expert terms		
C_1	C_{11}	C_{12}	C_{13}
C_{11}	-	SS	FS
C_{12}		-	SS
C_{13}			-
	Matrix in fuzzy terms		
C_1	C_{11}	C_{12}	C_{13}
C_{11}	1	(2, 3, 4)	(4, 5, 6)
C_{12}	(1/4, 1/3, 1/2)	1	(2, 3, 4)
C_{13}	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	1
Note: The weight vector is calculated as W_{C1} = (0.629, 0.264, 0.107)			

Table 9. Evaluation of the sub-criteria with respect to C_2.

	Matrix in expert terms		
C_2	C_{21}	C_{22}	C_{23}
C_{21}	-	E/SS	SS
C_{22}		-	E/SS
C_{23}			-
	Matrix in fuzzy terms		
C_2	C_{21}	C_{22}	C_{23}
C_{21}	1	(1, 1, 2)	(2, 3, 4)
C_{22}	(1/2, 1, 1)	1	(1, 1, 2)
C_{23}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	1
Note: The weight vector is calculated as W_{C2} = (0.483, 0.313, 0.203)			

Step 5: Performance Evaluation in terms of Sustainability Factors

The economic performance criteria values and their importance weights for three alternatives are shown in Table 11, and Table 12 shows the results of all sustainability factors.

Table 10. Evaluation of the sub-criteria with respect to C_3.

	Matrix in expert terms		
C_3	C_{31}	C_{32}	C_{33}
C_{31}	-	SS	E/SS
C_{32}		-	E/SS
C_{33}			-
	Matrix in fuzzy terms		
C_3	C_{31}	C_{32}	C_{33}
C_{31}	1	(2, 3, 4)	(1, 1, 2)
C_{32}	(1/4, 1/3, 1/2)	1	(1, 1, 2)
C_{33}	(1/2, 1, 1)	(1/2, 1, 1)	1
Note: The weight vector is calculated as W_{C3} = (0.488, 0.241, 0.271)			

Table 11. Evaluation of alternative 1 with respect to C_{11}.

Alternatives	Matrix in expert terms		
A	A_1	A_2	A_3
A_1	-	E/SS	E/SS
A_2		-	E/SS
A_3			-
	Matrix in fuzzy terms		
A	A_1	A_2	A_3
A_1	1	(1, 2, 2)	(1, 2, 3)
A_2	(1/2, 1/2, 1)	1	(2, 2, 3)
A_3	(1/3, 1/2, 1)	(1/3, 1/2, 1/2)	1
Note: The weight vector is calculated as W_C = (0.454, 0.351, 0.195)			

Table 12. Criteria performance of alternatives A1–A3.

Expert Groups	Main Criteria	Sub-Criteria	A1	A2	A3
G1 G2 G3	C1: Economic (0.566)	C11	0.454	0.351	0.195
		C12	0.403	0.302	0.295
		C13	0.391	0.322	0.287
	C2: Environment (0.324)	C21	0.401	0.382	0.217
		C22	0.522	0.302	0.196
		C23	0.446	0.287	0.267
	C3: Social (0.110)	C31	0.359	0.311	0.330
		C32	0.397	0.301	0.302
		C33	0.356	0.335	0.309

5. Results

In this section, the results obtained from the FAHP method will be presented and discussed. The MCDA approach and framework model have been explained in Section 3.

The results of the criteria weights for the evaluation matrices, including local and global weights, are presented in Table 13 (expert groups 1–3). In this study, all expert groups are assumed to give the same weights for the weights.

Table 13. Evaluation criteria weights with respect to G1.

	Experts	Main Criteria	Sub-Criteria	Local Weight	Global Weight	Rank
Multi-criteria analysis results	G1 G2 G3	C1: Economic (0.566)	C11	0.629	0.356	1
			C12	0.264	0.149	3
			C13	0.107	0.061	6
		C2: Environment (0.324)	C21	0.483	0.156	2
			C22	0.313	0.101	4
			C23	0.203	0.066	5
		C3: Social (0.110)	C31	0.488	0.054	7
			C32	0.241	0.027	9
			C33	0.271	0.030	8

The fuzzy decision-making matrix, utilizing the global weights of all sub-criteria obtained through the FAHP, is designed to evaluate and rank alternatives. This matrix, shown in Table 14, systematically integrates these weights to provide a comprehensive assessment and prioritization of each alternative.

Table 14. Final ranking results.

Sub-Criteria	Global Weight	A1	A2	A3
C11	0.356	0.162	0.125	0.069
C12	0.149	0.060	0.045	0.044
C13	0.061	0.024	0.020	0.018
C1 Total	0.566	0.246	0.190	0.131
C21	0.156	0.063	0.060	0.034
C22	0.101	0.053	0.031	0.020
C23	0.066	0.029	0.019	0.018
C2 Total	0.323	0.145	0.109	0.071
C31	0.054	0.019	0.017	0.018
C32	0.027	0.011	0.008	0.008
C33	0.030	0.011	0.010	0.009
C3 Total	0.111	0.041	0.035	0.035
Total	1.000	0.431	0.333	0.236
Ranking	N/A	1	2	3

In Table 14, it can be seen that the weights within all criteria levels and importance ranking for the three alternatives have been exhibited. The results show that the most salient one of the main criteria levels is the economic indicators (0.566), followed by the environmental indicators (0.323). In the sub-criteria level, C11—construction (0.356) is the best performance within this level. This criterion is trailed by C21—CO_2 emissions (0.156) and C12—maintenance (0.149). Therefore, for sustainable structural design, economic (construction cost) is considered the most important factor, whereas social (aesthetic) is viewed as the least important decision-making factor. Figure 6 clearly shows that in terms of sustainability indicators, priority is given to the economic factor for all three alternatives, and the environmental factor is placed in the second spot. That means the economic dimension is the most influential dimension among the three sustainability indicators. Consequently, structural engineers shall put in more resources to improve the contributions of top-ranked criteria during the early design stage.

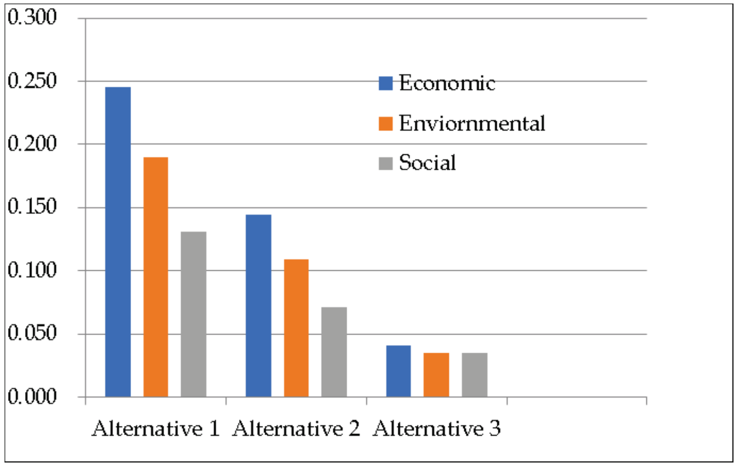

Figure 6. Final ranking.

In this case, economic considerations by experts continue to dominate the selection criteria for pin-connected new building structural systems, overshadowing sustainability assessments. The pin connection new structural system offers several advantages that align well with low-cost considerations, lower maintenance costs, and enhanced building lifespans, especially in terms of reuse, retrofitting, and ease of assembly and disassembly.

A critical discussion point is the tendency of structural engineers and project stakeholders to emphasize immediate cost savings over sustainable practices. Despite the availability of green building codes and sustainable design principles, the higher upfront costs associated with environmentally friendly materials and energy-efficient construction methods often deter their adoption. This cost-centric approach overlooks the potential long-term benefits and savings that sustainable practices can offer, such as reduced energy consumption, lower maintenance costs, and enhanced building lifespans.

Moreover, it is crucial to explore whether the proposed sustainable approach can effectively influence the opinions of owners and designers if it is perceived as financially burdensome. Even if sustainable methods are proven to be beneficial, their adoption hinges on demonstrating economic viability. Therefore, further discussion and strategies are recommended to align economic incentives with sustainability goals. This could include presenting case studies where sustainable practices have led to cost savings, advocating for regulatory incentives, or proposing financial models that highlight the long-term economic benefits of sustainable building practices.

Sensitivity Analysis

Sensitivity analysis is a crucial step in multi-criteria decision-making (MCDM) methods, as it examines how variations in input data or criteria weights affect the final ranking of alternatives. It helps test the robustness of our results, ensuring that conclusions are not overly sensitive to specific weightings. Through sensitivity analysis, we can identify which criteria have the most significant impact on the final decision. This is particularly useful for policymakers and practitioners in the building industry, as it highlights where efforts and resources should be focused to achieve substantial sustainability improvements. The traditional AHP is valued for its straightforward implementation, ease of understanding, and widespread acceptance. However, it can sometimes struggle with handling the inherent uncertainties and vagueness present in real-world decision making, especially in complex fields, like building sustainability. The Fuzzy AHP extends the traditional AHP by incorporating fuzzy logic to address these uncertainties. In this study, we explore the Fuzzy AHP to further refine the decision-making process in building sustainability evaluations.

Conducting sensitivity analysis for MCDA methods involves selecting the best option that meets the following requirements and conditions: (a) maintaining priorities in most scenarios despite changes in weight coefficients, (b) preserving the rankings of alternatives when the measurement scale changes, and (c) keeping the ranking of alternatives consistent when modifying the criteria formulation. The three typical approaches to perform sensitivity analysis include:

(1) Changes to the weight of the criteria.

The results of the MCDA methods mostly depend on attributed weights on the criteria. The ranks of the alternatives vary with changes in the weight assigned to the criteria.

(2) Changes to the measurement scale.

Measure the qualitative attributes on the 1, 2, 3, 4, and 5 scale or the 1, 3, 5, 7, and 9 scale. The final ranking list of alternatives should not change or should have a minor change based on the sensitivity analysis results.

(3) Different criteria formulations are identified.

Some criteria are shown in two normatively equivalent ways (benefit type and cost type or income and expenditure), which will generate magnificent impacts on the outcome by decision makers.

In this research, to investigate and verify the results' stability over a range of input variable values, the sensitivity analysis is performed by employing the method suggested by Shankha [51]. Three factors and nine subfactors have been involved by changing the weight of the criteria. The first step is to evaluate the most sensitive factor for the three criteria without changing the weight. A sensitivity analysis has been conducted to determine the impacts of global weights for each criterion or sub-criteria. The effects of the final results can be reflected by a sensitivity analysis if the input data are not modified or if there are no changes in the main criteria, sub-criteria, weight, and alternatives. Criteria and sub-criteria were carried out for this sensitivity analysis, and the analysis was performed by the local and global weights of each criterion.

As depicted in Figure 7, the FAHP method shows that the economic impact (58%) is the most important criterion for assessing the sustainability of the structural system, followed by the environment with 31%. The social aspect contributes 11% to this method, and it is ranked as the least important criterion. The evaluation of technology encompasses a comprehensive analysis of various sub-criteria, each contributing differently to the overall assessment.

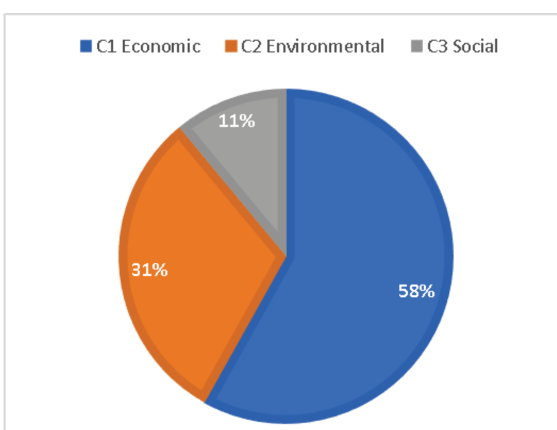

Figure 7. Criteria priority by the FAHP (%).

Figure 8 provides insights into the relevance of nine such sub-criteria, shedding light on their respective importance in decision-making processes. Construction emerges as the most pivotal factor, commanding a weightage of 36%. Its significance lies in its direct contribution to and support of economic criteria, making it a focal point for evaluation. Following closely are management and maintenance, with contributions of 15% and 10%, respectively, to the cost aspect. Notably, social indicators C31, C32, and C33 demonstrate low sensitivity to decision making, as depicted in Figure 8. Environmental considerations are dominated by CO_2 emissions and are given weights of 15%. Waste management follows suit, with weights of 10%, while energy consumption garners comparatively lesser emphasis, with 7%. This underscores the experts' prioritization of mitigating CO_2 emissions and managing waste, indicative of heightened environmental consciousness. In contrast, the social aspect assumes a lesser role in decision-making processes. Safety, aesthetics, and noise, collectively accounting for around 10%, are considered less critical compared to economic and environmental factors. This suggests a prevailing sentiment among experts that social impacts, while not disregarded, hold less weightage in technology evaluations. The evaluation of technology involves a nuanced consideration of various sub-criteria, with construction and CO_2 emissions standing out as paramount concerns. While economic and environmental factors carry significant weight, social considerations are comparatively less influential.

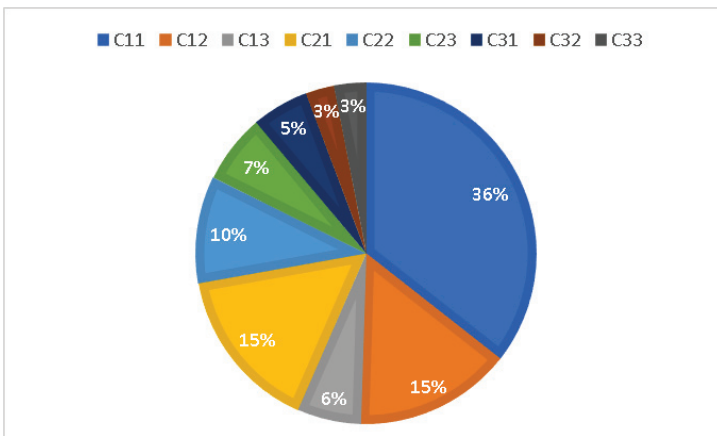

Figure 8. Sub-criteria priority by the FAHP (%).

A sensitivity analysis has been conducted to determine the impacts of global weights for each criterion or sub-criteria (as depicted in Table 15 and Figures 7 and 8). The effects of the final results can be reflected by a sensitivity analysis if the input data are modified, including changes in the main criteria, sub-criteria, weight, and alternatives. Nine sub-criteria were carried out for this sensitivity analysis, and the analysis was performed by local and global weights of each criterion. Table 15 and Figure 7 show that social indicators C31, C32, and C33 are generally not sensitive to decision making.

Table 15. The results of the sensitivity analysis.

Indicator	Criteria	Global Weights			Ranking
		A1	A2	A3	
1	Economic	0.246	0.190	0.131	A1 > A2 > A3
2	Environment	0.145	0.109	0.071	A1 > A2 > A3
3	Social	0.041	0.035	0.035	A1 > A2 = A3

The experts were international and Chinese engineers and academics who compared the criteria and sub-criteria of MCDA methods in pairs to understand their performance. Figures 9 and 10 provide the experts' comparisons between the selected alternatives in terms of criteria and the individual sub-criteria. Most stakeholders and experts emphasized the economic indicator, which has the highest acceptance. In contrast to social criteria, environmental aspects have more capacity, which is more preferred by the public. Social is the one with less impact on sustainability development, so it was ranked the lowest level for all the three alternatives.

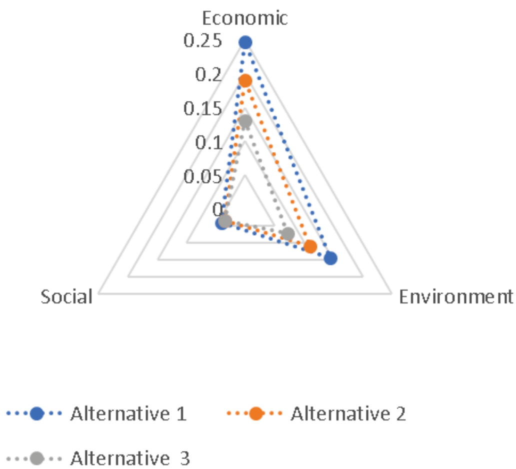

Figure 9. Alternative sensitivity analysis.

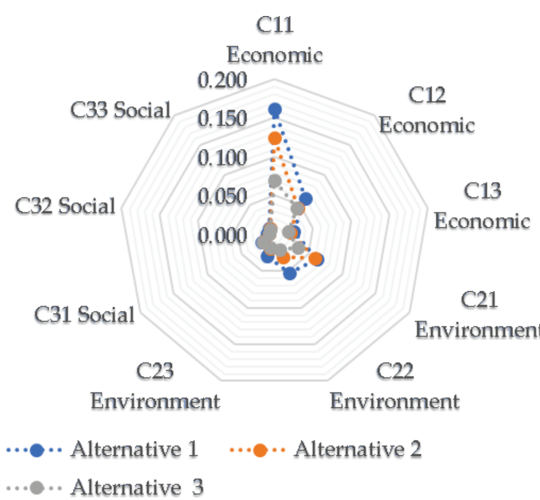

Figure 10. Criteria sensitivity analysis.

Construction, maintenance, and management were ranked the most important aspects by the majority of the experts for all of the alternatives. Economics has a prominent place in the process of structural sustainable design. Similar to economic indicators, such as CO_2 emissions, waste, and energy, the experts assigned high rankings to all three alternatives. However, for the sub-criteria related to social aspects (aesthetics, noise, and safety), the three alternatives showed some slight differences but received the lowest rankings.

6. Conclusions

This research proposes a sustainable design process for building structural systems and assessing environmental, social, and economic impacts using a multi-criteria decision-making (MCDA) method. Additionally, it presents a decision-making and computational model for evaluating and ranking different structural systems. A thorough literature review and expert consultations identified nine structural design perspectives, which were consolidated into three main criteria: environment, society, and the economy. To assess sustainability during the design phase, three alternative structural solutions were developed: one innovative new structural system and two traditional systems.

The key conclusions derived from this research are as follows:

- The framework empowers structural engineers to evaluate and select the most efficient system by considering various decision-making factors.
- The MCDA approach's validity was confirmed through practical applications, demonstrating its effectiveness as a tool for developing new structural systems.
- The proposed model (the hierarchical tree) is flexible, allowing users to modify it without restricting alternatives.
- This research offers significant benefits for engineers and society by enhancing the potential of structural design to minimize its negative impacts.

Future research directions include expanding the framework to incorporate additional criteria and more detailed substances. The theoretical framework should be tested on a broader range of building structures than those covered in this study to identify crucial assessment factors. Moreover, adopting different MCDA approaches will ensure a comprehensive measurement of all relevant factors through a comparative analysis of the results. Lastly, economic considerations still dominate the selection criteria for building structural systems and need further elaboration. It is crucial to note that structural engineers often prioritize cost considerations over strict adherence to green building codes when circumstances require it. This prioritization arises from the industry's focus on short-term financial gains rather than long-term sustainability goals.

In conclusion, this research makes a substantial contribution to sustainable structural design by introducing a systematic method for evaluating multiple criteria. The adaptability of the proposed model and the validation of the MCDA approach underscore its potential as a valuable tool for engineers. Further development and testing of the framework on diverse building structures will enhance its robustness and applicability, ultimately contributing to the creation of more sustainable built environments. Future studies can refine this framework, ensuring precise and comprehensive assessments by incorporating additional criteria and employing various MCDA methods. This research shows that MCDA methods are effective in guiding engineers in improving sustainable design selection processes. The validated decision model proposed in this study can be applied to similar projects and evaluating different structural systems, providing a robust framework for enhancing sustainability in engineering practices. This research thus provides a foundation for advancing sustainable practices in structural engineering, benefiting both the profession and society at large.

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Appendix A

Questionnaire 1: Validating the selection of the sustainability indicators

From your perspective, how important are the following indicators to the sustainability performance assessment of alternatives? Please indicate whether you Strongly agree (SA), Agree (A), Neutral (N), Disagree (D), or Strongly disagree (SD) that each performance indicator is essential.

Expert's Opinion	Strongly Disagree SD	Disagree D	Neutral N	Agree A	Strongly Agree SA
A.1 CO_2 emission	☐	☐	☐	☐	☐
A.2 Energy efficiency	☐	☐	☐	☐	☐
A.3 Land use	☐	☐	☐	☐	☐
A.4 Abiotic depletion potential	☐	☐	☐	☐	☐
A.5 Acidification potential	☐	☐	☐	☐	☐
A.6 Eutrophication potential	☐	☐	☐	☐	☐
B.1 Revenue generation	☐	☐	☐	☐	☐
B.2 Total cost	☐	☐	☐	☐	☐
B.3 Landfill-cost savings	☐	☐	☐	☐	☐
C.1 Job creation	☐	☐	☐	☐	☐
C.2 Noise emission	☐	☐	☐	☐	☐
C.3 Human toxicity	☐	☐	☐	☐	☐
C.4 Health and Safety	☐	☐	☐	☐	☐
C.5 Social Commitment	☐	☐	☐	☐	☐
C.6 Information Disclosure	☐	☐	☐	☐	☐

Appendix B

Sample of the Questionnaire

Dear respondent,

The following questionnaire is crafted to explore the selection criteria for contractors. Your input will aid us in determining the significance of various factors such as "good records,"

"financial capabilities," "planning and project control abilities," and "technical expertise" in the contractor selection process. Additionally, your insights will help establish the relative weights of relevant sub-criteria associated with these main criteria. Your participation is invaluable to this research, and your time and contribution are greatly appreciated.
In this study, the comparative values of criteria and sub-criteria are denoted by options A to E for relative assessment.
A: Very more important
B: More important
C: Equally important
D: Less important
E: Very less important
The following questions assess the comparative importance of specific criteria in the selection of contractors.: "environmental", "social", and "economic".
Please indicate the relative importance of each criterion by checking the appropriate boxes:

1. How important is the criterion of "environmental" as compared with the criterion of "social"?

   A ☐ B ☐ C ☐ D ☐ E ☐

2. How important is the criterion of "environmental" as compared with the criterion of "economic"?

   A ☐ B ☐ C ☐ D ☐ E ☐

3. How important is the criterion of "economic" as compared with the criterion of "social"?

   A ☐ B ☐ C ☐ D ☐ E ☐

The following questions compare with each other the importance of the following sub-criteria relating to the criterion of "Construction, Maintenance, Management, CO_2 emission, Energy consumption, Waste, Noise, Aesthetic, Safety".
Please indicate the relative importance of sub-criteria by checking the appropriate boxes.

4. How important is the criterion of "Construction" as compared with the criterion of "Maintenance"?

   A ☐ B ☐ C ☐ D ☐ E ☐

5. How important is the criterion of "Maintenance" as compared with the criterion of "Management"?

   A ☐ B ☐ C ☐ D ☐ E ☐

6. How important is the criterion of "Construction" as compared with the criterion of "Management"?

   A ☐ B ☐ C ☐ D ☐ E ☐

7. How important is the criterion of "CO_2 emission" as compared with the criterion of "Energy consumption"?

   A ☐ B ☐ C ☐ D ☐ E ☐

8. How important is the criterion of "CO_2 emission" as compared with the criterion of "Waste"?

   A ☐ B ☐ C ☐ D ☐ E ☐

9. How important is the criterion of "Energy consumption" as compared with the criterion of "Waste"?

   A ☐ B ☐ C ☐ D ☐ E ☐

10. How important is the criterion of "Noise" as compared with the criterion of "Aesthetic"?

   A ☐ B ☐ C ☐ D ☐ E ☐

11. How important is the criterion of "Safety" as compared with the criterion of "Aesthetic"?

    A ☐ B ☐ C ☐ D ☐ E ☐

12. How important is the criterion of "Safety" as compared with the criterion of "Noise"?

    A ☐ B ☐ C ☐ D ☐ E ☐

Perhaps the questions in this questionnaire are limiting your ability to fully express your thoughts on the selection criteria for contractors. If that's the situation, please feel free to share your views in the provided space below.
Personal data:
Name: Surname:
Place of service: Organizational position:
Work record:
Date when the questionnaire was filled out:
Your highest educational degree:
High school diploma ☐ Associate's degree ☐
Bachelor's degree ☐ Master's or a higher degree ☐
Lower ☐
In which one of the following fields do you have experiences?
Technical and commercial committee ☐ Contract affairs ☐
Project execution ☐ Practices of contractors ☐
How long did you work in the above fields?
Less than a year ☐ One to three years ☐
More than three years ☐
Thank you for your honest cooperation. Please review the questionnaire again to ensure that no questions were overlooked, and then kindly return

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sustainability

Article

Building Information Modeling Technology Capabilities: Operationalizing the Multidimensional Construct

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Abstract: The identification and leverage of the Building Information Model (BIM) technology are at the core of the successful digital transformation of the construction industry. However, due to its ability to integrate with various digital technologies and platforms, facilitating the digital and sustainable construction of the entire lifecycle of a building, BIM technology cannot be simply defined and operationalized with a single dimension of the construct. Based on the importance of multidimensional structures called for in the viewpoint of existing research and the resource-based view, we develop a second-order construct model to measure BIM technology capabilities. We define and operationalize the BIM technology capabilities, based on theory, as a reflective–reflective higher-order construct by developing and validating a 17-item scale that captures three first-order constructs. The measurement model results show strong reliability, dimensionality of the first-order measurement model, convergent validity, and discriminant validity. The multidimensional structure and instrument provide researchers with an opportunity to test the theories about the antecedents and outcomes of BIM technology capabilities, as well as the process and conditions.

Keywords: BIM (Building Information Modeling) technology capabilities; scale development; multidimensional construct; construction industry

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1. Introduction

BIM has been attracting great interest from academics and practitioners for its critical role as an innovative resource that offers potential competitive advantages to construction organizations [1]. However, most studies are focused on the adoption, implementation, and capability maturity model of BIM technology [2–5], and construction companies are still struggling to fully leverage the pros of BIM to achieve an above-average return, as well as to implement their digital first strategy to transform the construction industry to achieve sustainability.

The gap between the seemingly prosperous literature and unresolved emerging new challenges to optimize the BIM technology resources can be largely attributed to the lack of understanding of the technology. Due to BIM technology's ability to integrate with various platforms and technologies, such as GIS, IoT, AI, 3D Scanning, and other technologies or platforms [6–9], the concept of BIM technology is often vague and prone to confusion. Thus, BIM technology cannot be simply defined and operationalized with a single dimension of the construct, and Law et al. (1998) [10], Polite et al. (2012) [11], and Wright et al. (2012) [12] emphasize the significance of the multidimensional construct in defining and measuring a complex technology like BIM. Law et al. [10] argue that the multidimensional structure can be conceptualized within an underlying theoretical framework and call for using this overarching framework to represent the complex structure of the dimensions. Thus, we employ the multidimensional construct to comprehend and define the complex BIM technology capabilities conceptually and operationally. This approach will provide a firm foundation for both researchers and practitioners to explore new theories and business opportunities.

Although the measurement methods are not completely consistent, there has been a considerable amount of research related to assessment frameworks and models associated with BIM maturity. Giel and McCuen (2014) [13] reported that there were more than a dozen measurement models for BIM maturity at the time, including those for internal organizational assessments and assessments of the extent and stages of BIM technology application. Wu et al. (2017) [14] compared nine mainstream measurement models and concluded that there was no universally applicable maturity measurement tool. Each tool had its own focus and advantages and disadvantages, with most having limited usability. Alankarage et al. (2022) [15] conducted a review of BIM maturity measurement models within organizations. They observed that while the number of maturity models was increasing, many of them were essentially repetitive. There was a lack of clear differentiation regarding which model is suitable for an organization or project, as well as the clarity in identifying potential application areas for these models. Adekunle et al. (2022) [16] also noted that BIM maturity models are typically developed based on independent research and, to date, most of them have not followed a rigorous approach.

Despite all of these efforts, the reason why the adoption and the implementation of BIM technology encounter various obstacles and challenges [17,18] is the perception that the economic benefits are often vague and intangible [5]. On one hand, the stagnation of theory development and empirical findings between BIM technology and firm performance can largely be attributed to the lack of a clear definition and operationalization of BIM technology; on the other hand, a new perspective on BIM technology as firm-wide IT capabilities is needed [19]. By integrating the resource-based view and institutional theory, Huang et al. (2014) conceptualized the IT capabilities as a multi-dimensional construct and empirically tested the mechanism and context for influencing the firm's performance [19]. Therefore, there is a need to develop multi-dimensional measurement instruments for assessing BIM technology capabilities instead of measuring BIM technology as fragmented IT assets.

In summary, the identification and leverage of the application of Building Information Model (BIM) technology are at the core of the successful digital transformation of the construction industry. However, due to its ability to integrate with various digital technologies and platforms, facilitating the digital and sustainable construction of the entire lifecycle of a building, BIM technology cannot be simply defined and operationalized with a single dimension of the construct. Based on seminal work by Olowa et al. (2022) [20], a resource-based view, and Law et al.'s (1998) [10] call for a multidimensional construct, we develop a second-order construct model to measure BIM technology capabilities. Based on a resource-based view, we follow the recommendations by Wright et al. (2012) [12] to define and operationalize the BIM technology capabilities as a reflective–reflective higher-order construct by developing and validating a 17-item scale that captures three first-order constructs.

2. BIM Technology Capabilities (BIMTC)

Regarding the definition of BIM technology capabilities, scholars have provided various definitions based on different BIM technology application scenarios and purposes. Building Information Modeling (BIM) is a technology based on three-dimensional visualization modeling that can store a large amount of drawings, documents, and parameter information [21] and connect various tools to create an information exchange platform for information retrieval and technical intervention throughout the entire construction process [2–4]. Ku and Mahabaleshwarkar (2011) [22], with the aim of constructing a virtual world based on BIM modeling for Second Life, introduced the concept of 'BiM' (Building Interactive Models). They defined it as a web-based virtual world that allows users with minimal software skills to participate in collective decision-making processes through role-playing scenarios, thus combining the virtual world with BIM. Building upon this, Olowa et al. (2022) [20] defined 'BLE' (BIM Learning Environment) as a web-based platform designed to facilitate education and training supported by BIM. This innovative teaching approach aims to meet the demands of students for new job skills and capabilities.

However, the focus of our research is on the practical application of BIM technology, with the ultimate goal of enhancing BIM technology capabilities to improve the competitiveness of teams and organizations. In the construction industry, BIM technology capabilities stand as the core driving force behind the industry's digital transformation, regarded as an innovative resource that offers potential competitive advantages to construction organizations [1]. Therefore, our conceptualization of BIM technology capabilities aligns closely with Bharadwaj et al. (1999) [23], who includes the concept of IT capabilities encompassing both technology and organizational aspects. Scholars consider IT capabilities as a company's ability to continually restructure resources based on information technology (IT) to maintain a competitive edge.

Over time, the strategic value of IT for organizations has captivated considerable attention from both scholars and practitioners [24–27]. In a similar vein, Bhatt and Grover (2005) [25] conducted an extensive review of the trajectory of IT research concerning competitive advantage, shedding light on classical, economic, complementary resources, and the Resource-Based View (RBV) perspectives. Likewise, BIM, classified as an enterprise-level information technology, has also attracted scholarly investigation by addressing its fundamental technological underpinnings [28,29], facets of economic value creation [30], and dimensions of competitiveness [31]. However, the uncertainties and ambiguities surrounding the returns on investment and the underexploited potential benefits of BIM technology have emerged as shared concerns within both the academic community and the industry, paralleling Carr's (2003) [32] argument concerning the diminished economic contribution of IT. Bhatt and Grover (2005) [25] advocated for the assessment of IT's significance through the lens of RBV, as IT underscores the capacity for leveraging capabilities rather than undifferentiated IT assets. Huang [19] and King [33] further argue that firms exhibit considerable disparities in their ability to cultivate IT capabilities, transcending the mere expenditure on disparate IT components.

Consequently, IT capabilities are constructed as a dynamic, organization-wide competence, going beyond a specific array of intricate technical functionalities to encompass an enterprise-wide competence characterized by combining the technological and organizational resources.

In line with the RBV perspective, we conceptually define BIM technology capabilities as the strategic competences that are applicable to teams and enterprises alike. BIM technology capabilities stand as a significant resource, and as competency is poised to empower teams and enterprises in achieving and sustaining a strategic competitive advantage, it should encompass multiple dimensions. Some researchers focus on BIM technology as an information technology's basic operational capabilities, emphasizing certain aspects, such as software interoperability [5,14], modeling issues [14], and so forth. Some researchers emphasize BIM technology's ability in coordination and collaboration, including conflict detection in design [34,35], BIM-based model checking [36], and the interaction between BIM technology and construction organization workflows [1]. There are also researchers who focus on BIM technology's expansion capabilities, where integration with various applications is necessary to facilitate cross-organizational, interdisciplinary, and project stage development [37]. For example, this includes BIM's ability in learning modules [38], integration with the Internet of Things [7], combination with AI [8], integration with 3D scanning [9], incorporation with VR and AR [39], and integration with GIS [6].

Based on the literature review, we conceptualize BIM technology capabilities into three complementary dimensions: the BIM infrastructure capabilities dimension (BIC), the BIM collaboration capabilities dimension (BCC), and the BIM expansion capabilities dimension (BEC), which are consistent with the multi-dimensional structure of IT capabilities developed by Huang et al. (2014) [19].

2.1. BIM Infrastructure Capabilities

BIM infrastructure capabilities primarily refer to the fundamental functionalities inherent in BIM technology, such as modeling, storage, linking, and visualization. These capabilities enhance the competitiveness of organizations or teams. BIM infrastructure capabilities serve as the prerequisite and foundation for improving the level of technological application within the industry. To fully harness the advantages of BIM infrastructure capabilities, it is essential to have comprehensive hardware and software support, systematic technical training, as well as well-structured task assignments and reward mechanisms [40–42].

2.2. BIM Collaboration Capabilities

BIM collaboration capabilities pertain to the ability of teams or organizations to enhance mutual collaboration and coordination through the use of BIM technology, thereby increasing the competitiveness of both teams and organizations. Coordination and collaboration have long been significant challenges in the construction industry, where traditional design coordination settings are known for their inefficiency and susceptibility to errors [43]. Building Information Modeling (BIM) has proven to be valuable, as it can improve satisfaction with the meeting process and reduce disputes over issues. Scholars have confirmed that conflict detection and resolution solutions based on BIM can lead to cost savings [35].

2.3. BIM Expansion Capabilities

BIM expansion capabilities refer to the abilities of teams or organizations to leverage BIM technology in combination with other technologies to expand their functional scope or venture into other domains, thereby enhancing competitiveness. Within this dimension, BIM expansion capabilities are regarded as an innovative resource that offers potential competitive advantages [1], enabling collaboration across multiple domains. In recent years, the capabilities for real-time connectivity to sensors deployed in the environment have given rise to the concept of the digital twin in the built environment [7]. BIM-AI integration plays a role in advancing intelligent construction management [8]. The creation of learning modules supported by BIM [38] and the deep integration of BIM with other technologies have facilitated the extensive development of BIM application areas.

After further developing the concept of BIM technology capabilities, our focus has shifted to constructing and preliminarily validating a scale to measure the three dimensions of BIM technology capabilities in our research. Study 1 concentrates on identifying the sources of BIM technology capabilities items and evaluates the adequacy of their content using a diverse sample. Study 2 utilizes samples from various organizations to verify the scale's reliability, validity, dimensions, and factor structure.

3. Research Methodology

3.1. Study 1: Project Generation and Content Adequacy Assessment

3.1.1. Item Generation

We employed both deductive and inductive methods to generate items [44]. Building upon the structural characteristics summarized for BIM Learning Environments from an adaptive structural perspective by Olowa et al. (2022) [20], we initially generated 33 items to assess BIM technology capabilities. These items representatively encompass the three dimensions theoretically constituting BIM technology capabilities.

Subsequently, we engaged in in-depth discussions and interviews with nine experts involved in BIM technology applications and management roles to further refine and identify projects suitable for representing the three dimensions. Through this iterative process, we compiled a total of 35 indicators for BIM technology capabilities in the Chinese context (Table 1).

Table 1. Indicators of BIM technology capabilities.

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
1	BIM model viewing.	The ability to visually inspect components in the model.	-
2	Capabilities to input, access, and extract BIM model data.	Availability of input data in the model, accessible to users and easily extractable.	Data handling and data transmission.
3	BIM model sharing.	Capabilities to share the model for communication and collaboration purposes.	Enhancing communication effectiveness by adding annotation and navigation tools around the model. Adding view linking functionality around the model.
4	BIM model version management.	Ability to track and manage different versions of BIM models.	Software version compatibility; synchronization and interoperability among multiple forms of software.
5	BIM model editing.	Meaningful data input into the model is necessary.	Low modeling efficiency.
6	BIM model collaborative viewing and editing.	Collaborative viewing and editing of the model, ideally utilizing collaborative viewing and editing features in team collaboration.	Collaboration using a central file and work sets. Issues with assigning permissions for collaborative design.
7	Repository of example BIM models.	Capabilities to accommodate a repository or database for storing high-quality, consistent, and error-free models.	Product industry libraries. Cloud storage and local storage.
8	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment.	Ability to host project data consistently and persistently. Project data are not limited to data incorporated into the BIM model. Therefore, a common data environment is a necessary attribute.	Data barriers among multiple forms of software; preserving information after importing software to ensure model continuity; data interfaces that can integrate multiple forms of software.
9	Simulation of the project development process (realistic BIM workflow, key stakeholder roles, etc.).	Ability to simulate real-life project development processes, serving the roles of relevant stakeholders and BIM-based workflows.	Clear milestones, complete documentation, explicit requirements, and comprehensive records in the collaborative process.
10	BIM model creating.	Capabilities to create BIM models.	Refining modeling to improve modeling efficiency.
11	BIM model checking.	Ability to perform process and model standard checks on BIM models.	Adding generic nodes and rule checks for automated model validation.
12	Capabilities to integrate other advanced technologies (extended reality, artificial intelligence, Internet of Things, etc.).	Integration of extended reality features: Augmented Reality (AR), Mixed Reality (MR), Virtual Reality (VR).	Integration of BIM with GIS; integration of BIM with AI; digital twin combining BIM and the Internet of Things (IoT).
13	BIM object creation and editing.	Creation and editing of BIM components.	Bringing together individuals with different specialties and backgrounds based on project requirements.
14	Group formation (Different majors and backgrounds).	Stakeholders can collaborate in creating group work.	Communication features integrating the functionality of WeChat documents.
15	Collaboration in groups (communication and cooperation within the team).	Capabilities to create and manage teams, enabling communication and collaboration within the team.	Face-to-face communication.

Table 1. *Cont.*

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
16	Collaboration between groups (interaction and cooperation between teams).	Possibility for communication and interaction among the working or learning community, where stakeholders engage in interactions for project development.	Real-time collaboration, real-time updates, real-time visualization of results are required. Implementation of clash detection; communication challenges when dealing with a large number of people; real-time information sharing with high-quality data exchange; the need for quick file updates and iterations.
17	Instructor access and monitoring of groups and group work.	Capabilities to create teaching permissions for access and group work monitoring, where instructors interact with teams and individuals.	Permission issues in collaborative work sets; software permission problems.
18	Collaborative viewing and editing of documents and spreadsheets.	Collaborative viewing and editing of documents and spreadsheets (not just limited to BIM models) are crucial for executing learning tasks within a group.	-
19	Live interactions between users.	Ability to engage in real-time interactions with users, enhancing the convenience and time efficiency of teaching and group work.	Enhancement of interaction through features like WeChat voice calls; addition of view linking functionality; inclusion of annotation and navigation tools to directly locate model issues and improve communication effectiveness.
20	Capabilities to record group meetings and courses/Ability to record informal communication	Capabilities to record group meetings and courses.	Lack of archiving in communication processes.
21	Registration of users (learners/instructors).	Ability to register and unregister users.	Authentication of different stakeholders' identities.
22	Data security/password protection.	Capacity to protect user data and information, especially data and information related to registered users and their activities.	Concerns about the risk of damaging the shared master files.
23	Capabilities to host multiple courses or promote multiple projects simultaneously.	Capabilities to host multiple courses.	Platform's model hosting capacity, software's information hosting capabilities; capacity to handle and store information.
24	File upload, storage, download, sharing, editing.		File format conversion.
25	Video playback.	Ability to play course content videos and access external (video) materials.	-
26	Capabilities to link to additional learning materials or other professional information.	Capabilities to link to additional learning materials, including course content and access to various materials.	Ability to accommodate large amounts of data, extensive information; drawbacks of linking; digital assets.
27	Individual learners' storage for learning materials.	Ability to allow individual learners to store learning materials.	-
28	Capabilities to link various courses or projects together.	Ability to connect multiple courses to reinforce the outcomes of previous courses and track the impact on future course engagement.	Learning from completed projects or transferring knowledge to new projects.
29	Assessment/grading.	Capabilities to assess and grade learners—inputting scores for individuals/groups, grade book—for learning management, quality, and learner assessment purposes.	-

Table 1. *Cont.*

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
30	Questionnaire creation, completion, submission.	Creation and analysis of questionnaires, quizzes, and surveys.	-
31	Student feedback.	Ability to gather feedback from users and learners for quality assurance and improvement purposes.	-
32	Gamification support.	Capabilities to integrate gamification features, combining elements of gaming. Enhancing competition as a way to motivate learners—high scores/leaderboards, etc.	-
33	Integration of platform with external systems/business.	Ability to integrate with external platforms—for example, integration with institutional research information systems.	Integration with enterprise management platform.
34	Capabilities of lightweight BIM operation.		Web-based lightweight platform; cloud-based platform.
35	Capabilities of conducting post-model generation sustainability analysis.		Green building analysis, cost analysis, carbon emissions, emergency evacuation simulation, etc.

"-" indicates not mentioned in the interview.

3.1.2. Content Adequacy Testing

Content adequacy testing was conducted using the quantitative method proposed by Schriesheim et al. (1993) [45], ensuring that the content of a measure encompasses a representative sample of the domains to be assessed.

Sample and Procedure

The sample comprised technical managers and educators involved in BIM technology applications in China, representing a diverse range of institutions, including consulting and training, enterprises, and universities. This broad sample scope aimed to cover various sectors of BIM application within the Chinese construction industry. The age distribution of the sample primarily ranged from 21 to 40 years, with 7.48% having 6–9 years of experience using BIM technology, 13.08% with 3–5 years, and 79.44% with 1–2 years, representing the main group of individuals who have learned and applied BIM technology.

Analysis and Results

In the preliminary survey, a questionnaire was created based on the first 33 indicators (items 1–33) of BIM technology capabilities. Respondents were asked to rate the level of importance of BIM technology capabilities in terms of their impact on practical work and learning using a 5-point Likert-type scale: "1—Not Important", "2—Slightly Important", "3—Moderately Important", "4—Very Important", and "5—Extremely Important".

A total of 107 questionnaires were collected. After excluding those with response times less than 55 s, a total of 95 valid questionnaires were retained. Exploratory factor analysis was conducted on the questionnaire data. The data were subjected to a KMO test and Bartlett's sphericity test using SPSS Statistics version 27. The analysis yielded a KMO value of 0.898 for the questionnaire data, and Bartlett's sphericity test was significant at the 0.01 level, indicating that the sample data in this study were suitable for exploratory factor analysis.

From the scree plot, it was observed that the inflection point appeared at position 3. The cumulative variance explained by the three common factors reached 66.7%. Principal component analysis was chosen, and the maximum variance rotation method was used to extract factors with specified eigenvalues set at 3. Items that loaded on two or three factors, had loadings exceeding 40%, and lacked clear discriminant validity were removed. This initial analysis resulted in a factor structure with three factors and 26 items, with factor loadings for each item ranging from 0.60 to 0.82.

Subsequently, factors with lower factor loadings were further eliminated, and two new items (34, 35) from the interviews were added. This led to a final factor structure with three factors and 19 items (Table 2).

Table 2. Dimensions and indicators of BIM technical capabilities.

	Sub-Dimension	Item Number	BIM Technology Capabilities Indicator	Factor Loading
BIM Technology Capabilities (BIMTC)	BIM Infrastructure Capabilities (BIC)	3#	Capabilities to share the model for communication and collaboration purposes	0.795
		4#	Capabilities to track and manage different versions of BIM models	0.772
		5#	Capacity to edit the BIM model	0.867
		6#	Capabilities for collaborative viewing and editing of models	0.785
		7#	Repository of example BIM models	0.819
		8#	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment	0.811
	BIM Collaboration Capabilities (BCC)	14#	capabilities for Group formation	0.912
		15#	Ability to collaborate within a group	0.928
		16#	Ability to collaborate between groups	0.918
		17#	Instructor access and monitoring of groups and group work	0.857
		19#	Ability to engage in real-time interactions with users	0.833
		34# [1]	Capabilities of lightweight BIM operation	
	BIM Expansion Capabilities (BEC)	20#	Capabilities to record group meetings and courses /Ability to record informal communication	0.798
		23#	Capabilities to host multiple courses or promote multiple projects simultaneously	0.833
		26#	Capabilities to link to additional learning materials or other professional information	0.872
		27#	Ability to allow individual learners to store learning materials	0.826
		28#	Capabilities to link various courses or projects together	0.894
		29#	Ability to assess and grade learners	0.855
		35# [1]	Capabilities for conducting post-model generation sustainability analysis	

[1] 34# and 35# are the newly added items after the expert meeting and were not included in the pre-survey questionnaire.

3.2. Study 2: Reliability, Validity, Dimensions, and Factor Structure

3.2.1. Sample and Procedure

In Study 2, a structural validity test was conducted on the 19 items retained from Study 1. A survey was conducted to collect data from enterprises within the Chinese construction industry that use BIM technology. Questionnaires were distributed to experienced professionals familiar with and knowledgeable about BIM technology and BIM project management. From the statistical data, it was observed that 58.1% of respondents had more than 10 years of work experience, 25.7% had 6–9 years of experience, and the majority of respondents (40%) had been using BIM for 3–5 years, with 21.9% using it for 6–9 years and 14.3% for 10 years or more. Overall, the sample had rich work experience, ensuring the quality of the collected questionnaires.

The questionnaire content was based on the 19 indicators of BIM technology capabilities. A scale was constructed to measure BIM technology capabilities. Questions in the scale were framed as: "Compared to other companies in your industry in the past 3–5 years, how strong is your company's ability in BIM model version management?" Responses were recorded on a 7-point Likert scale, ranging from "1—Strongly Disagree" to "2—Disagree", "3—Somewhat Disagree", "4—Neutral", "5—Somewhat Agree", "6—Agree", and "7—Strongly Agree". A new scale was used for the second round of questionnaire surveys to validate the scale's reliability

In this round, a total of 90 questionnaires were collected. Two questionnaires with excessively short response times were excluded, leaving a total of 88 valid questionnaires, all of which had response times exceeding 82 s.

3.2.2. Analysis

The questionnaire data were analyzed using AMOS to construct a measurement model. The overall fit of the model was satisfactory. However, items 20# (bec1) and 29# (bec6) showed a strong correlation in both the BCC and BEC dimensions. Some individuals may perceive items related to recording group meetings (20#) and assessing learners' capabilities (29#) as necessary abilities during the collaboration process. Therefore, the two potentially confusing items, bec1 and bec6, were removed. The final measurement model fit indices are as follows (Table 3): CMIN/DF is 1.673, which is less than 3; TLI is 0.964 and CFI is 0.970, both of which are greater than 0.9; RMR is 0.064; and RESEM is 0.088. The overall fit of the model is good.

Table 3. Measurement model fit indices.

	CMIN/DF	TLI	CFI	RMR	RESEM
Actual Value	1.673	0.964	0.970	0.064	0.088
Fit Value	<3	≥ 0.9	≥ 0.9	<0.08	<0.1

An analysis of the reliability and validity of the BIM technology capabilities scale, consisting of the final 17 items, yielded the following results, as shown in Table 4. The standardized factor loadings for all items were above 0.86, indicating that the items could effectively explain the underlying constructs. The composite reliability (CR) values for each dimension were 0.979, 0.978, and 0.968, all exceeding 0.9, indicating good composite reliability. Convergent validity was examined using the Average Variance Extracted (AVE), where a higher AVE suggests that the measurement indicators better represent the variables. The analysis results (as shown in Table 4) revealed that the AVE values for BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities were 0.885, 0.882, and 0.859, respectively, all exceeding 0.7, indicating good convergent validity for the dimensions of the scale.

According to the Fornell and Larcker criteria [46], the square root of the Average Variance Extracted (AVE) should be higher than its bivariate correlation values with all other constructs [47]. The square root of the AVE values for each component (as shown in Table 5) exceeds 0.9 and is greater than their intercorrelations. This indicates that the discriminant validity of the three dimensions of BIM technology capabilities is also satisfactory.

Table 4. Reliability and validity analysis of the scale.

Potential Construction	Path	Items	Std.	*p*	CR	AVE
BIM Infrastructure Capabilities (BIC)	bic1←BIC	Capabilities to share the model for communication and collaboration purposes	0.938	***	0.979	0.885
	bic2←BIC	Capabilities to track and manage different versions of BIM models	0.951	***		
	bic3←BIC	Capacity to edit BIM model	0.944	***		
	bic4←BIC	Capabilities for collaborative viewing and editing of models	0.927	***		
	bic5←BIC	Repository of example BIM models	0.953	***		
	bic6←BIC	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment	0.930	***		
BIM Collaboration Capabilities (BCC)	bcc1←BCC	Capabilities for Group formation	0.927	***	0.978	0.882
	bcc2←BCC	Ability to collaborate within a group	0.917	***		
	bcc3←BCC	Ability to collaborate between groups	0.940	***		
	bcc4←BCC	Instructor access and monitoring of groups and group work	0.925	***		
	bcc5←BCC	Ability to engage in real-time interactions with users	0.960	***		
	bcc6←BCC	Capabilities of lightweight BIM operation	0.965	***		
BIM Expansion Capabilities (BEC)	bec2←BEC	Capabilities to host multiple courses or promote multiple projects simultaneously	0.956	***	0.968	0.859
	bec3←BEC	Capabilities to link to additional learning materials or other professional information	0.863	***		
	bec4←BEC	Ability to allow individual learners to store learning materials	0.947	***		
	bec5←BEC	Capabilities to link various courses or projects together	0.939	***		
	bec7←BEC	Capabilities for conducting post-model generation sustainability analysis	0.926	***		

*** $p < 0.001$.

Table 5. Discriminant validity test table.

	BIC	BCC	BEC
BIC	**0.941**		
BCC	0.895	**0.939**	
BEC	0.780	0.883	**0.927**

The bold numbers on the diagonal represent the square root of AVE.

Based on the above, the final validated BIM technology capabilities scale with good reliability and validity is obtained. It is divided into three dimensions: BIM infrastructure capabilities, BIM collaboration capabilities, and BIM extension capabilities, consisting of a total of 17 measurement items.

3.2.3. Dimensions and Factor Structure

Types of Multidimensional Structures

BIM technology capabilities are a multidimensional structure consisting of three sub-dimensions: the BIM infrastructure capabilities dimension, the BIM collaboration capabilities dimension, and the BIM expansion capabilities dimension. Within the BIM infrastructure capabilities sub-dimension, there are six measurement indicators, while the BIM Collaboration capabilities sub-dimension comprises six measurement indicators, and the BIM expansion capabilities sub-dimension includes five measurement indicators. The relationships between indicators and sub-dimensions, as well as those between sub-dimensions and the BIM technology capabilities construct, were distinguished following the approach of Jarvis et al. (2003) [48] and Diamantopoulos A et al. [49]. This differentiation was based on the form and summary of questions and practical analysis. Scholars suggest assessing the form of the structure from multiple perspectives, including causal relationships, structural characteristics or manifestations, whether changes in indicators (items) and structural variables lead to changes in each other, the content of indicators with respect to the theme, the conceptual domain of the structure, expected antecedents, and consequences.

Firstly, an analysis was conducted to determine the relationships between lower-order indicators and sub-dimensions by assessing causal relationships. Measurement indicators reflect specific aspects of BIM technology capabilities within sub-dimensions, such as specific modeling editing capabilities, model sharing capabilities, etc. These measurement indicators are reflective indicators of BIM infrastructure capabilities. Additionally, a reduction or change in these indicators does not lead to a change in the first-order structure (BIM infrastructure capabilities); therefore, they are reflective in nature at the first-order level.

Following this, in accordance with the recommendations of Law et al. [10] and Poliet et al. [11], an analysis of the relationships between the multidimensional structure of BIM technology capabilities and their sub-dimensions was conducted. The three sub-dimensions (namely, BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities) collectively represent overall BIM technology capabilities. A reduction or change in any one sub-dimension of BIM technology capabilities may not necessarily affect the overall BIM technology capabilities. Focusing on the development of a specific dimension of BIM technology capabilities can also lead to strong competitiveness. Therefore, a higher-order structure exists at a deeper level than its dimensions [10], and relationships flow from this structure to its dimensions. Consequently, from a theoretical perspective, the structure of BIM technology capabilities is a multidimensional structure with reflective dimensions, meaning it is a higher-order latent structure with reflective–reflective characteristics.

Testing the Multidimensional Structure

Following the advantages of PLS and PLS-SEM for analyzing small-sample data and higher-order structures, as indicated by Chin et al. [50], Ringle et al. [51], and Sarstedt et al. [52], the PLS-SEM method was applied to test the reflective–reflective higher-order structure of BIM technology capabilities. The primary method employed was the repeated indicator approach. The measurement model of the higher-order construct was primarily assessed for its reliability, convergent validity, and discriminant validity between the lower-order indicators and sub-dimensions.

Contemporary methodologists recommend modeling multidimensional structures as second-order factor models. To achieve this, the higher-order construct was modeled as a second-order factor, with the dimensions being modeled as first-order factors and the dimension measures being modeled as observed variables [53,54].

First, using Smart PLS 4 software, a first-order measurement model was constructed using the repeated indicator method (Figure 1). The statistical data obtained are presented in the following table (Table 6). In accordance with the recommendations of Hair et al. [47], the internal consistency reliability, convergent validity (CV), and discriminant validity (DV) of the lower-order measurement model were assessed.

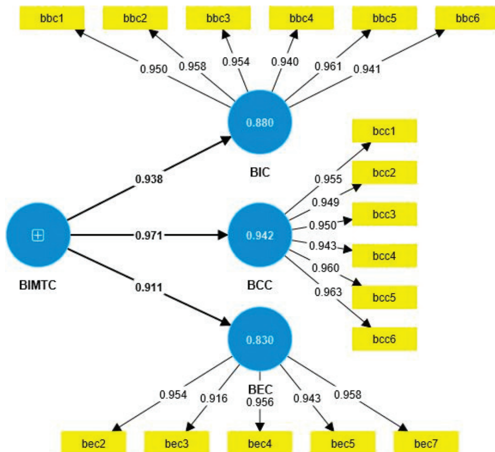

Figure 1. PLS high-order measurement model.

Table 6. Statistical table of measurement model parameters.

High-Order Construction	First-Order Construction	Form	Index	Factor Loading	Cronbach's α	CR	AVE
BIM Technology Capabilities		Reflective			0.986	0.987	0.796
	BIM Infrastructure Capabilities (BIC)	Reflective	bic1 bic2 bic3 bic4 bic5 bic6	0.950 0.958 0.954 0.940 0.961 0.941	0.979	0.983	0.904
	BIM Collaboration Capabilities (BCC)	Reflective	bcc1 bcc2 bcc3 bcc4 bcc5 bcc6	0.955 0.949 0.950 0.943 0.961 0.963	0.980	0.984	0.909
	BIM Expansion Capabilities (BEC)	Reflective	bec2 bec3 bec4 bec5 bec7	0.954 0.916 0.956 0.943 0.958	0.970	0.977	0.894

The Cronbach's α values for BIM technology capabilities as a whole and within each dimension are all greater than 0.95 (0.986, 0.979, 0.980, 0.970), indicating good internal consistency. The reliability coefficients for BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities are 0.983, 0.984, and 0.977, respectively, and the CR values for each dimension are all above the 0.80 standard (as shown in Table 6), indicating good construct reliability.

Further analysis of the results (as shown in Table 6) reveals that the Average Variance Extracted (AVE) values for the three factors of BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities are 0.904, 0.909, and 0.894, respectively, all exceeding the threshold of 0.50. This indicates good convergent validity.

To examine the discriminant validity of the constructs, a measurement model cross-loading table (Table 7) is used. The factor loadings for each dimension are well-distributed and correspond well to their respective dimensions.

Table 7. Cross-loading table of the measurement model.

High-Order Construction	First-Order Construction	Index	BIMTC	BIC	BCC	BEC
BIM Technology Capabilities (BIMTC)	BIM Infrastructure Capabilities (BIC)	bic1	0.856	**0.950**	0.811	0.654
		bic2	0.886	**0.958**	0.845	0.700
		bic3	0.897	**0.954**	0.838	0.751
		bic4	0.881	**0.940**	0.839	0.722
		bic5	0.901	**0.961**	0.848	0.734
		bic6	0.877	**0.941**	0.820	0.719
	BIM Collaboration Capabilities (BCC)	bcc1	0.912	0.831	**0.955**	0.794
		bcc2	0.907	0.826	**0.949**	0.782
		bcc3	0.914	0.835	**0.950**	0.803
		bcc4	0.922	0.826	**0.943**	0.828
		bcc5	0.948	0.856	**0.961**	0.853
		bcc6	0.928	0.843	**0.963**	0.811
	BIM Expansion Capabilities (BEC)	bec2	0.905	0.747	0.847	**0.954**
		bec3	0.805	0.631	0.737	**0.916**
		bec4	0.894	0.730	0.828	**0.956**
		bec5	0.886	0.728	0.815	**0.943**
		bec7	0.871	0.706	0.794	**0.958**

According to Fornell and Larcker's criteria [46], the square root of AVE should be higher than its bivariate correlations with all other constructs [47]. The square root of AVE values for each component (Table 8) are all above 0.9 and greater than their intercorrelations. This indicates good discriminant validity among the three dimensions of BIM technological capabilities.

Table 8. Discriminant validity of first-order constructs.

	BIC	BCC	BEC
BIC	**0.951**		
BCC	0.895	**0.953**	
BEC	0.769	0.872	**0.946**

The bold numbers on the diagonal represent the square root of AVE.

When evaluating the second-order structural model, researchers should adhere to the heuristic method provided by Gefen et al. [55]. Subsequently, an overall assessment of the model is conducted. As shown in Table 9, the external weight values for the three indicators are 0.969, 0.910, and 0.874, with T-values of 105.949, 25.024, and 19.118, respectively, all of which are significant. Therefore, all three indicators are considered important and significant factors for the BIM technology capabilities construct. Additionally, the VIF (Variance Inflation Factor) values for the various dimensions of BIM technology capabilities are 4.330, 6.881, and 3.643, with both inner and outer VIFs exceeding 5. As shown in Table 7, the factor loadings indicate that the indicators load significantly on their respective dimensions, but the cross-loadings also exceed 0.7. These data suggest the possibility of multicollinearity among the indicators. In theory, it is acceptable for reflective–reflective multidimensional constructs.

Furthermore, Wright et al. (2012) argue that researchers should evaluate the model fit alongside alternative models [12]. The assessment of model fit should be supplemented by comparisons with other models [56] (Anderson and Gerbing, 1988). In this study, the model fit was compared between a single-factor model that combines all three dimensions, a two-factor model that combines any two dimensions, and a three-factor model. Their model fit was compared (see Table 10), and the results in the table below indicate that the three-factor model exhibits the best fit.

Table 9. Assessment of the structural model.

High-Order Construction	First-Order Construction	Factor Loading	T-Value	Confidence Intervals (Bias Corrected)		R-Square	Sig.
				2.50%	97.50%		
BIMTC	BIC	0.938	28.103	0.847	0.977	0.880	0.000
	BCC	0.971	104.726	0.947	0.985	0.942	0.000
	BEC	0.911	26.936	0.814	0.955	0.830	0.000

Table 10. Model fit indices.

	CMIN/DF	TLI	CFI	RMR	RESEM
Single-Factor Model	4.813	0.798	0.828	0.174	0.209
Two-Factor Model	3.155	0.886	0.904	0.151	0.157
Two-Factor Model	4.032	0.840	0.865	0.210	0.187
Two-Factor Model	2.921	0.898	0.914	0.118	0.149
Three-Factor Model	1.673	0.964	0.970	0.064	0.088

Therefore, it can be further concluded that BIM technical capabilities have been validated as a reflective–reflective higher-order multidimensional structure.

4. Discussion

4.1. Key Findings and Contributions

This study offers several key theoretical and practical contributions.

First and foremost, we offer a validated multi-dimensional structure and measurement scale of BIM technology capabilities by drawing upon existing theories. The inherent ambiguity that has encumbered research and theory development calls for both theoretical and operational understanding of this concept. To advance the field, we have integrated insights from works by Law et al. (1998) [10], Bharadwaj et al. (1999) [23], Olowa et al. (2022) [20], Polite et al. (2012) [11], Huang et al. (2014) [19], Bhatt and Grover (2005) [25], and King (2003) [33]. Consequently, we decided to use the notion of BIM technology capabilities to further develop the measurement scale. Thus, drawing upon the resource-based view (RBV) framework, we conceptualize BIM technical capability as a strategic competency that aids teams and enterprises in attaining and preserving a sustainable competitive advantage. Our proposition posits BIM technology capabilities as a reflective–reflective multidimensional structure comprising three distinct dimensions: (1) BIM infrastructure capabilities, (2) BIM collaborative capabilities, and (3) BIM expansion capabilities. These dimensions synergize, laying the foundation for a comprehensive grasp of BIM technology capabilities between and among subdimensions. Furthermore, this offers researchers and practitioners a robust framework to explore novel theories and business prospects in this domain, which can profoundly impact the effectiveness and efficiency of the whole construction industry.

Secondly, we have rigorously identified and validated the theoretically grounded BIM technology capabilities scale. The 17 measurement items retained, following two rounds of validation, exhibit commendable reliability and validity. This multidimensional structure and measurement instrument not only furnishes researchers with the means to develop new theories pertaining to the antecedents and consequences of BIM technology capabilities but also offers insights into the inherent mechanisms and contextual conditions. This holds particular significance for quantitative research within the construction industry's BIM technology applications. It aids in addressing pivotal questions concerning the nexus between BIM technology capabilities and organizational performance, demonstrates the mechanisms through which it leads to sustained competitive advantages, and underscores the factors that catalyze digital transformation and sustainability within the construction sector. The empirical outcomes of future quantitative research are poised to facilitate grassroots advocacy for the widespread adoption of BIM technology, thus assuming equal importance in propelling BIM technology applications and steering the construction industry's digital transformation.

Lastly, we responded to the call by Olowa et al. (2022) [20] by externally validating and extending the analysis of 33 features, primarily conducted with European samples, to regions beyond Europe—notably, emerging economies, such as China. The generalization of the measurement in the context of the Chinese construction industry will contribute to savings in both resources and costs while championing the digitization and sustainability of the entire construction lifecycle, because this expansion engenders a more comprehensive perspective of the constituents of BIM technology capabilities. It also ensures content fidelity while amplifying the scope of applicability of BIM technical capabilities in diverse contexts.

4.2. Limitations and Future Research

This study has several limitations.

Firstly, the sampling methodology employed in this research was non-random, focusing exclusively on firms engaged in proactive utilization of BIM technology within their operational framework. While this non-random approach may potentially circumscribe the extent of generalizability of our findings, it is important to note that this strategic selection affords a more laser-focused and pragmatic vantage point, notably enriching the depth and pertinence of insights gleaned for the construction and validation of the BIM technology capabilities scale.

Secondly, while there is a reasonable presumption that BIM technology capabilities exert an influence on organizational performance outcomes, further inquiry is warranted to meticulously explicate the specific mechanisms by which they precipitate performance enhancements. Simultaneously, it becomes imperative to discern the nuances of the contextual factors that may moderate the relationship. These prospective research endeavors hold the potential to furnish a more profound comprehension of the multifaceted relationships intertwined with BIM technology capabilities and their impact on organizational performance.

5. Conclusions

Drawing from the existing body of research, we constructed a second-order structural model to assess the construct of BIM technology capabilities. Subsequently, we meticulously developed and validated a measurement scale encompassing three dimensions and comprising a total of 17 items. This comprehensive scale affords us the capability to conduct a more granular investigation into the procedural mechanisms governing the application of BIM technology. Furthermore, we have deliberately delineated the interrelationships between BIM technology capabilities and their constituent sub-dimensions, ensuring the alignment of conceptualization with operationalization.

It is worth noting that the process of scale development is inherently iterative in nature. Although we employed a two-step validation process in this study to craft and initially validate the BIM technology capabilities scale, it is imperative to underscore that these findings necessitate further validation and corroboration. We extend a cordial invitation to scholars with an interest in BIM technology capabilities to incorporate our scale into their research surveys, and, concurrently, we encourage them to embark on the task of refining and empirically validating the BIM technology capabilities model. We anticipate that this collective effort will provide a firm foundation that will promote further insights and in-depth scholarly investigations into this pivotal research domain.

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Research on Green Modular Disaster Prevention Product Design and Spatial Configuration Strategy Based on AHP-GIS

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Abstract: Facing persistent natural catastrophes, the necessity for disaster prevention products in afflicted cities becomes paramount. Modular design has proven to be a viable method for streamlining transportation and manufacturing processes for disaster prevention products. However, existing post-disaster prevention products often fail to incorporate the green modular concept, with limited research on spatial allocation strategies. In response to the current challenges, a new breed of green post-disaster prevention products is urgently warranted to mitigate the impact of major natural disasters and safeguard lives and property. To achieve the goal, this study employs a combined analytic hierarchy process (AHP) and geographic information systems (GIS) analysis to propose an inflatable cabin for emergency disaster prevention, specifically designed for flood scenarios. Using the inflatable cabin as an empirical case, this study introduces a layered design approach progressing from macro to meso and then to micro levels to construct an objective decision-making model to prioritize key design elements, develop spatial post-disaster prevention strategies, and analyze the mechanical performance. Results indicate that at a distance of 30 m from the base of the slope (SPIC), the impact force is most significant, reaching up to 1.8×10^7 kN. As the distance increases from 30 m to 150 m, the maximum impact force decreases by an order of magnitude, and the average impact force decreases by approximately two orders of magnitude. Furthermore, this comprehensive approach, which starts from a holistic design perspective and culminates in optimizing individual disaster structures, offers practical significance for engineering design research.

Keywords: modular design; disaster prevention; product design; AHP-GIS analysis method; flood refugees; numerical simulation; sustainability

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1. Introduction

The combination of excessive urbanization and global climate change has exacerbated the escalation of natural disasters in magnitude, frequency, and severity in afflicted cities. The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) is one of China's most open and economically dynamic regions, characterized by rapid urbanization and a sharp growth in population within China's coastal regions. The frequent human activities have jeopardized the region landform and accordingly relocated the population [1]. Such combination has amplified the vulnerability of weaker communities to disasters, therefore leading to a significant portion of residents being exposed to disasters in the GBA. Additionally, due to global climate change, excessive rainfall and flooding pose year-round challenges to the region's inhabitants [2]. Natural catastrophes underscore the unpredictable nature of disasters, the scarcity of resources in affected areas, and the swift environmental transformations that exacerbate vulnerabilities [3]. These calamities engender a rise in "environmental refugees", individuals compelled to seek new habitats due to environmental degradation.

Considering these challenges, the necessity for disaster prevention products in afflicted cities becomes paramount. Such products provide safety, protection, emergency response, rescue, and recovery functions before, during, and after a disaster [4]. The adoption of modular design in disaster prevention products has led to benefits such as reduced manufacturing costs, increased productivity, and lower energy consumption [5], therefore enhancing the adaptability and promptness of these solutions. Modular design has therefore been widespread applied in various disaster prevention products, including earthquake emergency housing, flood protection walls, air purification, and domestic waste treatment.

However, limited research has concentrated on post-disaster prevention products [6]. The current research emphasizes pre-disaster and disaster prevention products, neglecting the significance of post-disaster prevention products [7]. Despite this, the existing research may also guide critical pathways for the optimization of post-disaster product designs in terms of environmental sustainability awareness [8,9], humanization and personalization [10], ease of operation and maintenance difficulty [11], traditional form and functionality [12], and comfort and ergonomics [13]. A new breed of post-disaster prevention products is urgently warranted to mitigate the impact of major natural disasters and safeguard lives and property.

Another gap is the absence of post-disaster prevention products incorporating the concept of modular design at multiple scales. While modular design can streamline transportation and manufacturing processes for disaster prevention products [5], its integration into post-disaster solutions remains limited, lacking a holistic approach and struggling to balance individual design aspects with spatial allocation strategies at different scales [14,15]. The concept of module design can make the post-disaster products more extensively applicable and comprehensive at multiple scale.

Therefore, utilizing the design of the emergency disaster prevention inflatable cabin (EDPIC) in Zhuhai City as an empirical case, this study aims to: (i) formulate spatial strategies of post-disaster prevention products based on population density and disaster-affected areas; (ii) construct an objective decision-making model to prioritize key design elements and develop a disaster prevention product strategy using the concept of modular design; and (iii) discuss the mechanical performance of the EDPIC in earthquake-prone regions through numerical simulations across various scales.

2. Literature Review

2.1. Hazards of Natural Disasters

The combination of natural hazards and vulnerabilities that jeopardize weaker communities that cannot overcome the resulting adversities is known as a natural disaster [16]. Humans are constantly in danger from both natural and man-made disasters, which frequently cause enormous harm, human misery, and detrimental effects on the economy. Figure 1a shows that flood disasters manifest in two primary forms: ordinary flooding and debris flow disasters. It is essential to distinguish between these two forms, understand their unique characteristics, and comprehend their interrelation. Ordinary flooding occurs when a water body, such as a river or a lake, overflows its banks due to heavy rainfall, snowmelt, or dam failure. Frequent human activities can lead to ordinary floods, causing damage to infrastructure, property, and agriculture. They can also lead to community displacement and threaten human life [17]. Debris flow, often called mudflow, is a rapid mass movement of water, sediment, and debris down a slope. It is usually triggered by intense rainfall or rapid snowmelt. Debris flows contain a significant proportion of sediment, including rocks, boulders, and mud. The mixture rushes and can have devastating consequences. These severe consequences can include the loss of human life; the destruction of houses and facilities; damage to roads, rail lines, and pipelines; vehicle accidents and train derailments; environmental damage from product spills; damage to agricultural land, livestock, and forest lands; the disruption of water supply system; the devaluation of fisheries; and many other losses that are difficult to quantify [18].

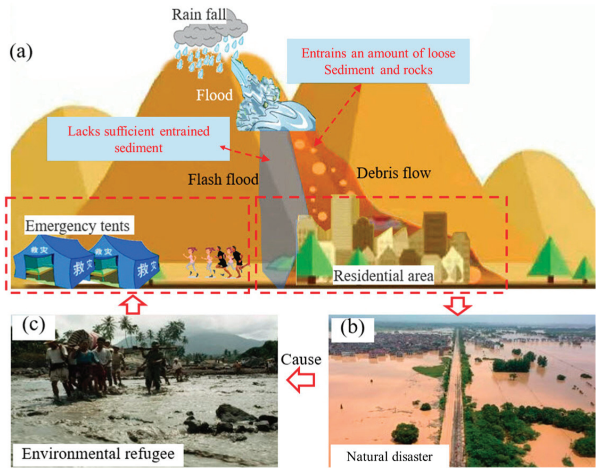

Figure 1. Current situation of a natural disaster. (**a**) The forms and consequences of flood disasters. (**b**) Natural disaster (https://cn.nytimes.com/china/20220624/china-floods-heatwaves/ (accessed on 24 June 2022)). (**c**) Environmental refugees.

Figure 1b presents natural catastrophes characterized by their unpredictable nature, the availability of few resources in the affected areas, and rapid environmental changes [2]. Due to different natural disasters, there are "environmental refugees". They are individuals who, due to drought, soil erosion, desertification, and other environmental issues, can no longer make a stable living in their former homelands. Figure 1c shows that they feel they have no choice but to look for safety elsewhere out of desperation, no matter how risky the endeavor [19]. Thus, disaster prevention products in disaster-stricken cities are essential, and according to the number of individuals affected by disasters over the years, the demand level for disaster prevention products is also worth considering. Taking emergency tents as an example, the existing ones have the following disadvantages: (1) the internal comfort is poor, and the thermal insulation ability is not good; (2) they require a workforce to build, and the scrapped tents are not correctly disposed of, which will quickly cause environmental pollution; (3) storage issues need to be considered for emergency tents to be used, which require ample storage space and are inconvenient to transport; (4) their impact resistance is poor, and their ability to protect against debris flow disasters caused by floods is weak. Therefore, there is an urgent need to develop a new type of green disaster prevention product to deal with major natural disasters and ensure the safety of people's lives and property.

Additionally, due to global climate change, extreme precipitation has increased in the GBA in magnitude, frequency, and severity. Climate change and urbanization have contributed to increased extreme precipitation occurrences and severe urban inundations in the GBA [17]. Thus, taking the GBA as an example, flood disasters have had a specific impact on the mega-urban agglomeration. For instance, the super typhoon "Mangkhut" from 2018 made landfall in Guangdong with maximum winds of 45 m/s in the center at touchdown, resulting in direct economic losses of 5.2 billion yuan, affecting roughly 3 million people, and evacuating and relocating 1,161,000 people. In Guangzhou in 2020, the "5-22" downpour caused the amassing of water in 443 locations throughout the city, flooding in numerous areas, and the suspension of Metro Line 13 [18]. For Guangzhou, the active application of disaster prevention products is imperative.

2.2. Current Status of Disaster Prevention Product Development

Disaster prevention products are products designed to provide safety, protection, emergency response, rescue, and recovery functions before, during, and after a disaster;

they should have the characteristics and needs of protection, reliability, adaptability, environmental friendliness, maintainability, intelligence, and economy [4]. The US Federal Emergency Management Agency (FEMA) emphasized the protective, emergency, and sustainable nature of disaster prevention products [20].

However, most of the disaster prevention design products focus on the pre-disaster and disaster period while neglecting the post-disaster period [6]. In the face of diverse and complex natural disasters, existing disaster prevention products have certain advantages and characteristics regarding safety, reliability, functionality, and inclusiveness, but they still need to be improved. In this regard, the following points are summarized as critical directions for the optimization of post-disaster product design:

(1) Environmental sustainability awareness: Priority should be given to the use of environmentally friendly materials to improve the sustainability and quality of disaster prevention products [8], while sustainability is essential in post-disaster recovery and reconstruction [9].
(2) Humanization and personalization: Based on the user's physical and mental experience, post-disaster product design should meet specific environmental integration and visual aesthetic needs [10] and be dedicated to providing a "human-centered" humane recreation experience.
(3) Ease of operation and maintenance difficulty: Most disaster prevention products have a complex operation process and must be more convenient. Maintaining and cleaning the products is also problematic, requiring professional staff to handle and replace them [11].
(4) Traditional form and single function: Many existing disaster prevention products are only for a particular natural disaster or an emergency scenario, cannot meet comprehensive disaster prevention needs, and require more innovation [12].
(5) Comfort and ergonomics: When responding to natural disasters, the comfort and ergonomics of equipment are crucial [13].

Finally, existing research on post-disaster prevention product design needs to do more to explore the relationships among the distribution strategies of disaster prevention products within the affected area to form a complete design strategy. Mainly based on supply and demand matching, this can better meet the refuge requirements of demand points and improve the rationality of the spatial layout of disaster prevention products [21].

2.3. Current Status of Green Modular Product Design Research

In modular design, complex products are decomposed into standardized modules in the design and manufacturing process through system integration principles to achieve efficiency and excellence in product design, resulting in lower manufacturing costs, higher productivity, lower energy consumption, and lower waste generation. Masato explored the application of modularity in product design [22].

Conducting a product life cycle assessment allows for a comprehensive measurement of the environmental impact of a product, which identifies the best strategies for using, maintaining, and disposing of the product to reduce environmental hazards. The life cycle model [23], developed by Japanese electronics manufacturer Panasonic, enables developers to assess, plan, and implement the environmental impact of product manufacture, use, and recycling from the design stage onwards.

The application of modular design in the field of disaster prevention is mainly for the development and manufacture of disaster prevention products, which are currently applied in four areas: modular design of earthquake emergency housing, modular design of flood protection walls, modular design of air purification, and modular design of domestic waste treatment.

Modular designs are widely employed for earthquake-resistant emergency housing. Amatrice Town utilized lightweight, eco-friendly materials and modular manufacturing to greatly reduce cost and time in producing post-earthquake emergency housing [24], which is shown in Figure 2a. To prevent flood damage to buildings and crops, flood protection walls commonly adopt modular designs with better waterproof performance and adaptability. Chen Su proposed the extensible mobile flood control wall in underground using a modular design approach, which, depending on the environment and needs, is shown in Figure 2b. The extensible mobile flood control wall in underground can be flexibly assembled and disassembled according to different settings and needs [25]. To cope with the impact of natural disasters and environmental pollution on indoor air quality, the air purification modular design offers different functions and filtration effects on various pollution sources [26]. For waste and domestic waste caused by large natural disasters, the modular design for domestic waste treatment uses renewable energy and environmentally friendly materials with flexible and efficient treatment capacity and low energy consumption characteristics [27].

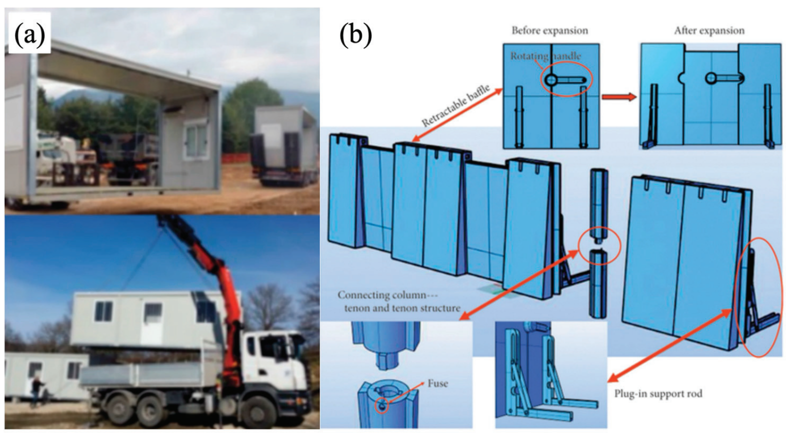

Figure 2. Application of the green modular concept in the field of disaster prevention product design. (**a**) Temporary housing in Amatrice Town after earthquake. (**b**) Extensible mobile flood control wall in underground.

Modular design should continue to be vigorously developed in the future design process of disaster prevention product development [28]. Based on the inevitable trend of sustainable development, the promotion and application of green modularity in the field of disaster prevention product design is expected to improve the adaptability, sustainability, and intelligence of products; reduce manufacturing costs and time; and lay a good foundation for enhancing the physical and mental experience of users after disasters [2].

3. Research Methodology

The whole methodology was divided into four steps, namely literature analysis, user need assessment, and mechanical performance simulation (Figure 3). The details of the research methodology are as follows: (1) Literature analysis: A thorough review of existing literature helps to highlight the gaps and areas for improvement in disaster prevention strategies and identifying the shortcomings of current disaster prevention products, with a particular focus on post-disaster scenarios. This foundational research provides the context and rationale for developing more effective solutions tailored to the needs of flood refugees in the GBA. (2) GIS method: Utilizing geographic information systems (GIS), we analyze and visualize population density in disaster-affected areas within the GBA. This spatial analysis helps to develop a comprehensive spatial configuration strategy for EDPIC. (3) AHP method: We construct an objective decision-making model to prioritize key design elements and develop a disaster prevention product design strategy based on the green modular concept. This strategy guides the spatial configuration and design of the inflatable cabin. This model helps to develop a disaster prevention product design strategy rooted in the green modular concept. By quantifying user needs and preferences, the AHP method ensures that the design of the inflatable cabin aligns with the practical requirements and expectations of flood refugees. (4) Modular design: The final step involves discussing the mechanical performance of the EDPIC in earthquake-prone regions through numerical simulation. This phase includes performing finite element analysis (FEA) to simulate the structural integrity and performance of the inflatable cabin under various load conditions. The mechanical performance simulation ensures that the design meets safety and durability standards, making the EDPIC a reliable and effective solution for disaster prevention. The insights gained from the simulations are used to refine the design and enhance its resilience in challenging environments.

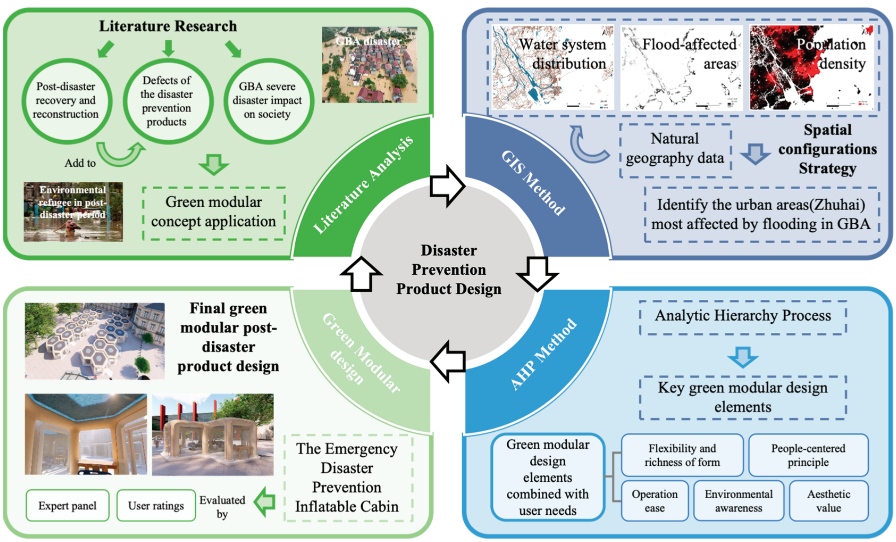

Figure 3. The scientific research steps of this study.

3.1. Geographic Information System

3.1.1. Overview of Geographic Information System Method

The definition of GIS, similar to the discipline of geography, lacks a universally accepted, definitive definition due to its interdisciplinary nature. Over the past decade, GIS has emerged as a critical tool for resource management and urban development. Its capacity to store extensive geographical data and facilitate the retrieval, analysis, modeling, and mapping of such data has been instrumental [29].

3.1.2. Disaster Prevention Geographic Information System

The application of GIS is widespread, particularly in spatial analysis, modeling, visualization, and data processing and management (Figure 4). The following aspects highlight its significance.

(1) Mapping locations: GIS enables the identification and mapping of specific places. GIS facilitates the creation of maps by employing automated mapping techniques, data collection, and analytical tools.

(2) Mapping quantities: To fulfill particular requirements or comprehend relationships between locations, individuals map quantitative aspects, such as identifying areas with the highest and lowest quantities. This approach provides more comprehensive insights than solely mapping feature locations.

(3) Mapping densities: In areas with multiple features, merely mapping the feature locations may not effectively reveal variations in concentration. Through density

mapping, one can employ a consistent areal unit, such as acres or square miles, to quantify the number of features and visualize their distribution.

(4) Finding distances: GIS enables the exploration of activities occurring within a specific radius of a feature.

Figure 4. Disaster prevention geographic information system use process.

For this study, spatial data, including water system distribution, flood-affected locations, and population density in the GBA, are collected. GIS is employed to create visual maps by conducting overlay analysis and comparing these three types of information. The most severely affected areas are identified, representing urban regions prone to flooding. From a macro perspective, this approach determines the locations within the city that require post-disaster disaster prevention products.

Based on the overlay of population data and affected areas, we determined which user groups were most likely to need disaster prevention products. Areas with high population densities and frequent flood occurrences were prioritized. The analysis involved layering maps of water systems, flood zones, and population densities to identify hotspots where the demand for disaster prevention products would be highest. These maps were then used to guide the spatial configuration of resources and the strategic placement of disaster prevention products.

3.2. Analytic Hierarchy Process

3.2.1. Overview of Analytic Hierarchy Process Method

The analytic hierarchy process (AHP) is a valuable and efficient technique for multi-criteria decision-making that enables the systematic analysis and quantification of subjective judgments. The analytic hierarchy process is a practical and effective multi-criterion decision-making method for systematically analyzing and quantifying human subjective judgments [30]. This methodology combines qualitative textual subjective descriptions with quantitative numerical objective comparisons, allowing for the systematic analysis of a sample based on mathematical and rational models. Analyzing and deciding complex problems using hierarchical analysis can effectively avoid subjective one-sidedness in demand transformation.

3.2.2. Green Modular Analytic Hierarchy Process

The factors necessary for achieving green modular design are complex and diverse, making hierarchical analysis suitable for comparative analysis of multiple factors under complex conditions. To obtain accurate user needs, the green modular analytic hierarchy process (AHP) (Figure 5) was applied to conduct qualitative and quantitative research and analysis on the target group. This methodology explored the core pain points and disaster prevention needs of Zhuhai flood refugees, analyzed important factors, calculated the weight values of the influencing factors, and arranged the results in order from highest to lowest to produce scientifically sound results.

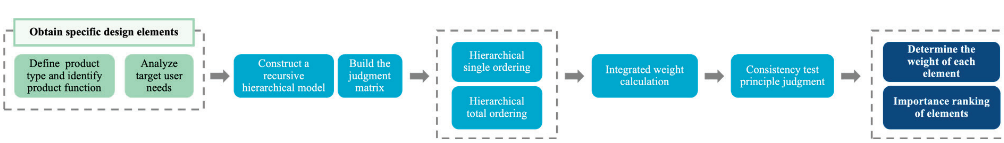

Figure 5. Green modular analytic hierarchy process use process.

3.3. Research Step Analysis

This study integrates GIS and AHP to design green modular disaster prevention products. GIS was employed to gather and analyze spatial data, including water system distribution, flood-affected areas, and population density in the Greater Bay Area, sourced from government databases and satellite imagery. Using ArcGIS, we identified high-risk zones and optimized resource allocation. For the AHP, we selected criteria such as cost, durability, and environmental impact through literature reviews and expert consultations. User needs were assessed via surveys and interviews with a diverse sample of residents from flood-prone areas. We constructed a hierarchical model and performed pairwise comparisons to calculate priority weights, ensuring consistency with ratio checks. This combined GIS and AHP analysis provided a robust framework for designing effective and user-centered disaster prevention products (refer to Figure 6):

(1) Collection of spatial data: Spatial data, including water system distribution, flood-affected locations, and population density in the GBA, are collected and imported into the geographic information system to generate digital visual maps.
(2) Identification of highly affected urban areas: Through the analysis of the visual maps, the urban areas within GBA megacities that are most vulnerable to flooding are identified. Based on the natural geography of these areas, a spatial configuration strategy for disaster prevention products is formulated.
(3) User needs exploration: Quantitative and qualitative research is conducted on the target groups, involving user interviews and questionnaires. The research aims to understand the requirements and expectations of flood refugees in Zhuhai in terms of the products' post-disaster recovery and reconstruction functionalities.
(4) In-depth analysis of research results: The research findings are thoroughly examined to uncover the target group's implicit needs and underlying motivations. This analysis helps to refine and translate the identified needs into specific design requirements.
(5) Qualitative analysis of design requirements: User requirements are further classified and summarized, leading to a qualitative analysis of design requirements. Design elements and directions are determined based on this analysis.
(6) Hierarchical modeling and quantification: The hierarchical analysis method transforms user requirements into a recursive hierarchical structure model. The design elements are quantified using appropriate mathematical methods, clarifying the design objectives.
(7) Weight determination and analysis: The total weight values of all design elements are computed and sorted. Each design element is thoroughly analyzed and understood, leading to the selection of the most appropriate design solution.
(8) Numerical simulation and professional evaluation: In the objective quantitative aspect, numerical simulations are conducted to examine the mechanical performance of EDPIC in earthquake-prone regions. In the subjective qualitative aspect, the scientific validity of the solution is verified through expert scoring and user feedback evaluation after using the product.

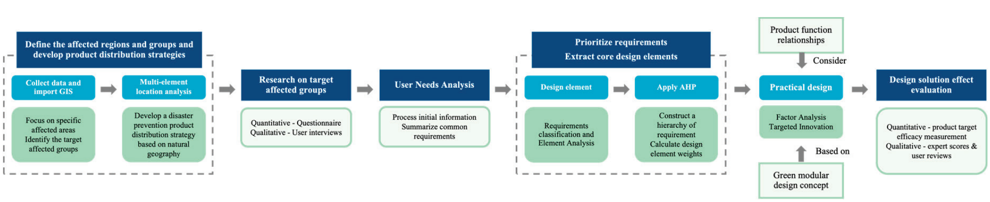

Figure 6. The design flow chart of the green module-based disaster prevention products with AHP-GIS analysis.

4. Research Process and Data Analysis

4.1. Natural Geography Data Analysis

4.1.1. Data Analysis Based on GIS

(1) Water system distribution

A geographic information system (GIS) is utilized to create detailed maps that visually represent various quantities. In the context of the GBA, data on the water system's distribution are collected. Given the geographical location of the GBA within the Pearl River Delta (PRD), it is characterized by a dense river network. The delta's water system is notable for the convergence of three major rivers and the divergence of eight rivers, making it a prominent feature of the region.

Specifically, the Lingdingyang estuary is formed by the Humen Waterway, Jiaomen Waterway, Hongqimen Waterway, and Hengmen Waterway in the east. The Modao Gate estuary comprises the Modao Gate Waterway and Jicimen Waterway in the south. The Hutiaomen Waterway and Yamen Waterway constitute the Yamen estuary. Moreover, the distribution of the river network extends across each city in the area (Figure 7), allowing for the identification of urban areas susceptible to flooding based on the location of the water system distribution.

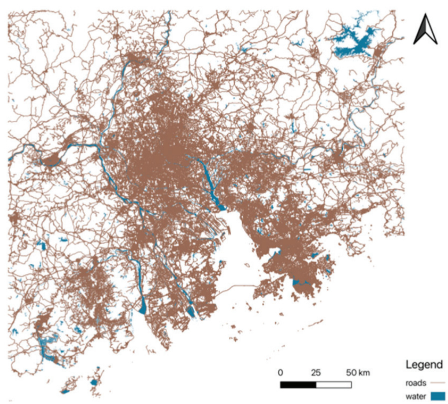

Figure 7. Water system distribution in the GBA.

(2) Population density

The geographic information system (GIS) maps population densities within the PRD. The PRD stands out as one of China's most highly populated regions, characterized by rapid commercialization and urbanization. It is recognized as one of the most densely populated areas worldwide. The visual representation (refer to Figure 8) clearly illustrates the concentration of the population in urban areas. The urban regions exhibit relatively high population densities, indicating that many flood refugees will likely be found there.

(3) Flood-affected areas

The geographic information system (GIS) helps to visualize and explain both the hydro-geomorphic (trenches along barrier beaches, erosion, deposition, etc.) and hydraulic (urban streams along the streets, flow directions, flood extent) factors in the GBA. It also facilitates better highlighting of the affected areas.

The GBA experiences a subtropical marine monsoon climate, resulting in an uneven rainfall distribution, with an average annual precipitation ranging from 1600 to 2300 mm [31]. Consequently, extreme precipitation events have increased, leading to a higher risk of flooding in the GBA (Figure 9). The figure illustrates that areas affected by flood disasters are predominantly located along the coast or in regions traversed by river networks. The varying distribution of these locations also influences the severity and duration of the disasters. Flooding can sometimes extend up to 43 days, inflicting significant damage across affected areas.

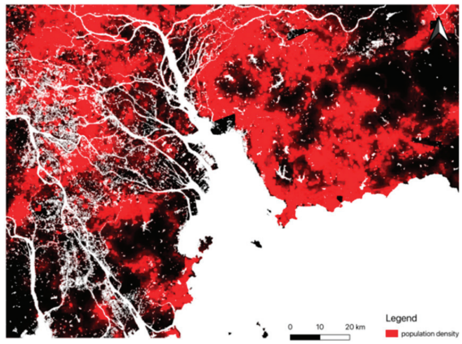

Figure 8. Population density of the GBA.

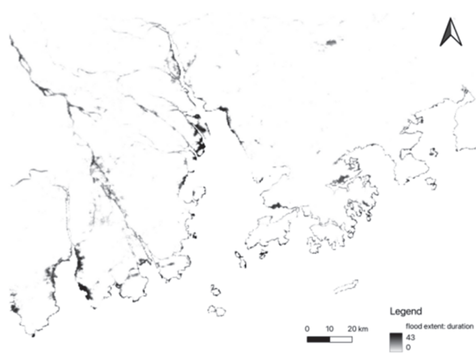

Figure 9. Flood-affected areas of the GBA.

4.1.2. Study Area and Spatial Configuration Strategy Development

After analyzing the combined data on water system distribution, population density, and flood extent in the GBA, it was observed that Zhuhai, among the megacities in the GBA, exhibits a significant vulnerability to flood disasters. Consequently, this study selects Zhuhai as the study area to focus on the implementation of disaster prevention products in this region.

Zhuhai is located between 113°03′ and 114°19′ east longitude and 21°48′ and 22°27′ north latitude. It consists of three administrative districts—Xiangzhou, Doumen, and Jinwan—with a total land area of 1736.45 km^2 as of 2020. Zhuhai City encompasses 15 towns and nine streets. Within the Pearl River Delta, Zhuhai possesses the most significant number of islands, the longest coastline, and the most significant oceanic area. According to the seventh national census, the population of Zhuhai City reached 2.44 million by the end of 2020. The region experiences an average of four typhoons annually from June to October, and torrential rains occur approximately five times yearly. On average, one of these disasters severely impacts Zhuhai City [32]. The Xiangzhou, Doumen, and Jinwan districts, undergoing extensive urban development and infrastructure construction, are particularly susceptible to flood disasters, with significant impacts on the natural and social systems. The recovery process following a flood disaster is protracted, and many flood refugees emerge due to the need to evacuate from flood-affected areas.

Considering these factors, Zhuhai serves as a suitable case study for implementing effective disaster prevention products in response to its vulnerability to flood disasters and the significant population of flood refugees it experiences.

4.2. User Research and Needs Analysis

Utilizing the analytic hierarchy process (AHP), this study focuses on comprehensively understanding the specific requirements of the target user group, namely flood refugees in Zhuhai. To achieve this, an analysis and research were conducted to gain insights into their needs. Through a combination of quantitative research using questionnaires and qualitative research through user interviews (Figure 10), this research aimed to delve into the challenges associated with post-disaster recovery and reconstruction. By doing so, we identify the core pain points experienced by flood refugees and analyze the factors that hold relatively significant influence.

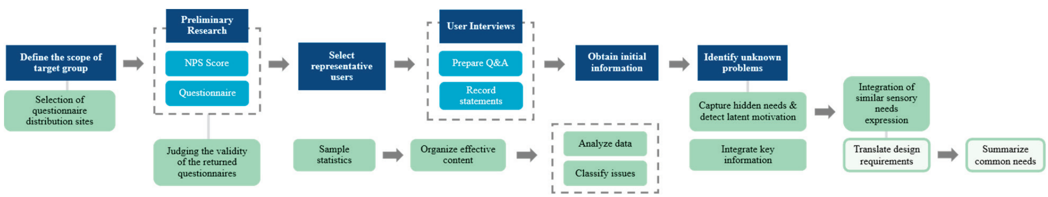

Figure 10. User research and modular design requirement analysis flow chart.

4.2.1. Preliminary Research

To assess the satisfaction of the target group and gain insights into the existing disaster prevention products, this research employed the net promoter score (NPS) and a carefully designed questionnaire. This facilitated the exploration various aspects, including product types, styles, and performance.

A targeted approach was adopted to ensure the accuracy and reliability of the interviews. Specifically, 100 questionnaires were distributed in specific locations known for their vulnerability to flood disasters: Lovers' North Road in Xiangzhou District, the waterway of Maodaomen in Doumen District, and Middle Road and South Road in Jinwan District, all of which were heavily impacted by floods. These efforts collected 82, 68, and 66 valid questionnaires in Xiangzhou, Doumen, and Jinwan Districts, respectively.

4.2.2. User Interview

In order to gather comprehensive insights into the target group's needs, thirty flood refugees in Zhuhai, selected as representative users from the preliminary research, were engaged in in-depth user interviews. These interviews were conducted to record the interviewees' perspectives and capture valuable preliminary information regarding their requirements. The objective was to uncover hidden needs, identify potential motivations, and address previously unknown issues. The information obtained from these interviews is a foundation for the designer to develop a deeper understanding of the target group's requirements.

4.2.3. Analysis of Research Results

The results obtained from the net promoter score assessment indicate that the target group exhibits lower levels of satisfaction with the current market situation of disaster prevention products. Significantly, more than three-quarters of the respondents expressed high expectations for disaster prevention products that specifically address post-disaster recovery and reconstruction. Furthermore, 91.2% of the respondents expressed their desire to integrate the green modular concept into disaster prevention products.

These findings highlight the importance of developing innovative solutions that effectively address the needs and expectations of the target group. The integration of green modular concepts holds particular significance, as it aligns with the preferences expressed by most respondents, indicating a strong desire for sustainable and environmentally friendly approaches to disaster prevention.

In response to these user insights, the present research explicitly connects user needs to the final product design by employing the analytic hierarchy process (AHP). The study systematically quantifies user requirements and prioritizes them based on their importance. This approach ensures that the design recommendations are directly informed by user research findings. The final product design incorporates these prioritized needs, ensuring that the disaster prevention products not only are effective in post-disaster recovery and reconstruction but also align with the concepts favored by the majority of respondents.

4.2.4. Summary of Recognition of Green Modular Concept and Product Design Elements

Through a systematic analysis, the practical information obtained from the questionnaire research and user interviews was carefully categorized, integrated, and refined from a design perspective. Additionally, by considering relevant design elements, the users' potential motivations and ambiguous needs we analyzed, and their language was translated into a concrete overview of user requirements. To facilitate this process, all design elements related to modular design were summarized for each requirement, and a qualitative requirement analysis was performed using an affinity diagram methodology.

Based on this comprehensive analysis, the essential requirements for post-disaster products targeting flood refugees in Zhuhai can be summarized as follows:

(1) Water and moisture resistance: Given the damp environment following a flood, the product must effectively safeguard property and health by protecting against water and moisture.
(2) Safety and stability: The product should exhibit sufficient stability and durability to withstand the potential damage and risks associated with flooding.
(3) Rapid deployment: The ability to swiftly erect and dismantle the products is critical, enabling refugees to adapt to rapidly changing environments and cater to their evolving needs.
(4) Spatial flexibility: The product should offer ample space and flexibility to accommodate the diverse requirements of refugee families and individuals.
(5) Human comfort: The products must create a comfortable, warm, safe, and hygienic environment, prioritizing the physical and psychological well-being of the refugees.
(6) Sustainability: Environmental impact and sustainability considerations are paramount. The products should utilize environmentally friendly materials and energy sources while minimizing waste and pollution.
(7) Ease of transportation and storage: Products should be easily transportable and storable, facilitating rapid deployment and disassembly when needed.

4.3. Primary and Secondary Analysis of Combination of Modular Design Elements and User Needs

4.3.1. Calculation of Design Evaluation Level Index Weights

Based on the findings from the study mentioned above, the prominent indicators for modular design encompass the utilization of environmentally friendly materials, the integration of energy-efficient design features, and the reduction in waste and pollution. Based on these insights, post-disaster products were developed specifically to address the needs of flood refugees in Zhuhai and employ a set of criteria to establish the significance levels of the design elements, presented in Table 1.

The weights of the aforementioned secondary indicators were determined using the expert questionnaire method. The study assumed the participation of L experts and employed the Delphi technique for the questionnaire-based investigation. This process obtained a ranking matrix based on the recorded statistical results.

$$A = (axi)L \times M(x = 1, 2, \ldots, L, i = 1, 2, \ldots, M)$$

Table 1. Evaluation level index of modular design.

	Tier 1 Indicator	Tier 2 Indicator		
Importance of post-disaster product design (U)	U1: Safety and comfort	U11: People-centered principle	U12: Structural stability	U13: Thermal insulation
	U2: Sustainability	U21: Modularization	U22: Life cycle assessment and optimization	U23: Use of renewable energy sources
	U3: Operational practicality	U31: Easy-to-use construction steps	U32: Ease of transportation and storage	U33: Adaptability to different environments
	U4: Aesthetic ornamental	U41: Honeycomb shape and aesthetic ornamental features	U42: Color and texture	U43: Visual harmony with surroundings
	U5: Flexibility and richness of form	U51: Inflatable membrane structure and foldable design	U52: Customizability	U53: Expandability and modularity

Upon acquiring the scores provided by the experts, the entropy theory was applied to calculate the entropy values associated with their evaluations. By leveraging the theoretical foundation mentioned above, the weights of the indicators were calculated, thereby elucidating the significance of the secondary indicators within this study.

Based on the derived weightings, all secondary indicators were categorized into "major impact", "medium impact", or "minor impact" groups. Subsequently, the importance level of each secondary indicator was scored. The final scores for the Tier 1 indicators were then computed by their respective weights, as depicted in Table 2.

Table 2. Secondary indicator score.

Symbol	Secondary Indicator	Scoring Interval	Final Score for Level 1 Indicators
p1	U11: People-centered principle	[90, 100]	
p2	U12: Structural stability	[80, 90]	P
p3	U13: Thermal insulation	[0, 80]	
w1	U21: Modularization	[90, 100]	
w2	U22: Life cycle assessment and optimization	[80, 90]	W
w3	U23: Use of renewable energy sources	[0, 80]	
c1	U31: Easy-to-use construction steps	[90, 100]	
c2	U32: Ease of transportation and storage	[80, 90]	C
c3	U33: Adaptability to different environments	[0, 80]	
m1	U41: Honeycomb shape and aesthetic ornamental features	[90, 100]	
m2	U42: Color and texture	[80, 90]	M
m3	U43: Visual harmony with surroundings	[0, 80]	
n1	U51: Inflatable membrane structure and foldable design	[90, 100]	
n2	U52: Customizability	[80, 90]	N
n3	U52: Expandability and modularity	[0, 80]	

4.3.2. Analysis of Design Elements

The calculation results indicate the following importance arrangement for the design elements: safety and comfort > sustainability > operational practicability > flexibility > aesthetics. These importance rankings should guide the distribution of importance for each design attribute in the subsequent design scheme.

Within the safety and comfort category, the people-centered principle emerges as the most crucial factor, prioritizing the physical and emotional well-being of the refugees. Sustainability emphasizes modularization, encompassing environmentally friendly materials, energy efficiency, and waste and pollution reduction to promote environmental protection and product sustainability. Operational practicality places emphasis on easy-to-use construction steps, quick and effortless assembly and disassembly, and operational feasibility with minimal personnel requirements. The flexibility and richness of form highlight inflatable membrane structures and foldable designs, enabling product flexibility, portability, and adaptability to unique and catastrophic environments. Aesthetic ornamental aspects center on honeycomb shapes and aesthetic design features, emphasizing the visual appeal and morphological richness of the products.

4.4. Green Module-Based Disaster Prevention Design Practice for Flood Refugees in Zhuhai

Using the green modular hierarchy analysis, we ranked the design requirements, leading to developing the final design solution: the emergency disaster prevention inflatable cabin. This design concept, rooted in the principles of modular design, specifically caters to the needs of post-flooding disaster recovery and reconstruction efforts. The design fulfills functional requirements and offers a comfortable and visually appealing environment for flood refugees.

4.4.1. Sustainability

The product design integrates modular design principles, facilitating efficient assembly and disassembly processes that minimize waste generation in the post-disaster phase. In addition, incorporating solar power devices contributes to energy conservation and reduces the carbon footprint. The product is constructed using a lightweight and durable polytetrafluoroethylene (PTFE) membrane structure, which is environmentally friendly and resilient. Figure 11a depicts the flexible top structure of the cabin, designed to effectively mitigate the impact force caused by small gravel during the post-disaster reconstruction period.

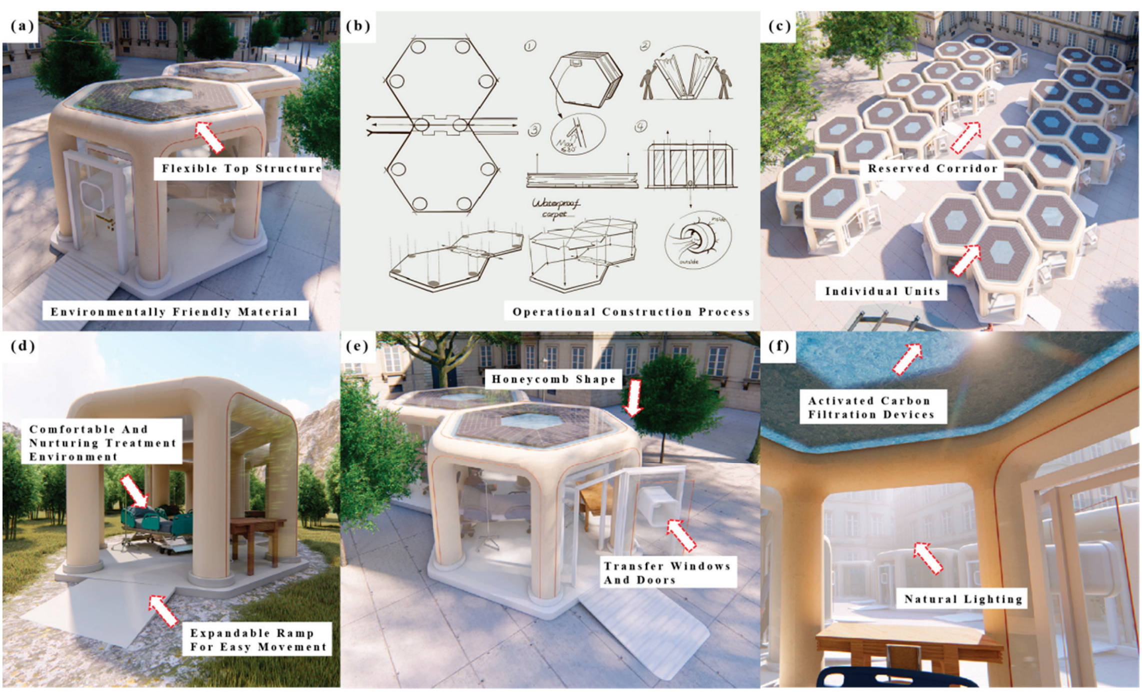

Figure 11. Product performance introduction, (**a**) sustainability, (**b**) operational practicality, (**c**) flexibility of form, (**d**) richness of form, (**e**) aesthetic ornamental, and (**f**) safety and comfort.

4.4.2. Operational Practicality

Regarding operational practicality, the unit body is designed for ease of construction. Just two individuals can build it. The construction process involves pulling the handle of the chassis in the merged state, which opens and closes the hexagonal chassis using a pivot structure. Once the chassis is fully expanded, the lower inflatable port connects to the inflatable device, allowing gas to support the unit's membrane structure. When the gas reaches saturation, the inflatable device is removed, the inflatable port is closed, and the unit is successfully built. To close the unit, the air outlet on the opposite side of the inflatable port is opened to release the gas inside the body. The complete process is illustrated in Figure 11b.

4.4.3. Flexibility and Richness of Form

The disaster prevention cabin adopts an inflatable membrane structure with a foldable design, ensuring its light weight, simplicity, convenience, and ease of storage, transport, and assembly. This design caters to the urgent needs of flood refugees. Figure 11c shows the mass production of individual units, addressing the requirement for large-scale isolation during flood disasters. To mitigate safety risks associated with inflatable structures, such as susceptibility to strong winds, the stability of the base has been meticulously considered. Additionally, the cabin incorporates necessary transfer windows and doors and an expandable ramp for the easy movement of beds, which is shown in Figure 11d,e.

4.4.4. Safety and Comfort

The cabin design adheres to the people-centered principle. The interior space planning considers the physical and emotional well-being of the refugees, ensuring a comfortable and nurturing treatment environment. Figure 11f shows that the cabin incorporates considerations for natural lighting, ergonomic principles, and activated carbon filtration devices located on the top to maintain a clean and healthy environment. Given the centralized application scenario of the product, the reserved corridor design acts as a buffer zone, enhancing the safety of medical staff, which is shown as Figure 11c.

4.4.5. Aesthetic Ornamental Aspects

Furthermore, Figure 11e shows that the cabin's honeycomb shape and aesthetic ornamental features contribute to its form's flexibility and richness, making it both functional and visually appealing.

4.4.6. Summary of Design

Post-disaster emergency products, as a branch of disaster prevention products, need to meet both shelter and protection requirements. Common secondary impacts of natural disasters include injuries and destruction caused by falling debris in seismic events, as well as inundation and erosion resulting from floods, which is shown in Figure 12a–c. Our products are designed to address the secondary hazards associated with these two types of disasters. As depicted in Figure 12d, the protective shelters used in this study feature an inflatable layer that envelops the outer shell. This design effectively dissipates the impact energy of small falling rocks, reducing their potential to cause harm, which is shown in Figure 12f. Traditional tents, on the other hand, lack this capability and are more susceptible to damage from falling rocks, leading to secondary harm to people and property, which is shown in Figure 12e. Additionally, the independent inflatable structure of these shelters can effectively prevent immersion in floodwaters and can float on the water's surface, serving as temporary kayaks with strong protective capabilities against the secondary hazards of floods.

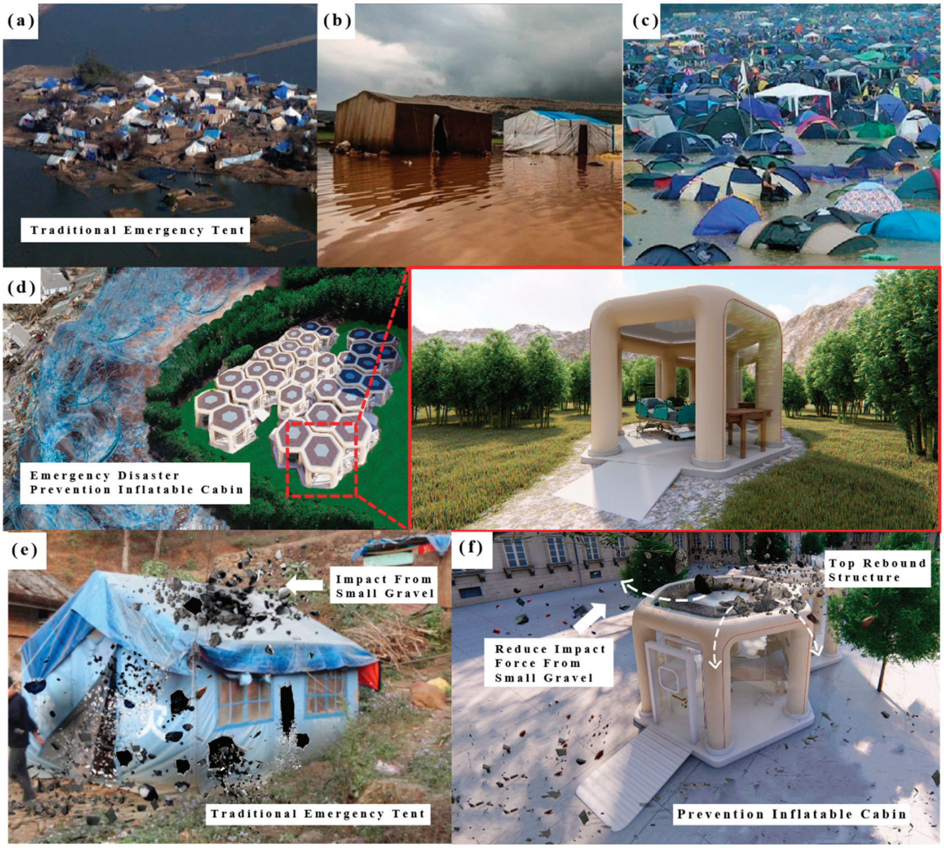

Figure 12. A comparison of traditional emergency tents and the disaster prevention inflatable cabin. (**a**–**c**) Different types of traditional emergency tents. (**d**) The emergency disaster prevention inflatable cabin. (**e**) Traditional tents face significant impact from small rubble. (**f**) Optimized roof elastic structure to effectively mitigate the impact of small gravel.

4.5. Design Evaluation Processes

4.5.1. Expert Panel

To ascertain the fulfillment of the target group's needs, a comprehensive evaluation and user feedback test were conducted as part of the modular design process for the disaster prevention product. A panel of twenty experts from design, materials, and relevant fields was assembled to evaluate whether the design objectives were achieved. The evaluation employed a seven-point scale as the scoring criteria, with the horizontal axis representing the evaluation metric and the vertical axis indicating the corresponding scores.

The scoring criteria were as follows:

(1) Functionality: The extent to which the product performs its intended function effectively.
(2) Usability: The ease of use and user-friendliness of the product.
(3) Durability: The product's ability to withstand environmental conditions and wear over time.
(4) Safety: The degree to which the product ensures the safety of its users.
(5) Aesthetics: The visual appeal and design quality of the product.
(6) Sustainability: The environmental impact and use of sustainable materials in the product's design.

(7) Cost-effectiveness: The balance between the product's cost and its overall value and performance.

Each criterion was scored on a scale from 1 to 7, where 1 indicated poor performance and 7 indicated excellent performance. The scoring system demonstrated a positive correlation between the score and the degree of meeting user needs. This evaluation aimed to provide a professional assessment of the design's effectiveness and alignment with the intended user requirements (Figure 13).

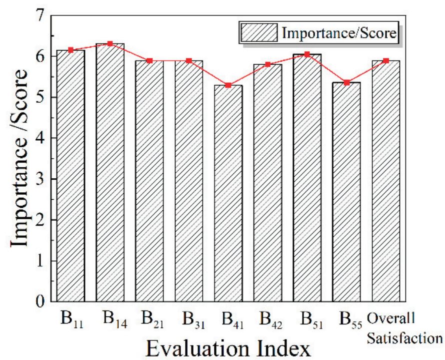

Figure 13. The evaluated result of the expert panel.

4.5.2. User Ratings

In order to gauge user satisfaction with the proposed solution product, we conducted a survey involving thirty individuals who had previously interacted with the design. The net promoter score (NPS) was utilized as a scoring criterion, with the horizontal axis representing the scores and the vertical axis indicating the number of respondents. It is important to note that a positive correlation exists between the respondents' NPS values and their satisfaction and loyalty toward the product (Figure 14). The cumulative NPS score of 48.9 reflects a high level of alignment with the target users' needs, underscoring the design solution's success. This positive outcome further reinforces the viability and effectiveness of the proposed design in meeting user expectations.

Figure 14. User NPS rating results.

5. Discussion

5.1. Analysis of Application Scenarios and Engineering Mechanical Characteristics

The mechanical performance of the EDPIC holds immense significance during design. Specifically, a critical scenario arises following an earthquake event in regions prone to seismic activities. In this scenario, residential buildings may collapse, necessitating the relocation of residents to emergency tents. However, secondary hazards, such as debris flows induced by rainfall, can cause severe damage to these temporary shelters. Due to precipitation in gullies or slopes, debris flows involve the transportation of substantial solid materials, including mud, rocks, and boulders. The impact forces exerted by debris flows surpass those of floods by a considerable margin.

Consequently, the lack of impact resistance in emergency tents, typically constructed from non-woven fabrics, becomes a pressing concern. In order to address this issue, substituting emergency tents with robust and impact-resistant EDPICs becomes imperative in these application scenarios. This strategic replacement ensures enhanced safety and protection for residents in areas susceptible to seismic activities and subsequent hazards like debris flows. (Figure 15).

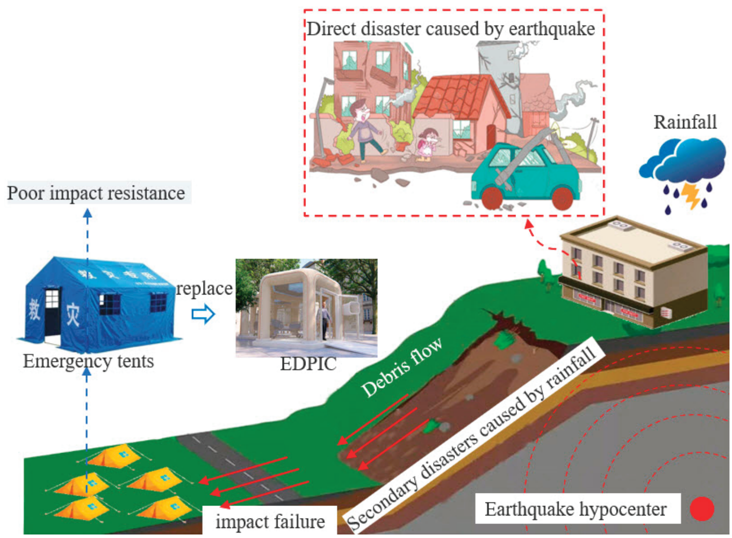

Figure 15. Application scenarios of EDPIC for debris flow protection.

As illustrated in Figure 16a, this study draws upon the physical model introduced by Bi et al. [33,34]. In this context, H_{PIC} = 100 m, α = 45°, and S_{PIC} varies at intervals of 30 m, 60 m, 90 m, 120 m, and 150 m. The primary focus of this investigation lies in the analysis of the impact force variations on the protective cabin at different distances. Figure 16b depicts the three-dimensional discrete element model established in PFC3D, specifically addressing the mechanical characteristics following debris flow impact on its frontal surface. This model serves as theoretical guidance for the mechanical aspects of EDPIC design. The independent variable examined in this study is the distance of the EDPIC from the base of the slope, referred to as S_{PIC}, ranging from 30 m to 150 m, encompassing varying debris flow impact force patterns on the EDPIC. The granular size distribution and specific parameters for this debris flow are derived from the research findings of Zhou et al. [35] (as shown in Table 3).

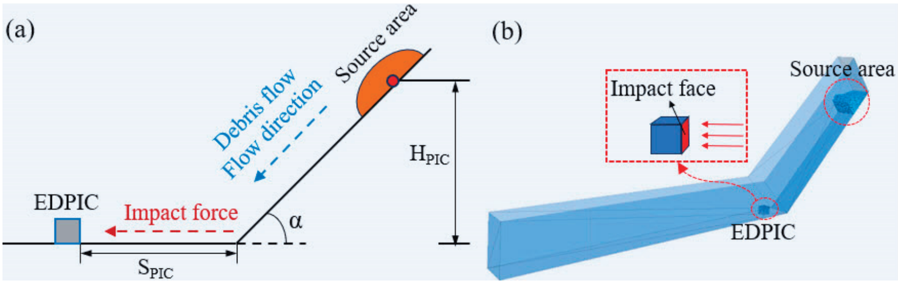

Figure 16. The model for debris flow impact on an EDPIC: (**a**) physical model; (**b**) numerical simulation model.

Table 3. The parameter values for the debris flow in the DEM model.

Parameters	Values
Gravitational acceleration, g (m/s^2)	9.81
Particle density, ρ (kg/m^3)	2650
Normal stiffness coefficient, Kn (N/m)	10^5
Tangential stiffness coefficient, Kt (N/m)	10^5
Interparticle friction coefficient, μ	0.5
Restitution coefficient, e	0.5
Volume fraction, Φ	0.7

According to Figure 17, it is evident that prior to the 70th second, the debris flow velocity exhibits pulsating fluctuations over time. However, after the 70th second, the debris flow velocity displays a gradual decrease over time. Notably, when S_{PIC} = 150 m, the average velocity is relatively low, whereas for S_{PIC} = 30 m, the average velocity is higher, although the difference between them is not substantial.

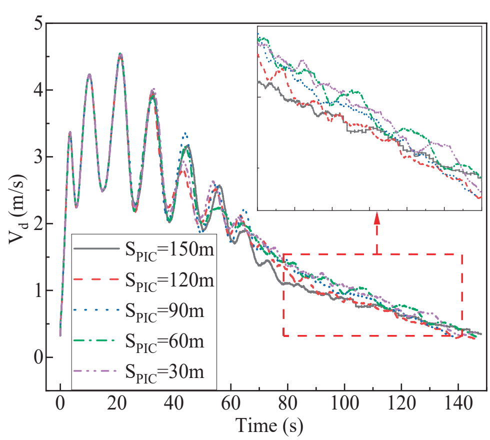

Figure 17. The temporal variation pattern of debris flow velocity.

Figure 18 illustrates the variation in debris flow impact on an EDPIC under different S_{PIC} conditions. As shown in Figure 18a, when S_{PIC} is 30 m, the debris flow exerts a significant impact on the EDPIC, reaching up to 1.8 × 10^7 kN. With increasing S_{PIC}, the impact force gradually decreases. The impact force on the EDPIC generally follows a pattern of increasing with time and eventually stabilizing.

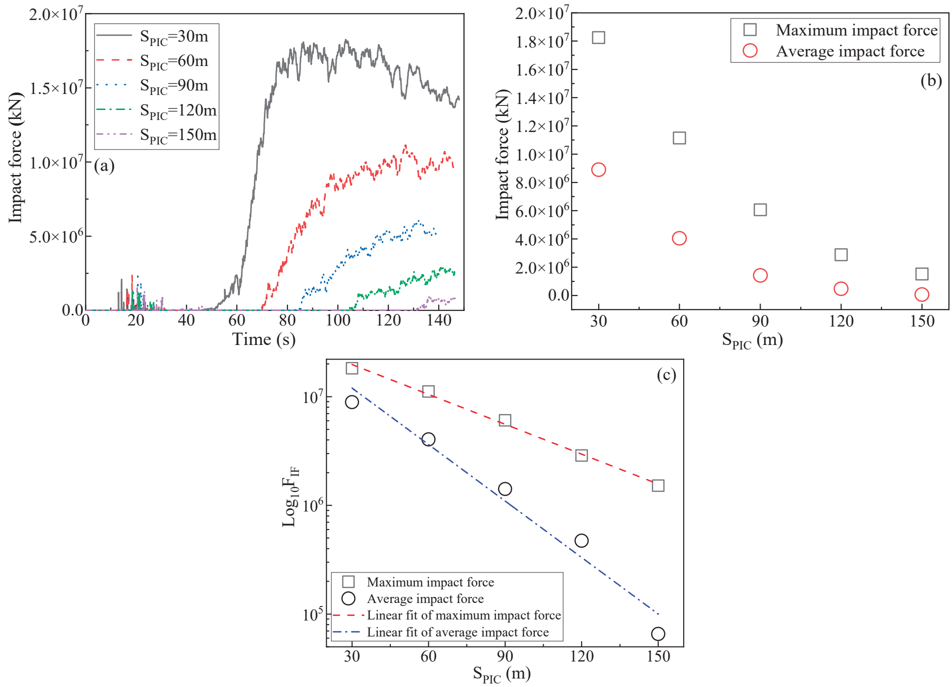

Figure 18. Variations in debris flow impact on an EDPIC: (**a**) temporal evolution of impact force under different S_{PIC} conditions; (**b**) trends in maximum impact force and average impact force with respect to S_{PIC}; (**c**) empirical formulas fitted for maximum impact force and average impact force variation with S_{PIC}.

Figure 18b presents the trends in maximum impact force and average impact force with respect to S_{PIC}. It is evident that as S_{PIC} increases, both the average and maximum impact forces exhibit a gradual decrease. When S_{PIC} increases from 30 m to 150 m, the maximum impact force on the EDPIC decreases by approximately one order of magnitude, while the average impact force decreases by approximately two orders of magnitude.

Figure 18c provides a fitted function for the variation in maximum impact force with S_{PIC}. It reveals that the logarithmic function of impact force is linearly related to S_{PIC}. The specific fitting results are summarized in Table 4. Consequently, this linear relationship allows for the approximate calculation of debris flow impact force based on the position of the EDPIC relative to the slope toe, thereby providing guidance for engineering design.

Table 4. Empirical formulas for calculating maximum impact force and average impact force.

	Maximum Impact Force	**Average Impact Force**
Equation	$y = a + bx$	
Intercept	7.571	7.599
Slope	−0.009	−0.017
COD	0.995	0.968

5.2. Strategies for Disaster Prevention Products and Management at Multiple Levels

This paper develops a comprehensive disaster prevention product strategy by integrating macro, meso, and micro research levels into a unified model. No previous studies have proposed such a holistic approach. Each research level offers distinct advantages, as detailed in Table 5. While most studies focus on examining a single aspect or, at most, combining two, our approach leverages the strengths of all three levels.

Table 5. Analysis of disaster prevention and management at the macro, meso, and micro levels.

Research Level	Specific Performance in Disaster Prevention and Management	Feature
Macro	Measure and assess affected areas	Clarify the importance and scale of the disaster for disaster prevention and planning for recovery and development
Meso	Identify prioritized disaster prevention product design needs	Focus on human and environmental needs, meeting the needs of users, and better following the principles of sustainability in terms of materials, colors, and shapes
Micro	Measure the structural resistance of the product	Functionality is the core of disaster prevention products and is closely related to user safety
Macro–meso–micro	GIS-AHP mixed with numerical simulation analysis	More comprehensive and systemic

In the research on disaster prevention products at a macro level, a geographic information system (GIS) is utilized to create detailed maps that visually represent various quantities. A GIS-based model could be used to characterize the affected areas and interpret both the hydro-geomorphic (trenches along barrier beaches, erosion, deposition, etc.) and hydraulic (urban streams along the streets, flow directions, flood extent) factors.

In the research on disaster prevention products at the meso level, the focus is on identifying and prioritizing the design needs of disaster prevention products. This level emphasizes the importance of understanding human and environmental needs to create products that are both effective and sustainable. Factors such as material selection, color, and shape are considered to ensure the products meet the users' requirements while adhering to sustainability principles.

In the research on disaster prevention products at the micro level, the emphasis is on measuring the structural resistance of the product. The core functionality of disaster prevention products is closely related to user safety, necessitating rigorous testing and the evaluation of structural integrity. This level ensures that the products can withstand the specific conditions they are designed to mitigate, thereby providing reliable protection during disasters.

5.3. Limitations

This research acknowledges several limitations, including potential biases in user feedback, which may arise from the subjective nature of surveys and interviews. Additionally, the research design may have constraints related to the generalizability of findings due to the specific geographic focus on the GBA. To address these limitations, future research could expand the similar geographical environment and include more diverse geographic regions.

Applying the methodologies used in this study involves adapting the GIS and AHP frameworks to local contexts. For instance, spatial data collection should encompass local water systems, flood-prone areas, and population densities relevant to the new region. User needs exploration should involve engaging with local populations through tailored surveys and interviews, ensuring cultural and contextual relevance. In regions with different geographic and socio-economic characteristics, the criteria for AHP may need to be adjusted to reflect local priorities and conditions.

Compared with previous research results, this study confirms an innovative application of disaster prevention products in the post-disaster period. Studies in different geographic areas have also emphasized the necessity of aligning disaster prevention strategies with local needs and conditions. However, this study introduces novel insights into the application of GIS and AHP for optimizing product design and resource allocation, demonstrating that these tools can significantly enhance disaster preparedness and response strategies. These comparisons underscore the effectiveness of integrating spatial data analysis and hierarchical modeling to improve disaster prevention product designs, suggesting that similar approaches can be successfully applied in other regions prone to natural disasters.

6. Conclusions

This study introduces a comprehensive design approach progressing from macro to meso and then to micro levels, as illustrated in Figure 19. At the macro level, GIS analysis is employed to delineate risk zones and formulate product distribution strategies. The meso-level design involves using the AHP method to select and design the basic structure and additional features of post-disaster emergency products. At the micro level, numerical simulations are conducted to assess the impact resistance of product materials.

Figure 19. "Macroscopic—mesoscopic—microscopic" design model.

Guided by the principles of green modularization and sustainable development and driven by core concepts of human care and safety in post-disaster product design, this study utilizes the GIS-AHP design method to explore the post-disaster needs of environmental refugees and devise strategies for emergency product design. Numerical simulations are then used to validate these design strategies. This holistic approach, from a global to a local perspective, holds practical significance for engineering design research.

Addressing the challenges faced by refugees affected by natural disasters is a crucial area of research. Consequently, this study focuses on developing emergency disaster protection products tailored explicitly for flood and inundation scenarios. By employing the AHP method within a GIS analytical framework, the study investigates the requirements of environmental refugees concerning the modular design of disaster products. Through a comprehensive process of user research, demand analysis, weight computations, and detailed analysis, the study identifies user requirements and formulates a product design strategy.

(1) A case study on post-disaster product design for flood refugees in Zhuhai was conducted. Utilizing GIS technology, the most affected areas were identified, leading to

the development of a targeted spatial configuration strategy based on natural geography. This approach improved product efficacy and resulted in a more comprehensive overall strategy.

(2) By prioritizing user demands, the study applied the AHP method to quantify requirements and prioritize user needs, directly translating these into design recommendations. This explicit connection between user research findings and final product design ensured enhanced design efficiency and user satisfaction, with the product's effectiveness verified. The research methodology and process, based on addressing natural disaster issues in the Greater Bay Area and utilizing the GIS-AHP analysis method, provide valuable insights for similar product research endeavors.

(3) Numerical simulations evaluated the protective efficacy of the EDPIC under debris flow impact conditions. As the distance between the EDPIC and the slope angle (S_{PIC}) increased from 30 to 150 m, the maximum impact force significantly decreased, while the average impact force diminished by approximately two orders of magnitude. This analysis resulted in an empirical formula that can serve as a valuable reference for engineering design purposes.

(4) This study presents a novel and integrated approach to designing post-disaster emergency products, combining GIS, AHP, and numerical simulations. Key findings include the identification of effective spatial strategies for product placement, improved design efficiency and user satisfaction through the AHP method, and the validation of product efficacy under diverse conditions. The AHP approach was crucial in quantifying requirements and prioritizing user needs, ensuring a clear connection between user research findings and final product design.

(5) A significant contribution of this study is the development of a comprehensive disaster prevention product strategy by integrating macro, meso, and micro research levels into a unified model. At the macro level, GIS analysis helps identify and prioritize areas most in need of disaster prevention products. At the meso level, the AHP method is used to systematically evaluate and prioritize user needs and design features. At the micro level, numerical simulations provide detailed insights into the material properties and structural performance under various disaster scenarios. This multi-layered approach ensures that the design process is both thorough and adaptable, addressing the complex nature of disaster prevention comprehensively. This holistic approach, which combines spatial analysis, user-centered design, and technical validation, has not been proposed in previous studies on disaster prevention products. By integrating these research levels, the study not only enhances the effectiveness and relevance of the products but also sets a new standard for future research in this field.

Future research will extend this study in several meaningful ways to advance the field of disaster resilience and sustainable design.

First, the approach could be applied to the design of products for other types of natural disasters, such as earthquakes, hurricanes, and wildfires, to assess the generalizability and robustness of the design framework. By adapting the GIS-AHP methodology and numerical simulations to different disaster scenarios, researchers can identify commonalities and unique requirements across various types of emergencies.

Second, further refinement of the empirical models through more extensive field testing and real-world data collection is essential. Enhancing the accuracy and reliability of the design recommendations will ensure that they are applicable in diverse conditions. This could involve longitudinal studies and real-time monitoring of product performance during actual disaster events.

Third, incorporating advanced technologies like machine learning and the Internet of Things (IoT) could provide more dynamic and adaptive design solutions in real-time disaster scenarios. These technologies can enable predictive analytics and automated responses, thereby improving the responsiveness and effectiveness of disaster prevention products.

Fourth, interdisciplinary collaborations with social scientists, environmental experts, and policymakers are crucial. Such collaborations can enrich the design process by ensuring that the products meet broader social and environmental needs. This includes understanding the social dynamics and environmental impacts of disaster prevention strategies, as well as aligning product designs with policy frameworks and regulatory standards.

Additionally, the results of this study have significant implications for possible modifications or adjustments to existing standards or codes. The comprehensive disaster prevention product strategy developed here can inform updates to building codes, safety regulations, and disaster preparedness guidelines, ensuring that they incorporate the latest research findings and technological advancements.

Finally, while this case study focused on flood refugees in Zhuhai, the methodology and findings can be extrapolated to other countries and regions. By adapting the GIS-AHP framework to local contexts and disaster types, researchers and practitioners can develop tailored disaster prevention strategies that address specific regional needs and conditions.

These extensions will not only broaden the applicability of the study's findings but also contribute significantly to the field of disaster resilience and sustainable design. By addressing the identified gaps and incorporating advanced technologies and interdisciplinary insights, future research can enhance the effectiveness and sustainability of disaster prevention products globally.

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Nomenclature

AHP	Analytic hierarchy process
GIS	Geographic information system
GBA	Greater Bay Area
FEMA	Federal Emergency Management Agency
PRD	Pearl River Delta
PTFE	Polytetrafluoroethylene
EDPIC	Emergency disaster prevention inflatable cabin
H_{PIC}	The vertical height of the center of mass of the prevention inflatable cabin from the ground
S_{PIC}	The horizontal distance between the prevention inflatable cabin and the foot of the slope

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Building Safety Evaluation and Improvement for Northern Vietnam Mountainous Environments Empirical Study Combining Japanese Experience with Local Conditions

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Abstract: This study addressed the insufficient structural strength and inadequate disaster resistance in building designs in the mountainous regions of Northern Vietnam. By integrating Japanese construction experience with local conditions, we proposed optimized building structures and simplified safety evaluation methods. Through an analysis of climate, terrain, geological hazards, soil conditions, and construction material costs, building design and foundation construction were optimized, and these optimizations were validated through wind tunnel experiments and finite element analysis. The results indicated that the optimized structures exhibited superior wind load stability, with external wind pressure coefficients ranging from −1.5 to −0.7, compared with the traditional structure's range of −1 to −3.5. The redesigned foundation improved landslide resistance, reducing excavation and foundation construction costs relative to Japanese methods. The foundation's safety factor reached 4.42–5.13, surpassing the standard of 2.5, and the retaining wall's sliding resistance safety factor reached 1.87, exceeding the requirement of 1.5. These enhancements dramatically boosted building safety under extreme weather conditions. This study provides practical solutions for building design in Vietnam's mountainous regions and serves as a valuable reference for similar research in other developing countries, underscoring significant practical and social implications.

Keywords: building design optimization; disaster resistance; structural safety evaluation; cost-effective construction

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1. Introduction

1.1. Building Design Challenges in Southeast Asian Rural Areas

In Southeast Asia, excluding Singapore, most countries and regions remain underdeveloped. Building designs in these developing countries and regions often rely on traditional experience or adopt foreign construction standards without adequately considering local disasters, terrain, and structural strength factors [1–4]. This approach has led to numerous issues regarding the strength and comfort of buildings. In addition to environmental and climatic factors and the lack of detailed building construction standards set by the governments of these Southeast Asian developing countries [1], the poor quality of local infrastructure, limited use of new technologies, and low levels of education among the population also result in the rough construction of building foundations, low construction efficiency, and, consequently, high construction costs and poor disaster resistance in local buildings [2–7]. In the context building design challenges in Southeast Asian rural areas, it is crucial to consider local conditions when adopting foreign construction standards. The study "Key Assessment Criteria for Organizational BIM Capabilities: A Cross-Regional Study" by Rajabi illustrates how BIM implementation strategies must be tailored to the specific cultural and infrastructural context of each region. For instance, while Malaysia emphasizes the availability of infrastructure and technology adoption, Iran places greater importance on staff experience and formal agreements. This finding underscores the necessity of adapting international best practices to align with local needs, ensuring that BIM capabilities are both effective and sustainable in different regional contexts [7]. Particularly in regions of developing countries that are vulnerable to natural disasters, it is necessary not only to optimize building structures to improve disaster resistance and functionality but also to develop adaptive building construction systems based on the local social environment [2,3].

The countries surrounding the South China Sea region are particularly vulnerable to the severe destruction caused by typhoons. The strength and position of the western Pacific subtropical high significantly influence the formation and intensity of typhoons in this region and the area east of the Philippines. During the cold phase of the Pacific decadal oscillation (PDO), sea surface temperatures in these regions are lower, and the subtropical high is weaker, contributing to the intensification of typhoons. Consequently, a higher proportion of strong typhoons affect the South China Sea and the Philippines during these periods [8]. These climate changes have resulted in a gradual increase in the frequency of typhoons passing through Vietnam in recent years.

Currently, there is a gap in the research on optimizing building structures under the existing conditions and environments of developing countries, as well as for developing straightforward safety evaluation methods suitable for the local environment and educational levels.

1.2. Research Questions

To address the aforementioned research gaps, this research proposed the following questions:

How can disaster-resistant buildings be designed considering the local climate and existing conditions?

While referencing construction methods from developed countries in developing nations, how can the issue of performance overspecification and incompatibility caused by directly applying these methods to local foundations be minimized, ensuring building safety while lowering costs associated with these unnecessary features?

How can building performance evaluation methods be simplified so that they can be used effectively by individuals with a high school education or less for preliminary safety assessments of planned buildings?

1.3. Research Methods

To address the aforementioned questions, this study selected the building land in the mountainous region of Tan Lap District, Luc Yen City, Yen Bai Province, Northern Vietnam, as the research area. Local building facility design projects were utilized to analyze these issues and develop a design process, as shown in Figure 1.

In the research on building structure and foundation construction methods, the study analyzed the local climate, terrain, geological disasters, soil conditions, building material costs, and existing building problems. It also referenced the experiences of Japan, which faces similar disaster threats [9]. Based on this analysis, the study refined construction methods and compared various indicators with the original methods to propose customized optimized construction solutions [5].

For the preliminary establishment of a building safety evaluation system, the study investigates and evaluates the educational level of local residents [10], their comprehension of construction drawings, and other aspects of knowledge understanding. Combining these factors with local geological conditions, the study designed a building safety evaluation system tailored for mountainous terrain that is accessible for local residents.

These solutions encompassed optimizing structural design to improve wind load resistance, redesigning economical and practical foundation construction methods to bolster resistance against mudslides, and utilizing local materials and traditional building techniques to attenuate construction costs and simplify the construction process for local residents. Additionally, based on the survey of local residents' educational levels and their proficiency in mathematics, a relatively easy-to-understand preliminary building safety evaluation formula was developed.

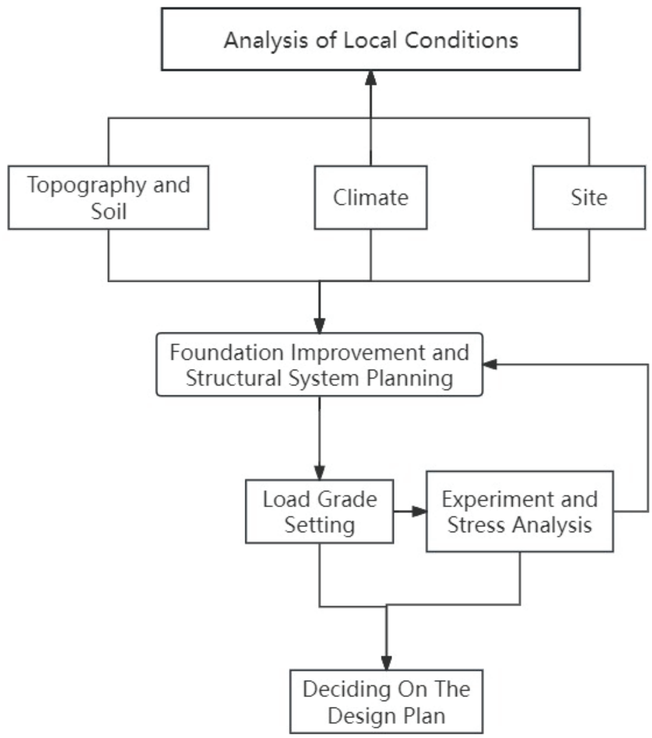


Figure 1. The process of optimizing the design.

The methods for generating experimental data included the following:

Soil sampling and testing: Soil samples were randomly extracted from the mountainous building land. The liquid limit and plastic limit of the sample soil were measured using the thread-rolling method and a liquid limit device [1–7,11,12]. Subsequently, the plasticity index was calculated to delve into the properties of the local soil.

Deriving soil parameters: Using data from the aforementioned experiments, the soil's friction angle and cohesion were determined. Terzaghi's bearing capacity formula was employed to analyze the maximum bearing capacity of the foundation, and the constant values for the parameters needed in the simplified formula were deduced [1–6].

Wind tunnel experiments: Wind tunnel experiments were conducted to assess and compare the wind load resistance of optimized building models and traditional building models [4–7,11–13].

Coulomb's earth pressure theory: Coulomb's earth pressure theory formula was adopted to evaluate the safety of building components on the retaining wall and to assess its resistance against sliding and overturning [14].

Finite element analysis with SAP2000: The SAP2000 finite element analysis software was introduced to simulate and analyze the deformation of the building structure under local extreme weather and extreme load conditions, thereby verifying its structural safety.

To scientifically validate that the optimized construction method is more suitable for local conditions than directly adopting Japanese construction methods, we employed the particle swarm optimization (PSO) algorithm [15]. This algorithm allowed us to compare the Japanese construction methods with the newly optimized approach.

1.4. Research Results

The study demonstrated the following:

The refined building structural design exhibited enhanced stability in wind load tests, showing substantial reductions in the variation of external and internal wind pressure coefficients [4–7,10–13,16,17].

Redesigning the foundation of the mountainous building land effectively mitigated damage caused by mudslides [18]. Comparing the new construction methods with the existing referenced methods revealed reduced performance overspecification, improved economic efficiency, and lowered construction costs while ensuring building safety.

By assessing the local soil quality through soil experiments and referencing Terzaghi's bearing capacity formula and Coulomb's earth pressure theory formula [7], certain constant parameters in these formulas can be derived. This simplification ensures that the formulas are comprehensible to residents with a high school education level [2–7,11–13,19].

Considering different construction methods as particles in the model, we used their anti-sliding coefficients, anti-overturning coefficients, ratio of unit building area to unit foundation volume, and ratio of construction area to excavation volume as the coordinates in the PSO algorithm program that was defined. After six iterations, the results demonstrated that the optimized method exhibited the most stable trend in fitness variations. Among all particles, it required the fewest iterations to reach the near-optimal solution region. Therefore, this further validated the rationality of the optimized method.

1.5. Research Significance

This study aims to address diverse challenges in building design and construction in developing countries, particularly in disaster-prone regions, through the optimization of structural design and streamlining of building performance evaluation methods. This effort holds substantial practical and social implications, including the following:

Improving building safety: Through the analysis of the specific conditions in Tan Lap District, Luc Yen City, Yen Bai Province, Northern Vietnam, the study proposed a range of optimized building structural design methods, including improving the wind load resistance of buildings and redesigning foundation construction techniques. Such optimizations can significantly enhance building stability and safety under extreme weather conditions, thereby mitigating damage from natural disasters and safeguarding the lives and property of local residents.

2. Materials and Methods

2.1. Survey of Yen Bai Province

2.1.1. Local Typical Wind and Landslide Damages to Buildings

The study site is situated in a village in Tan Lap District, Luc Yen City, Yen Bai Province, surrounded by mountains and lakes, and characterized by a tropical monsoon climate. The annual average temperature in this area ranges from 22 °C to 24 °C. Summers, particularly from June to September, experience elevated temperatures, heavy rainfall, and short-term intense rainfall. Given Yen Bai Province's mountainous topography, heavy rainfall can destabilize the soil, increasing the risk of landslides [16].

According to the wind speed and rainfall data from 2022 to 2023 for Yen Bai Province and the adjacent Lao Cai Province [3], along with annual data on wind direction and speed [20], it was observed that the prevailing annual wind direction in this area was southeast. Wind speeds in both provinces exhibited remarkable seasonal fluctuations over the two years. The annual average wind speed was approximately 5 km/h, with variations ranging from 3 to 7 km/h. Wind speeds were higher in summer and winter, and relatively lower in spring and autumn.

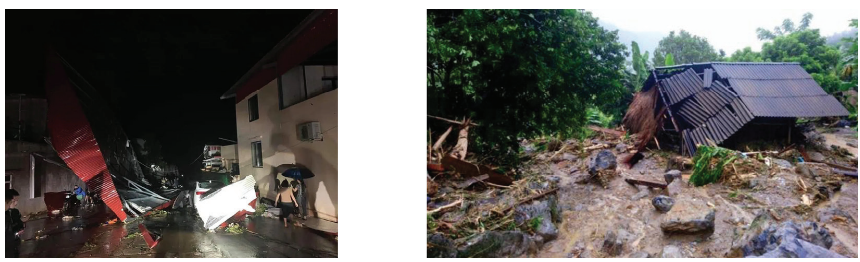
The rainfall in both provinces showed notable variation over the span of two years, characterized by distinct seasonal patterns. The annual average rainfall ranged from 5 to 15 mm, with a maximum rainfall of up to 50 mm. The rainy season predominantly occurred during summer (June to September), marked by substantial increases in precipitation [21].

Landslide disasters were particularly concentrated from June to September, coinciding with rise in the frequency of intense rainfall in recent years.

To provide an overview of wind and landslide disasters, this study examined their impacts on both non-engineered houses and typical wind damage to engineered buildings. Strong winds can inflict severe damage on buildings primarily through high wind pressure and the impact of flying debris. Inadequate wind resistance further heightens the likelihood of damage. Typical manifestations of wind damage include roofs being blown off, windows breaking, and exterior walls peeling off.

Regarding landslides, Yen Bai Province features numerous mountainous and hilly regions predominantly composed of clayey soils. The inadequate drainage of these soils renders them susceptible to loosening during heavy rainfall, thereby increasing the likelihood of landslides. Typical landslide damages include houses being buried, building foundations being destroyed, and roads being cut off [16].

The following content illustrates instances of wind damage, large-scale landslides, and floods triggered by heavy rains in Yen Bai Province in August 2023 [22]. Figure 2a depicts the damage to residential buildings in the town, with roofing materials blown off and roof structures damaged.



(**a**) (**b**)

Figure 2. This is the damage to buildings in urban (**a**) mountainous settlements (**b**) caused by heavy rainfall and strong winds in Yen Bai Province in 2023.

Figure 2b displays the damage to residential buildings located on a mountainside slope. As illustrated, local residents construct houses on slopes by leveling the ground for the foundation, resulting in varying heights between the front and back of the ground. The absence of foundation enhancements or retaining walls leads to complete destruction of buildings during landslides. This lack of measures heightens the vulnerability of buildings on slopes.

As demonstrated by these examples, enhancing the strength of existing buildings solely from the perspective of wind engineering is insufficient [4]. Therefore, designing a systematic building safety evaluation system based on local environmental characteristics is imperative.

2.1.2. Characteristics of Local Buildings

Yen Bai Province is situated in the mountainous regions of Northern Vietnam, where residential buildings exhibit the following distinct local characteristics, as shown in Figure 3:

Stilt houses: Due to the mountainous terrain and heavy rainfall in Yen Bai Province [16], many residents opt to build stilt houses. This type of construction can prevent flooding and moisture intrusion, while also mitigating animal infestation.

Use of wood: Local buildings primarily utilize wood for supporting columns, walls, and roofs. Wood is readily available and offers excellent insulation and ventilation properties [23].

Roofing: Traditional houses commonly employ thatch or bamboo for roofing, which provides good insulation and waterproofing. This reflects the utilization of local natural resources. The roofs are steeply pitched to facilitate faster drainage [3–7,10–13,16,21,23].

(a) (b)

Figure 3. The appearance of engineered buildings (**a**) non-engineered buildings (**b**) in the mountainous areas of Yen Bai Province.

Open space design: These houses typically embrace open layouts with expansive interiors and minimal partitions, fostering family interaction and enhancing ventilation [4–7,10–13,16,21,23].

On the other hand, as displayed in Figure 3, Figure 3a illustrates houses in Yen Bai Province's tourist areas that incorporate traditional elements. Aside from tourist spots, local residents frequently construct non-engineered (or partially non-engineered) houses, as shown in Figure 3b. These self-built houses are structurally vulnerable and have poor disaster resistance. In such contexts, the escalating impacts of climate change, with their unpredictable consequences, are likely to heighten the vulnerability of these houses, posing potential threats to residents' safety [2–7,10–13,16,21,23,24].

2.2. Analysis of the Village in Tan Lap District

2.2.1. Village Topography and Current Building Status

According to Figure 4, villagers' homes are generally distributed based on their industries. The village residences are primarily situated on three types of terrain. Houses in mountainous areas are mostly built on slopes, rendering them susceptible to landslides during heavy rains. Houses in flat areas are surrounded by hills on both sides, creating a valley-like configuration that exacerbates the tunnel effect.

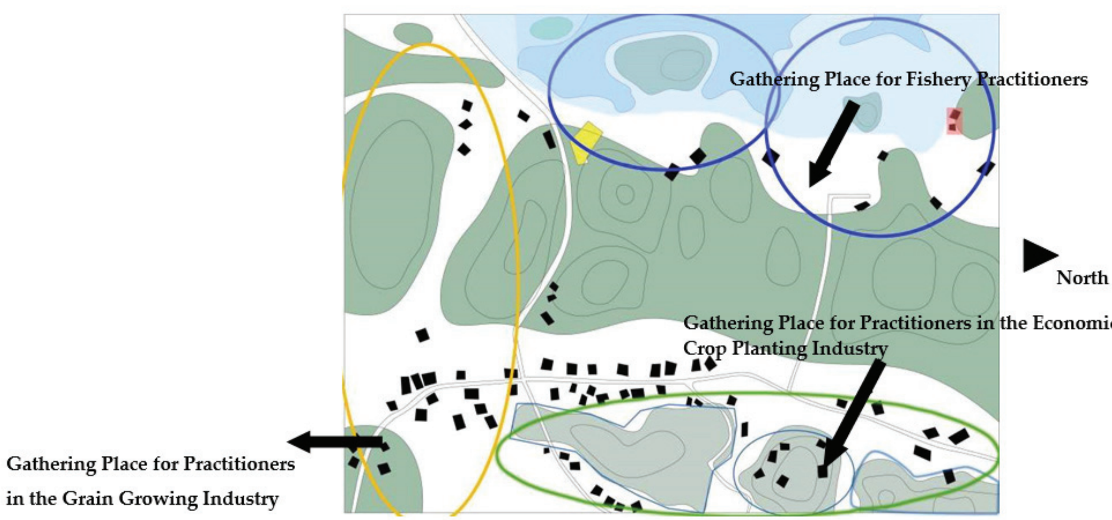


Figure 4. Distribution of target rustic settlements.

Additionally, Northern Vietnam features a tropical monsoon climate characterized by frequent occurrences of strong monsoon winds [21]. These winds intensify significantly as they funnel through valleys. During Vietnam's monsoon season, the interaction of strong winds with valley topography and the tunnel effect significantly augments wind speeds [25].

Alongside the topographical survey, an assessment of the current building status in the village was conducted. The village buildings were categorized into waterside buildings, mountainous buildings, and flatland buildings. The survey revealed that the proportions of non-engineered buildings in each settlement area are 66.6%, 70%, and 57.9%, respectively. This indicates that more than half of the buildings in the village lack adequate structural strength and exhibit poor disaster resistance.

2.2.2. Soil Analysis for Building Foundations

Since the planned facilities are wooden structures with a maximum height of three stories, the building foundations are classified as shallow foundations. Given the location in a mountainous area, an accurate determination of soil properties is crucial. Soil samples were extracted from four locations at a depth of 50 cm in the mountainous building land. Each soil sample was divided into five parts, resulting in a total of four groups with twenty samples.

Plastic limit and liquid limit tests were conducted using the thread-rolling method and a liquid limit device [11] to ascertain the soil properties [12]. The density of the soil samples was measured using the ring knife method. Table 1 presents the water content, plastic limit, liquid limit, and plasticity index of the soil samples. Formula (1) represents the calculation formula for the plasticity index, where *PI* denotes the plasticity index, *LL* signifies the liquid limit, and PL represents the plastic limit.

$$PI = LL - PL \quad (1)$$

Table 1. Soil sample plastic limit index and density experimental data.

Sample Serial Number	Water Content	Liquid Limit	Plastic Limit	Plasticity Index	Wet Density	Density
1-1	15.2	49.87	28.11	21.76	1.86	1.62
1-2	14.8	52.45	29.64	22.81	1.82	1.59
1-3	16.1	55.23	31.79	23.44	1.89	1.63
1-4	15.5	51.1	28.87	22.23	1.94	1.68
1-5	14.9	52.65	29.96	22.69	1.82	1.59
2-1	15.3	49.65	28.28	21.37	1.83	1.59
2-2	15.0	51.56	28.7	22.86	1.93	1.68
2-3	16.0	54.36	31.01	23.35	1.90	1.64
2-4	14.7	51.10	29.09	22.01	1.81	1.58
2-5	15.4	53.21	29.55	23.66	1.88	1.63
3-1	14.9	51.52	29.1	22.42	1.81	1.58
3-2	15.6	54.47	30.67	23.8	1.82	1.58
3-3	15.2	51.33	27.56	23.77	1.85	1.61
3-4	15.1	52.71	30.45	22.26	1.72	1.5
3-5	15.3	51.68	29.46	22.22	1.74	1.51
4-1	15.5	54.68	32.31	22.37	1.81	1.57
4-2	15.0	49.8	26.81	22.99	1.78	1.55
4-3	14.8	52.02	28.6	23.43	1.86	1.62
4-4	15.4	53.93	31.18	22.75	1.79	1.55
4-5	15.1	52.79	29.94	22.85	1.76	1.53

Figure 5 is the Atterberg limits chart, utilized for soil classification based on its liquid limit and plasticity index. Different colored areas on the chart denote various soil types [26]. The blue cross marks indicate the data points of the soil samples. As depicted in the chart, the majority of sample data points fall within the red area, indicating that these soil samples consist of high plasticity clays. This information is pivotal for guiding foundation optimization strategies and calculating bearing capacities.

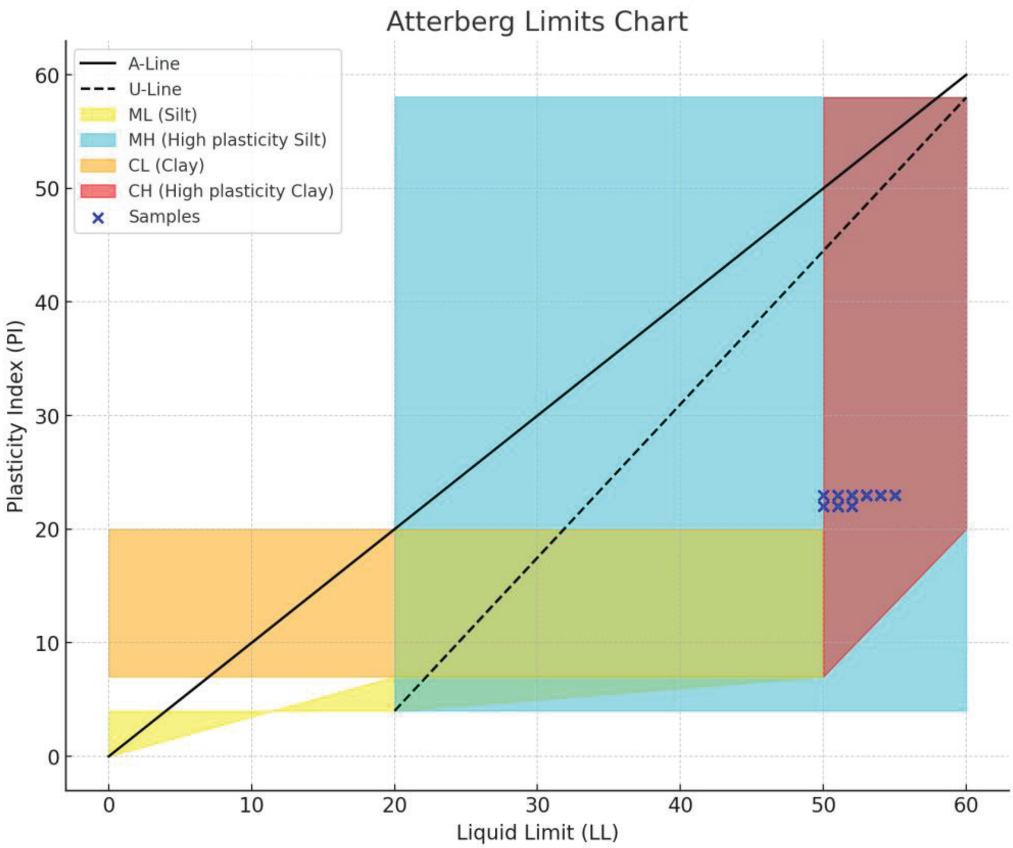


Figure 5. Atterberg limits chart.

2.3. *Foundation Analysis of the Actual Project Site*

As exhibited in Figure 6a,b, the dimensions and the restored foundation conditions of the building site were surveyed. Situated in the yellow area of Figure 4, the site features sloped terrain with a height difference of 3.4 m between the rear 20 m and the front of the building site. The existing public facilities consist of non-engineered structures self-built by villagers. Construction involves leveling the sloped ground and installing wooden structural poles on basic foundations, with excavated soil piled at the rear of the building site.

This primitive construction method not only results in inefficient land use but also increases the height difference by depositing excavated soil at the rear, without proper foundation construction and retaining structures. Coupled with the inherent fragility of the buildings, this heightens their vulnerability to significant damage or potential collapse during landslides.

To address these challenges and optimize site utilization, the design of facilities in Tan Lap District should prioritize the following points.

Ensuring structural safety is paramount in local facility planning. Given the frequent incidence of strong winds and landslides, it is essential to account for not only permanent loads but also dynamic loads, such as wind loads. Building on slopes necessitates a meticulous assessment of slope stability and lateral earth pressure, distinct from construction on flat terrain.

(**a**)

(**b**)

(**c**)

Figure 6. The current state of local buildings captured during on-site surveys. (**a**) is the appearance of existing buildings and the site plan of the current residence, (**b**) is the terrain of the building site recreated in the modeling software, (**c**) is a simplified diagram of the terrain.

Construction costs: Given the constraints of the local government budget, it is imperative to employ cost-effective approaches for enhancing building site foundations and redesigning structures while ensuring safety.

2.4. Optimization Design for the Actual Project

2.4.1. Foundation Improvement

Mainland Japan predominantly consists of mountainous terrain, with a summer climate characterized by typhoons and heavy rainfall, similar to Yen Bai. Typhoons often bring strong winds and intense, short-term rainfall, leading to secondary disasters, such as landslides [27]. Compared with Yen Bai Province in Vietnam, Japan faces more severe disaster challenges. Consequently, the disaster prevention standards in Japanese building codes are set higher than in other regions [28,29]. The foundation design methods and safety standards for mountainous areas in Japan provide valuable references for Vietnam.

Figure 7 illustrates the four primary construction methods used for building sites on slopes in Japan [9]. Method A involves leveling the slope before constructing buildings. This method is commonly employed in urban slope construction because the building site has a good road foundation in both the front and back [1–7,9–13,16,19–26,28,30–36]. Method B involves constructing the foundation up to the height of the highest point of the building site, followed by the construction of houses on this prepared foundation [37]. Methods C and D are suitable for rural mountainous areas where there are no engineered structures or disaster prevention facilities in the front and back. These methods necessitate the installation of retaining walls or the reinforcement of the first floor of buildings [9,19–26,28–37].

Method A requires robust surrounding infrastructure and stable soil conditions, limiting its suitability to specific environmental settings.

Method B involves considerable expense and aims to improve seismic resistance through extensive foundation reinforcement.

Methods C and D align well with the project's requirements. However, implementing them at the building site depicted in Figure 7 would potentially compromise land use efficiency.

The Indochina Peninsula, home to Vietnam, has relatively stable geological activity, with earthquakes being a low-priority disaster. Given the region's low income levels, the design budget prioritizes enhancing resistance to landslides and wind disasters [24].

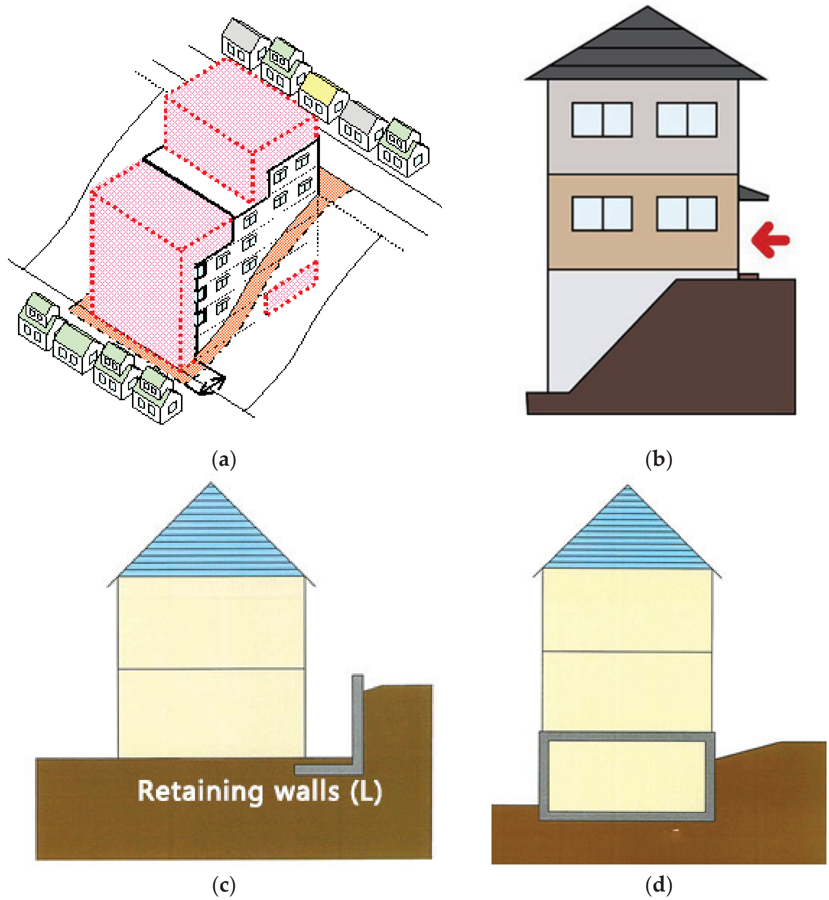


Figure 7. The four main construction methods for sloped building sites in Japan, with red arrows indicating the entrances of circulation paths. (**a**) Method A, (**b**) Method B, (**c**) Method C, (**d**) Method D.

Given the site conditions, when constructing buildings on sloped terrain, retaining walls must be placed where there are height differences in the foundation [29] to resist soil pressure. Unlike earthquake-prone Japan, statistics show that Vietnam's geological environment is relatively stable. Since records began, Yen Bai Province has not experienced an earthquake above magnitude 5. Therefore, as shown in Figure 8a, the modification plan references the retaining wall design from Method C, reducing the amount of excavation and incorporating buttressed retaining walls at height-differential points. This approach not only improves land use efficiency and attenuates excavation costs, but also enhances the foundation's ability to withstand landslides.

The design prioritizes structures that can resist soil pressure and are cost-effective. Therefore, the retaining wall design can draw upon commonly used, cost-efficient retaining walls in civil engineering, which have relatively simple safety calculation formulas to improve the building site's foundation [7].

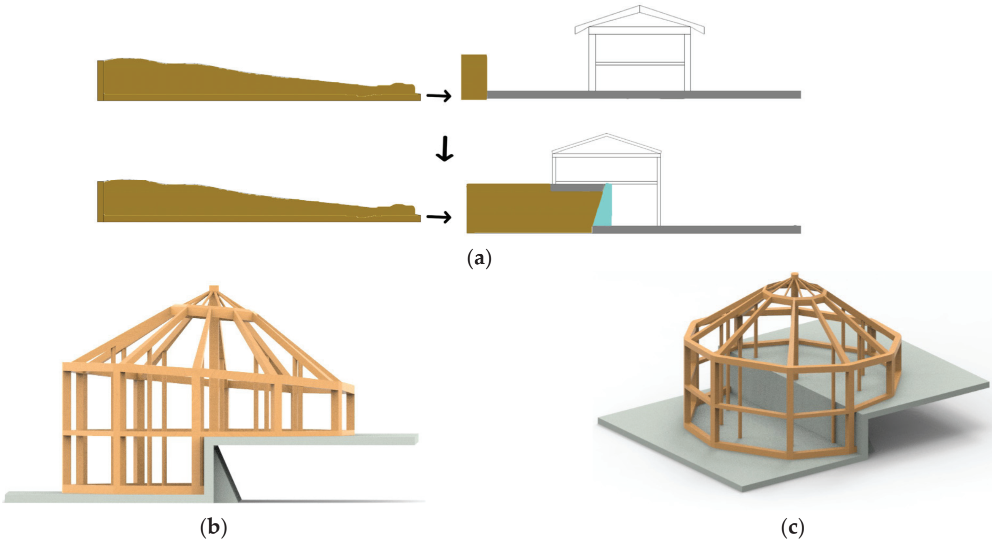


Figure 8. The foundation and building structure construction methods optimized based on the construction method shown in Figure 7c to adapt to local conditions (**a**), (**b**,**c**) are renderings of the optimized house construction and foundation structure.

2.4.2. Design for Landslide and Wind Load

Design for Landslides and Soil Pressure

In order to enhance the building's resistance to mudslides and soil pressure, a buttressed retaining wall was designed based on the aforementioned comparison of retaining wall data [3–7,10–13,16,20–26,28,30,31], due to the 3.4 m height difference at the site. The height of the buttressed retaining wall was 3.4 m. To prevent the formation of a secondary failure plane and to resist soil pressure, the length of the heel slab was restricted to between 1.5 m and 3.4 m, with a thickness of 0.4 m.

Reducing Wind Load from Strong Winds

To resist strong winds, the roof was designed with a 5° incline towards the northwest, inspired by the concept of tilting an umbrella against wind pressure during strong winds.

Columns and Beams Structural System

As shown in Figure 8b, the structural system of columns and beams was modified based on the Japanese Yamagata frame design. Given the building's diameter of 17.5 m, the wind-induced bending moments on the columns and beams, as well as the roof load, are significant. To address this, a primary column with a diameter of 1 m was placed at the center of the second floor, connecting the other columns and beams. Additionally, ten slender columns were arranged around the main column to enhance structural stability.

2.4.3. Selection of Retaining Walls

Table 2 displays the performance of five main types of retaining walls. In the design of this project, both load-bearing performance and maintenance and material costs were considered [31]. Ultimately, a counterfort retaining wall was chosen due to its high hardness, load-bearing capacity, and low maintenance costs.

Table 2. Comparison of different types of retaining walls.

Type of Retaining Wall	Stability	Load-Bearing Capacity	Construction Difficulty	Material Cost	Maintenance Requirement
Gravity retaining wall	7	6	5	6	3
Cantilever retaining wall	8	7	7	5	4
Reinforced earth wall	9	8	6	7	3
Embedded retaining wall	9	9	8	6	5
Counterfort retaining wall	8	8	7	5	4

Given the priority focus on construction costs and stability, the counterfort retaining wall was selected based on the data from the chart. It offers low construction and maintenance costs while still providing adequate stability and load-bearing capacity. Compared with the cantilever retaining wall, which has similar construction and maintenance costs but higher earthquake resistance, the counterfort retaining wall is less seismic-resistant [32]. Nevertheless, considering the stable geological activity in the area, the counterfort retaining wall was ultimately chosen to improve the building site's foundation.

Figure 9 illustrates the stress diagram of the buttressed retaining wall in the new construction method. Due to Japan's mountainous volcanic terrain, most of the soil consists of sandstone. Compared with Vietnam's hard clay, sandstone has a friction angle exceeding 35°. Additionally, Japan's sliding coefficient ranges from 0.45 to 0.5, compared with Vietnam's 0.35 to 0.4 [38]. Therefore, when designing structures based on Vietnamese soil conditions, it is crucial to increase the soil pressure angle to enhance the wall's overturning resistance. According to the overturning resistance calculation in Formula (11) and the overturning force calculation in Formula (14), it can be analyzed that, under the same soil and wall material conditions, a greater angle of soil pressure on the wall results in higher overturning resistance. As depicted in Figure 9, vis a vis other retaining wall structures, the heel slab behind the buttressed retaining wall increases the angle of the soil pressure on the wall, thereby enhancing its overturning resistance. According to Formula (10), the greater the vertical pressure the retaining wall bears, the stronger its sliding resistance. Since the buttressed retaining wall itself has relatively weak sliding resistance, in general civil engineering projects, it is typically considered only when the height difference exceeds 5 m in general civil engineering projects due to its reliance on self-weight and heel slab soil weight for vertical pressure [18]. However, in the new construction method, the weight of the building structure and the foundation built on the retaining wall serve as additional sources of vertical pressure, compensating for the insufficient sliding resistance caused by the inadequate height of the buttressed retaining wall. Therefore, choosing a buttressed retaining wall as part of the building in the new construction method enhances the building's resistance to landslides and compensates for the inadequate sliding resistance of the retaining wall. Considering all factors, the buttressed retaining wall stands as the most economical choice in the new construction method.

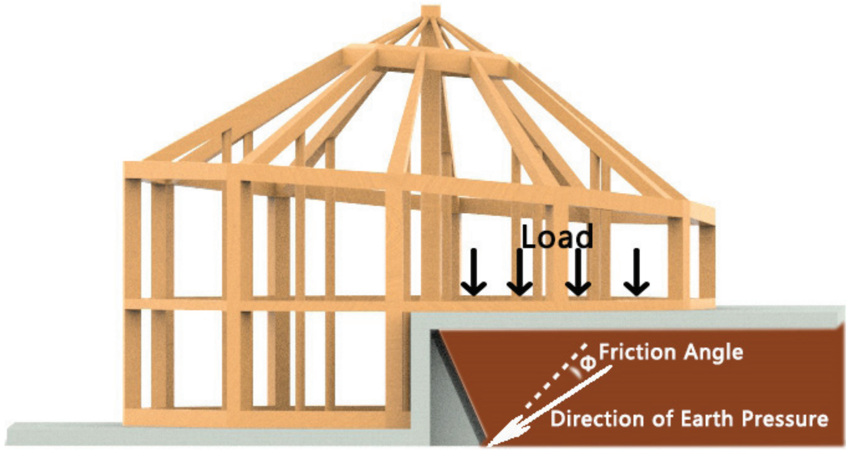


Figure 9. Retaining wall stress analysis.

2.4.4. Wind Tunnel Experiment

To verify the performance of the new structure in resisting strong winds compared with traditional structures, a wind tunnel experiment was conducted in an Eiffel-type wind tunnel based on local climate data [4].

The model for the wind tunnel experiment was scaled at 1:25. The measurement height was set to the height of the experimental building model's roof, which is 732 mm. The boundary layer flow index (α) was set to 0.3, and the turbulence intensity (I) was set to 0.2. Due to the complex terrain and high surface roughness in the northern mountainous regions of Vietnam, wind speed variation with height is more pronounced, resulting in a higher vertical wind speed exponent (α). According to data from the Engineering Toolbox, the vertical wind speed exponent in mountainous and hilly areas is generally around 0.25 [39]. However, given the intricate terrain of Northern Vietnam, a conservative estimate of 0.3 was chosen to more accurately represent local environmental conditions and to conservatively assess the wind resistance of buildings. According to data from the GLOBALWINDATLAS, the annual average wind speed at a height of 50 m in the mountainous regions of Yên Bái Province is 5.19 m/s, with a standard deviation of 1.12 based on data from 2010 to 2024 [20]. Using the ratio of the standard deviation to the mean wind speed, the turbulence intensity was calculated to be 0.216. For conservative estimation, a value of 0.2 was adopted. The vertical distribution of the average wind speed and turbulence intensity is exhibited in Figure 10.

During the experiment, wind direction simulations for the improved structure and the original framework model were applied based on the local climate, varying from 90° to 165° at 15° intervals. At each direction, two wind pressure time series data points were measured for each measurement point. The duration of each time series measurement corresponded to 10 min at full scale. The effective wind pressure at each measurement point was determined by calculating the difference between the external and internal wind pressures. The effective wind pressure time series was then normalized using the reference velocity pressure to calculate the effective wind pressure coefficient time series. The wind tunnel experiment parameters are shown in Table 3. The assumed maximum wind speeds were the local historical record maximum wind speed of 28 m/s and 1.1 times that, resulting in 31 m/s.

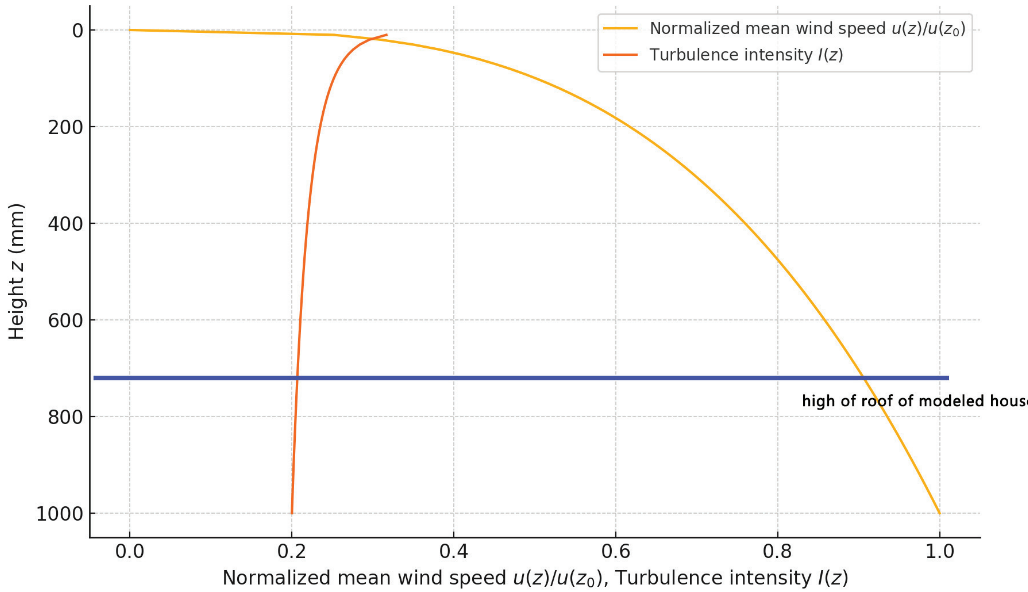


Figure 10. Relationship between height (z) and two key variables: normalized mean wind speed and turbulence intensity. (0–1000 mm).

Table 3. Parameters of the wind tunnel experiment.

Reference Wind Speed at Roof Height	4.6 m/s
Exponent of the vertical mean wind speed Profile	$\alpha = 0.3$
Wind direction	90° to 165° at 15° interval
Sampling frequency	200 Hz
Geometrical scale	1:25
Time scale	40:200
Assumed wind speed in full scale	28 m/s, 31 m/s
Averaging time in full scale	1 s
Evaluation time in full scale	600 s
Number of time series	2

Based on the trends in wind pressure coefficients depicted in Figure 11, the following analyses can be inferred.

External Wind Pressure Coefficients:

Existing structure: The external wind pressure coefficients ranged from approximately −1 to −3.5, exhibiting large negative values and significant variation.

Circular structure: The range of external wind pressure coefficients narrowed to −1.5 to −0.7, with notably reduced variation.

Internal Wind Pressure Coefficients:

Existing structure: The internal wind pressure coefficients were nearly zero, exhibiting minimal variation.

Circular structure: The internal wind pressure coefficients remained close to zero, with further reduced variation.

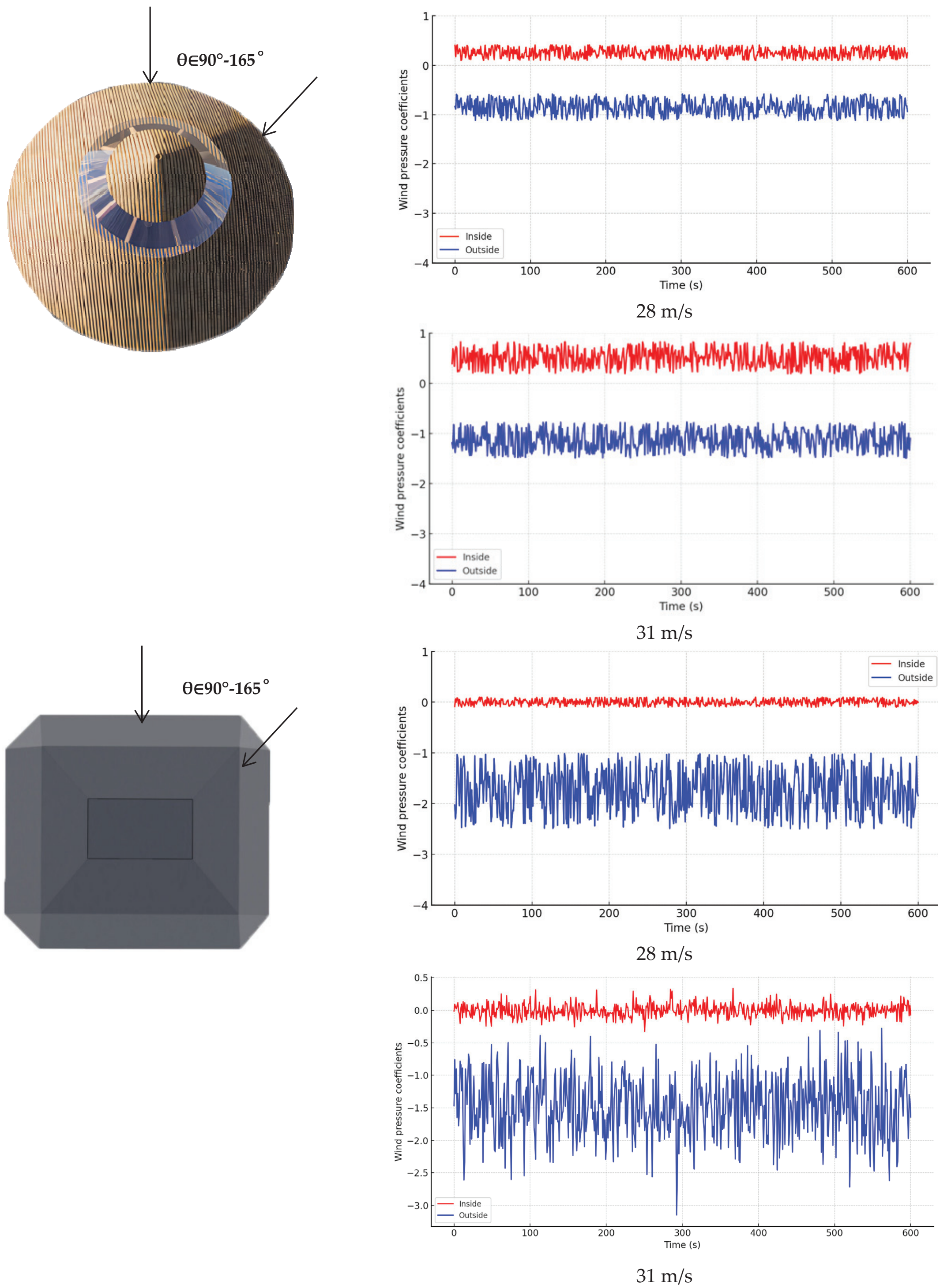


Figure 11. Comparison of wind pressure coefficients between the optimized structure and existing structure.

Summary:

Through a comparative analysis of wind pressure coefficient variations between traditional and circular structures, the circular structure exhibited superior stability in managing wind pressure. Both external and internal wind pressure coefficient variations were significantly reduced, contributing to enhanced overall building stability [17,33].

2.5. Impact Analysis

Reduced Variation in External Wind Pressure Coefficients:

Compared with the existing structure, the optimized structure displayed smoother edges, resulting in reduced variation in external wind pressure coefficients. This reduction indicated decreased fluctuations in wind loads exerted on the building's exterior components, including walls, windows, and roofs. As a result, the impact on the building exterior was reduced, and the structural stress and fatigue caused by localized wind pressure were also abated [6,7,10–13,16,20–26,28,30–33].

Stability of Internal Wind Pressure Coefficients:

The reduced variation in internal wind pressure coefficients ensures a stable indoor air pressure environment, effectively reducing the stress concentration within the internal structure. This stability contributed to maintaining indoor environmental stability and mitigating internal structural damage.

Reduced Effective Wind Pressure Coefficients:

The decrease in effective wind pressure coefficients (the difference between the external and internal wind pressure coefficients) signified a reduced pressure differential across the building's structure. This reduction is advantageous for overall structural integrity, as lower pressure differentials lessen the total wind load acting on the structure, thereby decreasing the risk of structural deformation and damage.

Conclusion:

In summary, the circular structure demonstrated several advantages over the traditional structure based on changes in wind pressure coefficients:

Reduced external wind pressure variation: Decreased impact and stress concentration on the building exterior.

Stable internal air pressure: Maintained indoor environmental stability and mitigated internal structural damage.

Reduced effective wind pressure coefficient: Lowered overall wind load and reduced risk of structural deformation and damage.

2.6. Simplified Load Safety Calculation Formula for Foundation Structures

Table 4 presents findings from a survey on the educational attainment of local residents. Ten respondents from each age group in the area were surveyed regarding their educational attainment. The results showed that, due to recent economic development and educational outreach in Vietnam, more than half of the young population had received at least a secondary school education and could understand basic functional expressions. The Vietnamese middle school mathematics curriculum incorporates functions and basic quadratic functions as part of its teaching content [19,34,35]. This survey provided a reference for streamlining the formulas used in building safety assessments.

Table 5 outlines the definition of each symbol used in the formula according to the optimized foundation construction method. To simplify the formula and calculation process, the load safety assessment of the foundation was divided into the following three sections:

Table 4. Sample survey on educational attainment of local people of different age groups.

Age Range of Respondents	High School and Above	Middle School Education	Primary Education Level	Able to Understand Simple Functions
18–25	5	7	10	7
26–35	3	5	5	4
36–45	1	4	6	2
45+	1	2	4	0

Table 5. Nomenclature.

Θ	Internal friction angle	W_1	Wall weight
C	Cohesion	W_2	Soil weight
Fs	Safety factor	Mr	Withstand overturning moment
Qu	Ultimate bearing capacity of foundation	Mo	Overturning moment
Γ	Unit weight of soil	S_1	Total building area acting on the underlying foundation
B H L	Foundation width Foundation height difference Foundation length	S_2	Total building area acting on the upper foundation
Df	Foundation depth	Kc	Anti-slip safety factor
Nc	Cohesion load factor	Fa	Safety factor against overturning
Nγ	Soil weight bearing capacity coefficient	O	Overturning moment action point
Nq	Ground additional sum in coefficient	R	Retaining wall volume
Kp	Passive earth pressure coefficient	Tγ	Soil load on heel plate
Wh	Retaining wall height	μ = 0.35	Slip coefficient
Wc	Retaining wall thickness	S = 0.7	Earth pressure coefficient
Wl	Retaining wall length	∑n	Lower foundation load
Hi	Heel plate length	∑N	Upper foundation load
Hc	Heel plate thickness	A	Area of the building on the heel plate
D	Foundation and retaining wall density	Pa	Active soil pressure

Assessing whether the safety factor of the lower foundation meets the standard.

Assessing whether the safety factor of the upper foundation meets the standard.

Assessing whether the safety factor of the retaining wall's overturning and sliding resistance meets the standard.

If the evaluation outcomes of the aforementioned three sections meet the standards, it can be preliminarily determined that the building complies with safety standards.

The formula for foundation bearing capacity is based on Terzaghi's bearing capacity formula [13,35]. Evaluation of the sliding and overturning resistance of the counterfort retaining wall structure incorporates Coulomb's earth pressure formula [6,34]. To conservatively evaluate building safety, safety factor standards were referenced from the implementation regulations of the Basic Building Law of Japan's Ministry of Land, Infrastructure, Transport, and Tourism [36]. The safety assessment of foundation bearing capacity primarily relies on the following formulas:

$$Qu = C \times Nc + \frac{1}{2}\gamma \times B \times N\gamma + \gamma \times Df \times Nq \tag{2}$$

$$Nq = Kp \times e^{\pi \tan \phi}\ Nc = (Nq - 1) \cot \phi\ N\gamma = 2(Nq + 1) \tan \phi \tag{3}$$

$$C = 0.2 \times (LL - PL)\phi = 28 - 0.15PL \tag{4}$$

$$Kp = \frac{1 - \sin \phi}{1 + \sin \phi} \tag{5}$$

$$Pa = \frac{1}{2}\gamma \times Wh^2 \times K\mathrm{p} \tag{6}$$

$$E\mathrm{x} = Pa \times L \tag{7}$$

Based on the experiments summarized in Table 1, the density and plasticity index of the soil samples were determined. To standardize the parameters, the average soil density was set at 18.5 KN/m^3, and the plasticity index was conservatively estimated at 22. Considering the potential variability in soil properties, a conservative estimation approach was adopted. Specifically, for each parameter, the range of values was determined using both the parameters of the sample with the minimum confidence interval (17.2 KN/m^3) and the average parameters of all samples. This method ensures that the variability is adequately captured and addressed in the analysis. As a result, the soil cohesion (C) was derived to be in the range of 4.2–4.4 Kpa, and the internal friction angle (φ) was determined to be between 23.35° and 24.7°.

Based on these values, we further derived Kp ≈ 0.41–0.43, Nq ≈ 1.67–1.74, Nγ ≈ 2.3–2.53, and Nc ≈ 1.55–1.61. Consequently, the local foundation safety assessment Formula (2) was simplified to the following Equation (8):

$$Qu = [7.9462 + 1.978B, 8.6935 + 2.34B] \tag{8}$$

Based on the Japanese standard safety factor [36], which stipulates Fs ≥ 2.5, we derived Formula (9) as follows:

$$\frac{Q\mathrm{u}}{\Sigma\mathrm{n}} \geq 2.5 \tag{9}$$

Based on the derived formula (Equation (9)) and in accordance with the Vietnamese Land Law, which mandates that the land use coefficient must not exceed 70% of the total residential plot area [40], the parameter for the maximum residential width (B) can be derived. By substituting the value of B into the equation and dividing by the safety factor of 2.5, the ultimate load limit value for the residential land can be obtained. This value is essential for designing building dimensions, structural configurations, and material selections.

As illustrated in Figure 12, which depicts the relationship between ultimate load (Σn), building width (B), and the safety factor, the maximum width of the building plot can be used to determine a safe permanent load combined with a live load. Within this safe load value, decisions regarding the number of floors, structural design, and building materials can be made.

This enabled the derivation of two simplified linear equations for the foundation bearing capacity, thereby notably reducing the complexity involved in analyzing local building safety assessments.

The safety assessment formula for retaining walls is as follows:

$$Kc = \frac{0.35 \times \left[\sum N \times \frac{H\mathrm{i} \times L}{S_2} + T\gamma + W\mathrm{l} + D \times 0.5 \times L \times Hi\right]}{Ex} \geq 1.5 \tag{10}$$

$$F\mathrm{a} = \frac{Mr}{Mo} \geq 1.8 \tag{11}$$

$$Mo = Ex \times O \tag{12}$$

$$O = H \times C \times S \tag{13}$$

$$Mr = W_1 \times \frac{Hi}{2} + W_2 \times \frac{Hi}{2} + \Sigma N \times \frac{A}{S_2} \times \frac{Hi}{2} \tag{14}$$

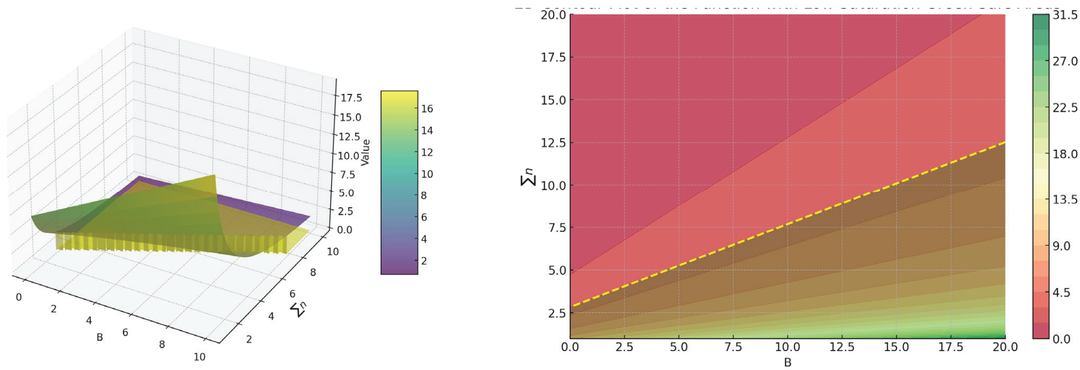


Figure 12. Relationship between ultimate load (Σn) and building width (B).

2.6.1. Verification of the Building Safety Evaluation System

According to the simplified Formula (8), we obtained the following:

Qu = [32.27, 37.47] KPa/m^2, ∑n/S1/2 = 7.3 KPa/m^2.

∑N/S2 = 2.4 KPa/m^2. Fs = [4.42, 5.13] > 2.5, Fs = [13.44, 14.36] > 2.5

Thus, it can be concluded that the foundation is capable of bearing the weight of the building.

Verification of Sliding Resistance of the Counterfort Retaining Wall:

Using Formulas (6) and (7), and the parameters mentioned in Table 6, we derived the following:

Pa = [40.7, 43.84]

Ex = [725.75, 767.22]

Tγ = [1659, 1784] KN,

The mass of the structure on the heel slab was 22.6 KN, and the mass of the foundation on the heel slab was 1345.56 KN, W_1 = 946.56. Using Formula (10), we calculated Kc = [1.87, 2.44] > 1.5

Table 6. Parameters.

Bdown	12.3 m
Bup	12.3 m
Df	0.5 m
Kp	0.41
γ	17.2–18.5 KN/m^3
Wh	3.4 m
Wc	0.5 m
Wl	17.5 m
Hi	1.9 m
Hc	0.4 m
D	24 KN/m^3
$\sum$n	340 KN
$\sum$N	78.4 KN
A	33.25 m^2
S_1	103 + 103 m^2
S_2	98 m^2
R	39.44 m^3

2.6.2. Verification of Sliding and Overturning

Substituting the parameters in Table 6 into Formulas (12) and (13), we obtained the following results: O = 1.19 m, Mo = 913 KN, Mr = 2910.95, Fa = 3.19 > 1.8.

Therefore, it can be concluded that the counterfort retaining wall meets the safety requirements for both sliding and overturning resistance.

2.7. Comprehensive Load Analysis

To further validate the stability of the optimized foundation and structure and to simulate the actual renovation effects, SAP2000 finite element analysis software was introduced for modeling. The structural model is depicted in Figure 13.

The structural model was subjected to fixed constraints at the bottom of the columns, as illustrated in Figure 13b. For conservative analysis, the load conditions included the self-weight of the structure, a dead load of 0.85 kN/m^2 required for important places, a live load of 5 kN/m^2, and a wind load of 0.4802 kN/m^2, applied according to the local coordinate system. The live load on non-pedestrian roofs was set to 0.5 kN/m^2.

Combo1: 1.3 times the dead load + 1.5 times the live load + 0.9 times the wind load.

Combo2: 1.3 times the dead load + 1.05 times the live load + 1.5 times the wind load.

The wind load was simulated at a 45-degree angle, as shown in Figure 13c.

Since this design is for a facility where local villagers work together, hold events, and store harvested grain, the extreme load simulation analysis will consider two load combinations: the live load generated by large quantities of harvest stored in the building or large-scale events during the harvest season, and the wind load generated during extreme weather conditions in the summer.

Based on the analysis results under the above conditions, the analysis yielded the following horizontal and vertical deformations:

The horizontal deformation for Combo1 was 2.38 mm, and the vertical deformation was 2.21 mm.

The horizontal deformation for Combo2 was 3.92 mm, and the vertical deformation was 2.04 mm.

These findings further confirmed the stability and effectiveness of the optimized foundation and structural design.

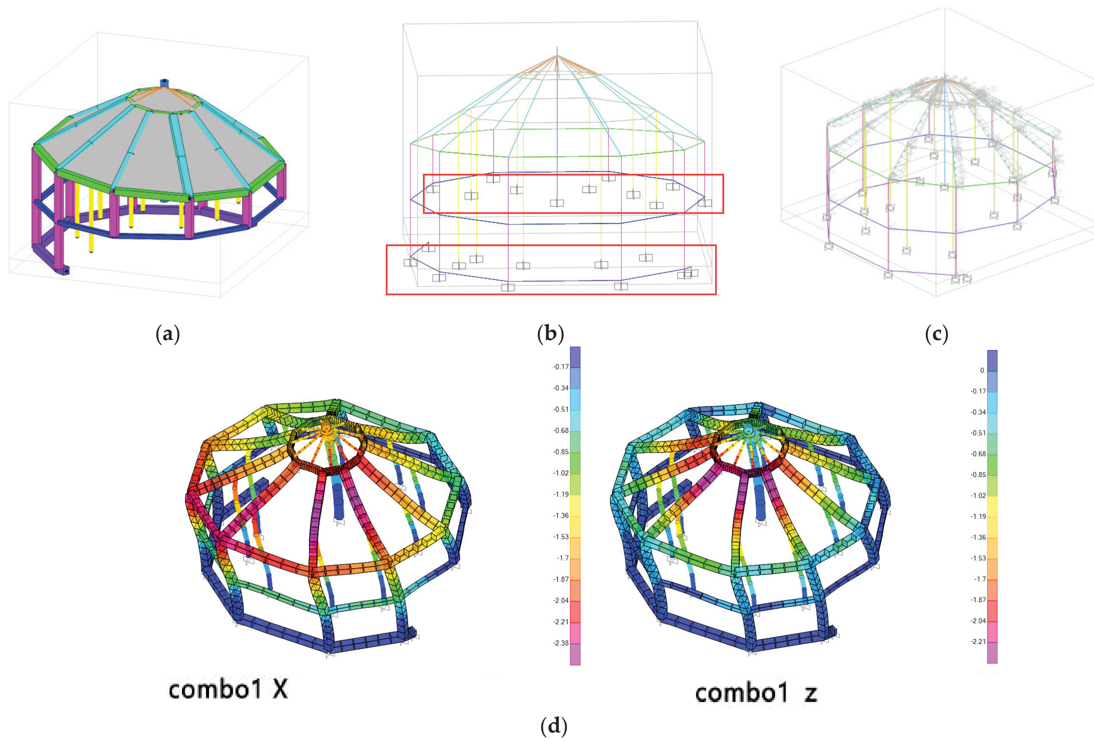
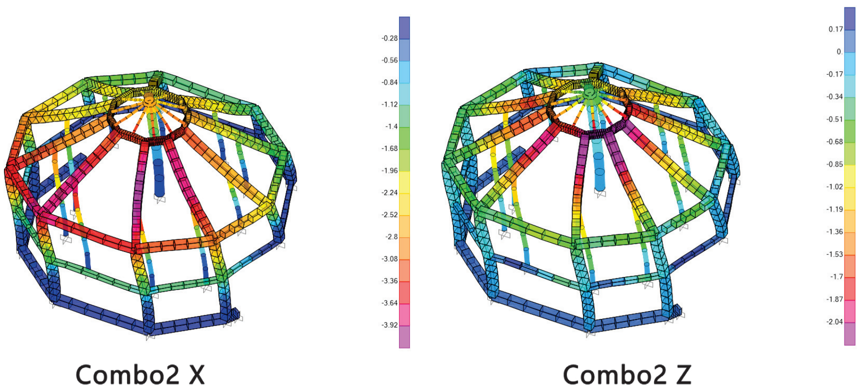


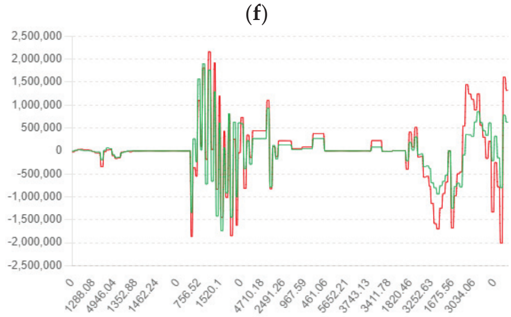
Figure 13. *Cont.*



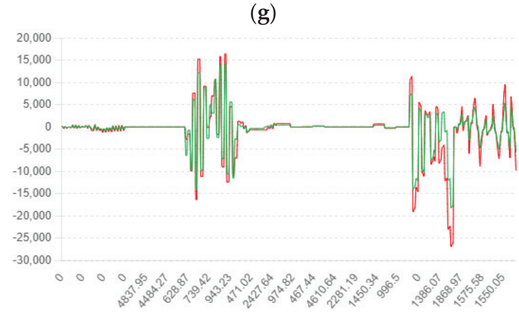
(**e**)

(**f**)

(**g**)



(**h**)



(**i**)

Figure 13. SAP2000 building model load analysis. (**a**) is the model structure, (**b**) is the fixed constraints, (**c**) is the wind load direction, (**d**) is the building deformation under the combo1 load combination, (**e**) is the building deformation under the combo2 load combination. The deformation of buildings under different loading conditions and the loads borne by structural members in the planar system (**f**–**i**).

In Figure 13d and e illustrate the displacements in the X and Z directions of the building under different load combinations, and f, g, h, and I represent different lengths of structural elements in the building subjected to axial force (P N), shear force V2, shear force V3, and torque (T N mm), respectively.

Figure 13f

X-axis: Represents the different measurement points along the structure.

Y-axis: Represents the force (N) at each measurement point under Combo1 (1.3 times the dead load + 1.5 times the live load + 0.9 times the wind load).

Figure 13g

X-axis: Represents the different measurement points along the structure.

Y-axis: Represents the force (N) at each measurement point under Combo1.

Figure 13h

X-axis: Represents the different measurement points along the structure.

Y-axis: Represents the force (N) at each measurement point under Combo2 (1.3 times the dead load + 1.05 times the live load + 1.5 times the wind load).

Figure 13i

X-axis: Represents the different measurement points along the structure.

Y-axis: Represents the force (N) at each measurement point under Combo2.

According to the Japanese Agricultural Standard JAS 0600-2 [41] and the Vietnamese standard 1350FB-1 [9,19,20,22–37,41] for Vietnamese cedar, the primary load-bearing elements of the building have a cross-sectional area of 0.25 m^2. Based on the calculation results, the following conclusions can be drawn:

Axial stress: The axial stress (0.088 MPa) was significantly lower than the compressive strength of the timber used (22–30 MPa$\times$0.25 m^2), indicating that it will not cause compressive failure.

Shear stress: The shear stress (0.018 MPa) was much lower than the shear strength of the timber used (4–6 MPa$\times$0.25 m^2), suggesting that it will not cause shear failure.

Torque stress: The torque stress (0.0393 MPa) was much lower than the bending strength of the timber used (50–70 MPa$\times$0.25 m^2), denoting that it will not cause torque failure. Therefore, Vietnamese cedar with a cross-sectional area of 0.25 m^2 will not fail under the applied forces and moments.

According to the "Wooden Building Standards Act" [41] and the "Building Standards Law Enforcement Order" [36], for wooden structures, the overall horizontal displacement must be within 10 mm to ensure safety under seismic and wind loads. Typically, the design requires that the horizontal displacement of a building does not exceed 1% to 2% of the building's height.

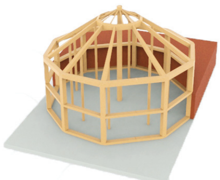
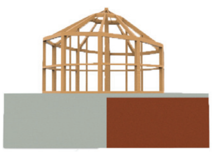
Based on the analysis results in Figure 12 and adherence to Japanese standards, the structural design was deemed safe. Thus, it can be inferred that this structure would also be considered safe in Northern Vietnam, where typhoons are infrequent and seismic hazards are absent.

Under local climatic conditions, designing the roof on the windward side to be lower than the leeward side can enhance the building's wind resistance and reduce the deformation caused by wind loads.

2.8. Comparison with Reference Construction Methods

Table 7 compares the four construction methods (a, b, c, and d) exhibited in Figure 7 with the optimized method under the conditions in Figure 6. Under the condition that the building structures are identical across the five methods, different foundation construction methods were compared to verify whether the new method achieves the highest overall performance in the local context. The comparison is based on cost-effectiveness, safety, and the cost per unit foundation area relative to the constructed building area.

Table 7. Comparison of foundation construction methods.

Construction Method	Excavation Volume (m^3)	Foundation and Wall Volume (m^3)	Wall Overturning Resistance	Wall Slip Resistance	Construction Area (m^2)	Ratio of Unit Building Area to Unit Foundation Volume	Ratio of Construction Area to Excavation Volume
	1065.05	258.1	1.09	5.76	402	1.55	0.377
	731.85	947.1	/	/	402	0.692	0.55
	1487.5	245	3.27	1.67	402	1.64	0.27
	1065.05	250.125	3.07	5.76	402	1.6	0.377
	731.85	245.94	3.19	1.87	304	1.236	0.415

MethodA references the construction method shown in Figure 7a, where only the necessary building area is leveled before constructing the building structure. Since the building has a circular structure, the walls resisting earth pressure function similarly to an arch dam. The arch-shaped structure better distributes earth pressure, thereby enhancing anti-sliding and anti-overturning properties, which in turn improves disaster resistance [42].

MethodB references the construction method shown in Figure 7b, which utilizes cement-stabilized soil technology, where the weak load-bearing hard clay is excavated and replaced with stronger load-bearing cement, filling it up to the level of the highest point of the building site. By enhancing the disaster resistance of the foundation, this method improves the overall disaster resistance of the building [43].

MethodC references the construction method shown in Figure 7c, where the entire building site is leveled before constructing the foundation and building structure. To prevent damage from debris flows, an L-shaped retaining wall is designed at the rear of the building site, where there is a height difference with the hillside.

MethodD references the construction method shown in Figure 7d, where disaster resistance is improved by enhancing the material strength of the building itself. Cement shear walls are installed between the columns to strengthen the structural integrity, prevent collapse mechanisms, and improve the distribution of the building's center of gravity and mass. This, in turn, increases the building's anti-overturning capability and seismic resistance [44].

The safety factor for foundation bearing capacity was calculated using Formula (9).

The overturning resistance of the walls functioning as retaining walls was evaluated using Formula (11).

For Method C, which employs L-shaped retaining walls, the sliding resistance safety factor was calculated using Formula (15).

The parameters for the retaining walls and foundation are detailed in Table 6. Equation (15) is as follows:

$$Kc = \frac{\Sigma n \times \tan \phi}{Ex} \quad (15)$$

Table 7 compares the performance, cost, and material utilization of buildings constructed using the optimized foundation method and the reference construction methods under identical conditions. Figure 14 illustrates the comparison of anti-slip coefficients and anti-overturning coefficients for various structural methods. The safety standard is denoted by the red line.

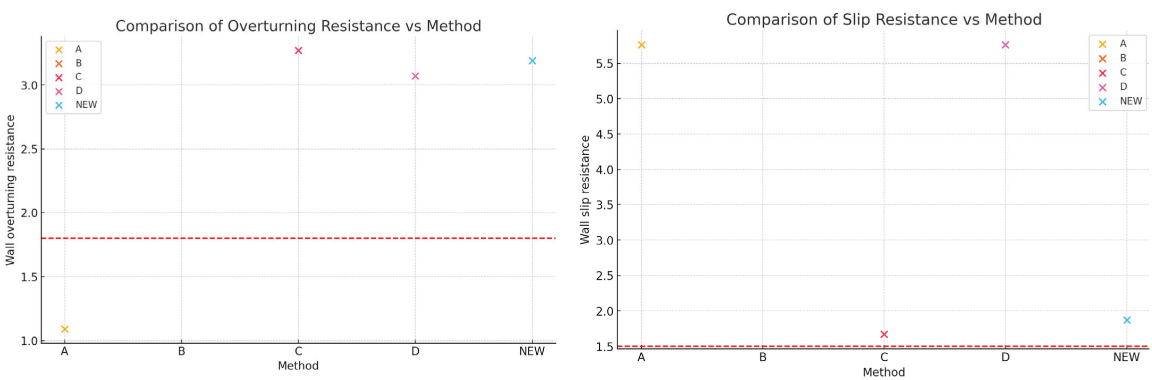


Figure 14. Comparison of anti-slip and anti-overturn coefficients.

Characteristics of Each Method:

Method A:

Application: Designed for constructing high-rise buildings on urban slopes, requiring highly stable surrounding soil.

Drawbacks: The building would face soil pressure from three sides, and the wall height, designed to function as a retaining wall, would be insufficient, resulting in overturning resistance below the standard threshold.

Method B:

Application: Compensates for height differences in sloped areas by building up the foundation, which must bear the soil pressure.

Drawbacks: High costs for foundation construction and excessive resistance to seismic and soil pressure.

Method C:

Application: Utilizes L-shaped retaining walls, suitable for scenarios requiring high slip resistance.

Drawbacks: Significant costs for excavation and foundation construction, making the construction expenses 755.65 units higher than the optimized method.

Method D:

Application: Reinforces the first-floor structure to enhance seismic resistance.

Drawbacks: Overperformance in seismic resistance not necessary for local buildings, resulting in low material-to-building area efficiency and unnecessary costs.

Method NEW:

Advantages: Prioritizes cost-effective foundation construction and material utilization while ensuring building safety.

Advantages of the optimized foundation construction method:

The optimized foundation construction method proposed in this study prioritized cost-effective foundation construction and material utilization while ensuring building safety. Compared with the four construction methods (A, B, C, and D), the optimized approach attenuated performance overshoot for the local environment, converting these excesses into cost savings while marginally sacrificing building area. This improved the ratio of building area to materials used.

Cost Analysis:

Excavation cost:

Method NEW and Method B exhibited the lowest excavation costs, both at 731.85 cubic meters.

Method C showed the highest excavation cost at 1497.5 cubic meters.

Foundation and wall volume:

Method B recorded the highest foundation and wall volume at 947.1 cubic meters.

Methods C and NEW displayed the lowest foundation and wall volumes, at 245 cubic meters and 245.94 cubic meters, respectively.

Construction area:

Methods A, B, C, and D all had construction areas of 402 square meters.

Method NEW boasted the smallest construction area at 304 square meters.

Material utilization efficiency:

Method C achieved the highest ratio of unit building area to unit foundation volume at 1.64.

Method B exhibited the lowest ratio of unit building area to unit foundation volume at 0.692.

Method NEW achieved a ratio of unit building area to unit foundation volume of 1.236.

Method NEW achieved the highest ratio of construction area to excavation volume at 0.415.

Method C displayed the lowest ratio of construction area to excavation volume at 0.27.

Building Maintenance Costs

Given that the main structure of the building is wooden, the maintenance differences primarily arise in the upkeep of the concrete structural walls. The maintenance of concrete structures involves regular inspections for cracks, corrosion, and spalling, as well as vegetation management and drainage checks. As compared with methods C and D, where the concrete structural walls and retaining walls are fully exposed, the new method places the walls indoors as part of the building. This setting reduces the rate of environmental erosion relative to methods C and D and eliminates the need for regular cleaning of moss and vegetation growing on the walls and around the corners. Consequently, all maintenance costs and the difficulty of the new method are the lowest among the feasible options.

PSO Algorithm Analysis

Based on Table 7, the optimal design direction for local building structures can be preliminarily identified. The key criteria include ensuring that both the anti-sliding coefficient and the anti-overturning coefficient exceed the safety threshold, and that the unit building material and unit excavation volume yield as much building area as possible. Under the same set of requirements, an economically optimal design can be determined if a solution produces more building area with lower construction costs while maintaining safety.

Following this logic and Table 8's parameters, a four-dimensional space can be constructed, with each axis representing the anti-overturning coefficient, the anti-sliding coefficient, the ratio of unit building area to unit foundation volume, and the ratio of construction area to excavation volume, respectively. Each design solution can be visualized as a particle within this space, with its coordinates determined by the calculated values of these coefficients. A global optimum region is then defined within this space at the coordinates (1.5, 1.8, Rfv > 0, Rev > 0) [15]. If a particle enters this optimum region, the iteration process should first focus on adjusting the anti-overturning and anti-sliding coefficients, striving to bring them as close as possible to 1.5 and 1.8, respectively, thereby reducing functional overshoot. Subsequently, the iterations should target the ratio of unit building area to unit foundation volume and the ratio of construction area to excavation volume to maximize economic efficiency while ensuring safety.

Table 8. Nomenclature.

$\omega = 0.8$	Inertia weight
C1 = 0.5	Self-awareness coefficient
C2 = 0.5	Social cognition coefficient
V^t	The velocity of particle i in generation t
P^t	The best position of particle i in generation t
g^t	Global optimal position
X^t	The position of particle i in generation t
$\gamma 1, \gamma 2$	Random number between [0, 1]

From this, we can derive the function for the following Equation (16):

$$f(x) = x_3 + x_4 - [\max(0, 1.8 - x_1) + \max(0, 1.5 - x_2)] \quad (16)$$

where x_1 represents the anti-sliding coefficient, x_2 represents the anti-overturning coefficient, x_3 represents the ratio of unit building area to unit foundation volume, and x_4 represents the ratio of building area to excavation volume.

The terms MAXf(x)(0, 1.8 − x_1) and MAXf(x)(0, 1.5 − x_2) serve as penalty functions, representing the deviation from the target region when the coefficients do not meet the specified thresholds.

The fitness function f(x)f(x)f(x) integrates the maximization of the target parameters with the degree of compliance to the defined region, thereby driving the optimization process towards solutions that satisfy all specified conditions.

Equation (17) represents the velocity update formula for the particle.

$$V_i^{\,t} = \omega \times V_i^{\,k} + C_1 \times \gamma_1 \times (p_i^{\,t} - x_i^{\,t}) + C_2 \times \gamma_2 \times (g^t - x_i^{\,t}) \quad (17)$$

Since the coefficient values of the solutions are all less than 10, the position limit is set to [0, 10] to control the range. Given that the coefficients are accurate to two decimal places, the initial velocity is set to [−0.1, 1] to allow particles to more precisely approach the global optimal region. If a particle’s distance from the global optimal region is less than 0.5, the velocity is further restricted to [−0.2, 0.2]. The five schemes from Table 7 are then treated as particles, with the four coefficients representing their coordinates in the space. (Since Method 2 uses concrete to fill the height difference of the building site, its anti-sliding and anti-overturning coefficients are set to the maximum value of 10 in the space.) The PSO algorithm is then applied to run the optimization.

Figure 15 shows the fitness trend chart generated by the PSO algorithm execution. To ensure accurate results, the program was run six times. The path curve results indicate that methods 1,2, and 4 require more than 40 iterations to approach the global optimal region and stabilize, whereas methods 3 and 5 only need fewer than 20 iterations to reach the global optimal region. Among the six program runs, Method 5 consistently found the direction of the global optimal solution more rapidly than Method 3 and surpassed Method 3’s curve after 10–15 iterations, stabilizing shortly thereafter. This further demonstrates the rationality of the optimized scheme based on local conditions.

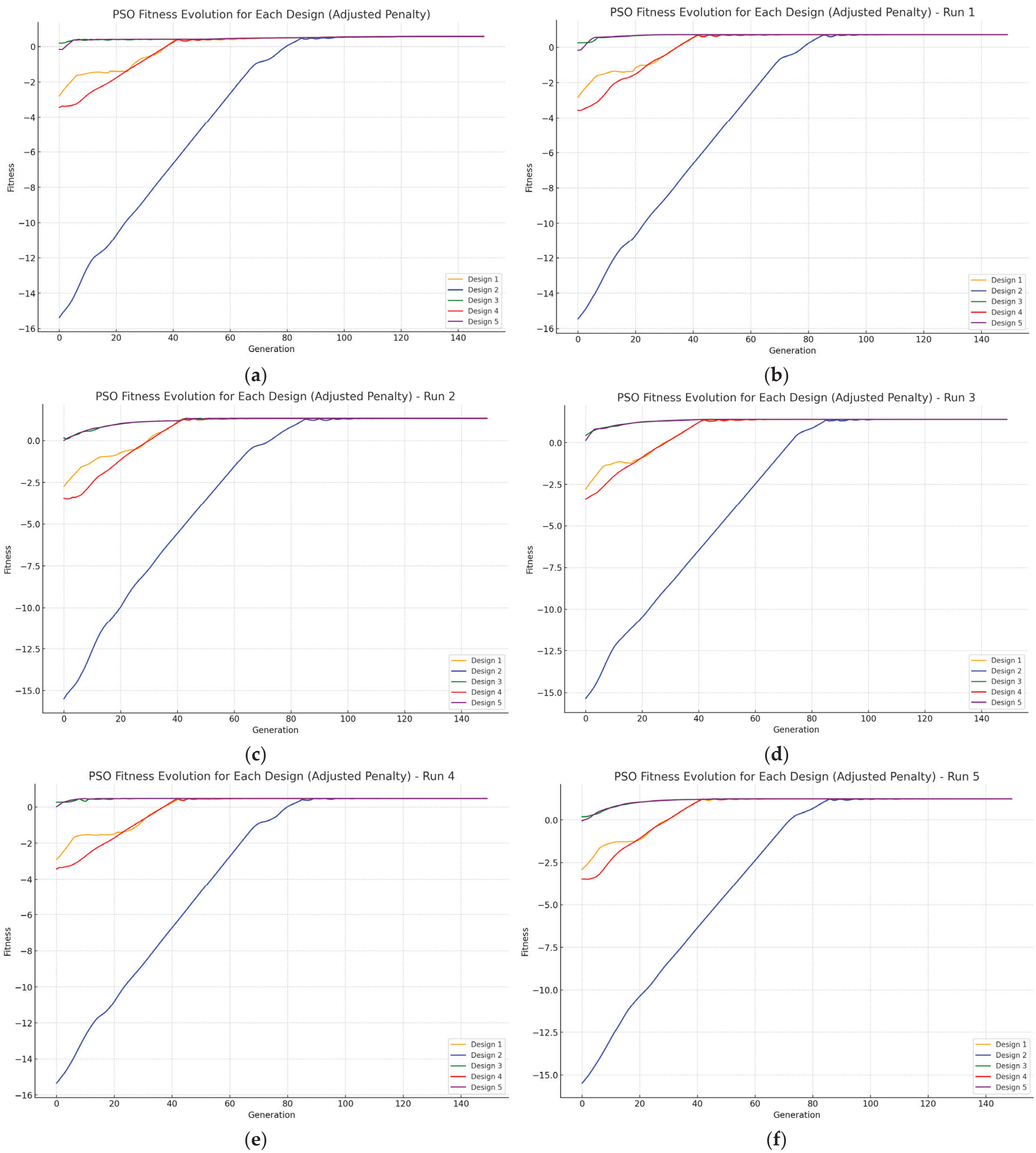


Figure 15. The trend chart of the distance from the global optimal solution after 150 iterations of the PSO algorithm for the five methods over six runs (**a**–**f**).

Comprehensive Construction Cost Summary:

Method A: Despite high excavation costs and a relatively large foundation and wall volume, it failed to meet overturning resistance standards and demonstrated relatively low material utilization efficiency.

Method B: While it features low excavation costs, it suffered from excessively large foundation and wall volumes, resulting in the lowest material utilization efficiency among the methods.

Method C: With the highest excavation costs, Method C met both overturning and slip resistance standards and boasted the highest material utilization efficiency but incurred high construction expenses.

Method D: Method D entailed high excavation costs, as well as moderate foundation and wall volume. It met both overturning and slip resistance standards with high material utilization efficiency.

Method NEW: Method NEW exhibited the lowest excavation and foundation construction costs, surpassed safety standards for both overturning and slip resistance, demonstrated high material utilization efficiency, and represented the best overall economic efficiency.

Conclusion:

Method NEW performed the best in terms of comprehensive construction costs, with the lowest excavation and foundation construction costs. It also exceeded safety standards for both overturning and slip resistance and exhibited high material utilization efficiency. Therefore, Method NEW emerges as the optimal choice, displaying exceptional performance across all evaluated aspects.

3. Results

3.1. Findings

This study conducted a preliminary investigation into building conditions in developing countries in Southeast Asia, focusing on Tan Lap District, Luc Yen City, Yen Bai Province, Vietnam. The main findings are as follow.

Building Design and Disaster Resistance:

In Southeast Asia, excluding Singapore, many regions remain underdeveloped, relying on traditional practices or foreign standards that may not consider local disasters, terrain, and structural strength factors. The optimized building structural design significantly enhanced disaster resistance, particularly against wind and landslides.

Building Costs and Efficiency:

Despite the annual improvement in urban construction due to industrial transfers from Western, Japanese, and American companies to Southeast Asian developing countries [41], rural areas continue to face challenges, such as poor infrastructure, limited adoption of new technologies, and low educational levels among the population. These factors contribute to rough foundation construction and low construction efficiency, resulting in compromised disaster resistance and high construction costs. The optimized design and simplified evaluation methods introduced in this study effectively lowered construction costs and improved efficiency.

Soil and Foundation Analysis:

Soil sample analysis unveiled the prevalence of high plasticity clay in the local soil, which is prone to landslides during heavy rainfall. The redesigned foundation construction method improved landslide resistance and economic efficiency by employing straightforward structural calculations, thereby avoiding the performance overshoot associated with other methods.

3.2. Observations

During the course of the study, the following observations were noted,

Vulnerability of Traditional Buildings:

Non-engineered buildings suffered severe damage from wind and landslides, displaying structural fragility and poor disaster resistance.

Soil Characteristics:

Soil samples presented with high plasticity clay properties, making them prone to landslides during heavy rains, thus posing a threat to building safety.

Trends in Local Residents' Education Levels and Their Understanding of Simplified Safety Assessment Methods:

Although the overall educational level of local residents is generally low, there is an increasing trend among the younger generation (under 35 years old) of receiving at least a junior high school education. This observation suggests that through the utilization of local soil properties and experimental data, the parameters in the building safety evaluation formulas can be converted into constant values, simplifying the formulas to a level that can be understood by those with a high school education or less for preliminary safety assessments.

To facilitate local residents' understanding of safety value assessment principles, a visual function graph (Figure 11) was created based on Equation (9). This graph illustrates the correlation between safety values, building design width, and load, with the safety factor represented by colors.

After the purpose and usage of this chart were explained to villagers with at least a middle school education, they can use the land size information from their Vietnamese rural residential land use right certificates to identify the safe load range for their residential plots within the chart and perform necessary calculations. They can also elucidate the principles of building safety assessment to others.

Thus, through this visual chart, residents can more intuitively find the safe load range for their building plots and better understand the method of residential land safety assessment. This chart not only helps local residents comprehend the principles of foundation load safety assessment for local residences but also assists in the structural design and material selection for residential buildings, thereby making local residential design more efficient.

Construction Experience from Developed Countries:

The construction methods from Japan, which frequently experiences wind and landslide disasters, can serve as important references for local building design. However, given Japan's seismic activity, seismic performance remains a primary focus in their construction methods. Directly importing Japanese methods to the local context may lead to significant performance overshoot.

3.3. Conclusions

Based on the findings and observations from the optimized design of the foundation to the building structure, the following conclusions were drawn:

Improved disaster resistance: The optimized building structural design significantly enhances the ability of buildings to withstand wind loads and landslide disasters. This improvement ensures greater stability and safety, particularly under extreme climatic conditions.

Reduced construction costs: Through the optimization of foundation construction methods, the utilization of cost-effective materials, and the elimination of unnecessary construction costs, overall construction costs are effectively minimized while construction efficiency is enhanced.

Simplified evaluation methods: A simplified building safety evaluation system was developed based on the educational level of local residents. This enables individuals with a high school education or less to conduct preliminary safety assessments, fostering greater community participation and self-awareness. Moreover, it can be adapted for the renovation of other non-engineered buildings within the village.

Customized design: Tailored structural solutions and safety evaluation algorithms were proposed based on local climate, terrain, soil, and geological disaster factors. This provided a reference for building renovation processes and models that can be applied to similar regions in other developing countries.

In summary, systematic building safety evaluations and optimized designs can significantly improve the disaster resistance of buildings in Tan Lap District, ensuring the safety and stability of the structures. This study not only filled the theoretical gap in building structure optimization and safety evaluation in developing countries, but also provided practical references for improving building safety and construction efficiency.

4. Discussion

4.1. Summary of Findings

This study developed optimized structural designs and safety assessment methods tailored for developing countries, specifically in Southeast Asia. The main findings are summarized as follows:

Structural design and disaster resistance: The optimized building structures demonstrated substantial improvements in resisting wind and landslide disasters. Wind tunnel experiments and finite element analysis revealed reduced deformation under wind pressure and load conditions.

Cost and efficiency: The new design methods and simplified evaluation systems effectively lowered construction costs and improved construction efficiency, which is particularly crucial for rural areas in developing countries with poor infrastructure and limited resources.

Soil and foundation analysis: Soil sample analysis identified the prevalence of high plasticity clay in the local soil, making it susceptible to landslides during heavy rainfall. The new foundation construction methods, including the use of retaining walls and simplified structural calculations, markedly improved landslide resistance and economic efficiency.

4.2. Consistency with Existing Research

The findings of this study are consistent with other research in structural engineering and disaster resistance. For example, Tamura et al. demonstrated that modifications to building corners can significantly mitigate wind loads, supporting this study's conclusion that optimized building designs exhibit enhanced stability under wind conditions [3–7,9–13,16,19–37,41,45,46]. Similarly, Mandal et al. pointed out that rounded corners perform well in reducing wind resistance and lift [17], which corresponds with the optimization results in this study.

Moreover, using retaining walls to enhance slope stability is a common strategy in geotechnical engineering. Numerous studies emphasize the importance of integrating factors, such as soil properties, soil pressure, slope stability, design loads, and seismic considerations, into retaining wall design. For instance, RetainPro elaborates on the need to integrate these factors to ensure stability and durability [47].

This study primarily focuses on the optimization of local building structures and construction methods, which are based on the actual public facility construction project in the region. As described in the finite element analysis section, the main purpose of the project is to provide local residents with a venue for communal activities and collaborative workspaces. Beyond the engineering considerations of optimizing building structures, from a sociological perspective, the construction of public activity facilities plays a crucial role in providing a space for residents engaged in various industries to interact, thereby maintaining social cohesion within the community. This is consistent with the emphasis by Nostikasari et al. (2018) [48] on the critical role of community feedback in addressing transportation and infrastructure issues, particularly in enhancing community connectivity and safety. It also aligns with the challenges observed in Northern Vietnam, where inadequate infrastructural planning has adversely affected community cohesion.

4.3. Contributions to the Field

Customized solutions for developing countries: The study proposed practical solutions tailored to the specific needs and constraints of rural areas in developing countries. considering local materials, educational levels, and environmental conditions. These solutions were crafted with considerations for local materials, educational levels, and environmental conditions, offering a more pragmatic approach compared with the direct importation of foreign standards and technologies without adaptation.

Simplified safety assessment methods: Through the development of streamlined safety assessment formulas, the study facilitated people with basic educational backgrounds to understand and apply these formulas for building safety assessments, and increased community participation and self-awareness.

4.4. Taking into Consideration the Impact of Future Extreme Weather Events in the Design

Due to the dramatic climate changes in recent years, the frequency of strong typhoons in the South China Sea region has increased significantly. This escalation poses severe climate challenges for the countries surrounding the South China Sea [8]. Therefore, future building designs must not only incorporate reinforced structural elements but must also consider the recent typhoon trajectories. For instance, in this design, the recent typhoons passing through Northern Vietnam have typically made landfall from the southeastern South China Sea region, resulting in southeastern wind directions in the affected areas. Based on this information and inspired by the concept of tilting an umbrella to withstand wind pressure during rain, we designed a building structure with enhanced wind resistance. Therefore, it is essential for future designs to thoroughly understand the characteristics of current extreme weather and to take proactive measures to anticipate even more severe climatic conditions.

4.5. Limitations

Despite significant progress, this study has certain limitations.

Generalizability: The research was conducted under specific conditions in Yen Bai Province, Vietnam. While the principles can be adapted to similar regions, further studies are needed to validate their applicability in different environments and socioeconomic contexts or to extend the solution's applicability to broader regions [18].

Educational level survey: The simplified safety assessment methods were tailored to the educational level of the local population. In regions with lower educational attainment, additional training or further simplification may be necessary. Developing a visual operating system could ensure the effective implementation of these methods.

Resource constraints: Implementing the optimized design and construction methods requires initial investment in materials and training, which can be challenging in resource-constrained environments. Future research should explore strategies to promote these solutions more economically.

In this study, the PSO algorithm was used to verify the optimized foundation construction method. However, the PSO algorithm has certain limitations, specifically: it requires a specific value or range of values to define the global optimal solution, thereby guiding the design in the correct direction [15]. If the design of the building is further refined, it will not only involve fixed values but will also be influenced by local traditions and religious factors. Additionally, adjustments to local government land policies may also become a variable in the design process.

4.6. Future Research Directions

Future research should focus on the following areas.

Adapting methods to different regions: It is important to conduct similar studies in various geographical and cultural contexts to refine and validate the generalizability of the findings [18].

Long-term monitoring and evaluation: It is important to etablish long-term monitoring of implemented structures to assess their performance under different environmental conditions.

Enhancing community engagement: It is important to develop comprehensive training programs to empower local communities in effectively applying safety assessment methods and construction techniques.

Addressing these areas will further enhance the safety and disaster resilience of buildings in developing countries, building upon the foundation laid by this study.

A more scientific algorithm: In future research, efforts will be made to optimize the algorithm to more comprehensively guide building design and evaluate design schemes for local mountainous terrain.

Exploring lower-cost construction methods for debris flow mitigation: Field investigations revealed that in the local area, the mineral content of soil near water bodies is higher than that of the hard clay found in mountainous regions. Geological studies of Luc Yen District in Yen Bai Province also confirm that due to the region's proximity to mining areas, the soil near water bodies has a higher mineral content [49]. Therefore, it can be inferred that soil near water bodies is denser and has a larger friction angle. By mixing the hard clay from the mountains with the mineral-rich soil from near the water and compacting it, followed by mechanical stabilization [50], the soil's load-bearing capacity would increase due to the higher density. This would also improve the soil's drainage performance, all at a relatively low cost. As a result, more cost-effective construction methods beyond just counterfort retaining walls can be employed, further optimizing the construction approach.

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Sustainable Construction through the Lens of Neoliberal Governance: The Case of Vernacular Building Systems in Catalonia, Spain

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Abstract: This paper asserts that neoliberal forms of governance are increasingly found in construction systems in Spain, a fact which becomes especially problematic when considering vernacular construction systems. Technological management and policy are both becoming more focussed on the promotion and consolidation of 'expert systems' at the expense of 'different' (and in particular) vernacular systems, which are processes which influence minds, and fundamentally shape subsequent actions. This paper adopts an ethnographic approach, undertaking investigation into the complexity of commonly found building systems, based upon empirical evidence gathered in the region of Catalonia. Focussing research on local vernacular construction systems reveals the extent to which the operation of distinct sets of managing 'technologies'—embedded in specific practices such as auditing—becomes instrumental in shaping local construction practices. Currently, locally distinctive practices are deeply impacted by social influences generated far away, which have the consequences of significantly influencing, diluting, or even erasing vernacular building systems, even where these represent an important source of sustainable building techniques.

Keywords: Spain; OCT; neoliberalism; vernacular building systems; construction governance; sustainability construction

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1. Introduction

Governance—if understood in terms of explaining the exercise and establishment of political power—involves the control and regulation of a populace through multiple technologies and institutions in society [1]. Prior to this observation, the majority of studies of governance were commonly abstracted away from existing spaces and subjects. For this reason, they did not adequately engage with the ways in which people are constituted and ruled as neoliberal subjects through a multitude of 'technologies' and 'assemblages' of power, a perspective insightfully illustrated by theorists such as the philosopher Foucault [1,2]. Much progress has now been made, however, with governance being studied from a variety of different fields, from the management of agro-environments, to child minding and education.

Although there are authors who have analyzed architecture through the lens of neoliberalism [3–6], the study of building systems from this perspective has largely been overlooked, and a deep analysis is missing, together with the wider stories this can tell.

The study of building systems is similar to other research areas which makes it possible to observe governance taking place, but until now very little study has been undertaken in this specific area of practice. This applies particularly to vernacular building traditions, which consist of specific types of building systems, but which have had little research into how relevant governance is applied (legislatively, regulatorily, or culturally), or into its consequences.

With regards to this, Rose and Miller [7] have usefully observed the relevance of knowledge and expertise for modern forms of governance, the extent of which cannot be overemphasised, especially where these are intrinsically linked to the administration of different kinds of construction, using (often competing) tactics which include education, inducement, incitement, encouragement, persuasion, and motivation.

Ultimately, these are concerned with certainty, with an interest in those technologies which aim to make reality "stable, mobile, comparable, combinable"; prerequisites which enable government to act upon it [7]. However, with regards to sustainability, these technologies induce universalist building systems which make it difficult to propose construction solutions linked to place, that is, those with low technology and/or low energy consumption [8,9].

Within this context, it is important to understand the concept of neoliberalism, as it defines the current era [10], yet it is neither objectively 'rational' or 'neutral'. In the study of governance—and its outcomes—the main focus of Foucault was to discover which kind of intrinsic rationality has been used, since political rationality is not a neutral form of knowledge but is instead an element of government that helps itself by creating a discursive field for framing thought and actions, in which exercising power is 'rational' [11].

However, Foucault rejected rudimentary 'capital logic' arguments on state-centred accounts and socio-economic development, with his analyses of discipline and governance attempting to explain the reasons behind economic exploitation and political domination [12]. His framework for interpretation and understanding investigated political strategies and the activities of authorities in their attempts to modulate decisions, actions, and events in the economy, the private firm, the family, and the behaviour and conduct of individuals [7].

To reiterate, this paper attempts to analyse neoliberal governance in building systems in Spain through an investigation into how management technologies have been applied, and their impacts on vernacular building systems in the region of Catalonia.

This paper is structured into four sections: firstly, a brief literature review of recent discussions on governance and neoliberalism is presented as foundation for the following sections. This is followed by a presentation of the methodology used in the research, then thirdly a presentation of management technologies applied to building systems in the specific case of Spain. The fourth section focuses on an analysis of the impact of this management technology on common vernacular building systems, particularly focussing on the specific case of Catalonia. The main conclusions are presented in the final section.

2. The Link between Neoliberalism and Construction Governance

2.1. Defining Concepts & Approaches

From the outset, it is important to establish definitions for key concepts and approaches used throughout this study, with regards to the main literature review, governance, and neoliberalism, and the ways in which these relate to the field of building systems.

The concept of governance is 'the regulation of conduct by the more or less rational application of the appropriate technical means' ([13], p. 106). Foucault approached this concept by focussing on the different meanings of conduct, both as 'personal conduct' and 'to conduct', or to be more precise, as 'the conduct of conduct', thus providing a term which ranges from 'governing the self', through to 'governing others'. That is to say, his efforts were focussed on showing how the modern state and the autonomous modern individual are entangled and co-dependent—what begins as an external directive is ultimately adopted as self-direction.

Governance is not normally conceived as a way to force people to comply with the will of the governor, but is instead a versatile equilibrium, balancing conflicts and complementarity between techniques that assure coercion, and processes through which the 'self' (of those governed) is constructed, modified, or controlled by itself [14]. Structuring and shaping the field of possible actions of a populace effectively creates a cage without bars, through a heterogeneous array of regulatory practices and technologies, which end up as a reformulation of how to apply coercion or consensus, in which the latter is applied from 'autonomous' individuals' capacity for self-control [15].

Governance refers to the systemic, reflected, and regulated modes of power which go beyond the simple exercise of power over others, and include following specific forms of reasoning and rationality, which define either the telos of action, or the means to achieve it. Therefore, 'technologies' of government refer to the procedures, strategies, and techniques, through which different authorities seek to implement or enact programmes of government in relation to available forces and materials, and the oppositions and resistances anticipated or encountered [16].

Through the concept of governance, Foucault related technologies of being (involving common practices) with technologies of domination. This article aims to use the concept of governance to relate the construction decisions made by architects and other technicians with the technologies of domination analysed by the philosopher. The intention is to introduce how these management technologies also act in the field of construction since, as with other areas of human activity, they follow guidelines set in the foundations of the formation of the neoliberal state. Therefore, governance is a 'key notion' [15] one can use to understand the path followed by construction and building systems in the late modern period.

Nevertheless, it is important to point out that it is not government programmes or technologies which act, but rather the social forces deploying these programmes and technologies for their own particular purposes [17]. From this perspective, political programmes can be explained in terms of the underlying rationalities that shape their development [18], and in this respect it is tenable to suggest that auditing (introduced in the opening Abstract as a management technology which can be understood as a technology of domination) is at heart an ideologically driven system for controlling and disciplining architects, contractors, and so on (cf. [2]). According to Habermas, a certain form of hidden political dominance is imposed in the name of rationality ([19], p. 54).

In this regard, an understanding of neoliberalism is key in order to analyse the transformations of social practice and space which define the current era [10]. Specifically, the production and adoption of neoliberal mentalities and values regarding governance, especially attempts to enforce market logics in order to create conditions in which competition can flourish, and to depoliticise (through disempowerment, disenfranchisement, or delegitimisation) various social struggles over resources and rights [20]. It is within this context that this paper is presented, exploring and revealing the ideologically driven systems which operate through auditing in the field of construction, together with their profound effects.

Neoliberal rationalities comprise a number of coherent, ideologically driven political precepts pulled together by a fundamental belief in the superiority of free markets over intervention by mechanisms of the State [21], or the validity of its social responsibilities, concerns, or functions. Therefore, neoliberal forms of governing attempt to extend market relations into every domain [22]. The increasing dominance of market instruments (or more broadly speaking, the 'market') over the governance and control of construction systems is a characteristic feature of what this paper identifies as the "neoliberalisation of building systems". In relation to 'building systems management', market instruments may be defined as those initiatives that 'aim to mobilize individual incentives in favour of positive outcomes', through a careful modulation and calculation of benefits and costs associated with the strategies of particular building systems. At the same time, it is important to question what is meant by 'positive outcomes', if sustainability (for example) has not been taken into account as part of the equation [23].

Neoliberal forms of governance are typically viewed as colonisation of the social, through processes of deregulation, marketisation, and privatisation, in which the state takes a minimal role [24], in spite of an increasing recognition of the importance of the role played by state agencies in enabling markets to work efficiently [25]. Critically, neoliberal forms of governance enable technical expertise to present an appearance of addressing safety in construction (for instance), while simultaneously creating and securing conditions for further capitalist accumulation (cf. [26]), and the achievement of narrowly defined ends which include financial gain, and/or positioning into power relationships. Today, domination is perpetuated and extended not only through traditional routes such as regulation, policy, or enforcement, but through technology as well, as this avenue provides the discrete legitimisation of an expansive political power that permeates and engulfs all areas of culture, including construction [19]. Until now, however, little attention has been given to the consequences of the neoliberalisation of building systems.

2.2. Relevance of Neoliberal Governance in Building Systems

The relevance (as well as the potential contribution) of the concept of neoliberal governance in building systems can be seen more clearly with regards to three main areas that intertwine with each other:

1. Concept of 'political knowledge'. Foucault appears to offer a useful and important way for understanding the relationship between governmental practices and territories, in particular how places are governed and shaped, in ways which are ostensibly subject to mathematical modelling and control [27], steering rather than dictating through processes of abstraction and simplification [28]. There is more to the process of state spatialization, however, than simple policing or repression, and it may be more important to look at the multiple, less dramatic, and mundane domains of bureaucratic practice, through which states reproduce scalar hierarchies and spatial orders. In other words, it is the 'know-how' or the practices which make government possible [7], including management technologies. In particular, it is the technology of efficiency which has transformed administration into bureaucracy, technologies upon which bureaucracies now depend [29]. Furthermore, it must be considered that states are not simply functional, bureaucratic, or mechanistic organisations, but also powerful centres of symbolic and cultural production [30].
2. Concept of market independence from state affairs. Foucault highlighted that the power of the economy rests on a previous 'power economy', since the accumulation of capital implies forms of work and production technologies that allow the use of multitudes of human beings in economically profitable ways. Foucault located strategy not in actors but in clear controls, which, in turn, are the outcome of, rather than a condition or determinants of, the dynamics in local settings, where microphysics of power continuously create new relationships between knowledge and the exercise of power [28].
3. Domination and technologies of the self: developing indirect techniques to lead and control individuals. Government is historically the matrix which articulates the dreams, strategies, manoeuvres, and schemes of authorities, seeking to shape the conduct and beliefs of others in desired directions, by acting upon their circumstances, their will, or their environment [7]. One key feature of neoliberal rationality is the congruence it works to create between the idea of a responsible and moral individual, and an economic-rational individual—that moral responsibility is somehow intertwined with and subject to fiscal imperatives and accountability.

In the field of building systems, auditing is an essential part of the 'new public management', as it highlights and stresses the 'control of control' through a characteristic focus on the reliability and effectiveness of expert systems, which are 'systems of technical accomplishment or professional expertise that organise large areas of the material and social environments in which we live today' ([31], p. 27). At the same time, expert systems rely heavily upon a 'power economy' characterised by well-established distribution and marketing processes which facilitate their imposition. These are further assisted by offering clear financial value chains (and excluding wider social or environmental accounting), driven by a neoliberal perspective that moral responsibility is indistinguishable from economic rationality. Therefore, audit management enables the effective functioning of a dispersed and decentralised state in controlling the construction activities of an individualised public, through mundane bureaucratic processes subject to mathematical modelling.

The task then is to draw attention to the creative and social processes, through which a state hierarchy becomes effective and authoritative in the field of building systems, and how this affects the sustainability of vernacular building systems in particular.

Vernacular building systems, until well into the modern age, have followed principles of tradition anchored to place. The predominant source of their organisation and construction was the established order of traditional society. Therefore, vernacular building systems are a critical field of study, where the profound effects of new (mundane and bureaucratic) practices can be easily seen, even though they often slide unnoticed and unremarked below the threshold of discourse. Where new systems of auditing become established, however, they bring the risk of damaging local cultures of first-order practice and its sustainable characteristics. To fully examine and interpret this practice-oriented concept an ethnographic approach is required.

3. Methodology

In conducting the research, an interpretivist paradigm has been used, conscious that the patterns (and associated data) sought and found in interpretations of social reality are not immutable, or 'laws' in the sense given to them by positivist sociology. Since there is no separation between the observer and the reality being studied, knowledge is produced from understanding. In other words, the key points of this research consist of situating itself in the perspective of all the participants in the construction process, the importance of the context, and the holistic and processual evaluation of the object of study, renouncing the imposition of closed hypotheses from the outset [32] by pursuing an inductive path of investigation. Therefore, an in-depth analysis and study of the cultural dimension has been favoured over simply parsing quantitative data, providing a new filter for understanding not only the technical approach used in the vernacular building system, but also the forces influencing construction technology more generally as well.

The nature of this study does not attempt to be conclusive. Instead, it seeks to explore and discuss ideas for progressing the academic study of sustainability, and the need to study building systems from a social perspective. For this reason, the anthropology of building systems has been the focus, and an interpretivist paradigm appropriate to the nature of the subject has been used (coupled with a qualitative methodology), identifying how governance through management technologies affects the sustainability of traditional building systems. This has required an exploration of the relationships between communities, building systems, and neoliberal governance. This is most accurately achieved (according to [33]) by means of the ethnographic method, which helps to identify underlying causes, while attempting to address the complexities involved by studying relationships between micro-level behaviours and macro-level phenomena.

This study does not attempt to be definitive or an end in itself, but instead to identify trends and potential relationships between variables in a way which invites and signposts avenues for further research.

As stated, an ethnographic approach has been used for this research, based on three main elements. This has included 63 semi-structured interviews with relevant individuals (within the context of refurbishment), specifically comprising 21 builders, 28 architects, and 14 masons, materials distributors, and other professionals. The principle used for conducting the interviews was based upon the 'saturation of the sample', which is to say that interviews were conducted until the answers became repetitive.

Participant observation of work sites in Catalonia has also been another key tool, and the professional experience of the researchers allowed a close knowledge and understanding of the activities of the agents involved. This also enabled a deeper investigation into the complexity of the most commonly used construction solutions.

On this basis a representational account of the interactions between actors and processes (operating on diverse spatial scales) will be attempted, together with the ways in which these interactions eventually emerge into specific building systems.

4. Management Technologies in the Construction Systems Field in Spain

On 6 May 2000 the Spanish Building Ordinance Law came into force [34]. As a result, it was the developer who became responsible for construction insurance. Therefore, at this time, the audit processes developed by insurance companies were also indirectly established by the new law. Insurance Companies in Spain, most of them grouped in the Spanish Union of Insurance and Reinsurance Entities (UNESPA), try to develop technical documents approximating a real risk assessment. As a basis, these are tied to Decennial Insurance, Spain's only compulsory insurance, which offers ten years' cover for any defects in construction.

It may be that an institutional lack of faith in architects and technicians related to construction issues has led to the emergence of an oversight industry, in order to satisfy a demand for signals of order. Regardless, the key point to be understood is that 'any' level of risk is now considered unacceptable; risk must be avoided at all costs [35]. It is what Amoore and de Goede [36] named precautionary risk, the 'risk beyond risk'.

Claim statistics recognise that 43% of these risks are due to project errors, 30% to poor execution, 15% to material defect, and 8% to lack of proper maintenance, with the remaining claims due to other factors [37]. Given the importance of the risks, the immediate approach of the insurance companies was to find the right people or organisations to carry out the inspection and technical assessment work; that is, those with sufficient knowledge, responsibility, and independence to support the insurance offered. This was carried out through the performance of recognised expert technicians [37], and the establishment of a definition and control system for the different construction processes. The creation of a company with the necessary economic solvency that could take on this new task was also necessary, hence the emergence of the so-called Technical Control Organisations (OCT—Organismo de Control Técnico). In order to qualify for ten-year insurance cover, an OCT must be hired, which will be in charge of the technical control of the work, and for issuing a series of essential reports before the ten-year insurance can be obtained, and which address three points: project control, execution control, and control of trials.

The control of the project assesses the rationale(s) for the chosen construction solutions, the adequate definition for a correct execution, the qualities and characteristics of the different elements, as well as an adequate and correct definition of the budget. The control of the execution consists in verifying that it is carried out following the definition established in the project, the current regulations, as well as the technical knowledge sanctioned by practice. The control of tests verifies the follow-up of the quality control plan, and the suitability of the tests carried out, as well as the request for new ones if necessary.

At the same time, there are three basic criteria to be met by OCT technical agents: independence, technical expertise, and non-biased assessment. Independence is guaranteed with the absence of conflicts of interest with the works being audited. On the other hand, non-bias does not yet have a defined method of control. Technical expertise must be accredited, but in Spain this has been difficult to control due to the official absence of this as a recognised field of activity [38]. This fact has initially caused other control processes to be initiated and implemented by the OCT themselves, in order to ensure correct and consistent standards based on the experience of technicians and types of work to be audited, and the volume and height of the work, as well as the type of terrain, and its construction characteristics. Behind this, there is the principle that regulatory systems increasingly rely upon the 'control of control' [2].

OCT is the technology of government implemented in the building field, through which political rationalities become capable of deployment. In this way, the complex assemblage of diverse forces comes to be regulated by authoritative criteria through mundane mechanisms that enable rule 'at a distance'. Since 2000, the auditing of this internal control for self-checking arrangements has continued to grow as an industry (cf. [39]).

5. How Management Technology (OCT) Affects Vernacular Construction Systems

This area of study focussed on one of the regions of Old Catalonia (Catalunya Vella), the Baix Empordà.

The transformation of the practices in vernacular building systems which the OCT mandated can be evidenced by analysing three particular building systems of the region: the tile vaults, the structural use of ordinary masonry walls, and the use of local wood species.

5.1. Construction of Tile Vaults

The traditional tile vault has three defining characteristics: construction without formwork, the use of gypsum paste or plaster as a binder, and the use of brick (Figure 1).

Figure 1. Traditional tile vault.

Traditionally, the construction of the first layer was the most delicate stage, since it required the most mastery and skill. The binding material was gypsum due to its rapid setting; an important factor, as this is what made it possible to dispense with formwork in most cases. The low weight of the ceramic tiles or bricks was also an important consideration, and once the first layer was complete, additional layers (if any) could be easily added to increase strength, or to provide aesthetically pleasing finishes.

With the entry of the OCT, the continued use of this vernacular construction system depended on validation through mathematical tools, to model future behaviour in the face of different situations throughout its useful life. Despite centuries of use, insurers demanded the introduction of a layer of concrete, which would provide the security afforded by a predictive mathematical model that is associated with this material. Up until that point the tile vault was anchored to tradition, one of the legitimate bases of management of the actions of community life in the past.

OCT have also become influential agents of change, since ways of understanding human progress have increasingly come to be governed by trust in and reliance upon the scientific-technical domain, with less consideration given to the empirical knowledge of artisans and communities accrued over time [40]. This is further compounded by neoliberal rationalities which have created conditions in which various social struggles over resources and rights have been depoliticised, and communities become disconnected from historic practices and perspectives, including ideas of stewardship. The benefits of traditional systems with proven track records over time are not taken into account, such as the use of materials with low embodied energy, rooted in an integrated approach to practice, and strictly linked to a conception of the world based on the careful management of local resources [41].

5.2. Structural Use of Ordinary Masonry Walls

Walls traditionally fulfilled two specific functions: as a structural element, supporting either wooden beams or vaults; and as room dividers (exterior and interior), with both of these functions reliant on the thickness of the walls themselves. With the appearance of OCT, however, traditionally constructed walls were no longer considered able to fulfil a structural function, even in the refurbishment of vernacular buildings—a situation which effectively illustrates the extent to which governance can structure and shape the field of possible actions of subjects. Instead, walls became relegated to use only as envelopes, in favour of new structural techniques, materials, and practices which could be validated using mathematical models predictive of future behaviour. However, these changes often bring with them greater environmental impacts and energy costs, both in obtaining the material, and for future recycling, while at the same time creating and securing conditions for further capitalist accumulation (as noted earlier) (Figure 2).

Figure 2. Typical (traditionally constructed) masonry walls.

5.3. Use of Local Wood Species

There are around 30,000 different species of wood in the world, but only 2000 of these are used commercially, and of the 150 of these marketed in Spain, of which only a few are used for structural purposes.

Traditionally, both white and black poplars were used for construction in the area of Baix Empordà, however, Spanish regulations consider black poplar unsuitable for structural use, and it is no longer used for creating roof beams. Therefore, it is very difficult to build using local woods [42]. Instead, the commercially available (and approved) wood comes from the forests and wetlands of Northern Europe, which are better adapted to existing technologies for efficient cutting and harvesting. At the same time, the faster growth rates and smaller dimensions make this timber largely unsuitable for use as structural beams, which has led to its extensive use in laminated timber, that is, wood cut into small pieces of homogeneous length and joined with resins. A higher reliability and predictability are cited as the reasons for the preferred use of laminated timber, and since the preferences of architects are shaped through the effects of social forces (including education, knowledge, budgets, personal liability, and so on), this does not preclude them from intervening creatively to transform existing social structures (cf. [43]) which in turn affect wider attitudes. There is also a belief held (and promoted) that pathologies caused by hygroscopic movements are lower for laminated timbers, as are the risks of biotic attacks.

It is mainly this predictability factor—promoted by the OCTs—that makes this type of wood more favourable over local solid natural wood, which traditionally defines the character of roof construction in the region. In summary, what lies behind this preference is the legitimacy achieved by architects as 'objectifiers of chance', reducing construction (as well as professional and budgetary) risks, whilst exercising not only an ability to reject traditional alternatives, but to erase them as well [44]. One of the principles of sustainable construction is the favoured use of local materials with minimal entropy and closed lifecycles [45], however, these end up becoming a less viable option as a result. This is accompanied by inducements of further capitalist accumulation, supported by neoliberal forms of governance and an appearance or guise of addressing safety in construction.

Although OCTs have a tightly defined regulatory function, rather than holding opinions on the ideology of which solutions become adopted or executed, OCT for audit inevitably force changes in building systems' practices [44]. These effects end up being systematically recorded and iteratively fed back into the design process, and because audits do not operate neutrally, they end up having effects on the audited. Structuring and shaping the field of possible action of architects and technicians effectively creates an unacknowledged and invisible force modulating the 'autonomous' individual's capacity for self-regulation. Eventually, architects and technicians themselves change or reject the traditional vernacular construction systems which require acceptance by OCT (Figure 3).

Figure 3. Wooden structure.

6. Final Considerations

The impacts of new systems of auditing upon vernacular building systems is a critical field of study, as they bring the risk of damaging local cultures of first-order practice and associated sustainable characteristics.

The task has been to draw attention to the creative and social processes through which a state hierarchy becomes effective and authoritative in the field of building systems, and how this affects the sustainability of vernacular building systems in particular.

Decennial insurance issued by the OCT is the main governmental technology which has led to the dismantling of traditional forms of construction in Spain. OCT is the unquestionable authority mandating a precautionary approach to risk reduction, which in turn destabilises and reshapes the basis of vernacular construction systems, since the risk–security complex inadvertently, but effectively, puts managerial technology in the driving seat. Generally, security and liberty are viewed as forming a zero-sum game, so measures of security may be used as justification to occasion a reduction of a technician's individual liberty (c.f. [35]) since there is a close relationship between risk rationalities and 'targeted governance' [46].

Quality assurance programmes require the establishment of aims, objectives, and design performance criteria, as well as measures for implementation and delivery. Therefore, any departure from contemporary norms which involve the use of vernacular construction systems involve two risks. The first involves the higher costs associated with the non-standard (non-standardised) or bespoke construction which historic solutions have come to represent. At the same time, these solutions must also be justified by extraordinary trials and tests to ensure their safety and durability for each specific project. Within this context, it is also important to consider that neoliberal forms of governing do not take the existence of oligopolies into consideration, which compete under unequal conditions.

Secondly, there is a burden placed upon the technician, who must assume the responsibility for not using solutions recommended by the various different regulations. In this case, the difficulty becomes even greater, since the effectiveness of traditional techniques depends on interactions between many factors which must be taken into careful consideration. To be successful, vernacular architecture must follow the principle of tradition anchored to place and requires an understanding of both materials and building systems, together with how these relate to the site and context.

Under these conditions, even well-established and locally distinctive traditions are deeply affected and reconfigured by external social influences that have been made blindly at a distance. As a result, vernacular construction systems have become diluted, if not erased, as neoliberal government practices (born from and supported by rational–legal systems), manage to penetrate to differing extents to the very heart of the local level [44]. Auditing has unwittingly been introduced as an agent of change without a measured consideration of benefits relative to any possible dysfunctional effects—risk assessments effectively aimed at protecting capital, but without similar regard given to social or environmental protections, since auditing (and related ideas of monitoring) are uncritically understood as 'positive' measures, within the paradigm of safety and security as the normal concern and purview of government. Thus, it is argued that neoliberal government abdicates its responsibility when it comes to delivering public goods (including benefits or services), by denying (or even destroying) them under the directives of related management technologies, as illustrated by the subjugation of vernacular building systems to technological systems instead (c.f. [29], p. 19). For this reason, the use of vernacular building systems requires tailored policy, giving full consideration to triple-bottom line benefits and disbenefits, within the context of community, identity, and environment. As Elionor Ostrom [47] pointed out, increasing the authority of local people and communities to devise their own rules, may well result in processes which allow vernacular building systems to flourish and evolve, taking sustainability into account and solving problems through collective action.

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Challenges That Impact the Development of a Multi-Generational Low-Carbon Passive House in a Small City

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Abstract: The impact of the building and construction sector on climate change is becoming more important and recognized. Multiple initiatives around the globe have been utilized to design and develop residential structures, aiming to reduce energy consumption and carbon emissions; yet, there are several barriers to effective construction processes. This research outlines the gaps and barriers encountered by key stakeholders that were engaged during the preconstruction phase of a three-story multi-generational low-impact Passive House in Fayetteville, Arkansas. Through direct observation and open-ended interviews, the primary data are collected, and secondary data from a comprehensive literature review are detailed to capture the challenges faced during different phases of the implementation of sustainable residential dwellings. This study highlights the limited knowledge and experience in sustainable building design as a common barrier among participants along with the insufficiency of the regulatory framework governing adopted building codes in Arkansas, in facilitating sustainable building design implementation. These challenges, among others, are then thoroughly examined, and recommendations to address them are described.

Keywords: passive house; energy efficiency; residential buildings; barriers; sustainable design

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1. Introduction

The building and construction sector is a major contributor to global carbon emissions through construction and energy consumption, and addressing climate issues and carbon reduction has become a vital goal worldwide [1]. Passive Houses, Net-Zero-Energy (NZE) Buildings, and Zero-Carbon Buildings are examples of building types developed to achieve this goal and that aim to minimize embodied and operational energy use and carbon emissions throughout the building's life cycle. Passive Houses are one of these typologies, which offer a promising solution for achieving exceptional energy efficiency and sustainability while ensuring occupant comfort [2].

The construction process can be divided into three main stages: preconstruction, construction, and postconstruction phases. The preconstruction phase focuses on the planning and design, where the project's size, location, architectural, structural, mechanical, and electrical designs are prepared and permitting is ensured to launch the construction works. The construction phase includes bringing down the design drawings' specification and procurement on site and ensuring all specifications are met. The project completion stage is where the project is finalized and handed over to the owner [3]. Each of these phases presents its own challenges that emerge during the construction process and can affect project completion [4].

The design and construction of low-carbon and energy-efficient houses can have significant challenges during various phases of the project, especially in regions where the concept is still relatively new and unfamiliar [5], and where the design and construction involves a unique set of considerations, such as finding qualified and motivated engineers, complying with regulatory frameworks, managing the material and supply chain, and dealing with the special construction requirements for these types of buildings [2].

The purpose of this research paper is to shed light on these barriers, and to provide insights into the experience of the stakeholders engaged in the design and permitting of the Everly House, also known as the Caja House. The house was designed as a triplex multi-generational low-carbon Passive House in Fayetteville, Arkansas, in a city in a humid subtropical climate of the southern United States. This study is unique in its in-depth analysis of the preconstruction phase from the initial stages that can affect a low-carbon Passive House in the suburbs of a growing small city in the United States. This study provides an overview of the barriers faced by professionals engaged in this study that can inform future sustainable building projects, in areas where similar practices are not common. By examining these barriers and their potential solutions, this study seeks to contribute to the development of strategies and recommendations that can facilitate the design and permitting process for future Passive House projects in a similar context.

2. Literature Review

The Passivhaus standard is generally defined as a low-energy building that achieves indoor thermal comfort [6]. This concept was developed in Europe by the end of 1988 by Wolfgang Feist from Germany and Bo Adamson from Sweden [7]. The design of the first Passivhaus was established in 1991, resulting in a super-insulated building [8]. The concept was formulated according to Passivhaus standards that are reviewed through the Passivhaus Institute (PHI), an internationally recognized research institution that was established in 1996 to provide the guidance, design, and certification of houses meeting the performance standards [2]. In North America, the term Passive House is often used to refer to energy efficiency buildings, where the Passive House Institute (US PHIUS) provides certification for buildings that meet the requirements of PHIUS Standards for building energy modeling. Originally part of PHI, PHIUS was established to tailor the standards to North American climate. A break in the agreement resulted in the two institutions providing for separate Passive House certification in North America [9] with differences in criteria for heating and cooling, air tightness, energy, and the energy modeling tools [10]. For the modeling tool, PHIUS uses Wärme Und Feuchte Instationär (WUFI) while PHI uses the Passive House Planning Package (PHPP) as an informing tool for project certification [11]. The decision to choose one of these options for the Passive House certification solely depends on the architect, engineer, and owner [2,12]

The US Department of Energy (DOE) defines an NZE building as an energy-efficient edifice that generates as much or more energy than it consumes over a year through onsite renewable energy sources [13], resulting in a net-zero balance of energy use and emissions [14]. The design of an NZE building demands the implementation of specific energy performance strategies, design concepts, and technologies [15]. The measurement and classification of NZE performance varies, contributing to common challenges and barriers encountered during the implementation of NZE building projects [16]. These challenges result from multidimensional factors that are related to technical knowledge and expertise of professionals, efficient project management, project cost implications, policies and regulatory requirements, and dealing with market barriers [17].

Research conducted in both developed and developing countries has identified many challenges in implementing sustainable building practices that are related to the cost, timing, regulations, knowledge gap, and lack of incentives and support [18]. For instance, a recent study conducted in New Zealand about the slowdown in construction of NZE buildings concluded that legislations and policies are the main challenges in incentivizing and encouraging the adoption of these types of buildings while the impact of financial and technical challenges is limited [19]. The challenges, however, can be different among countries, cities, and states. For example, a study conducted in Nigeria found that the main challenges to adopting sustainable construction practices are related to the lack of experience among professionals, lack of clear strategies to promote sustainable constructions, and lack of demand among different stakeholders to adopt sustainable construction [20].

As for other examples, a study conducted in southern Europe has highlighted technical and social challenges in implementing Nearly Zero-Energy Buildings (NZEB) [21], and a study in Portugal found that the main obstacles to implementing the Passive House concept were related to a lack of knowledge among building industry technicians and key actors [22].

This literature review highlights eight categories of barriers and challenges that affect the project implementation phases. The first phase is comprised of the issues arising during the project inception period and includes cultural and social constraints and project management [17,20]. The second phase, or preconstruction phase, covers design and permitting, and includes the technical challenges, knowledge gap, legislative and regulatory barriers, and financial constraints [20–23]. During the last phase or the construction work, delays are caused by barriers arising from knowledge gaps and project management [23,24].

Results of this literature review highlighting the common barriers and challenges (CBCs) to sustainable buildings including Passive Houses and NZE buildings are summarized in Table 1 below.

Table 1. List of Common Barriers and Challenges Identified in Literature.

Categories	Phase	Challenges	References
Knowledge Gaps	All Phases	Lack of awareness, understanding, experience, information, findings, and studies	[17]
Development and Evaluation	All Phases	Scarcity in methods, tools, applications, technologies, and adopting models for design, construction, and assessment	[17]
Technical Challenges	Preconstruction and Construction	Lack of construction skills and quality assurance mechanisms	[21]
	Preconstruction and Construction	Inappropriate use of design methodologies coupled with limited input from performance evaluation	[20–22]
	Preconstruction and Construction	Barriers related to professionals' knowledge and practice in dealing with new technologies and standards	[20,21]
Legislative and Regulatory Barriers	Preconstruction	Absence of mandatory standards for innovative construction methods, materials, and design	[20,23,24]
	Preconstruction and Construction	Legal and construction barriers leading building owners to invest in renewable energy sources instead of energy efficiency	[21,22]
	Preconstruction	Variation between climate zones requiring different approaches to achieve NZE	[21]
	Construction	Lack of experience and knowledge among developers, contractors, and builders	[23,24]
Timing	All Phases	Cooperation and networking	[23]
	All Phases	Knowledge, tools, and methods	[23]
	All Phases	Regulations and client understanding	[23]
Cultural and Social Constraints	Preconstruction	Preferences of suppliers/institutional buyers	[23]
	Preconstruction	Limited acceptance of the concept itself in the market	[22]
	Inception Phase	Focus on short-term construction industry benefits rather than incorporating sustainability principles in the design phase	[20]
	Inception Phase	Lack of client demand	[20]
Managerial Constraints	All Phases	Lack of commitment of senior management; lack of sustainable project management	[23]

Table 1. *Cont.*

Categories	Phase	Challenges	References
Financial Constraints	Preconstruction	Financial limitations, insufficiently developed proactive strategies, and constraints related to both financial resources and planning efforts	[23]
	Preconstruction	Lack of public policies and incentives for PH-concept-based construction	[22]

3. Methodology

Everly Passive House is the case study under investigation for the specific challenges and barriers faced during the preconstruction phase. The Everly Caja residence is a three-story residential house with a total area of around 300 m^2 (3300 ft^2). The house is designed to operate as a Passive House with low operating energy demand. The house design also considers the material enclosure used to lower carbon emission as well as providing low energy demand.

- Suite A—An elderly accessible single bedroom house located on the 1st floor; designed for couples; includes one bedroom, and one large bathroom with curb-less shower and wheelchair modification ready.
- Suite B—Designed as a small family residential floor, and includes three bedrooms, two bathrooms, an office space, an open kitchen, and a living room.
- Suite C—Designed as a studio and can be combined with Suite B.

This study employs a triangulated approach that combines the use of data from multiple sources [25], among them a literature review, direct observations, and open-ended interviews. The collection of data from multiple sources enhances the validity and reliability of the findings [26], and allows the development of a complete understanding of the problem [25]. The preconstruction phase is critical as it sets the foundation for the project, as it involves finalizing the design, securing permits, and planning for variations. It is during that phase that many challenges are faced, which could potentially lead to not completing the project. These barriers are often related to regulatory and code compliance, design modifications, material selection, and other factors specific to sustainable building practices.

The use of a literature review in this study allows capturing the different barriers faced by sustainable buildings, providing a comprehensive thematic review of these barriers and confirming the findings of this study [27]. On the other hand, the direct observation offers unique opportunities to the researchers to capture, through direct engagement in a real-world setting, interactions and incidents that other methods can miss or misinterpret and help fill the gap between theory and practice [28]. The open-ended interview through purposeful sampling offers selecting participants that play pivotal roles in the preconstruction phase of the Everly Passive House. The richness of the information provides a comprehensive understanding of the challenges. This approach ensures that each participant could offer substantial insights into the encountered challenges and barriers [29].

(a) Literature Review

A systematic approach is followed in the literature search to ensure a rigorous and comprehensive identification of relevant articles. The review process is focused on the discovery of scientific documents that specifically identify the challenges faced during the preconstruction and construction of sustainable buildings. A combination of keyword searches and database filters are used to identify relevant articles. The search criteria include terms such as "barriers to sustainable building design", "challenges in sustainable building permitting", "obstacles in sustainable construction", and related variations. These documents are then screened based on relevance to the research topic and included for a detailed analysis. Only articles that provide insights on challenges faced during the implementation of sustainable buildings are included for further analysis. Next, the identified challenges are categorized and segregated according to the stage of construction in which they mostly occur. This approach enabled a structured analysis of the challenges, providing a deeper understanding of the barriers at each stage of the construction process.

(b) Interviews

Interviews were conducted and the key barriers were identified and categorized. The barriers are then classified into themes that share common elements (e.g., communication channels, technical skills, design implementation). The elements represent the factors contributing to each identified barrier, which are identified through a process of a thematic analysis of the interview transcripts. The categorization is based on the nature of these barriers (e.g., technical, regulatory, financial) and its impact on the project (e.g., delay, cost increase). Barriers are grouped into themes that share common elements. Themes are analyzed based on the frequency of response, which is quantified by counting the number of times each barrier is mentioned across all interviews [30]. Themes are weighted based on their observed impact on project time and goals, which is assessed by considering the severity of the delay or cost increase caused by each barrier, as reported by the interviewees. Selected comments and quotations from the interviews are included in the analysis to provide a richer understanding of the identified barriers. These direct quotes serve as supporting evidence and offer firsthand perspectives and insights from the respondents [31]. The comments and quotations are selected to represent a range of perspectives and to highlight the challenges faced during the preconstruction phase.

This study employed a purposeful sampling strategy where interviews are directed at city officials, engineers, and architects engaged in the Everly House preconstruction phase, as well as the owner. A total of nine professionals responsible for developing geotechnical, structural, architectural, and mechanical design were identified. The interview questionnaire was shared with these professionals, along with two city representatives and the project owner. We received responses from the structural and mechanical engineers (E1 and E2), the two architects from the architectural firm (A1 and A2), and the two official representatives from the city of Fayetteville (R1 and R2), in addition to the owner who also acts as the main contractor of the house. These seven interviews represent the entirety of this group, thus providing a complete picture of challenges faced during this phase. Follow-up interviews and questions are also shared with some participants for clarification and requesting additional information for this study. The interview questions are conceived to capture the interviewees' viewpoints and experience in the design and permitting of this house as well as their experience as part of professional bodies and regulatory agencies in the challenges and barriers to implementing sustainable buildings in fast-growing cities. The questions ranged from exploring the dynamics of collaboration and communication among stakeholders to understanding the detailed design challenges and material selection, in addition to the potential challenges that could impact the success of similar projects in the future.

(c) Direct observation

In addition, the research is based on direct observation to gain insights into the process of developing similar projects as well as to understand common challenges faced during the preconstruction of Everly House. The observation period spanned from August 2022 to May 2023. During this period, the authors closely observed the design and permitting process through direct engagement with the project owner. This engagement consisted of weekly meetings, recorded in written meeting notes, which included progress updates, decisions made, and discussions. The discussions were centered around reasons behind any changes made to the project plan, issues related to design iterations, and other topics. The outcome of the direct observation assisted in scoring the barriers.

A scoring methodology was conducted using a binary scoring system to simplify the analysis in direct observation into 'observed' and 'not observed' [32], to understand the presence of a specific barrier in each stage of the preconstruction of the project. If the barrier was observed in the planning, conceptual design, or final design and permitting, it was given a score of 1; if not, it was scored as 0. The barrier is then weighed based on the sum of the scores across the three stages where the result ranged from 0 to 3. This method allowed the reflection of the cumulative impact of these barriers on the project, and provided an informative analysis of the relationship between the exploratory variables (observed and not observed barriers) and the dependent variable (the weight) [33].

Additionally, a collaboration folder between the owner and the architectural firm was shared by the project owner with the authors. The folder includes project architectural, mechanical, and structural design plans and material data sheets. This folder serves as an essential source for project documents during the follow-up period and represents a primary source of data for the analysis.

Relevant documents, such as mechanical design reports, structural design calculation notes, WUFI Energy simulation reports, permit draft documents, and relevant regulations such as Fayetteville, Arkansas Energy Code of Ordinances, 2009 International Energy Conservation Code (IECC), 2021 International Building Code (IBC) and 2021 International Residential Code (IRC), and Arkansas Fire Prevention Code Volume I, adopted by the state of Arkansas, are reviewed to supplement the observation data.

4. Results

The barriers can be summarized into six main categories, which were highlighted by the interviewees and observed during the follow-up period. The six categories include 20 barriers faced at different stages, where each barrier is represented as a theme; themes are related to elements representing factors causing these challenges depending on the nature of the barrier, and these elements are used to develop recommendations to overcome these barriers. Table 2 is a summary of the categories, themes, and elements along with weighing these barriers based on their impact on the project timeline ranking from low- to high-impact barriers, and the frequency of times they are mentioned in the interviews.

Table 2. Identified Barriers, Associated Themes, Their Impact, and Their Frequency.

Categories	Theme	Elements	Frequency	Weight
Management and Time Barriers	Theme 1: Ineffective project coordination and communication among stakeholders, causing delays and inefficiencies.	Communication channels, project meetings, documentation	2	High
	Theme 2: Insufficient project management skills and experience in implementing energy-efficient design strategies.	Project planning, selection of designers/firms, scheduling	1	Low
	Theme 3: Challenges in balancing project timelines and sustainability goals, leading to compromises and trade-offs.	Project objectives, project schedule, sustainability targets	2	Low
Sustainable Design Barriers	Theme 4: Engineers/designers prioritizing conventional design over sustainable building design strategy.	Lack of knowledge and experience in sustainable building design process, considerations, and criteria	3	High
	Theme 5: Limited consideration of energy performance and environmental impact in the early design stages from designs/engineers.	Conceptual design, schematic design, design development	2	High
	Theme 6: Lack of integration between architectural design, mechanical systems, and structural design for optimal energy efficiency.	Building envelope, mechanical systems, structural systems	4	High

Table 2. *Cont.*

Categories	Theme	Elements	Frequency	Weight
Regulatory, Permitting, and Legislation Barriers	Theme 7: Challenges in complying with energy codes and outdated building energy codes.	Energy codes, building regulations, compliance requirements	1	Moderate
	Theme 8: Lack of integration between energy efficiency, carbon reduction, and sustainable building design priorities and urban planning requirements in regulatory frameworks.	Building codes, zoning regulations, urban planning guidelines	5	High
	Theme 9: Lack of clarity and guidance on sustainable building design/Passive House and energy-efficient design requirements in adopted building codes.	Outdated building codes, design criteria, code interpretations	4	High
Knowledge Gap and Experience Barriers	Theme 10: Gaps in knowledge and experience in designing energy-efficient/net-zero buildings, especially in Passive House design.	Design knowledge, technical expertise, training opportunities	5	High
	Theme 11: Limited access to training and educational resources on sustainable design practices.	Training programs, educational materials, industry resources	1	Low
	Theme 12: Lack of awareness and understanding of available energy-efficient technologies and best practices.	Energy-efficient technologies, innovative solutions, research advancements	3	Moderate
	Theme 13: Difficulty in translating theoretical knowledge into practical design solutions for energy-efficient buildings.	Design implementation, application of design principles, technical skills	3	Moderate
Material Selection Barriers	Theme 14: Difficulties in finding feasible and attainable ways to incorporate sustainable aspects in structural design and reducing reliance on concrete.	Structural materials, alternative design solutions, construction practices	1	Low
	Theme 15: Limited availability and high costs of sustainable building materials in the local market.	Sustainable materials, market supply, cost considerations	4	High
	Theme 16: Challenges in balancing aesthetic considerations and sustainability requirements in material selection.	Design aesthetics, sustainability criteria, client preferences	1	Low
	Theme 17: Lack of information and guidance on the environmental impact and life cycle assessment of building materials for the public.	Life cycle analysis, environmental product declarations, material databases	1	Low
Tools and Software Barriers	Theme 18: Lack of easily accessible tools and software that integrate sustainable design aspects.	Design software, energy modeling tools, simulation platforms	3	Moderate
	Theme 19: Inadequate integration and compatibility between different software platforms used by architects, engineers, and energy consultants.	Software compatibility, data exchange, interoperability	3	Moderate
	Theme 20: Insufficient training and expertise in utilizing software tools for energy-efficient design and performance analysis.	Software training programs, user proficiency, technical support, modeling capacities	1	Low

The preconstruction phase of the Everly project has three main stages: planning, conceptual design development, detailed design and permitting [31]. The barriers are not isolated to one stage but do rather overlap, interact, and result from the difficulties or gaps encountered by the various stakeholders involved in the project. To provide an understanding of the relationship between project participants, project stages, and identified barriers, a diagram has been developed (Figure 1). This diagram briefly explains the relationship between project participants, the three main stages during the preconstruction phase, and the main barriers encountered in these stages.

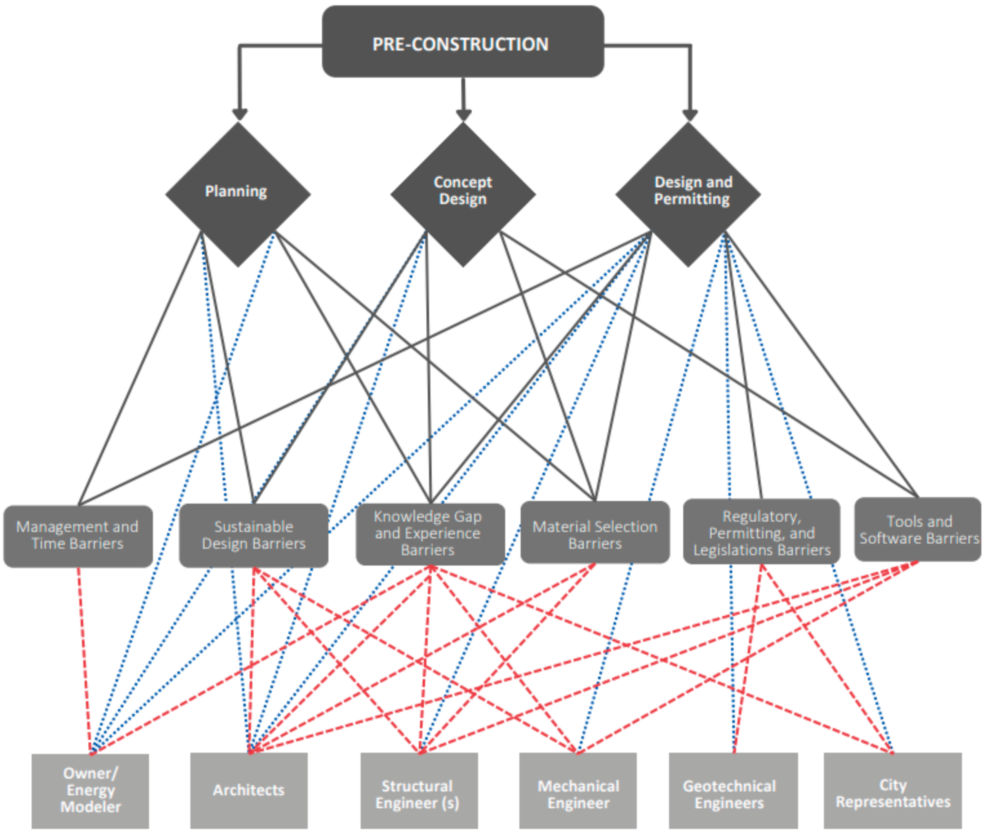

Figure 1. Relationship between construction barriers, project participants, and project stages.

5. Management and Time Barriers

> *"A lot of changes came but not all at one time so there were many iterations which made us constantly need to reevaluate how we are meeting the standards"*, said A1, a sentiment echoed by E1, *"One should get a schematic plan in front of the permitting people as early as possible and to get everyone on board as early as possible."*

For example, the design of the Everly House changed substantially in response to the discovery of zoning requirements for a property in a flood plain that required raising the residential quarters a minimum of 0.6 m from the surface (Figure 2). Moreover, WUFI modeling of the original design revealed the need for additional shading and insulation to meet Passive House energy goals (Figure 2).

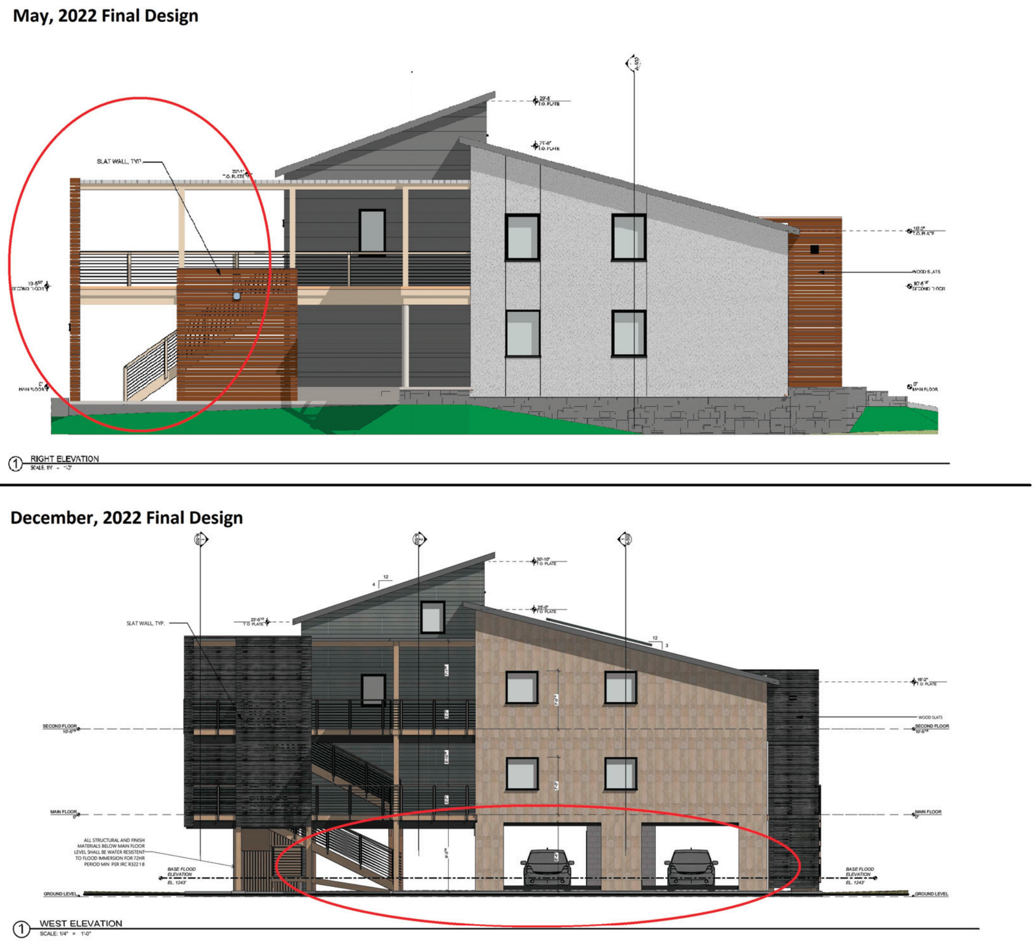

Figure 2. Everly House design from May 2022, building is ground-supported and 2 stories above ground level (circled in red) (**top**) to December 2022, building is raised on piles (circled in red) and three stories above ground level (**bottom**).

Challenges associated with management and time are common among sustainable building projects across the construction project phases (Table 1, e.g., Timing and Managerial Constraints). The Everly House faced similar challenges during the preconstruction phase, and one key barrier that had the highest impact on this project was the lack of an integrated design approach among architectural, structural, geotechnical, mechanical, and sustainable building designs that resulted in multiple design revisions. The inadequacy of coordination was mentioned several times by the design professionals during their interviews, indicating a recurrent theme. A1, for example, noted the multifaceted nature of design alterations stemming from diverse factors such as project location, structural modifications, and regulatory requisites.

To overcome this barrier, it is important to establish clear lines of communication and coordination between architects, structural engineers, geotechnical experts, mechanical engineers, and sustainable building designers from the very early stages of planning. Regular project meetings coupled with the comprehensive documentation of decisions foster alignment amongst all stakeholders with the overarching project vision and objectives.

Ultimately, this approach can reduce the number of design revisions, and reduce the project timeline.

6. Sustainable Design Barriers

> "*We seemed to be looking at the design process from two different directions*", *said the owner. In parallel, E2 pointed out that "The impact of design decisions and assumptions is greater than that of any specific tool in Mechanical Engineering and Plumbing (MEP) systems. These systems have historically been oversized due to outdated rules of thumb and dynamic design conditions*."

For example, there is a difference between conventional design and Passive House design assumptions for the thermostat settings. The conventional thermostat setting, initially used in the design of the Everly Passive House, is set between 21 and 24 degrees Celsius (70 and 75 degrees Fahrenheit); however, the Passive House paradigm mandates a much wider range of 20 to 25 degrees Celsius (68 to 77 degrees Fahrenheit). The indoor design temperature assumption affects the heating, ventilation, and air conditioning (HVAC) system, leading to oversizing due to disparities in thermal requirements, where heating transmission load increases and cooling transmission load decreases when increasing indoor design temperature [34] for the final design. The heating load estimated through WUFI was approximately 17,141 Btu/h while the estimated value through Hourly Analysis Program (HAP) was 14,321 Btu/h, and the cooling load estimated through WUFI was approximately 7737 Btu/h, while the estimated sensible and latent cooling loads calculated in HAP were 21,991 Btu/h and 1640 Btu/h, respectively.

Designers and engineers, by and large, prefer conventional design and material over sustainable design approaches (Table 1, Development and Evaluation and Technical Challenges). The common barrier illustrated in the above example is the lack of alignment between design decisions and the project vision and objectives, which results in suboptimal or incompatible design solutions.

Another barrier stems from the lack of integration between architectural design, HVAC systems, and structural design, hindering the quest for optimal energy efficiency. For example, the designer of a Passive House assumes the infiltration in the HVAC design in all zones to be negligible due to tight construction; however, real-world observations reveal a significant disparity between this assumption and the physical setting, where infiltration occurs through cracks in building envelopes and through natural ventilation caused by opening doors and windows, which allows outdoor air to enter [35]. These examples emphasize how such differences in design assumptions can lead to significant effects on system efficiency and energy consumption.

7. Regulatory, Permitting, and Legislation Barriers

> "*Additionally the house design doesn't meet the typical design requirements stated in the fire code for single house, and it was considered a Triplex that requires additional modification to meet standards," said R1, and "The codes are not written to address Passive [House] design explicitly," according to R2, who also noted that "The State of Arkansas does not give us much ability to regulate building materials for single-family homes in our zoning codes*."

Even though adopted regulations and policies related to sustainable building design differ among countries, states, and cities [20], regulatory barriers remain common among different projects. The analysis identified several barriers related to regulatory frameworks, permitting processes, and legislative aspects. The inadequate integration of energy efficiency, carbon reduction, and sustainable building design standards within building codes and urban planning regulations emerged as a critical barrier. The house was designed as a single-family house, there was a modification from two to three stories due to requirements for a property in a flood plain, and the house was reclassified as a triplex, which required interior modification and the installation of utilities on the premises. As highlighted by R1, this barrier of code non-compliance causes design modifications and delays in permitting. Even though these codes are not directly related to energy or carbon reduction, they, however, affect the shape and physical layout of the house originally decided on based on sustainable design principles such as the building orientation, number of floors, and internal loads, in addition to carbon reduction and ecological footprint principles that are related to the type of foundation, structural design, and type of material used in addition to the building layout.

The absence of specific and clear guidance on sustainable building design requirements in the adopted building codes can lead to uncertainty among project designers to integrate sustainable building practices into their projects and can also result in a lack of interest in designing for energy saving and carbon reduction. This gap highlights the need to advocate for adopting updated building energy codes and provide consistency and standardization through including clear requirements and guidance to make informed decisions and align the design with code requirements as well as sustainable building practices [18].

8. Knowledge Gap and Experience Barriers

> "*The lack of literature and experts who knew about these systems made our task more complex,*" *said E2, and A2 pointed out,* "*Most of the challenges faced during this [preconstruction] phase is primarily rooted in a general lack of experience in this region with Passive House design and the technologies being used in this house*."

A similar observation was made by the structural engineer (E1) regarding the challenges associated with nontraditional design approaches to reduce the carbon footprint such as the limited use of concrete structures in the project, as well as vertical capacities that include the use of fiberglass composite posts instead of using traditional materials like steel and concrete, and lateral capacities that use bracing systems to enhance lateral stability or hybrid systems such as glulam beams and timber for lateral bracing [36,37]. This lack of familiarity with advanced design strategies and technologies affects the delivery of design drawings in addition to several trade-offs that increase the carbon footprint and oversize the structural beams.

Challenges associated with the knowledge and experience of professionals engaged in the design and implementation of sustainable building projects are another common barrier among similar projects (Table 1, Knowledge Gap). One barrier identified in this study is associated with the gaps in knowledge and experience among design professionals. The lack of expertise and knowledge not only increases the pressure on designers to conduct extensive research but also affects their willingness to embrace innovative approaches during the design phase.

There have been other identified barriers associated with knowledge gaps and experience categories that had a moderate impact on the project and their effects were mainly on the project timeline; these barriers included the lack of awareness and understanding of available energy-efficient technologies such as the Passive House concept and energy-efficient HVAC systems and difficulty in translating theoretical knowledge into practice and were also highlighted by the architects and engineers. Addressing these barriers requires training architects and engineers on sustainable design practices, energy-efficient technologies, and best practices to enhance their knowledge and expertise, and utilizing knowledge-sharing platforms and resources to enhance designers' awareness and understanding of available energy-efficient technologies and practical design solutions.

9. Material Selection and Supply Chain Barriers:

Although the material selection and supply chain are not highlighted, they are mostly associated with the cost, material information, and decision-making process during the design process [38].

One of the challenges that this research identified is the lack of affordable and sustainable building materials within the local market. Specifically, materials such as hemp wool, cork, and rock wool, which hold immense promise for reducing carbon footprints, are not widely accessible. For example, cork is a material that has these qualities, but it was difficult to import due to supply chain disruptions and high costs. This means that the designers and owner had to spend a lot of time searching for suitable materials to meet the criteria of a low-carbon footprint, Passive House standards, and energy efficiency. This resulted in some compromises in the original envelope material selection and trade-off in the amount of carbon reduction and energy savings without affecting the Passive House thermal enclosure requirements for assemblies, which were thermal resistance values (R-values) of the roof at 11.27–15.15 $m^2 \cdot K/W$ (64–86 h ft^2 °F/Btu), above-grade walls, overhanging floors at 5.64–8.46 $m^2 \cdot K/W$ (32–48 h ft^2 °F/Btu), and below-grade walls and floors at 2.82–4.23 $m^2 \cdot K/W$ (16–24 h ft^2 °F/Btu) [26]. Figure 3 illustrates two wall section changes that occurred between May 2022 and August 2022 due to design changes and estimation of the carbon footprint associated with envelope assembly.

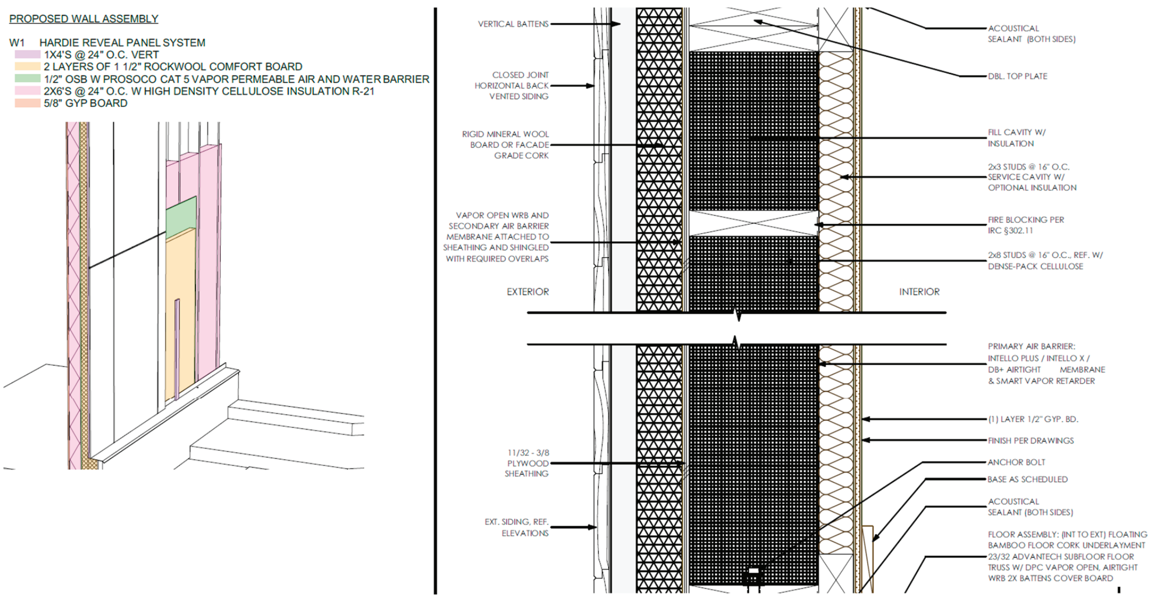

Figure 3. Wall assembly changes from May 2022 (**left**) to December 2022 (**right**).

Table 3 below provides detailed information on the thermal characteristics of three different envelope assemblies that were used in the WUFI Energy model of the Everly House. The name of each assembly, its thermal resistance (R-value), its heat transfer coefficient (U-value), and its thickness (inches) are indicated for the wall, roof, and floor/slab components. These values indicated that all selected building envelopes meet the building's insulation requirements.

The initial design envisioned the utilization of Nexcem blocks combined with mineral wool, and a slab-on-grade foundation, aligning with floodplain and Passive House design considerations. However, budget constraints, along with the carbon footprint associated with the Nexcem blocks and the floodplain permitting requirements for elevating the house on piles, affected the architectural design, leading to the selection of a 2 × 8″ wall configuration, filled with cellulose insulation. While this decision was, in part, driven by the need to navigate budget constraints and logistical hurdles, it represents a tangible example of the reasons why the consequential reduction in the envelope material carbon footprint is the first to be compromised. Although the barrier is related to many gaps from the manufacturer as well as professional knowledge, professionals need to have an early engagement with the supply chain to identify the whole life cycle cost as well as the carbon footprint before the design process, and should also understand the material physical performance, the carbon footprint, and the impact of energy efficiency to meet the project goal and vision.

Table 3. Thermal Performance Characteristics of Different Envelope Assemblies.

		Wall	Roof	Floor/Slab
Envelope Assembly 1	Name	12″R22 Nexcem with 1.5″Mineral Wool	16″TJI with DPC w 5/8 Zip, Intello+, Service Cavity	4″ Slab 5″ Mineral Wool
	Thermal Resistance (R-Value)	5 m²·K/W (27.1 h ft² °F/Btu)	11.72/12.4 m²·K/W (64.2/67.5 h ft² °F/Btu)	1.1 m²·K/W (19.4 h ft² °F/Btu)
	Heat Transfer Coefficient (U-Value)	0.2 W/m²·K (0.036 Btu/h ft² °F)	0.06 W/m²·K (0.015 Btu/h ft² °F)	0.2 W/m²·K (0.049 Btu/h ft² °F)
	Thickness	0.34 m (13.5″)	0.47 m (18.5″)	0.23 m (9″)
Envelope Assembly 2	Name	2 × 8 w DPC 24″OC W 7/16 Zip Service Cavity	16″TJI with DPC w 5/8″ Zip, Intello+, Service Cavity	16″ 2 × 4 Truss Floor with Cellulose, 3/4″ Hardwood Floor, Intello
	Thermal Resistance (R-Value)	5.36/6.6 m²·K/W (30.1/37.0 h ft² °F/Btu)	11.72/12.4 m²·K/W (64.2/67.5 h ft² °F/Btu)	11.77/12.08 m²·K/W (65.1/66.8 h ft² °F/Btu)
	Heat Transfer Coefficient (U-Value)	0.05 W/m²·K (0.032 Btu/h ft² °F)	0.06 W/m²·K (0.015 Btu/h ft² °F)	0.06 W/m²·K (0.015 Btu/h ft² °F)
	Thickness	0.3 m (12″)	0.47 m (18.5)″	0.45 m (17.6″)
Envelope Assembly 3	Name	2 × 8 w 7.5″ DPC w 1″ Thermacork	16″TJI with DPC w 5/8 Zip, Intello+, Service Cavity	16″ 2 × 4 Truss Floor with Cellulose, 3/4 Hardwood Floor, Intello
	Thermal Resistance (R-Value)	8/8.87 m²·K/W (34.6/38.26 h ft² °F/Btu)	11.72/12.4 m²·K/W (64.2/67.5 h ft² °F/Btu)	11.77/12.08 m²·K/W (65.1/66.8 h ft² °F/Btu)
	Heat Transfer Coefficient (U-Value)	0.03 W/m²·K (0.028 Btu/h ft² °F)	0.06 W/m²·K (0.015 Btu/h ft² °F)	0.06 W/m²·K (0.015 Btu/h ft² °F)
	Thickness	0.3 m (11.7″)	0.47 m (18.5″)	0.45 m (17.6″)

10. Tools and Software Barriers

> *"There are many tools being developed to make carbon-neutral design more achievable for designers, but there needs to be a lot more work done in this area to make it easier for architects to navigate the trade-offs involved in specifying materials and building processes for carbon-neutral buildings," according to A2. The architect's comments also extend to energy modeling.*

For example, the drawings for the Everly House were prepared in ArchiCAD 26, by Graphisoft, Hungary, 2021 software. For the energy analysis, the ArchiCAD file had to be imported into SketchUp and from SketchUp exported into WUFI. This illustrates the lack of integration and compatibility between different software platforms [11]

An attempt was initiated by the authors to develop an energy model for the Everly House using EnergyPlus 22.1 by the U.S. Department of Energy, Golden, CO, USA, and the ArchiCAD file was also faced with similar obstacles, including gaps in translating the geometry into an analytical model that can be used by EnergyPlus. This gap affects the exchange of critical project information, which, in turn, can lead to misunderstandings, discrepancies in data interpretation, and delays in decision-making and design development.

The identified barriers in this category were of moderate to low impact regarding this project; however, this analysis emphasized the importance of software integration, data sharing, and collaborative workflows as key elements to address these barriers, and the respondents emphasized the relevance of software integration, data sharing, and collaborative workflows for developing energy-efficient designs.

11. Conclusions

The research is based on a specific case study in Fayetteville, Arkansas, in the United States, and the findings may not be applicable to other contexts or regions. This study investigated the barriers faced during the preconstruction phase of the Everly Passive House as a case study, where sustainable building practices are not yet widely adopted and prioritized, both among local industry professionals and within state plans and regulations. Open-ended interview discussions were conducted among professionals engaged during this phase, and seven professionals including the project owner responded. A total of 20 barriers were identified through interviews and direct observation, and then were categorized in terms of the management and time, design, regulations and permitting, knowledge gap and experience, material selection, and tools and software. The findings of this study revealed a multidimensional relationship between different project stakeholders and barrier categories that affect the preconstruction phase. These findings align with the literature review conducted, in which technical challenges and legislative and regulatory barriers were more common during the preconstruction phase of this project, providing scientific evidence to support these results.

These barriers have significant impacts on each stage of the preconstruction phase; they affect the feasibility and viability of the project as well as the identification of possible risks and responsibilities. On the other hand, these barriers may compromise the adoption of carbon reduction goals, building energy-efficiency design, and compliance with certification requirements. Sustainable design and regulatory and permitting barriers were found to carry more weight, as they directly influence the foundational aspects of low carbon, energy-efficiency sustainable design, and approval processes, which are critical for the successful implementation of zero-energy and zero-carbon-emission residential buildings. It is important to address these barriers by adopting a multidisciplinary design approach that involves integrating all relevant design disciplines (architecture, HVAC, structural engineering) to work collaboratively during the concept development and final design stages and considering energy performance and environmental impact from the outset and prioritizing sustainable design principles.

In addition to that, the respondents provided valuable suggestions as solutions for problems faced, focusing on the importance of early collaboration and communication among professionals involved in the design and permitting stages; there is importance to developing knowledge and expertise of architects and engineers to implement sustainable building designs and preparing engineers and architects before graduation to incorporate sustainable approaches in their professions. These suggestions were compiled with researchers' recommendations to provide a comprehensive understanding of the challenges and necessary steps to overcome them.

This research is faced with certain limitations that need to be considered. First, some respondents were reluctant to respond to the project; however, the respondents who did participate represent key professionals who exert significant influence over the design and permitting processes of the house. Second, the identified barriers are context-specific and limited to a single case study. In other words, some identified barriers provided in Table 2 may not be relevant to other projects located in different contexts or regions where regulatory frameworks and policies prioritize and incentivize similar projects, while some barriers are identified in other studies, such as design-related challenges and knowledge gaps. Third, the research methodology relies on open-ended interview discussions to capture professionals' perspective who were directly involved in the project, and it is limited to their professional experience in this project. Fourth, the number of interviewees is limited to seven professionals, and while they provided valuable insights, the limited size may not fully represent multiple perspectives and experiences. Despite the limitations, the findings of this study are expected to be a valuable resource for project owners and professionals engaged in the initial stages of similar projects. The design modifications, retrofitting, and changes in envelope materials are all associated with professionals' knowledge, interest, and experience in Passive House design requirements and carbon reduction principles as well as the outdated and weak building energy codes and regulations that do not incorporate sustainable building design principles and do not provide comprehensive guidance on energy-efficient and low-carbon design, creating confusion and challenges for architects and engineers during the concept development phase and affecting the timeline of the project. These delays and modifications have affected the project budget and delayed the implementation of the project as well as finalizing the permit documents. Knowing the potential barriers, these stakeholders can utilize these recommendations and develop strategies to overcome them, to ensure successful project design and completion. Additionally, by understanding and addressing these barriers, policymakers, industry professionals, and researchers can work together to overcome these challenges and promote sustainable building typologies.

The research's novel contribution is its detailed examination of the barrier's professionals face during the initial stages, providing insights that are scarce in the literature, particularly in a similar context where sustainable building design is not integrated into designers' approaches and is not prioritized in municipal or state regulations. The aim of this study is to document these challenges and act as a catalyst for future research that could build on these findings and assess the applicability of the recommendations across various contexts. While this study highlights the barriers faced during the preconstruction phase of the Everly Passive House, these findings are specific to this case and may not be generalizable to other projects or regions. Future research could then extend this study to include participants from similar projects in both similar and different contexts.

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Article

Evaluating Techno-Eco-Efficiency of Waste Clay Brick Powder (WCBP) in Geopolymer Binders

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Abstract: The global focus on geopolymer binder production has increased due to the adoption of waste materials and industrial byproducts. Given the gradual decline in the availability of fly ash and ground granular blast furnace slag (GGBFS) resulting from the decarbonization process in electricity and steel production, waste clay brick powder (WCBP) could be a viable substitute for these pozzolanic by-products. This study presents the economic and environmental benefits of the use of WCBP as a replacement for conventional pozzolanic by-products in geopolymer binder production by assessing its techno-eco-efficiency, environmental impact, and cost-effectiveness performances. The favorable mechanical characteristics exhibited by the fly ash–GGBFS–WCBP-based geopolymer binder emphasize the importance of assessing its sustainability alongside its technical viability. The study employed life cycle analysis (LCA), following ISO framework, and using the Simapro software 9.2, to evaluate the environmental implications of the use of WCBP-based geopolymer mixtures. Human toxicity emerged as the primary impact. Moreover, the analysis of life cycle costs highlighted key financial factors, with around 65–70% attributed to alkaline activators of the total cost. The production of alkaline activators was identified as a critical point for both environmental impact and economic considerations due to energy consumption. While WCBP-rich samples exhibit a 1.7–0.7% higher environmental impact compared to the control mix (CM), their high mechanical strength and cost-effectiveness make them technologically and economically efficient geopolymer mixes. In conclusion, the portfolio analysis for techno-eco-efficiency affirms that mixes containing 40%, 30%, and 20% WCBP are more efficient than those using 10% and 0% WCBP, respectively.

Keywords: waste clay brick powder; fly ash; ground granular blast furnace slag; geopolymer; life cycle analysis; life cycle cost; techno-eco-efficiency

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1. Introduction

The construction sector contributes significantly to the socioeconomic progress of a nation resulting from human and economic growth that requires improved housing conditions and civil infrastructure. The construction industries are heavily reliant on the use of cement, which is widely manufactured, and its production causes significant environmental impacts [1]. Cement is produced from the calcination of limestone, which releases a substantial amount of carbon dioxide, and the production process is energy-intensive [2]. Resource extraction such as limestone and the associated waste generation during production also impact the ecosystem. To address these challenges, the industry is exploring the use of alternative fuels in cement production and environmentally friendly cementitious materials.

Geopolymers presents a promising solution to address the environmental concerns associated with cement production [3]. Unlike conventional cement manufacturing, geopolymers do not rely on the carbon- and energy-intensive calcination process. Instead, geopolymers utilize industrial by-products like fly ash or slag, which reduces the reliance on virgin materials for cement production and so mitigates the environmental impact by using recycled waste materials. Geopolymer production involves an alkaline activation process that reacts with these by-products to produce a binder similar to traditional cement [4]. This process requires less energy and may significantly reduce the carbon footprint associated with the manufacturing of cementitious binders. Alternatively, it diverts the industrial byproducts from the residue areas, which avoids land use changes.

A range of industrial by-products and mineral deposits, like metakaolin, fly ash, GGBFS, ferronickel slag, and ultrafine slag, have been used as geopolymer precursors. Among these materials, fly ash is particularly noteworthy for its wider availability and its high silica (SiO_2) and alumina (Al_2O_3) content, exceeding 70% [5]. Fly ash is often combined with various industrial by-products, such as GGBFS, to improve both the fresh and hardened properties of the geopolymer binder. The combination of fly ash and GGBFS in geopolymers demonstrated excellent mechanical and durability properties [6]. GGBFS, characterized by its high calcium content, complements the very low calcium content of fly ash when they are used together as binary precursors. When curing at room temperature, GGBFS contributes to improved mechanical and microstructural properties due to its elevated calcium content and enhances binding properties when activated by an alkali [6]. By replacing silicon-rich materials with a low calcium content with a small proportion of GGBFS, the setting time can be reduced and mechanical properties in both the early and later stages of geopolymer development can be enhanced [6].

The production of fly ash, a by-product from coal combustion, has been gradually decreasing due to several factors. The shift towards decarbonization processes, such as natural gas and renewable energy, will gradually reduce the reliance on coal-fired power plants [7], which will result in the decrease in fly ash generation. Additionally, advancements in pollution control technologies in these plants have resulted in the reduction in fly ash generation. Furthermore, as a part of the decarbonization process, the iron production process is switching from blast furnaces to electric arc furnaces, which will result in the reduction in GGBFS [8]. As a result, it is crucial to discover a substitute material for these industrial byproducts with high pozzolanic properties to produce geopolymer binders. The solution lies in the waste that is generated within the construction industry.

Globally, approximately 25–30% of the solid waste generated is attributed to the construction industry, posing an escalating threat to the environment in recent times [9]. Australia's construction industry contributes to a substantial portion of the waste annually (i.e., 76 million tons). Despite a relatively higher recovery rate within the sector, about 24% of the total construction waste remains unrecycled, leading to landfill disposal [10]. For every AUD 1 million contributed to the economy, the construction sector produces about 87 tons of waste, which could be eco-efficient [11]. The expenses allocated to waste services have surged since 2016, now exceeding AUD 17 billion annually, with AUD 2 billion attributed to the construction industry. This increase, amounting to a 35% rise since 2016–2017, underscores the concerns regarding the annual growth of waste production [11].

The bulk of waste, around 80%, generated from construction and demolition waste consists of concrete and brick waste [12]. Recycling this concrete and brick waste in concrete production not only alleviates waste disposal issues but also decreases the construction industry's reliance on natural raw materials. Currently, researchers have made significant strides in utilizing recycled concrete aggregate and are initiating large-scale recycling efforts [13–15]. Regarding brick waste utilization, the usual practice involves crushing it and then utilizing it as a fractional replacement for fine or coarse aggregates in concrete. Limited research has explored the utilization of this brick waste in the creation of geopolymer binders [16]. To address this research void, the authors previously examined the integration of waste clay brick into geopolymer binders as a partial substitute for fly ash. However, it is crucial to assess the environmental sustainability and techno-eco-efficiency level, along with the technical feasibility, to validate the geopolymer mix design employed in our prior study.

Salas et al. [17], Kastiukas et al. [18] and Kul et al. [19] demonstrated that geopolymer binders offer a more sustainable and environmentally friendly alternative to conventional cement, contributing to the reduction in greenhouse gas emissions by 27–64%. However, Yoris-Nobile et al. [20] argued that geopolymer mortars have a higher environmental impact than low-clinker cement mortars due to their use of energy-intensive sodium hydroxide. Bajpai et al. [21] found alkaline activators to be the major sources of high environmental impacts for geopolymer binders. Additionally, Abbas et al. [22] found that sodium silicate contributed to a high environmental impact in geopolymer concrete. Life cycle assessment has been undertaken widely as a sustainability assessment tool for civil and construction engineers [23].

Amari et al. [24] discovered that incorporating mining waste streams and GGBFS into geopolymer production enhances the mechanical behavior of these hybrid geopolymers, achieving a maximum strength of 40 MPa while also reducing the life cycle environmental impact by 40% compared to ordinary cement, highlighting the environmental benefits of geopolymer materials. Gopalakrishna et al. [25] exposed that the geopolymer binder has significantly lower values of embodied energy and global warming potential compared to the OPC-based mortar, with reductions of 94% and 97%, respectively. In contrast, despite the favorable characteristics of geopolymer binders, Raza et al. [26] found that while hybrid cement mortars outperformed geopolymers in most impact categories in a life cycle analysis, the overall environmental impact assessment using the 'coefficient of performance' indicated that hybrid cement mortars have a significantly lower environmental burden than geopolymers. Gopalakrishna et al. [27] conducted both durability performance and LCA analysis for the German specifications of geopolymer concretes based on recycled aggregate, fly ash and GGBFS and concluded that the recycled aggregate geopolymer concretes had an embodied energy of 4.48% and a global warming potential of 0.083, both markedly lower than conventional concrete. In a comparative LCA study, Ricciotti et al. [28] demonstrated that the production processes of porcelain stoneware-based products with geopolymer mortars made from waste materials can reduce energy use compared to other methods, making them environmentally and economically beneficial. Miyan et al. [29] discovered that incorporating recycled waste concrete powder consistently decreased the carbon emissions, cumulative energy demand, and cost of the resulting geopolymer mixes. Additionally, Occhicone et al. [30] emphasized the need for the use of LCA and life cycle costing analyses along with the structural analysis for geopolymer binders. These analyses provide valuable insights into the environmental impacts and cost-effectiveness of geopolymer materials, highlighting the need for a comprehensive approach in evaluating their suitability for future construction applications.

Nevertheless, only a few studies [31–33] have conducted LCA for geopolymer binders based on WCBP. Migunthanna et al. [31] performed LCA, comparing the environmental impact of conventional cement-based concrete and geopolymer concrete in rigid pavement construction, assessing CO_2 emissions and energy consumption across different stages. The substitution of conventional concrete with geopolymer binders resulted in a nearly 50% reduction in total CO_2 emissions and a 72% decrease in energy consumption. This study used waste clay bricks, slag, and fly ash as precursors, with anhydrous sodium silicate as the activator, to produce one-part geopolymer concrete. Mir et al. [32] performed LCA using GaBi software and followed the ISO 14040-44 guidelines [34] to assess the environmental implications of the use of geopolymers made from red brick waste and red ceramic waste. This study considered three optimized mixtures and curing methods for assessing environmental impacts including global warming potential (GWP), eutrophication potential (EP), ozone depletion potential (ODP), and acidification potential (AP), among others. In Phase I, using a binary composition, sodium silicate and electricity made significant contributions to the environmental consequences. In Phase II, a ternary mixture was observed that slightly increased the use of sodium silicate but exhibited lower overall environmental effects compared to binary compositions. In Phase III, similar environmental performance to Phase I was observed, a producing higher GWP from additional curing. An environmental LCA conducted by Fořt et al. [33] found that the CO_2 was reduced by 112% due to the replacement of a standard cement paste with a geopolymer paste sample. Despite other factors being considered, the analysis specifically focused on the embodied energy, highlighting that the substantial impact observed was directly associated with the utilization of alkaline activators in the studied context. They found that the manufacturing of sodium silicate requires significant energy inputs, resulting in a larger environmental impact compared to conventional binders. For instance, producing one ton of 48% Na_2SiO_3 consumes about 11.2 MJ of non-renewable energy, representing a substantial portion of energy utilized in geopolymer production.

However, the above-mentioned studies did not consider either life cycle costing or eco-efficiency portfolio analysis, particularly in the context of geopolymer concrete. These analyses are crucial in the engineering decision making process, as environmentally friendly materials are not always eco-efficient or economically feasible. Dynan et al. [35] followed the ISO framework, encompassing several stages from the goal and scope to creating an eco-efficiency portfolio, to assess geopolymer concrete as an eco-friendly alternative to traditional cement. While it proved effective in reducing emissions, particularly in terms of global warming potential, it encountered challenges in other environmental impact aspects. Nevertheless, this study did not consider techno-eco-efficiency portfolio analysis. Hence, there is inadequate research examining the techno-eco-efficiency performance of geopolymer binders to compare them against conventional ones that evaluates the economic and environmental implications of engineering or technical strategies.

The research significance of this study lies in its comprehensive approach. Initially, it studied a detailed LCA, specifically exploring the fly ash–GGBFS–WCBP binder to evaluate WCBP's environmental viability within the geopolymer mix. Additionally, this study performed life cycle costing (LCC) analysis for the geopolymer mortar mixes. The primary focus was on optimizing their cost-effectiveness. Through a meticulous hotspot analysis of these mixes, the research identified the specific areas characterized by the highest energy consumption. Lastly, the study utilized a techno-eco-efficient analysis to determine the eco-efficiency performance of the structurally sound fly ash–GGBFS–WCBP mixes as the techno-environmental benefits could be outweighed by the increased recycling costs.

2. Materials and Methods

To evaluate the suitability of WCBP as a substitute for fly ash in the production of a fly ash–GGBFS-based geopolymer binder, LCA was conducted following the guidelines outlined in ISO 14040 [34]. Brick waste aggregates (10–20 mm), collected from a local company specialized in brick recycling, were washed, dried, and ground into a powder using a laboratory ball mill for four hours to achieve similar particle size distributions to fly ash and GGBFS. WCBP has a higher SiO_2 content than fly ash and GGBFS but a lower Al_2O_3 content than fly ash, yet its combined alumina, silica, and iron oxide content of 91.47% qualifies it as a mineral admixture according to ASTM C618 [36]. The WCBP's chemical and mineralogical compositions are discussed in more detail in the authors' previous paper [37]. Four distinct mortar samples incorporating WCBP were compared with the control mixture, comprising fly ash and GGBFS as source materials. The LCA scope employed a 'cradle to gate' methodology, covering processes starting from raw material extraction, through the production and handling the construction materials, to transporting them to the construction site area, and encompassing all manufacturing phases. LCA was utilized to assess the environmental impacts and to conduct a life cycle cost analysis to evaluate the techno-eco efficiency of sample geopolymer mixtures. LCA consists of four key steps: outlining the goals and scope, performing an inventory analysis, calculating impact assessments, and analyzing the findings.

2.1. Goal and Scope

The objective of the LCA investigation was to evaluate and contrast the environmental effects of five different geopolymer mortar samples that were manufactured. Each mortar sample contained varying proportions of WCBP, which served as replacements for the fly ash component in the fly ash–GGBFS-based geopolymer mortar samples. GGBFS content was constant for each mix. A 12 M sodium hydroxide and sodium silicate solution was used as the alkaline activator to produce geopolymer mortar samples. Each variety of mortar mix underwent curing at room temperature. The LCA aimed to generate normalized data tailored to Australian economic and environmental conditions, enabling the creation of an eco-efficiency portfolio that evaluates the eco-efficiency of each mortar sample. The system boundary encompasses all stages from the mining to material production, transporting those materials to the construction site and manufacturing geopolymer mortar, as shown in Figure 1. The manufacturing phase comprises energy usage related to processes like mixing, compacting, and curing. Figure 2 illustrates the complete manufacturing and curing process of geopolymer mortar mix.

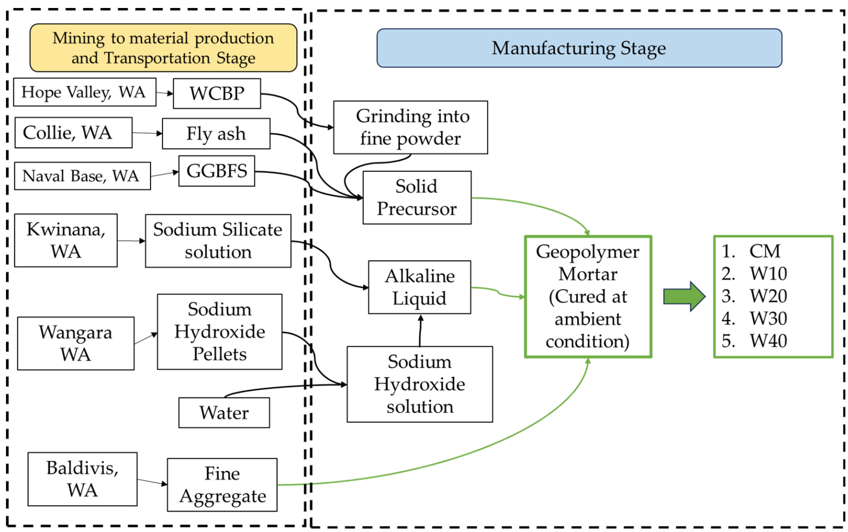

Figure 1. System boundary for conducting the LCA of 1 cubic meter of a geopolymer mortar.

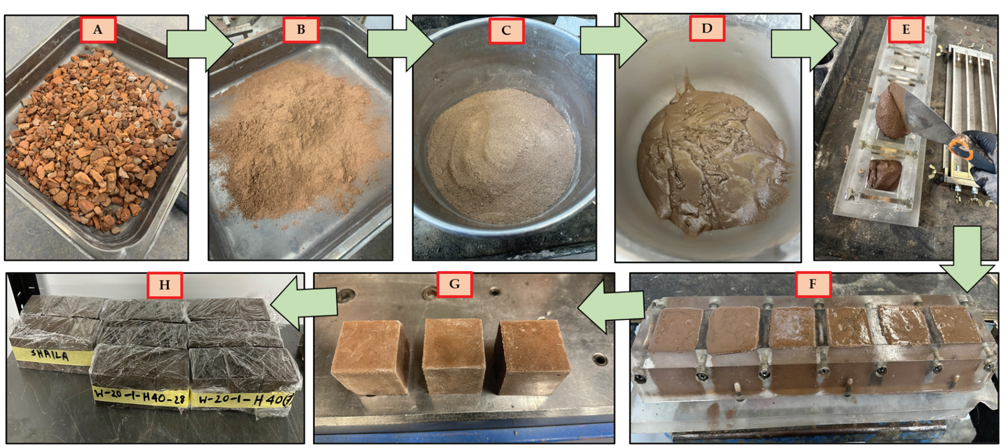

Figure 2. Manufacturing and curing process of WCBP-based geopolymer mortar (W40) ((**A**) Brick aggregate; (**B**) WCBP; (**C**) dry mixing; (**D**) geopolymer mortar mix; (**E**) pouring the mortar mix into mold; (**F**) after finishing casting; (**G**) 50 mm cube mortar sample after demolding; (**H**) curing).

In this LCA investigation, a compressive strength of 1 MPa was selected as the functional unit to identify the geopolymer mixture that could deliver the greatest strength in an eco-efficient manner. The research used the Simapro (version 9.2) LCA software that can compute environmental impacts for every cubic meter (m^3) of a geopolymer mortar. As a result, the environmental impacts were initially assessed for a 1 m^3 mortar mix. Subsequently, these impact values were divided by the corresponding 28-day compressive strength value. The selected unit for estimating emissions and economic factors in transportation stage was the t-km (ton—kilometer). This unit accounts for the effects of weight on material transport and processing, in addition to the transport distance. The reliable databases for the t-km measurements are readily available in the SimaPro (version 9.2) software, and t-km is the standard unit for impact measurement in LCA software. A distinct profile was established for WCBP, considering the energy required for grinding the raw material into a suitable solid precursor.

2.2. Life Cycle Inventory (LCI) Analysis

Developing an LCI is a necessary step prior to assessing the environmental consequences. The LCI is generated using data from the author's earlier research [37], which involved the assessment of the mechanical properties of the geopolymer mortar mixes. Table 1 presents the inventory analysis necessary for assessing the environmental impact of each mortar mix. This inventory includes raw materials such as fly ash, WCBP, GGBFS, sand, sodium silicate, sodium hydroxide, electricity used for manufacturing mortar samples, and transportation for the five different mortar mixes. It also specifies the source of material procurement. Curtin University was the site for manufacturing the geopolymer mortars. The transportation distance for different construction materials was between Curtin and the origins of these materials. The amount of WCBP differed in every trial, as the objective was to evaluate and contrast the mechanical properties of individual sample with varying proportions of WCBP.

Table 1. Life cycle inventory of geopolymer mortar samples (mix proportions taken from Sharmin et al. [37].)

Ingredients	Source Address	Distance (km)
GGBFS	BGC Cement, Address 32 Beard St, Naval Base, WA, 6155, Australia	33
Fly ash	Collie, WA	152
WCBP	192 Hope Valley Rd, Hope Valley, WA 6165	31
Sand	Baldivis sand quarry, WA	55
Sodium hydroxide pellets	Coogee Chemicals Pty Ltd., Kwinana beach, WA 6167	36
Sodium silicate solution	11 Challenge Boulevard Wangara WA 6065 Australia	35

Constituents	Mortar Mixes				
	CM	W10	W20	W30	W40
Fly ash (kg/m^3)	673	596	518	440	361
GGBFS (kg/m^3)	119	119	119	119	119
WCBP (kg/m^3)	0	80	160	240	321
Fine aggregate—sand (kg/m^3)	1268	1271	1275	1279	1282
Sodium hydroxide pellets (kg/m^3)	57	57	57	57	57
Sodium silicate solution (kg/m^3)	238	238	238	238	238
Total kg/m^3	2355	2361	2367	2373	2378
Transportation (t km)	187.35	148.66	121.98	106.99	100.79
Manufacturing (kWh)	10	10.03	10.06	10.08	10.11

2.3. Life Cycle Impact Assessment (LCIA)

The data derived from the inventory analysis for each mortar mix were manually input into the SimaPro 9.2 LCA software. Subsequently, these input values were linked to the appropriate emission factor database. In most cases, the emission database from Western Australia was utilized for the inputs to accurately reflect the local environmental conditions. Distinct profiles were established for each unique geopolymer mortar mix, each accounting for its specific environmental impacts stemming from mining, transportation, and the construction stage. A novel database specific to WCBP was developed from the experimental work conducted by the authors at Curtin University for inclusion in the Simapro (version 9.2) software. This database was based on the data on energy consumption during the process of crushing brick pellets (i.e., to 0.2 kilowatt-hours per kilogram of waste brick aggregate crushed). Since all of these inputs cannot be calculated using an Australian input method, this prompted the use of SimaPro 9.2 with the methods recommended by Bengtsson and Howard [38] and Renouf et al. [39] for this study. Four distinct impact evaluation techniques specified in Table 2 were employed to assess the valuation of fourteen environmental impacts.

Table 2. Impact category to evaluate environmental impact.

Impact Assessment Method	Impact Category	Unit
Australian indicator set V2.01/Australian per capita.	Global warming	kg CO_2
	Eutrophication	kg PO_4^{3-} eq
	Land use	Ha a
	Water use	M^3 H_2O
ReCiPe Midpoint (E) V1.12/Europe Recipe E	Ozone depletion	kg CFC-11 eq
	Terrestrial acidification	kg SO_2 eq
	Human toxicity	kg 1,4-DB eq
	Photochemical oxidant formation	kg NMVOC
	Terrestrial ecotoxicity	kg 1,4-DB eq
	Freshwater ecotoxicity	kg 1,4-DB eq
	Marine ecotoxicity	kg 1,4-DB eq
	Ionizing radiation	kBq U235 eq
CML-IA baseline V3.03/EU25	Abiotic depletion	kg Sb eq
TRACI 2.1 V1.03/Canada 2005	Respiratory effects	kg PM2.5 eq

Note: CO_2—carbon dioxide; PO_4^3—phosphate; eq—equivalent; Ha a—hectare years; CFC—chlorofluorocarbon; NMVOC—non-methane volatile organic compounds; U235—uranium 235; Sb—antimony; SO_2—sulfur dioxide; PM—particulate matter.

2.4. Life Cycle Cost Analysis

Utilizing the identical inventory evaluation, an economic assessment was conducted to ascertain the unit cost for five mortar mixtures. Consistency between economic and environmental evaluations was maintained by using the same functional unit as in the life cycle assessment, expressed in Australian dollars per megapascal of compressive strength (AUD/MPa).

The cost data in Table 3 represent the prices of raw materials for producing geopolymer mortars. These costs are based on prevailing market prices in the local market of Western Australia. WCBP was directly sourced from the regional supplier "Red Sand Supplies", situated at 192 Hope Valley Road, Hope Valley, Western Australia 6165, known for specializing in recycled materials.

Table 3. Prices of raw materials.

Raw Materials	Cost (AUD) per Ton Material
FA	135
GGBFS	300
WCBP	55
Sand	31.3
SS	834
SH	800

The cost of transportation was approximated at AUD 0.09 per ton–kilometer for road freight in accordance with the details provided by the Australian Government Department of Infrastructure and Regional Development [40]. The electricity cost during the manufacturing process was derived from publicly accessible information published on the Synergy website [41]. It was assumed that the electricity tariff corresponded to the Synergy business plan and was priced at 36.15 cents per unit (equivalent to 1 kWh) [41].

The total estimated life cycle cost for each of the mortar mixtures is presented in Table 4. This cost encompassed material costs, transportation expenses based on the t-km of materials in the LCI, and electricity costs for operating the mixing and compacting processes. It is worth noting that the labor costs were avoided as the author prepared these mixes as a part of their PhD project. The overall life cycle cost was subsequently divided by the corresponding compressive strength of the mixes to determine the cost in AUD per megapascal of compressive strength (AUD/MPa).

Table 4. Total cost of 1 m^3 geopolymer mortar sample.

Geopolymer Mortar Mix	Material Price (AUD)	Life Cycle Cost (AUD)
CMA	408	426
W10A	403	417
W20A	397	409
W30A	392	402
W40A	386	396

2.5. Techno-Eco-Efficiency Framework

Portfolio analysis is involved in the development of environmental and economical portfolios of structurally and technically sound mixes. This techno-eco efficiency combined the effects of both the economic and the environmental values to ascertain the eco-efficiency portfolio positions of technically sound mortar mixes in this study. To standardize the environmental impact data acquired from the Simapro software, it was necessary to normalize these impacts by dividing them by the corresponding impact values for a particular region. The normalized values of the impacts were multiplied by the corresponding weights to transform all impacts to the same unit (i.e., 'inhabitant equivalents') in order to combine them and achieve a unified environmental score for each mortar mix [42]. This study utilized the environmental impacts of Australia's gross domestic product (GDEI) (Bengtsson and Howard) [38] and corresponding weighting factors (WF) (Biswas) [42], as outlined in Table 5, to convert all impact values to a common unit, i.e., per inhabitant equivalent.

Table 5. The gross domestic environmental impact and weighting factor for environmental impact.

Impact Category	GDEI per Inh	WF
Global Warming	28,690	20%
Eutrophication	19	3%
Land use	26	21%
Water Use	930	6%
Ozone depletion	0.002	3%
Terrestrial acidification	123	7%
Human toxicity	3216	8%
Photochemical oxidant formation	75	10%
Terrestrial ecotoxicity	88	4%
Freshwater ecotoxicity	172	3%
Marine ecotoxicity	12,117,106	3%
Ionizing radiation	1306	2%
Abiotic depletion	300	3%
Respiratory effects	45	8%

The normalized value (NEI_v) for each environmental impact of every geopolymer mortar mixture (g) was determined using Equation (1), where $EI_{v,g}$ is the environment impact values from the SimaPro software and $GDEI_{v.g}$ is the gross domestic environmental impact in terms of the amount of impact per Australian inhabitant per year.

$$NEI_{v,g} = EI_{v,g}/GDEI_{v.g} \tag{1}$$

The normalized values for all environmental indicators were combined by applying an Australian weighting factor that reflects the significance of each environmental impact under Australian conditions and was incorporated using Equation (2). Here, EI_g is the normalized environmental impact for each geopolymer mix and $WF_{v.g}$ is the weighting factor.

$$EI_g = NEI_{v,g} * WF_{v.g} \tag{2}$$

Much like the normalization process for environmental impacts, the overall life cycle costs associated with every mix were adjusted via the most recent Australian gross domestic product (Table 4). This adjustment allowed the presentation of costs in terms of the number of inhabitants generating an equivalent GDP per year [43]. $LCC_{v,g}$ is the life cycle cost for each geopolymer mix. The normalized cost (NC_g) was articulated as the number of Australian inhabitants generating an equivalent annual GDP (GDP_{cap}), as indicated by Equation (3) [44].

$$NC_g = LCC_{v,g}/GDP_{cap} \tag{3}$$

The author used a Shimadzu 300 kN Universal Testing Machine (Shimadzu Corporation, Kyoto, Japan) to conduct compressive strength tests on 28-day ambient cured geopolymer mortar samples (50 mm × 50 mm cubes) in accordance with ASTM C1437 [45]. The normalized environmental impact and cost were divided by the corresponding compressive strength values to derive the figures in relation to MPa.

The preliminary portfolio position environmental ($PP_{e,g}$) and economic ($PP_{c,g}$) impacts for the geopolymer mixes "g" were determined by comparing their normalized cost and environmental impact values against the average normalized values of cost and impact of geopolymer mixes using Equations (4) and (5) [44].

$$PP_{e,g} = EI_g/(\frac{EI}{j}) \tag{4}$$

$$PP_{c,g} = NC_g/(\frac{NC}{j}) \tag{5}$$

The calculated portfolio positions were fine-tuned by applying the environmental-to-cost relevance factor ($R_{e,c}$) outlined in Equation (6). Its purpose was to ascertain whether cost or environmental impact holds more significance in determining the eco-efficiency of geopolymer mix. This determination involved comparing the average normalized environmental impacts against the average normalized costs.

$$R_{e,c} = \frac{\sum EI}{j}/(\frac{\sum NC}{j}) \tag{6}$$

Finally, the initial positions are enhanced by the relevance factor to attain a revised spot that strikes an equilibrium between environmental impacts and life cycle costs, as depicted in Equations (7) and (8) [44].

$$PP'_{e,g} = [\frac{(\sum PP_{e,g})}{j} + \{PP_{e,g} - \frac{(\sum PP_{e,g})}{j}\} * \sqrt{(R_{e,c})_g}]/[\frac{(\sum PP_{e,g})}{j}] \tag{7}$$

$$PP'_{c,g} = [\frac{(\sum PP_{c,g})}{j} + \{PP_{c,g} - \frac{(\sum PP_{c,g})}{j}\} * \sqrt{(R_{e,c})_g}]/[\frac{(\sum PP_{c,g})}{j}] \tag{8}$$

where $PP'_{e,g}$ represents the refined environmental portfolio locus of geopolymer mix "g", while $PP'_{c,g}$ denotes the amended cost portfolio position of the same mixture.

Figure 3 illustrates a two-dimensional diagram depicting the normalized costs and environmental impacts for eco-efficiency analysis. This depiction is commonly referred to as the eco-efficiency portfolio. The horizontal axis represents normalized costs, while the vertical axis corresponds to environmental impacts. The scale ranges from the lowest numbers indicating the lowest impact and least cost to the highest numbers representing the highest impact and the highest cost values. The utmost eco-efficient option is identified by its space above the diagonal line, with the mix farthest from this diagonal line representing the most eco-efficient mix (Kicherer et al.) [44].

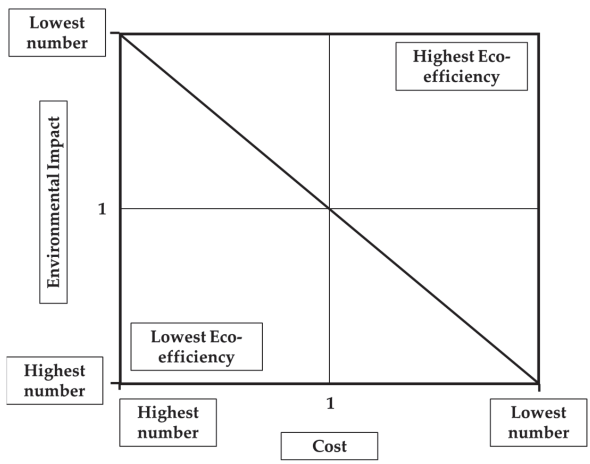

Figure 3. Eco-efficiency portfolio developed by Kicherer et al. [44].

This study used emission factors derived from both local and foreign databases for construction materials, which could affect the accuracy of LCA results to some extent. To address these uncertainties, a Monte Carlo simulation (MCS) was performed based on Clavreul's approach [46] to analyze uncertainties for each data point and forecast their influence on the LCA outputs for geopolymer mixes. The simulation process was performed for 1000 iterations for a confidence level of 95% [47].

3. Results and Discussion

3.1. Environmental Impact Analysis of Geopolymer Mortar Mix

Figure 4 illustrates the environmental impact analysis of five geopolymer mortar mixes in terms of the per inhabitant equivalent. The environmental impact is most pronounced in geopolymer mixes featuring 40% WCBP, followed by those with 30%, 20%, and 10% WCBP, as well as the CM mix, in that order. To provide specific percentages, the W40 sample exhibited a 1.7% higher environmental impact compared to the CM mix, W30 showed a 1.17% increase, W20 displayed a 0.69% rise, and W10 demonstrated a 0.31% increment.

Human toxicity emerged as the primary environmental impact, making up almost 95% of the overall impact across all geopolymer mixes. Subsequently, global warming constituted the second significant impact, contributing only about 2% to the total impact. The heightened inclusion of WCBP in geopolymer synthesis resulted in increased levels of both human toxicity and global warming impact. Specifically, the W40 sample demonstrated a 1.56% higher impact on human toxicity than the CM mix, while W30 showed a 1.07% difference, W20 indicated a 0.64% distinction, and W10 presented a 0.28% variation. Additionally, concerning global warming impact, the W40 sample exceeded that of the CM mix by 6.44%, with W30 showing a 4.55% difference, W20 indicating a 2.84% distinction, and W10 presenting a 1.32% variation.

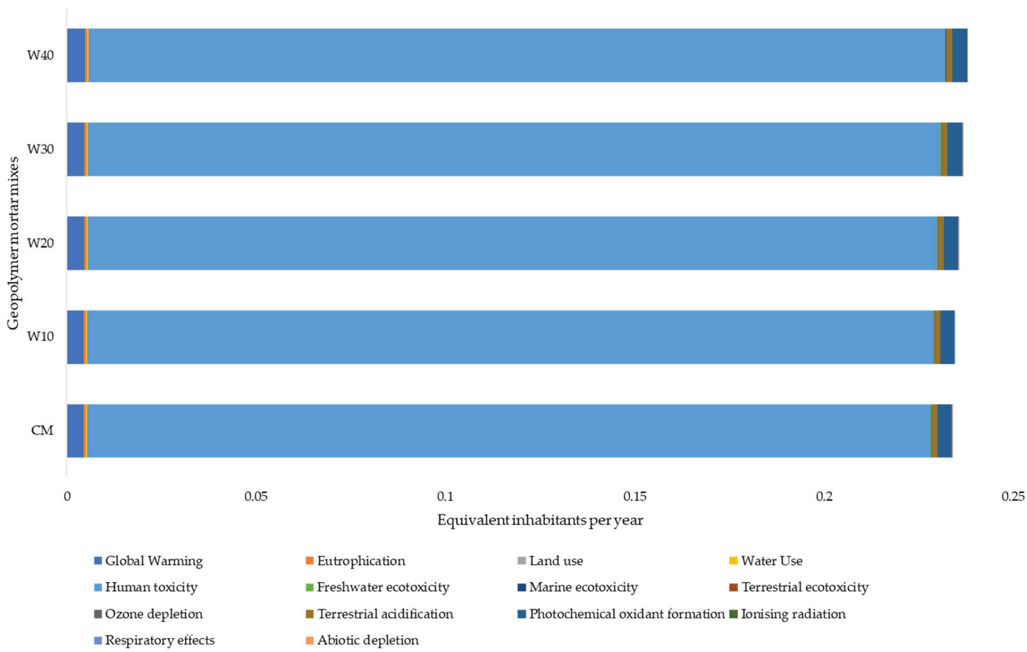

Figure 4. Environmental impacts per inhabitant equivalent of geopolymer mortar mixes.

Dynan et al. [35] also identified human toxicity as the dominant environmental impact category while performing LCA on geopolymer concrete using recycled glass aggregates. Li et al. [48] studied fly ash-based geopolymer concrete and observed that opting for fly ash geopolymer concrete over conventional alternatives can lead to a reduction in carbon emissions. However, this shift may result in an increase in other environmental impacts, specifically energy depletion in their specific scenario. Nikravan et al. [49] stated that alkali-activated geopolymer mixtures contributed to significant reductions in carbon emissions, although there were higher values in other environmental impact categories such as "marine eco-toxicity" and "ozone layer depletion".

In summary, substituting the conventional binder with the eco-friendly option in geopolymer binders has the potential to lower carbon dioxide emissions. However, this shift may lead to a significant increase in other environmental impacts due to the use of alkaline activators or grinding. Sbahieh et al. [50] confirmed that the geopolymer concrete has lower carbon emissions compared to OPC concrete during manufacturing, yet it presents minor adverse environmental effects, including abiotic depletion, human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, and acidification.

3.2. Hot-Spot Analysis

Figure 5 presents the flow network diagram for energy consumption for the CM and W40, created by SimaPro software. This flow network helps to identify the hotspots for each geopolymer mortar mix. In the case of the CM cured under ambient conditions, the mining to material stage was identified as the primary hotspot. This phase constituted 95.5% of the total energy consumption. Within this, 82.2% of the energy consumption was attributed to sodium silicate production at the batching plant, with an additional 9.04% stemming from sodium hydroxide production. In the case of the W40 mix, featuring a high WCBP content, 8.21% of the energy was consumed in grinding brick aggregate into WCBP. Subsequently, energy consumption was distributed as follows: 76.8% in the production of sodium silicate and 8.9% in the production of sodium hydroxide, both at the batching plant.

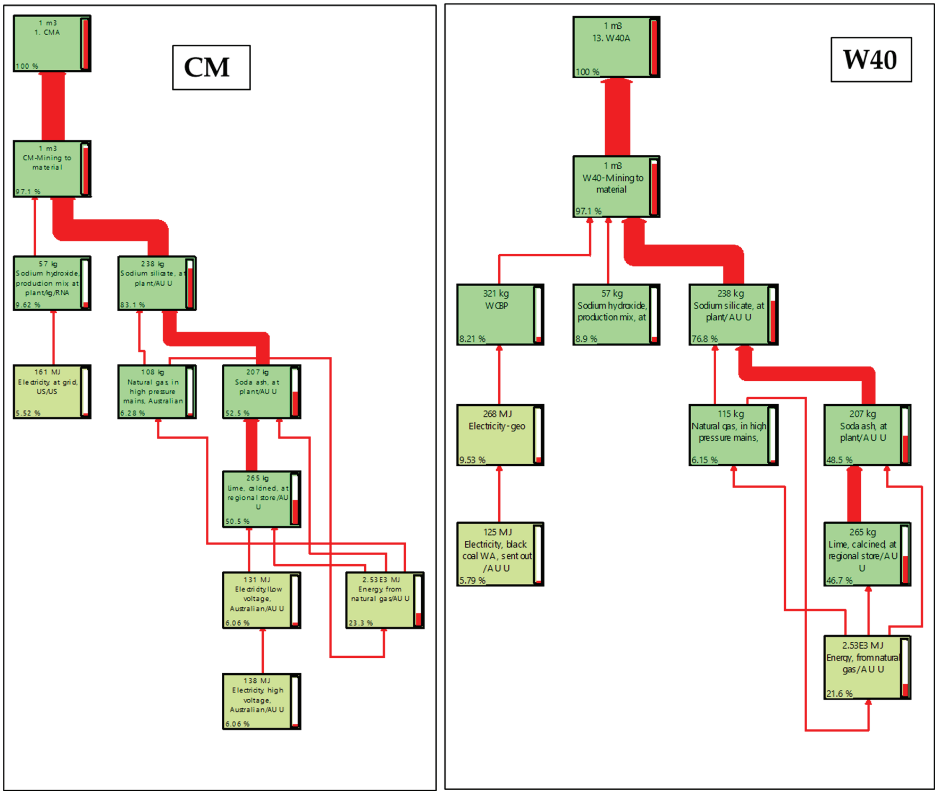

Figure 5. Hotspot analysis of geopolymer mortar mixes (CM and W40—left to right).

The results of this study are comparable with other studies, as Miyan et al. [29] found that recycled waste concrete consistently reduced carbon emissions, cumulative energy demand, and costs, where alkaline solutions are a hotspot accounting for a significant portion of the impacts [29,35,50]. Therefore, Munir et al. [51] obtained industrial-based geopolymer concrete with an improved environmental performance using lower quantities of sodium silicate.

In summary, the noteworthy energy hotspot in both the CM and WCBP-rich mixes is the production of sodium silicate, followed by the production of sodium hydroxide. Furthermore, in WCBP-rich mixes, 5–8% of the energy is utilized in the preparation of WCBP.

3.3. Monte-Carlo Simulation

Figures 6 and 7 depict the Monte Carlo analysis (MCA) of the major impact, "Human toxicity", as identified through LCA analysis, specifically for CM and W40. Table 6 presents the mean values and coefficients of variation (CV) for dominant environmental impacts resulted from the geopolymer mixes. The CV ranges from 0.82% to 1.85% for the primary impact "Human toxicity", suggesting that there is relatively low uncertainty in the calculated values for these impacts.

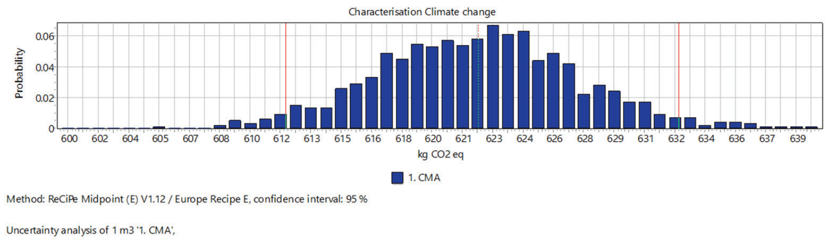

Figure 6. Monte Carlo simulation for human toxicity for CM.

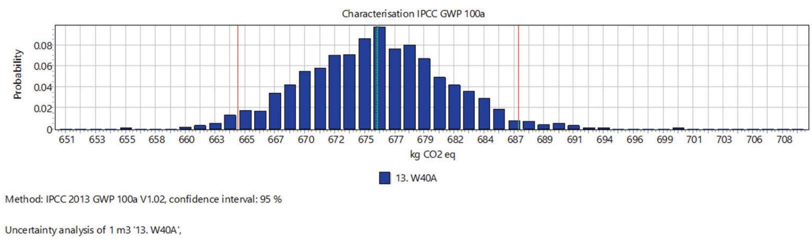

Figure 7. Monte Carlo simulation for human toxicity for W40 mix.

Table 6. Monte Carlo simulation outcome of LCA for three major impact categories in ambient cured geopolymer mixes.

Geopolymer Mix	Impact Category	Unit	Mean	CV (%)
CM	IPCC GWP 100a	kg CO_2 eq	635.27	0.89
CM	Human toxicity	kg 1,4-DB eq	8951.7	1.85
W10	IPCC GWP 100a	kg CO_2 eq	643.52	0.82
W10	Human toxicity	kg 1,4-DB eq	8979.66	1.75
W20	IPCC GWP 100a	kg CO_2 eq	653.12	0.83
W20	Human toxicity	kg 1,4-DB eq	9010.23	1.69
W30	IPCC GWP 100a	kg CO_2 eq	664.2	0.84
W30	Human toxicity	kg 1,4-DB eq	9048.77	1.71
W40	IPCC GWP 100a	kg CO_2 eq	675.5	0.84
W40	Human toxicity	kg 1,4-DB eq	9091.85	1.67

3.4. LCC Analysis

Figures 8 and 9 show the breakdown of LCC analysis for CM and W40 geopolymer mixes, respectively. In the study of the both CM and WCBP-rich sample, the cost analysis revealed that the costs of alkaline activator had the most significant influence, contributing to 95.9% and 97.6%, respectively, of the total material expenses. This cost was further broken down to identify the cost hotspot. Sodium silicate, constituting 48.56% of the cost for CM and 51.3% of the cost for W40, was identified as the hotspot, followed by sodium hydroxide (19.38% for CM and 20.47% for W40). The slightly elevated cost of fly ash is accountable for the increased expenses in the CM sample compared to the WCBP-rich samples.

The results of the current study are comparable with other studies, as alkaline activators have previously been found to be the economic hotspot. Singh et al. [52] also found that alkaline activators like sodium hydroxide and sodium silicate have the highest cost among all the raw materials used in geopolymer production. Fernando et al. [53] revealed that the use of alkaline activators accounted for 74% of the total initial cost for both fly ash geopolymer and blended alkali-activated concrete. Ramagiri et al. [54] showed that the contribution of alkaline activators to the total cost of the geopolymer binders ranged from 39.24% to 47.95%, highlighting that the absence of conventional activators in geopolymers leads to a cost-effective and environmentally sustainable mix. Therefore, this could affect the eco-efficiency performance of the geopolymer mixes, which is further investigated in Section 3.5.

To summarize, the expenditures associated with alkaline activators, specifically the prices of sodium silicate and sodium hydroxide, had the most significant impact on all geopolymer mixes.

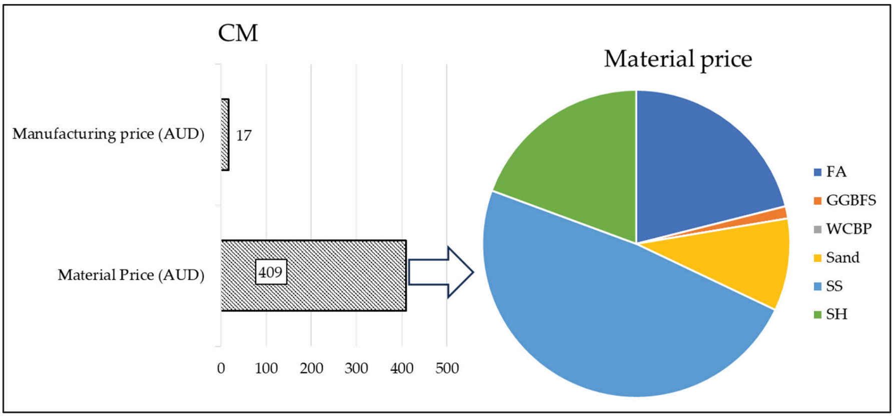

Figure 8. Breakdown of LCC analysis of the CM geopolymer mix.

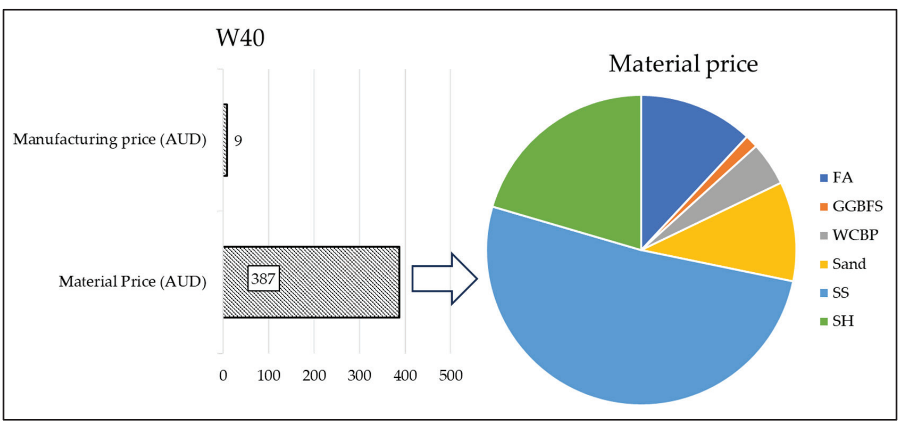

Figure 9. Breakdown of LCC analysis of the W40 geopolymer mix.

3.5. Techno-Eco-Efficiency Analysis

Table 7 presents the 28-day compressive strength results sourced from the author's previous study [37]. The compressive strength of each geopolymer mortar mix surpassed 40 MPa after a 28-day curing period, indicating their potential for use in structural applications. The geopolymer mortar mix incorporating 40% WCBP demonstrated the highest compressive strength among all the mixes. Following closely were the mixes containing 30%, 20%, and 10% WCBP and the control mix. This consistent trend strongly affirms the technical feasibility and effectiveness of employing WCBP as a solid precursor in the formulation of a geopolymer binder.

The analysis began by normalizing the characterized values of the environmental impact for each geopolymer mix using Equations (1) and (2). These normalized values were then multiplied by the corresponding weights and then by the corresponding compressive strength values presented in Table 7 in order to obtain all environmental impact values in terms of compressive strength (MPa). Similarly, the life cycle cost was also subjected to normalization, following a specific equation (Equation (3)). The resulting normalized cost figures were then divided by the respective compressive strength values from Table 7. This division aimed to ascertain the cost value per unit of compressive strength (MPa). The findings are presented in Table 8, illustrating the normalized environmental impact value per MPa (EI/MPa) and the normalized life cycle cost value per MPa (Costs/MPa) for a 1 m cube of the geopolymer mortar mixture. Notably, the study observed a trend where the costs/MPa reduced as a proportion of WCBP in the geopolymer mix increased. This reduction was primarily attributed to the lower material price of WCBP. On the other hand, although WCBP-rich samples have a high environmental impact arising from the grinding process, the EI/MPa exhibited a decrease with a higher content of WCBP in the mix. This decrease was due to the high compressive strength of WCBP-rich samples than the control one.

Table 7. Compressive strength of geopolymer mortar mix [37].

Geopolymer Mix	28 Days Compressive Strength (MPa)
CM	72.38
W10	72.73
W20	78.86
W30	81.41
W40	91.87

Table 8. Techno-eco-efficiency outcome of 1 m^3 geopolymer mixes.

Geopolymer Mix	EI/MPa	Costs ($)/MPa	$PP'_{e,g}$	$PP'_{c,g}$
CM	0.0032	5.89	1.0019	1.0031
W10	0.0032	5.74	1.0019	1.0024
W20	0.0029	5.19	0.9999	0.9999
W30	0.0029	4.95	0.9993	0.9988
W40	0.0025	4.32	0.9832	0.9881

The environmental to cost relevance factor, calculated as 0.000573 (which is less than 1), suggests that the financial cost outweighs the environmental impact in the analysis [43]. Following the calculation of initial portfolios ($PP_{e,g}$ and $PP_{c,g}$) using Equations (4) and (5), the refined portfolio positions ($PP'_{e,g}$ and $PP'_{c,g}$) were determined using the environment to cost relevance factor through Equations (7) and (8).

Subsequently, Figure 10 illustrates the techno-eco-efficiency portfolio for geopolymer mortar mixes. According to the portfolio analysis, W20, W30, and W40 geopolymer mixes exhibited techno-eco-efficiency, while CM and W10 samples are deemed not technologically and economically efficient. Despite the higher environmental impact observed in WCBP-rich samples outlined in Section 3.1, the EI/MPa values declined with an increasing WCBP percentage in geopolymer mortar mixes, owing to their elevated compressive strength. For instance, the W40 sample exhibits a total normalized environmental impact of 0.24 with a compressive strength of 91.87 MPa, while the CM has a total normalized environmental impact of 0.23 with a compressive strength of 72.38 MPa. Consequently, the EI/MPa value for CM is greater than that of the W40 sample.

The comparison between the W40 sample and the CM sample reveals a decrease in the EI/MPa value, dropping from 0.0032 to 0.0025. This indicates a favorable environmental impact per unit of compressive strength for the W40 sample. Additionally, the WCBP-rich samples exhibit lower costs (AUD)/MPa values due to their economical material pricing. Consequently, the $PP'_{e,g}$ and $PP'_{c,g}$ values surpass 1 for the CM and W10 samples, suggesting higher environmental and cost impacts. In contrast, the W20, W30, and W40 samples boast values below 1 for both indicators, establishing them as superior performers among the five mixes in terms of the environmental impact and cost-effectiveness.

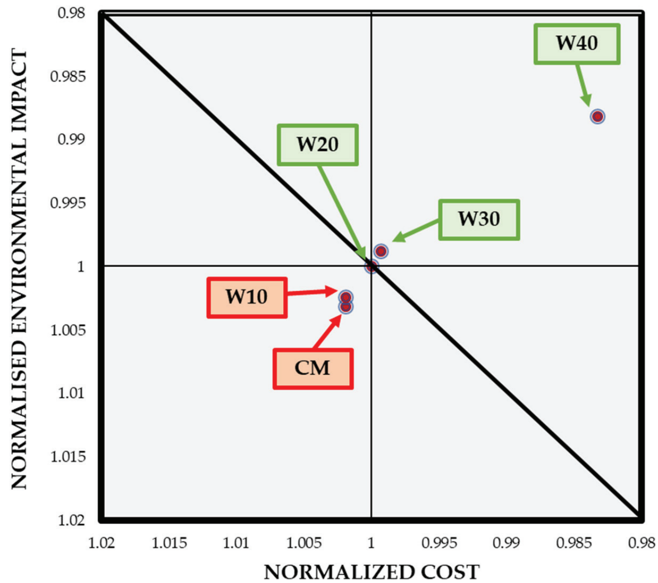

Figure 10. Techno eco-efficiency portfolio for geopolymer mixes.

4. Conclusions

This study was undertaken to assess the techno-eco-efficiency of WCBP-based geopolymer mortars, particularly focusing on the substitution of fly ash with WCBP in ambient cured conditions. The environmental impact was higher for the WCBP-rich sample (up to a maximum of 1.7% for W40) compared to the CM containing 0% WCBP. Among the fourteen impacts studied, human toxicity emerged as the dominant environmental impact, accounting for around 95% of the impact across all the mixes, followed by global warming at 2%. Similar outcomes have been demonstrated in prior studies on glass aggregate-based geopolymer concrete [35].

Next, the primary area of concern was pinpointed, specifically the energy utilized in the production of alkaline activators at the batching plant, which emerged as a significant factor across all geopolymer mixes. Simultaneously, the activity of grinding brick aggregate into WCBP consistently stood out as a crucial hotspot in the geopolymer mortar mixes that incorporated WCBP. These findings emphasize the critical role of these processes in the overall energy consumption and environmental impact of geopolymer production. Prior research has demonstrated analogous findings for alkali-activated geopolymer mix [33].

In the case of LCC, the examination revealed that the greatest cost contributor for all geopolymer mortar samples was associated with alkaline activators, specifically sodium silicate and sodium hydroxide. These components stood out as the primary factors influencing the economic aspects of the geopolymer production process. Furthermore, in the case of WCBP-rich samples, the total cost was found to be lower than that of the CM. This cost reduction is attributed to the economical pricing of WCBP, signifying its potential as a cost-effective alternative in the formulation of geopolymer mortars.

Eventually, the geopolymer mixes enriched with WCBP—namely W40, W30, and W20—were recognized as technologically and economically efficient (techno-eco-efficient). This designation is attributed to their favorable combination of higher compressive strength and lower costs. On the contrary, both the CM and W10 mixes were not considered eco-efficient due to their lower compressive strength and higher associated costs. This conclusion underscores the importance of both mechanical performance and economic considerations in determining the overall efficiency of geopolymer mixes. Future studies should integrate solutions to treat the hotspots to further enhance the techno-eco-efficiency of geopolymer mixes.

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Article

Investigation of Load-Bearing Capacity for Reinforced Concrete Foundation Retrofitted Using Steel Strut–Tie Retrofit System

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Abstract: To reduce the thickness of reinforced concrete foundation members used in construction and structural applications, a previous study developed and tested a strut–tie retrofit system installed in the foundations. This study proposes the optimum retrofit details of a steel-tie retrofit system for foundation members with reduced thickness via a finite element simulation-based load-bearing capacity assessment. The retrofit parameters (structural steel type, plate thickness, and number of strut frames) that significantly affected the load-bearing capacities were optimized by comparing the maximum effective stress and code-defined allowable stress limits. The optimum retrofit details were compared with those computed using a code-defined strut–tie model. Based on the load-bearing capacity assessment for the design of loading combinations, the optimum retrofit details can be reduced in transverse (by 55%) and longitudinal (by 87%) directions compared with those designed using the strut–tie model approach.

Keywords: reinforced concrete foundation; steel strut–tie retrofit system; load-bearing capacity assessment; nonlinear finite element simulation

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1. Introduction

1.1. Background

In general, the foundation members of bridges and building structures that are in direct contact with soil transmit shear and bending moments from the structures to the soil. Because building and bridge structures have recently become larger, the loads acting on foundation members have increased significantly. The increased loads, in turn, increased the thickness of the foundation members. In particular, the foundation members that resisted various loading types (e.g., axial force, shear force, and bending moment) acting on the column bases suffered from stress concentration, which contributed to an increase in the thickness of the foundation [1,2].

An increase in thickness of the foundation can lead to the following problems: (1) extensive ground excavation; (2) an increase in steel reinforcing bars; (3) thermal cracks in concrete; and (4) extensive CO_2 emissions [1–8]. Owing to the increase in thickness of the foundation, the volume of excavation must be increased, which leads to technical difficulties (e.g., rock crushing, equipment movement, and backfilling) during construction [3]. For deep foundation members, the number of steel reinforcing bars that resist the loads acting on the column bases needs to be significantly increased compared with other foundations. Accordingly, the labor and construction periods can be increased to manufacture a large number of reinforcing bars. Another problem is the control of thermal cracks in concrete members. During the concrete's curing time, the hydration heated in the foundation members is emitted; consequently, the hydration heat emissions produce the thermal cracks in the concrete. To control thermal cracks occurring in deep foundation members, a pipe cooling system that decreases hydration heat is often installed [4]. This additional process can lead to longer construction periods and higher costs. Finally, the extensive use of concrete materials owing to the increase in foundation depth causes an environmental impact because the production of the concrete material (raw material cement) is energy-intensive and generates a large amount of emissions of CO_2 [5,6]. Therefore, a method to reduce the thickness of the foundation is required.

In previous research [1], a steel strut-type retrofit system installed in the foundation was developed to resolve the structural and construction problems in foundations. Using this retrofit system, the localized concentrated load acting on the pier was uniformly distributed to the ground throughout the foundation. This retrofit method entailed the formation of a steel plate with higher strength and machinability than concrete into an arch and its installation on the base of the columns. Tension ties fixing the arch shape were prefabricated into a unit with the strut-type retrofit system and installed at the base of the columns to reduce the thickness of the foundation. Subsequently, the excavation and construction time for the foundation could be reduced because of the decreased amount of concrete and reinforcing steel. The use of jet-grouted micropiles in foundation members enhances the mechanical properties of soils and mitigates the liquefaction potentials induced by seismic loads. The effectiveness of this novel approach was verified using cone penetration test (CPT) and a standard penetration test (SPT)-based liquefaction assessment methods [9]. A previous study [6] investigated the load-bearing capacities of piled raft foundations (PRFs) with respect to various parameters (pile length, pile diameter, and raft thickness) using finite element (FE) analyses. A previous numerical study [10] demonstrated that the selected parameters significantly affected the reduction in the total and differential settlements, as well as the shear and bending moments on the raft. Recently, Stone et al. [11] optimized the details of a new composite foundation system with a caliche-stiffened pile (CSP) based on FE simulations. The optimum pile length was proposed without enhancing soil properties in a cost-effective manner. In addition, the CSP foundation member can reduce pile settlement.

The strut retrofit system used in this study represents the shape of the strut–tie model (STM) formed by the loads acting on the member. Figure 1 shows the basic configuration of the strut retrofit system. The arch-shaped strut frame transfers the compressive force acting on the column to the base of the foundation. The tie bar is installed to resist bending and tension [12,13]. In this study, we investigated the foundation member where the steel strut–tie retrofit system was applied. The results showed that the steel strut reinforcement improved the strength by over 60% compared with non-retrofitted foundation members. Thus, it was demonstrated that the strut reinforcement was effective in reducing the thickness of the foundation.

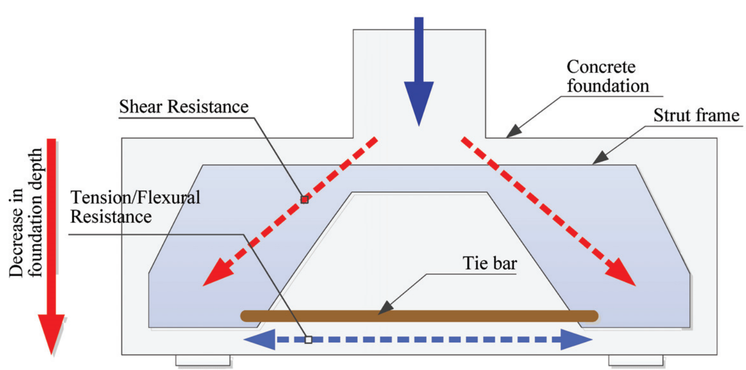


Figure 1. Reinforced concrete foundation installed with a strut–tie retrofit system.

The steel strut retrofit system used in this study was designed using the STM method for the load acting on the steel concrete column. The STM method is a truss model that is based on the application of plasticity theory and force equilibrium conditions. It is an efficient method for shear design in the load disturbance zone of a member [14]. The STM method accurately identifies the force flow. Therefore, the load-bearing capacity of the load disturbance zones can be determined more reasonably.

1.2. Research Purpose

This study proposes the optimum details of a steel strut–tie retrofit system for foundation members through a load-bearing capacity assessment. To accomplish this, a strut retrofit system with a thickness equal to 80% of that of a typical RC foundation was designed for mat and pile foundations using the STM method. Subsequently, a nonlinear FE analysis was conducted for an RC foundation incorporating a strut retrofit system. Furthermore, the load-bearing capacities of the foundation members were evaluated regarding the flexural moment and shear force. In addition, optimum retrofit parameters for the strut plate thickness that significantly affect the flexural performance were recommended for the given loading scenarios.

2. Design of Steel Strut Using Strut and Tie Model

2.1. Strut and Tie Model Approach

The STM approach is a shear design method that applies the truss model. It is formed based on the force flow and load distribution that are generated when a load is applied to a structure. As shown in Figure 2, the STM is composed of the strut, representing the compressive force of the structure, the tie, representing the tensile forces, and the nodal region where the strut and tie come in contact. This design method is applied in RC structural members with complex load distributions owing to corbels, joints, and deep beams. This method designs the structural details based on the load distribution. Therefore, it facilitates the application of new designs unlike conventional empirical equations derived from experimental studies [15–17]. In this study, a strut–tie retrofit system was designed according to the loading distribution on the foundation elements (unlike conventional foundation members composed of concrete, flexural, and shear reinforcements) and applied on the foundation within the concrete. Therefore, the thickness of the foundation could be reduced, compared with the case in which the conventional design method specified in current design codes was used [14,18], while maintaining the shear resistance performance.

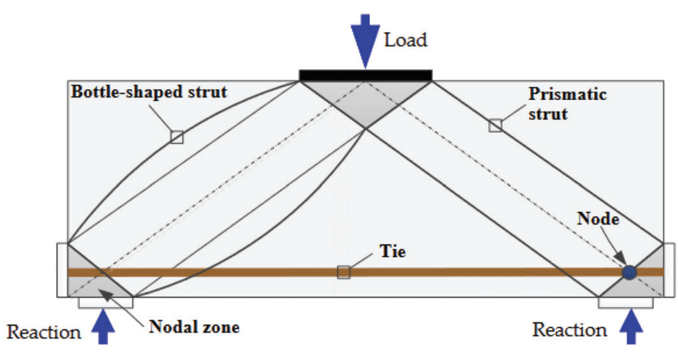


Figure 2. Strut–tie model (STM) in reinforced concrete member.

This study applies the existing STM design method to design a strut–tie retrofit system that can resist flexure and shear forces acting on the foundation. The application procedure of the design method is as follows:

(1) Develop an FE model to analyze the stress distribution for the given load combinations without the strut retrofit system.
(2) Propose a truss model (STM) for the longitudinal and transverse directions in a bridge structure based on the stress distribution of the FE model (STM shape determination).

(3) Calculate the axial forces of the compression and tension members of the truss model for each load combination.
(4) Design the strut based on the compressive axial forces (determine the required cross-sectional width and calculate the required number of struts).
(5) Design the tie based on the tensile force of the tension member (design the steel wire and reinforcement).

2.2. Design Process of Steel Struts and Ties

This section describes the design of a strut–tie stiffener for the load combinations presented in Table 1 according to the five-step design process mentioned in Section 2.1. The design information of the foundation considered in this study is presented in Table 2.

Table 1. Information on loading combinations in transverse and longitudinal directions.

Classification		Loading Combination	Shear (kN)	Axial Load (kN)	Moment (kN-m)
Transvers direction	Maximum axial load	LC-1	1265	54,229	21,027
	Maximum moment	LC-2	1265	51,656	21,027
	Earthquake	LC-3	2968	54,519	52,527
Longitudinal direction	Maximum axial load	LC-1	2431	54,229	180
	Maximum moment	LC-2	119	50,508	1945
	Earthquake	LC-3	5133	54,519	51,140

Table 2. Summary of design information of foundation.

Concrete Strength (f_{ck}, MPa)	Steel Reinforcing Bar		Steel Type	Tie (Steel Wire)		Foundation Thickness (mm)
	Yielding Strength (f_{sy}, MPa)	Diameter (mm)		Tensile Strength (f_{pu}, MPa)	Diameter (mm)	
35	400	29	SM490	1100	32	2000 (80% of typical foundation thickness)

Figure 3 presents an elastic FE model consisting of solid elements developed to estimate the loading distribution of the concrete foundation model subjected to the load combinations. LS-DYNA [19], a commercial nonlinear FE analysis program, was used to develop the FE model. The elastic FE model was modeled with the following dimensions: 7400 $\times$ 16,900 mm (the transverse and longitudinal directions, respectively). The thickness of the foundation was set to 2000 mm. This was 80% of that (2500 mm) computed using the conventional design method. Figure 3 presents an example of the loading distribution on the pile and mat foundations for the LC1-load combination. For the stress distribution, the sections on which the maximum effective stresses acted were analyzed. As shown in the figure, the stress was distributed diagonally along the depth of the foundation member relative to the loading point. It can be clarified that unlike the mat foundation, the stress within the concrete element (solid component) is distributed along the pile because the stress of the pile foundation is transferred to the piles.

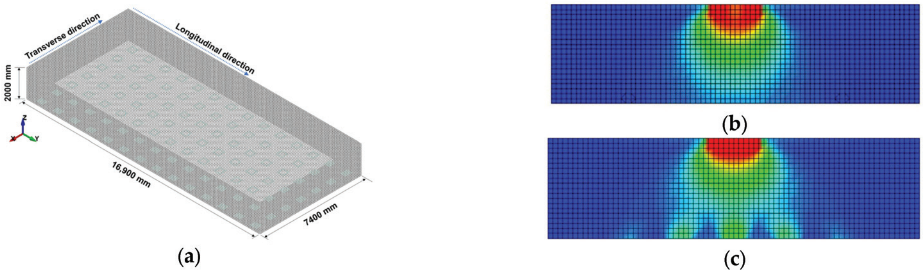


Figure 3. FE model with elastic material and effective stress distribution in the transverse direction. (**a**) Geometric finite element model. (**b**) Mat-type foundation. (**c**) Pile-type foundation.

The diagonal strut width (w_{sb}) was determined in order to design the strut frame. Here, θ indicates the angle between the strut and tension member of the foundation member. The width of the strut was determined as shown in Equation (1). Here, w_t is the tie width and l_b is the width of the tension point or support plate.

$$w_{sb} = w_t cos\theta + l_b sin\theta \tag{1}$$

In this design, the required member width (w_{req}) can be determined using the relationship between the member force and load (see Equation (2)). Here, β_s is the coefficient that considers the effect of the tie anchoring at the nodal point for the effective compressive strength of concrete. The bearing capacity of an individual strut can be calculated using Equation (3). The external force (axial force of truss member, F_u) and internal force (ϕF_{ns}) are compared to determine the number of strut members. The A_s (the total area of steel reinforcing bars) in Equation (3) represents the distance between the points (bs) upon multiplication with the thickness of the strut stiffener plate (t_{pl}).

$$w_{req} = F_u \ / \ (\phi 0.85 \ \beta_s \ f_{ck} \ bs) \tag{2}$$

$$\phi F_{nz} = (\phi 0.85 \ \beta_s \ f_{ck} \ w_{sb} bs + A_s f_y) \tag{3}$$

Finally, to design the strut member, the number of strut members is computed by comparing the required width (w_{req}) with the actual width (w_{sb}) of the strut. Based on this design, the required number of strut–tie frames for the LC-1 load combination in the transverse direction was calculated as four when the plate thickness was assumed to be 40 mm. Similarly, the number of required frames for the strut–tie retrofit design in the longitudinal direction was calculated to be three when the plate thickness was assumed to be 40 mm.

Finally, the tension ties were designed based on the axial force of the tension member calculated using the structural analysis of the truss model. The tension member comprises the steel wire and reinforcing bar connected to the strut–tie retrofit system. Equation (4) can be used to determine the number of steel wires (A_t) and reinforcement (A_s) based on the tensile force.

$$\phi f_{nt} = \left(A_s \ f_{sy} + A_t \ f_{ty}\right) \tag{4}$$

Table 3 summarizes the results for the strut–tie retrofit system determined using the strut–tie design method. The number of strut frames was calculated by modifying the plate thickness (t_{pl}).

Table 3. Summary of design information for strut–tie retrofitted foundation.

Direction	f_{ck} (MPa)	Size (mm)	Thickness (mm)	Strut Frame				Tie			
				Steel Type	Yielding Strength (MPa)	Plate Thickness (t_{pl}, mm)	Required Number	Tensile Strength (MPa)	Wire Diameter (mm)	Required Number
Transverse direction	35	7400	2000	SM490	315	40	8	1100	32	16
Longitudinal direction		16,900					3	1100	32	6

3. Finite Element Model

Figure 4 illustrates the geometric, material, and elemental information on the pile-type FE foundation model installed with the strut–tie retrofit system. The pile-type FE foundation model was fixed on the rigid elements in the all-direction sample representing the foundation piles. The mat-type FE foundation model differs from the pile-type model only in terms of the boundary condition location. The boundary condition on the mat-type model was adapted so the entire base resisted the load, excluding the rigid elements installed at the foundation base from the pile-type model. The solid elements composed of eight nodes were used for the concrete. The mesh size was set to 100 mm considering the computational time. The steel reinforcement was modeled with the Hughes–Liu beam element composed of two nodes, and the nodes of the reinforcement were separated from the concrete mesh nodes.

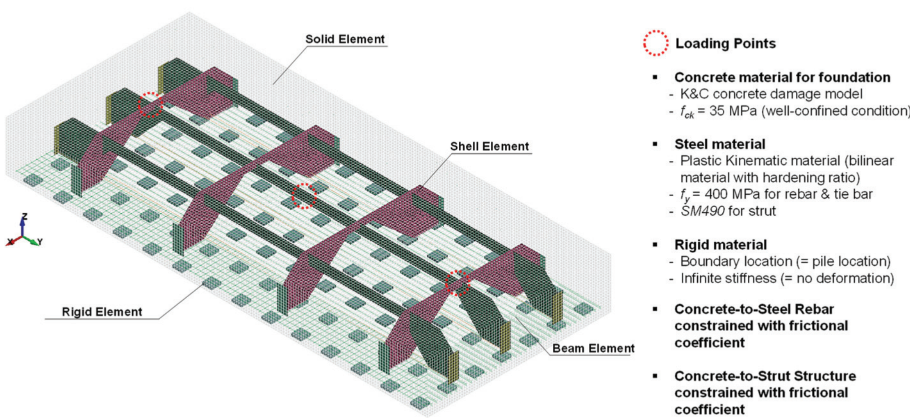


Figure 4. Pile-type finite element foundation model.

The concrete damage model of LS-DYNA (Karagozian and Case concrete model, KCC model) [20,21] was applied for the concrete material model used in this study. The KCC model has been widely used to analyze the element or building levels for explosions and earthquake loads. It can implement complex effects of confinement, strain hardening/softening, shear dilation, and stiffness reduction. The steel reinforcement was set to SD400 (f_{sy} = 400 MPa), and the steel type of the strut frame was initially set to SM490 (f_{ry} = 315 MPa). The yielding strength of the tie reinforcement was assumed to be 400 MPa. The plastic kinematic material model was used to depict the bilinear behavior of the reinforcement and strut frame, and the ultimate strength was reflected for the strain hardening. Tables 4 and 5 summarize the main material properties of concrete and steel reinforcing bars.

Table 4. Main parameters of concrete material.

Poisson's Ratio	Density (g/mm^3)	Compressive Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (MPa)	Max. Aggregate Size (mm)	Dilation Factor
0.16	0.0023	35	2.69	29937.9	6.35	0.8

Table 5. Main parameters of steel reinforcement material.

Type	Poisson's Ratio	Density (g/mm^3)	Elastic Modulus (MPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
D29 rebar	0.3	0.0078	206,000	400	512
SM490 strut	0.3	0.0078	206,000	315	490
φ47 steel wire	0.3	0.0078	206,000	400	512

The bonding condition between the beam elements and the surrounding concrete solid elements was modeled using the Constrained_Lagrange_In_Solid function of LS-DYNA. It can connect two models with the frictional force. This was conducted to develop the bond-slip effects that may occur after concrete damage occurs between the reinforcing bars and surrounding concrete. In general, the modeling approach shares nodes between the steel reinforcement and concrete models (node combination between two models). It effectively bonded the two models to depict the integrated behavior between the reinforcement and concrete models regardless of the concrete damage. Moreover, the method may exaggerate the behavior of RC structures. The FE models developed in this study implement the Constrained_Lagrange_In_Solid function that can reproduce the behavior between concrete and reinforcement with a friction coefficient to generate a realistic behavior between these elements [22–24]. The strut model from the strut–tie retrofit system was developed using a shell-type element with a mesh size of 100 mm. The beam element was utilized for the tie models (steel wire). The shell elements for the strut model set as a slave were coupled with the concrete solid elements set as a master using the Constrained_Shell_In_Solid function, which can control the bonding strength with the frictional coefficient. The steel reinforcing bars and steel strut–tie retrofit details in the FE foundation models were constrained using frictional forces between those steel materials and the surrounding concrete materials.

In this study, the boundary condition was differentiated to model the pile and mat foundations. A rigid element with infinite stiffness was used to model the location of the pile in the pile foundation. The boundary condition of each rigid component was set to be constrained in all the directions. In the mat foundation, the boundary conditions were set such that the bottom surface of the solid elements of the foundation could be constrained from all directions without rigid elements. To evaluate the serviceability of the strut–tie retrofit system, the service loads were applied to each load combination presented in Table 1, and a static nonlinear analysis was performed subjected to the loads. The loading locations in the FE model are indicated using a dotted red line in Figure 4. The loading locations were determined based on the pier shape.

4. Load-Bearing Capacity Assessment

4.1. Flexure Assessment

The FE models developed for the pile and mat foundations were used to perform a static nonlinear analysis for the service (design) loads presented in Table 1. The initial FE foundation models were designed according to the strut–tie design method. Here, the strut plate thickness (t_{pl}) was 40 mm, and the material was assumed to be SM490. In this section, the von Mises (VM) stress (effective stress) was evaluated based on the results of the FE analysis for the service loads. Consequently, the maximum effective stress computed from the VM stress distributions was used to determine the steel material type and plate thickness of the strut depending on whether the maximum effective stress of the steel strut exceeded the allowable stress limits specified in the design guidelines [25].

Figure 5 shows the VM stress distribution of the strut frame for the initial FE foundation models (with t_{pl} = 40 mm) computed with the nonlinear static analyses for each load combination. As presented in the figures, the maximum effective stress was observed in the transverse direction of the strut frame regardless of the load combination, and the stress concentration was detected at the loading points.

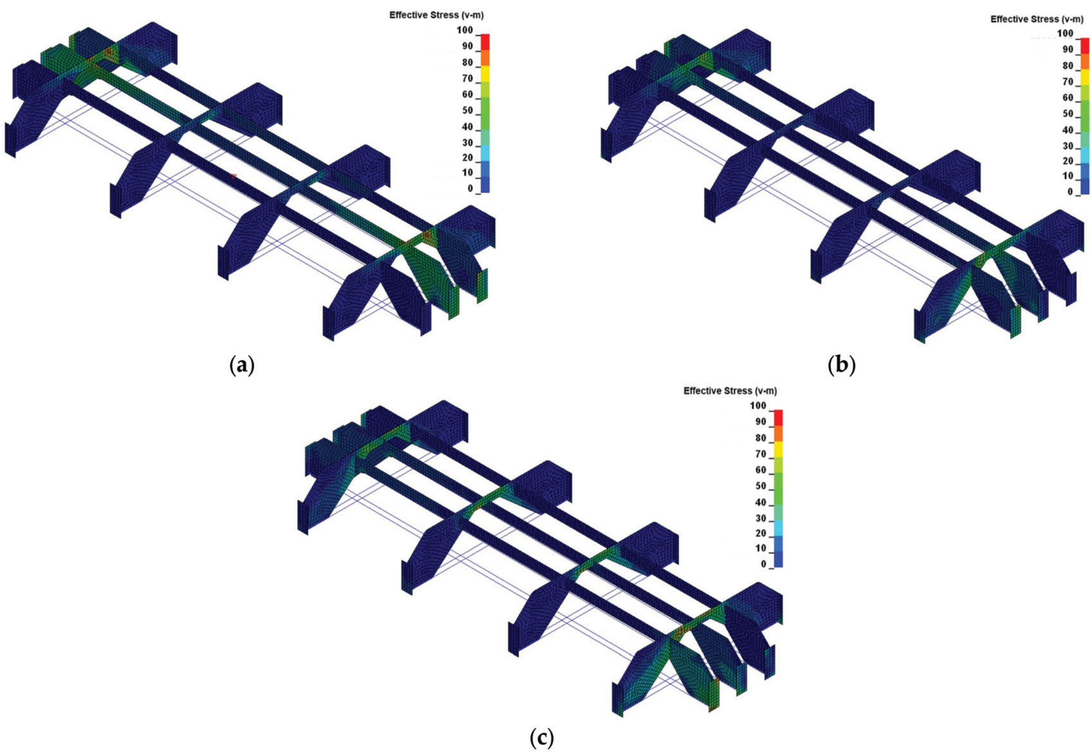


Figure 5. Effective stress distribution of strut–tie retrofit system. (**a**) LC-1. (**b**) LC-2. (**c**) LC-3.

The nonlinear static analyses of the FE foundation models while reducing t_{pl} from 40 mm to 10 mm were performed for each loading combination. Based on the FE simulations, the maximum effective stress for each loading scenario was compared with the permissible stress of structural steel (see Table 6), which was in compliance with the Railway Design Standard of the Ministry of Land, Infrastructure, and Transport published in 2015 [25].

Table 6. Summary of allowable stress for structural steel type [25].

Stress Type	**Plate Thickness**	**SS400 SM400 SMA400**	**SM490**	**SM490Y SM520 SMA490**	**SM580 SMA570**
Axial stress	≤40 mm	140 MPa	190 MPa	215 MPa	270 MPa
Flexural stress	≤40 mm	140 MPa	190 MPa	215 MPa	270 MPa

Figure 6 shows the relationship between the maximum effective stress and strut plate thickness for the pile and mat foundations in the LC-1 loading combination. Only the LC-1 loading scenario is presented in this paper because the maximum effective stress of the strut–tie retrofit system is observed in LC-1 among the loading combinations considered in this study. To determine the type of structural steel for the strut frame, the permissible stresses of SM490 and SS400 structural steels are also included in the figure. Overall, the maximum effective stress shown in the pile foundation model was higher than that for the mat foundation for all the loading combinations considered. Therefore, in this study, the plate thickness of the strut frame and type of structural steel were selected based on the LC-1 load combination for the pile foundation model by comparing the FE simulation-based VM stress with the code-defined permissible stresses. In addition, the reduction in the plate thickness caused the VM stress values on the strut–tie retrofit system to increase. This indicates that the initially assumed plate thickness (t_{pl} = 40 mm) can be reduced until the VM stress values are close to the permissible stress value to optimize the strut frame details.

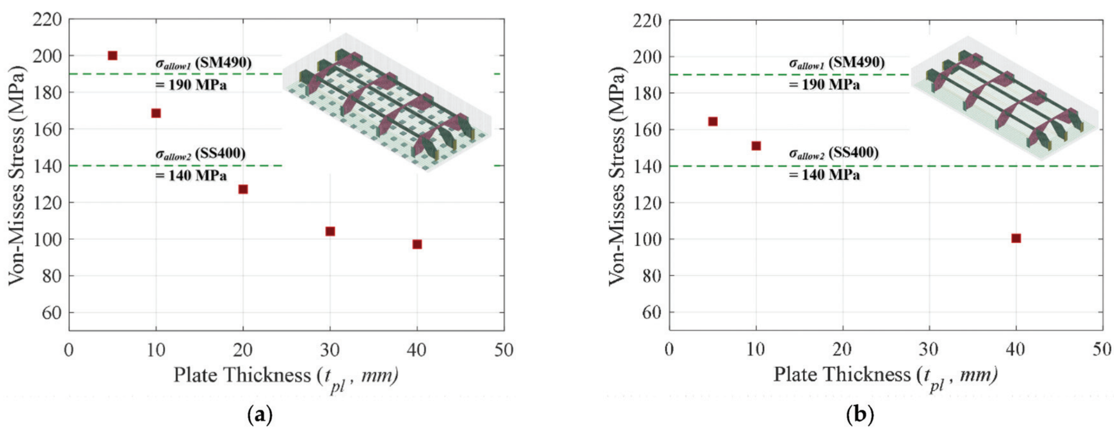
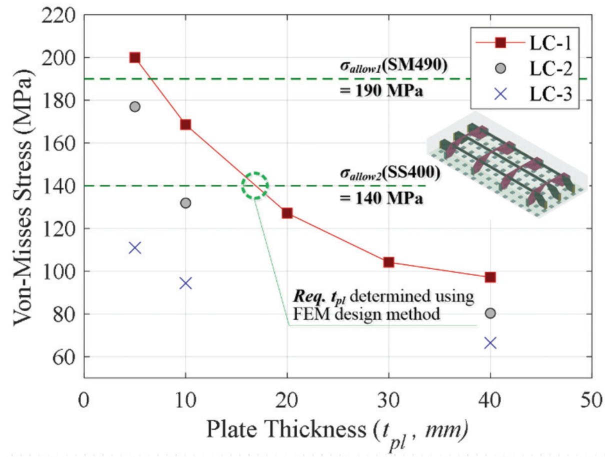


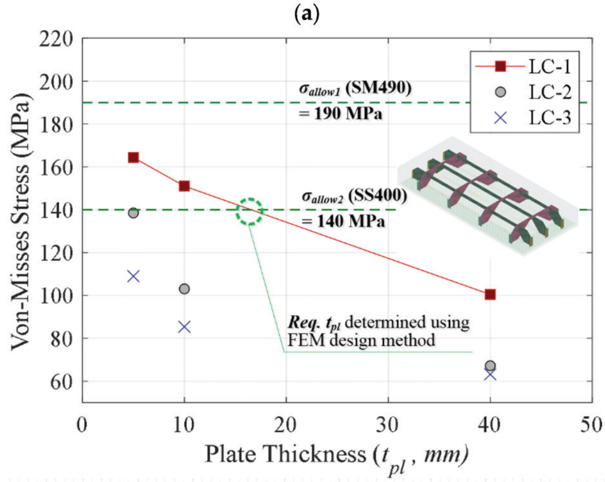
Figure 6. Maximum effective stress of strut frame with respect to plate thickness. (**a**) Pile-type. (**b**) Mat-type.

Figure 7 shows the maximum effective stress results with varying plate thickness for all the load combinations. For SS400 steel, the minimum plate thickness for the effective stress on the strut frame to be within the allowable stress was required to be at least 17 mm for the service loading scenarios. The optimum plate thickness computed using the FE simulations (FE simulation-based design method) was approximately 45% of the strut plate thickness (t_{pl} = 40 mm), which was determined based on the strut–tie design method. The FE simulation-based design method that determines the strut frame details considering the actual structural behavior is highly effective in reducing the material quantity as compared to the conventional code-defined design method.

The FE simulation-based design method introduced in this section significantly reduced the material quantity in the strut frame compared with the conventional code-defined design method. In addition, the maximum effective stress of the strut frame in the longitudinal direction was smaller than that in the transverse direction. Section 4.2 describes the implementation of the FE simulation-based design method considering the effective stress distribution, which can reduce the number of strut frames in the longitudinal direction, and further proposes the optimal strut–tie retrofit system.



(**a**)



(**b**)

Figure 7. Required plate thickness with respect to maximum effective stress. (**a**) Pile-type. (**b**) Mat-type.

4.2. FE-Simulation-Based Optimum Details

Figure 8 summarizes the procedure for deriving the optimum retrofit details. The initial retrofit details were proposed using the STM-based approach. Moreover, the retrofit details regarding the number of the strut frames and plate thickness were optimized using the flexural assessment. The flexural stress values computed using the FE foundation models with various strut frame numbers and plate thickness were compared to the code-defined allowable limits. After that, the FE foundation models with the optimum retrofit details were used to calculate the shear force with respect to the design loading combinations. The mean value of shear stress simulated from the FE models was compared with the allowable limits in transverse and longitudinal directions.

This section describes the estimation of the VM stress distribution (described in Section 4.1) of the FE foundation models after the number of strut–tie retrofit systems in the longitudinal direction is reduced from three to two. The LC-1 loading combination where the maximum stress values were found among the all-loading combinations was applied to the FE foundation models. The maximum effective stress of the FE models with the reduced plate thickness was compared with the code-defined allowable stress limits for each type of structural steel.

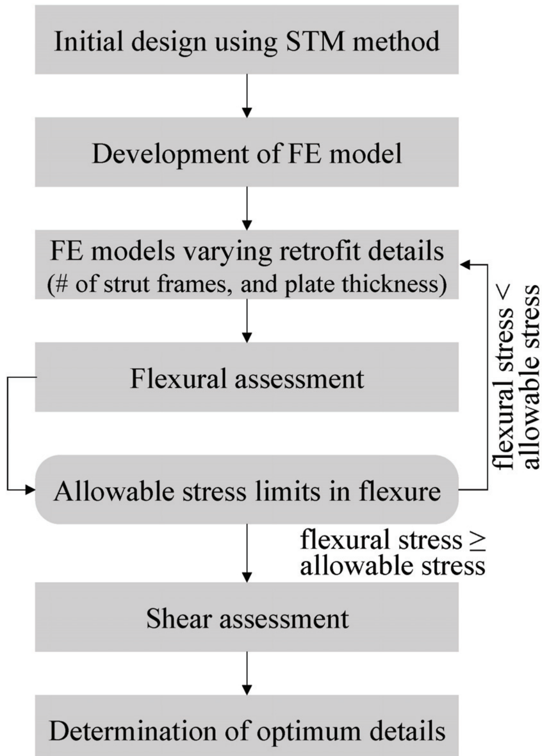
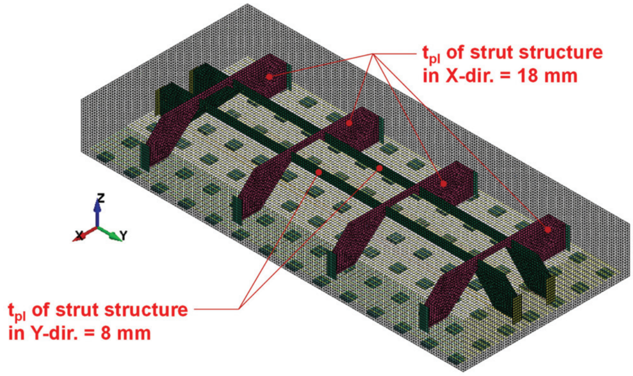


Figure 8. Optimum design procedure of strut–tie retrofit system.

Figure 9 shows the maximum effective stress of the FE foundation models under the LC-1 loading combination when the plate thickness was decreased from 40 mm to 10 mm. After the number of strut–tie retrofit systems (from three to two) was reduced, the plate thickness of the strut frame was set to approximately 18 mm so that the stress was close to the permissible stress of SS400. Using this FE-based design method, the required number of strut–tie retrofit systems in the transverse and longitudinal directions was determined to be four and two, respectively, and the required plate thickness of the strut frame was determined to be 18 mm. The detailed information regarding the reduced retrofit system is provided in Table 7.

Following the determination of the retrofit details of the strut–tie system, because the effective stress of the strut frame in the longitudinal direction was significantly lower than that of the strut frame in the transverse direction, the retrofit system was optimized by reducing the plate thickness of the strut frame in the longitudinal direction.

Figure 9 shows the effective stress of the FE foundation models after the plate thickness of the strut frame in the longitudinal direction is reduced to 8 mm. The plate thickness of the strut frame in the longitudinal direction was determined based on FE simulations with varying thickness values of the strut frame. Figure 9a illustrates the pile-type FE foundation model with the optimum plate thickness of the strut frame. As shown in Figure 9b, the maximum effective stress values of the strut frame in the longitudinal and transverse directions were less than the permissible stress (140 MPa) of SS400 structural steel notwithstanding the reduced plate thickness in the longitudinal direction.



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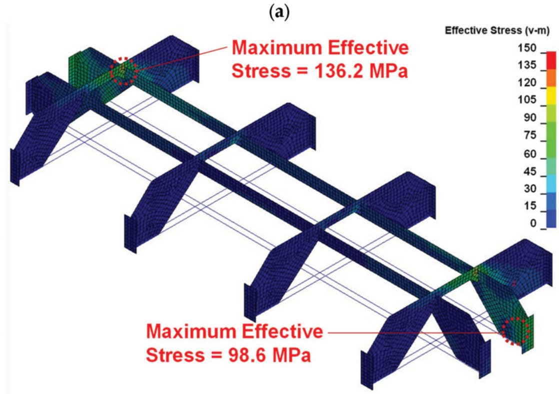

(**b**)

Figure 9. Effective stress distribution of foundation member with optimum retrofit details. (**a**) Finite element model. (**b**) Effective stress of strut–tie retrofit system under service load.

Table 7. Optimum details of strut–tie retrofit system.

Direction	Strut Frame				Tie		
	Steel Type	Yielding Stress (MPa)	Plate Thickness (mm)	Req. Number	Yielding Stress (MPa)	Steel Wire Diameter (mm)	Req. Number (Actual)
Transverse	SS400	235	18	4	400	50	7(8)
Longitudinal			8	2	400	50	6(6)

The optimum retrofit details determined using the FE-based design method are summarized in Table 8. These were compared with those of the strut–tie retrofit details computed using the conventional STM design method. The investigation revealed that the FE-based design method enabled reductions of approximately 55% and 87% in the transverse and longitudinal directions, respectively, compared with the retrofit details determined using the conventional STM design method. It should be noted that the quantities of the retrofit system were computed by multiplying the values for a unit volume of the retrofit system with the required numbers.

Table 8. Comparison between the initial and optimum design.

Direction	Initial Strut–Tie Retrofit System with STM-Based Design Method				Optimum Strut–Tie Retrofit System with FE-Based Design Method				Volume Reduction Ratio (%)
	Unit Area of Strut Frame (mm^2)	t_{pl} (mm)	Req. Number	Total Volume (mm^3)	Unit Area of Strut Frame (mm^2)	t_{pl} (mm)	Req. Number	Total Volume (mm^3)	
Transverse	6.62×10^6	40	4	1.06×10^9	6.62×10^6	18	4	4.77×10^8	55.0%
Longitudinal	9.96×10^6	40	3	1.15×10^6	9.96×10^6	8	2	1.53×10^8	86.7%

4.3. Shear Assessment

The pile-type FE foundation model with the optimum retrofit details evaluated the serviceability of the concrete elements in shear by comparing the maximum shear stress value with the code-defined limit. Figure 10 shows the stress distribution in the Z direction of the concrete solid elements in the transverse and longitudinal directions. This stress distribution reveals that unlike the conventional STM design method (i.e., resisting the shear forces with the strut–tie retrofit system), the retrofit system resists the shear with the concrete elements. To demonstrate the serviceability of the concrete elements under the shear forces, Figure 11 compares the shear stress values determined at the cross-sectional area where the maximum stress is observed with the maximum permissible stress of RC members with shear reinforcements ($\tau_{cc} = 0.37\sqrt{f_{ck}} = 2.19$ MPa) specified in a bridge design code [26,27]. The stress values calculated from the FE simulation were indicated as absolute values. Figure 10 shows that the stress concentration is observed at the loading points and pile locations. However, it is unreasonable to compare the shear stress values generated at certain specific elements with the permissible stress limit (2.19 MPa). Therefore, in this study, the current code-defined permissible stress was compared with the average stress values (indicated using red lines in the figure) of the solid concrete elements in the cross-sectional areas to ensure the serviceability of the concrete elements against shear forces. As shown in Figure 11, the average stress values calculated in the transverse (1.22 MPa) and longitudinal (1.52 MPa) directions did not exceed the permissible stress limits. The standard deviation (SD) values of the simulated data in transverse and longitudinal directions are 2.22 MPa, and 1.51 MPa, respectively. The 84th percentile values (mean + SD) in transverse and longitudinal directions were 3.44 MPa and 3.03 MPa, respectively. The 95th percentile values (Mean + 1.96 SD) is transverse and longitudinal directions were 5.57 MPa and 4.48 MPa, respectively. The 84th and 95th percentile values of the shear stress exceeded the allowable stress limit. This was attributed to the stress concentrations at certain specific elements, which were less than 30% of all solid elements in each direction.

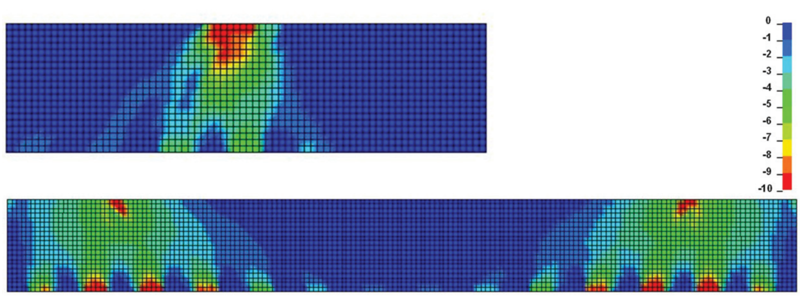

Figure 10. Z direction stress distributions in transverse and longitudinal directions.

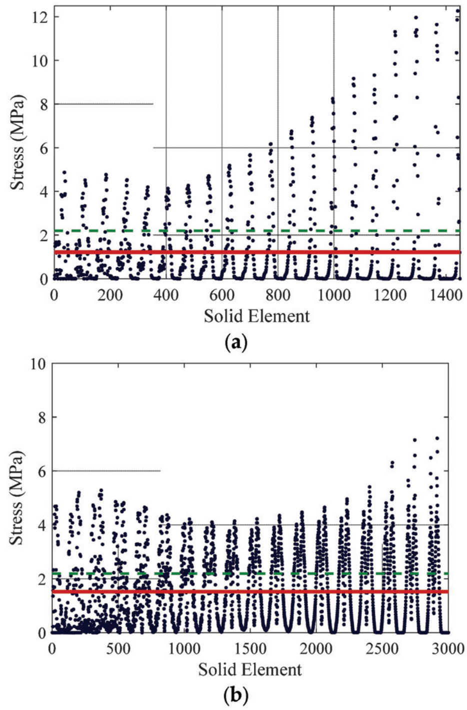

Figure 11. Comparison between Z direction stress and allowable shear stress. (**a**) Transverse direction. (**b**) Longitudinal direction.

5. Conclusions

This study proposed the optimum details of a strut–tie retrofit system for a deep-reinforced concrete foundation member with a reduced thickness. A retrofitting system was developed to minimize the consumption of concrete material (e.g., thickness of the foundation) in deep foundation members. Finite element (FE) models representing mat-type and pile-type foundation members strengthened with a strut–tie retrofit system were developed and simulated under various design loading combinations to estimate the corresponding load-bearing capacities. The initial design details of the strut–tie retrofit system in the foundation member were determined using a code-defined design method with a strut–tie model (STM), and were evaluated in terms of flexure behavior. Subsequently, the effective stress of the strut frame, computed using FE simulations, was compared with the code-defined allowable stress limits to optimize the steel type and strut plate thickness. Finally, the material quantities determined from FE simulations (FE-based design method) were compared with the conventional foundation details obtained using the STM-based design method. The following conclusions were drawn:

(1) The foundation with a strut–tie retrofit system developed using the STM-based design method specified in the current code reduced the thickness of the typical RC foundation by 20%. The numbers of strut–tie retrofit systems in the transverse and longitudinal directions when the strut frame thickness was 40 mm were four and three, respectively. In the FE simulations, the effective stress values obtained from the strut–tie retrofit system did not exceed the permissible stress limit for the LC-1 load combination where the stress values were maximized in all directions (approximately 70% of the permissible stress of LC-1 for SS400 structural steel).

(2) Based on the flexural assessment, a decrease in the plate thickness of the strut–tie retrofit system increased the effective stress in the retrofit system. A decrease in the

number of strut frames led to an increase in the flexural stress. This was attributed to the stress concentration caused by the decrease in the retrofit details. The flexural assessment of the foundation models with reduced material consumption in the strut–tie retrofit system continued until the strut frames exceeded the permissible stress limits specified in the current code.

(3) To optimize the design details of the strut–tie retrofit system (strut plate thickness and structural steel type), the FE simulation results (the maximum effective stress values) for the loading combinations were compared with the permissible stress specified in the current code. The FE simulation results with the loading combinations reveal that SS400 structural steel can be used. Furthermore, the strut plate thickness for the transverse direction (wherein the stress rate is higher than that in the longitudinal direction) is 18 mm. Although the number of strut–tie retrofit systems was reduced from three to two in the longitudinal direction, which had a lower load distribution rate than the transverse direction, the maximum effective stress of the retrofit system did not exceed the permissible stress of the structural steel type until the plate thickness was reduced to 8 mm.

(4) The FE-based design approach can reduce the material consumption of the retrofit details (number of strut frames in the longitudinal direction and the plate thickness) by 55.0% and 86.7% in the transverse and longitudinal directions as compared to the initial details determined from the STM model. The shear and flexural forces of the foundation members with optimum retrofit details under the given loading combinations were estimated to be within the code-defined permissible limits.

(5) Based on the load-bearing capacity assessment, the FE-based design method was more effective in minimizing the material quantities for the strut–tie retrofit system than the conventional design method. The conventional STM-based design method assumes that the arch-shaped strut frames resist the shear produced by the load combinations. However, the FE-based design method implemented for optimizing the retrofit details predicted the actual structural behavior relatively more accurately because it assumed that the concrete and arch-shaped strut frames resisted shear. In a previous study [6], the durability of reinforced concrete members associated with laboratory-based parameters, service life, and raw material demand was reduced due to decreases in the concrete material consumption (20% reduction in the foundation member's thickness). To propose eco-efficient retrofit details, in a future study, a durability-based life-cycle assessment will be conducted for a foundation member installed using a steel strut–tie retrofit system.

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Article

Prediction and Optimization Analysis of the Performance of an Office Building in an Extremely Hot and Cold Region

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Abstract: The White Paper on Peak Carbon and Carbon Neutral Action 2022 states that China is to achieve peak carbon by 2030 and carbon neutrality by 2060. Based on the "3060 dual-carbon" goal, how to improve the efficiency of energy performance is an important prerequisite for building a low-carbon, energy-saving, green, and beautiful China. The office performance building studied in this paper is located in the urban area of Turpan, where the climate is characterized by an extremely hot summer environment and a cold winter environment. At the same time, the building is oriented east–west, with the main façade facing west, and the main façade consists of a large area of single-layer glass curtain wall, which is affected by western sunlight. As a result, there are serious problems with the building's energy consumption, which in turn leads to excessive carbon emissions and high life cycle costs for the building. To address the above problems, this paper analyzes and optimizes the following four dimensions. First, the article creates a Convolutional Neural Network (CNN) prediction model with Total Energy Use in Buildings (TEUI), Global Warming Potential (GWP), and Life Cycle Costs (LCC) as the performance objectives. After optimization, the R^2 of the three are 0.9908, 0.9869, and 0.9969, respectively, thus solving the problem of low accuracy of traditional prediction models. Next, the NSGA-II algorithm is used to optimize the three performance objectives, which are reduced by 41.94%, 40.61%, and 31.29%, respectively. Then, in the program decision stage, this paper uses two empowered Topsis methods to optimize this building performance problem. Finally, the article analyzes the variables using two sensitivity analysis methods. Through the above research, this paper provides a framework of optimization ideas for office buildings in extremely hot and cold regions while focusing on the four major aspects of machine learning, multi-objective optimization, decision analysis, and sensitivity analysis systematically and completely. For the development of office buildings in the region, whether in the early program design or in the later stages, energy-saving measures to optimize the design have laid the foundation of important guidelines.

Keywords: convolutional neural network (CNN); NSGA-II algorithm; extremely hot and cold areas; office building performance optimization; sensitivity analysis

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1. Introduction

The world today is undergoing a major change not seen in a century, and human society is facing unprecedented global challenges and changes. These challenges and changes come from a variety of sources, including the economy, the environment, and energy, and their impact is far-reaching, comprehensive, and long-lasting. Among other things, in terms of energy consumption, China already accounts for 15% of the world in terms of GDP levels. Regarding the level of energy consumption, China has accounted for 23.2% of the world's total energy consumption and 33.6% of the world's energy consumption growth rate. Building energy use accounts for a significant proportion of China's energy consumption level. By the end of 2020, China's buildings with high energy usage will reach 70 billion square meters, and the amount of energy consumed by buildings will be equal to 108.9 billion tons of standard coal. In addition, buildings have relatively long life cycles with complex and dynamic behaviors. Therefore, more research is needed to incorporate building performance factors into building design standards. Under China's proposal to achieve a carbon peak by 2030 and carbon neutrality by 2060 (dual-carbon policy), it is especially important to know how to effectively save energy and reduce emissions at the office building level. The case studied in this paper is located in the city of Turpan, a region whose climate is characterized by hot summers, cold winters, extreme solar radiation, and annual precipitation of only 15 mm. As a result, there is an overconsumption of energy use in buildings, which also creates a series of problems in the built environment, e.g., excessive energy consumption in office buildings, excessive carbon emissions from buildings, high life cycle costs, and poor building thermal comfort, to name a few. Based on the above status quo, it is urgent to optimize how to improve these problems. At the same time, how to effectively optimize these issues is also in line with the concept of "Beautiful China" proposed by China in recent years. The so-called "Beautiful China" concept is to build a green civilization and integrate it into all aspects of cultural, economic, and social construction. It is specifically divided into two aspects: one is the establishment of a good ecological green environment, and the other is the implementation of low-carbon, green, and energy-saving forms of production and lifestyles. The measures proposed in this paper to optimize the performance of office buildings in Turpan fall into the category of green, energy-saving, and low-carbon production methods. At the same time, on the one hand, building performance optimization can guide the sustainable development of the construction industry, maximize the efficiency of energy use, and promote the effective implementation of energy-saving strategies. On the other hand, building performance optimization can drive change in human society, taking into account the energy—economy balance. Therefore, this paper conducts a performance optimization study for office buildings in Turpan to explore the climate adaptation law of office buildings in extremely hot and cold areas from the perspective of multiple performances, exploring practical optimization and design strategies applicable to local climate characteristics. This is of great practical significance for improving the energy consumption and economic costs of local office buildings, better tapping and inheriting the wisdom of construction, and even realizing China's "dual-carbon" target strategy. The article is divided into the following sections: The first part is the introduction to the article. The second part of the paper is a literature review. The third part is the methodology of the thesis, which includes various methods of analysis and the main framework of the thesis. The fourth part is a simulation study of the performance of office buildings in Turpan. The fifth part is a visual analysis of the results of predictive optimization of office building performance. The sixth part of the article is the discussion section of the paper. The seventh part is the conclusion of the paper and the coming outlook extension.

2. Literature Review

Currently, predictive optimization of office building performance focuses on energy consumption, economics, environmental impact, and thermal comfort. Specific detailing studies transition from building performance simulation to data-driven model creation, multi-objective optimization, sensitivity analysis, and more. In the following, we will analyze the research related to the optimization measures of office building performance prediction by scholars from different perspectives and in regard to several aspects.

2.1. At the Level of Building Energy Consumption

Building energy use has a profound impact on the performance issues of office buildings during their life cycle phases [1–17]. Several scholars have conducted relevant research on how to use effective energy saving and environmental protection optimization strategies to improve the energy performance of office buildings. Liu et al. studied the energy-saving strategies in terms of energy consumption in office buildings in Turpan. The article concludes that the west façade of the building, using double-glazed curtain wall circulation, combined with the east façade of the east-light south-oriented measures to reduce energy consumption, is the largest, affecting the program heating level by 64.14%, the cooling level by 77.12%, and the total energy consumption level by 69.67% [1]. Valladares-Rendón et al. investigated the effect of overhangs on the energy performance of the building, as well as on the light performance, while studying the effect of overhangs. The results show that the use of the Overhanging Device-Single Edge Single Level (OD-SEL) system has great potential to reduce the energy consumption of building cooling [2]. Khabir et al. investigated the effect of energy consumption in office buildings by studying the double skin façade. The results show that a double skin façade with cooling materials can reduce energy consumption by 62–63% and a double skin façade with cooling materials can reduce CO_2 emissions by 76–77% [4]. AI-Tamimi scholars found a 26.81% reduction in total building energy consumption by studying different building envelope optimization strategies, such as changing the window glazing type and adding insulation [6]. Huo et al. investigated the effect of external blinds on the energy performance of office buildings. The article shows that, by changing different shading performance measures such as shading angle, window-to-wall ratio, and orientation, it is possible to improve the energy efficiency of buildings and reduce the energy consumption of office buildings [8]. Hashemi scholars studied the impact of automatic reflective blind systems on the energy performance of buildings by showing that the measure can save up to 60% of a building's energy consumption [10]. Cuce scholars investigated an insulated solar glass (HISG) technology. The results of the study showed that HISG can reduce building energy consumption by 38% and 48% during the heating and cooling seasons, respectively [15]. Ihara et al. explored the impact on building energy consumption by examining four characteristics related to energy efficiency in office buildings. The article shows that improving the SHGC and U-value of windows and increasing the solar reflectance of opaque parts can efficiently reduce building energy consumption [16].

2.2. At the Building GWP Level

At the level of carbon emissions from buildings, excessive carbon emissions can lead to a sharp increase in greenhouse gases and waste of energy resources, which in turn can lead to building environmental problems such as the heat island effect. The issue of how to effectively reduce carbon emissions is critical to improving building performance [18–35]. For example, the following scholars have conducted relevant studies: Zhang et al. investigated the impact of three objectives, GWP, global cost (GC), and operational energy (OE), on the ability to optimize building performance. The article found that the use of meta-model optimization resulted in a reduction of 12.7%, 6.7%, and 7.4% in the three metrics, respectively [22]. Yu et al. optimized the design process by establishing a parametric optimization to minimize GWP, energy consumption, and life cycle costs (LCCs). The results showed that optimizing all variables can achieve good building performance results [23]. Wang et al. examined the abatement potential of HFC emissions. The results indicated that the total GHG reduction capacity by 2050 is approximately equal to 10% of the total carbon emissions from the Chinese construction sector [24]. Honarvar et al. examined the evolution of buildings over their life cycle, and the results showed that the environmental impact of new materials increases fivefold in terms of GWP. Additionally, according to the circular economy concept, 10% of old and 3% of new housing materials can be returned to the chain, which in turn can reduce the GWP of the building during the life cycle [26]. Zhang et al. examined the effectiveness of buildings in reducing emissions during energy efficiency retrofits. The results show that retrofitting existing buildings can reduce considerable CO_2 equivalent and economic costs [27]. Wang et al. went on to improve environmental issues by examining building performance issues at life cycle costs. The results of the study showed that optimizing energy consumption, thermal comfort, and GWP using a multi-objective optimization algorithm can save the designer time and costs while reducing the range of alternatives [29]. Ansah et al. examined the impact of different façade materials on the environmental and economic costs of buildings in Ghana. The results show that stabilized earth block curtain wall is the most energy-efficient façade material with the highest potential for development, which can reduce GWP by 18.07% and

LCC by 47.87% [30]. Javid et al. studied the impact of energy consumption and GWP on buildings. In their paper, economic cost and GWP are used as the optimization objectives, and the results show that the use of optimization can lead to a reduction of 17.79% and 20.8% CO_2 equivalent for the two case buildings in the paper, respectively. In addition, buildings should be retrofitted from a life cycle perspective [32]. Hossain et al. studied the impact of building materials on GWP. The results showed that the construction of a 1 m hoarding produces three tons of CO_2 equivalent GWP [34]. Van Ooteghem et al. conducted a life cycle perspective to investigate which part of the building's structure would have the greatest impact on energy consumption and GWP. The results show that the building operation energy level is more influential, accounting for about 91% of the total energy consumption and 88% of the total GWP in terms of GWP [35].

2.3. At the Level of Building Life Cycle Costs

Incorporating buildings into the study of life cycle costs in turn improves building performance issues from the perspective of the whole-life economics of buildings [36–56]. The following scholars have studied how to make improvements at the LCC level: Lei et al. examined the application of green building design costs across the life cycle stages. The results showed that the cost of the operational phase of the building was the highest at 65.4% [36]. Kazem et al. went on to explore the effectiveness of energy efficiency retrofits in Cairo buildings through a whole-life-cycle cost analysis. The results showed that the most cost-effective façade retrofit was the installation of 1 m long external shading facilities, which reduced LCC by 1.4% and energy consumption by 18% [37]. Weerasinghe et al. went on to analyze the impact of green building costs in Sri Lanka by examining the life cycle costs of the building in its aspect. The results show that, although the initial construction cost of green buildings is 29% higher than that of conventional buildings, green buildings can save 23% and 15% of economic costs in the operation and maintenance phases, respectively, over their entire life cycle [39]. Yuan et al. examined how the performance of buildings changes by looking at energy savings and life cycle costs. The results showed that the 16 buildings corresponding to the use of the 16 envelope schemes met the green building evaluation criteria. At the same time, the article shows that life cycle costs rise as energy efficiency rates increase [43]. Xue et al. developed an LCA-LCC model by targeting building sustainability. The article's research found that economic costs were highest during the operational phase of the life cycle and that ADP-fossil and GWP metrics were most prominent throughout the life cycle [45]. Dwaikat et al. studied the application of life cycle cost in the construction industry. The article showed that the future costs of the studied buildings were 3.6 times their initial investment and construction costs, also showing that energy consumption accounts for 48% of the total life cycle costs and that reducing energy consumption reduces the total life cycle costs [47]. Schwartz et al. investigated the impact of buildings on energy use by taking a life cycle perspective, and the article optimized the LCC and Life Cycle Carbon Footprint (LCCF) through a multi-objective optimization genetic algorithm. The results showed that LCCF and LCC could be reduced by this method [49]. Invidiata et al. analyzed four shading systems that affected the energy performance of buildings by looking at them from a life cycle cost perspective. The results showed that the use of wooden double-opening blinds and PVC roller shades was the most appropriate window shading solution, efficiently reducing the building's energy consumption [50]. Abdallah et al. went on to reduce the life cycle cost of buildings by studying building optimization measures. The article proposed a model that identified the best building optimization measures and also significantly reduced the life cycle cost of a building [51]. Han et al. used numerical sensitivity analysis to understand the role of life cycle analysis (LCA) in building design. The results showed a significant correlation between energy modeling and life cycle costs. Also, wall assemblies had a much greater impact on life cycle costs than window performance [52]. Kneifel scholars have verified this by examining the effectiveness of new buildings in saving energy, reducing carbon, and lowering economic costs over their life cycles. Research results have shown that conventional technologies can reduce the energy consumption of new buildings by 20–30%, while the carbon footprint can be reduced by 16% [55].

2.4. At the Level of Multi-Objective Optimization

The NSGA-II algorithm (a type of multi-objective optimization algorithm) uses a fast non-dominated sorting algorithm, which makes the computational complexity much lower than NSGA. At the same time, it introduces congestion and crowding operators that enable individuals in a quasi-Pareto domain to extend to the entire Pareto domain, ensuring population diversity. Finally, it introduces elite strategies that greatly increase the speed of computation in optimizing building performance metrics. Therefore, the method is widely used in the field of building performance optimization [57–63]. For example, the following scholars have performed relevant research in this area. Zhou et al. used a multi-objective optimization approach for building performance objective optimization, which in turn resulted in performance objective alternatives with optimal solutions [57]. Wang et al. performed a multi-objective optimization by targeting low energy consumption, better thermal comfort, and light performance. The results show that multi-objective optimization of the target indicators can reduce building energy consumption and improve energy efficiency [58]. Harkouss et al. present a method for simulating near-zero energy building (NZEB) optimization. The results show that the use of the NSGA-II algorithm can significantly reduce the thermal, electrical, and life cycle costs of buildings [63].

2.5. At the Machine Learning Level

The CNN deep neural network model is used to predict the building performance, and it can abolish problems such as the low prediction accuracy of traditional data-driven models. Meanwhile, CNNs with backpropagation algorithms can automatically adjust the network parameters to minimize the loss function, thus improving the performance of the network, i.e., it can enhance the predictive performance of buildings and minimize the time cost [64–77]. For example, the following scholars have conducted relevant studies at this level: Yue et al. investigated the application of data-driven modeling to building energy consumption and indoor environments by studying. Yue et al. investigated the impact of data-driven modeling on building performance through the application of data-driven models to building energy consumption and indoor environment. The results of the study showed that the use of data-driven models can greatly reduce the time cost, while, at the same time, the prediction results are more accurate [64]. Xu et al. went on to analyze issues such as improving the energy performance of buildings by studying building performance strategies. The results show that, by using the CNN data-driven model, building energy consumption can be optimized to reduce it by 24.53% [70]. Pal et al. went about predicting target metrics by employing a data-driven model using CNN combined with the NSGA-II algorithm. The results showed an accuracy of 94.83% and 94.96% on the two case datasets [73]. Bakar et al. attempted to optimize the target metrics by using a CNN combined with the NSGA-II algorithm, and the results showed that the CNN data-driven model has a better adaptive capability [77].

However, compared to the above literature studies, there are fewer studies on the building performance of office buildings throughout their life cycle in the cold regions of China. The Turpan region has increasingly hot summers and cold winters, and the maximum outdoor temperature in the Turpan region in 2023 reached 52.2 °C, the highest temperature recorded in China, indicating the relatively harsh environmental conditions in the region. In addition to this, after researching the office buildings in the region, it was found that several problems are common in the office buildings in the region, such as excessive building energy consumption, high carbon emissions from buildings, high building construction costs, and poor building thermal comfort. At the same time, office buildings in the region have relatively poor insulation and airtightness. A low-performing building envelope can cause a building to lose more heat in the winter. Poor airtightness increases the risk of cold air infiltration, which in turn leads to increased energy consumption and running time of the heating equipment. In addition to this, office buildings in the region still face many dilemmas when it comes to optimizing them during their life cycle phases. For example, it is known from the research that local office buildings are reluctant to fund improvements in performance optimization due to the limitations of the local economic level and environmental awareness. Government makers are more focused on reducing greenhouse gas emissions, while office workers are more concerned with improving indoor comfort. Therefore, it is challenging to carry out office building performance optimization strategies in this region. However, elsewhere, several researchers have improved and optimized the above problem. For example, Luo et al. proposed a framework for whole-life optimization of building performance that takes climate change into account, it was implemented in two case buildings in the UK. The results show that the life cycle cost of a building was underestimated by 2.0−1.7% and the carbon emissions were underestimated by 1.2−6.9% when the optimized scenario decided in 2019 was adopted in the years between 2021 and 2024 [78]. Zhang et al. studied building performance in extremely dry and hot climatic conditions. That is, the effects of wall thermal resistance, roof thermal resistance, hole-to-wall area ratio, and wall interior height on the indoor environment were analyzed by numerical simulation, and the results of the study found that the hole-to-wall area ratio is the most important parameter affecting the indoor environment of life cycle buildings [79]. At the same time, in the study of office buildings in the Turpan region, it is necessary to further explore more optimized designs of office buildings so that the buildings in the region can adopt low-cost optimization strategies and have high performances in order to improve the comprehensive performance of the life cycle of office buildings in the region.

Based on the above analysis and research, the research of this paper is shown below: (1) Creating data-driven predictive models with high accuracy. Data-driven models represent a capability for fast analytical calculations with an accuracy close to that of dynamic simulations. They can be used as a strategy for conducting independent variable parameter studies and optimizing future building performance predictions. In this paper, eight data-driven models are selected to predict each of the three target indicators. (2) Multi-objective optimization is performed for three objective values. In this paper, the NSGA-II optimization algorithm is used to optimize the TEUI, GWP, and LCC, which leads to the results of the optimization scheme. (3) Decision analysis. In this part of the article, two Topsis methods are used to evaluate the performance optimization of office buildings. They are the entropy law form and the subjective empowerment form, respectively. There is use of multiple decision research methods for analysis, which in turn can increase the transparency of decision design. (4) Sensitivity analysis of variables. Two sensitivity analysis methods are used in this paper: the RBD-FAST method and the DMIM method. The article uses the method to visualize the variables analytically.

The main innovations of this paper are shown below:

(1) In this paper, the CNN data-driven model is used to predict the performance target. Under the condition of guaranteeing accuracy, the target is realized to optimize quickly. Compared with the traditional prediction method, it improves the performance-driven design efficiency.
(2) In this paper, the NSGA-II multi-objective optimization algorithm is used to quickly optimize the performance objectives, and the resulting optimization can provide ideas for builders in the area when performing building design.
(3) The article provides an entropy-based decision-making method for Topsis. The method can help designers to make trade-off judgments in decision-making.

3. Methodology

3.1. BPS

Building Performance Simulation (BPS) is a powerful tool for studying the performance of a building's physical environment, and it can be used to achieve desired results with its easy hands-on capabilities. Therefore, it is increasingly used for research and prediction of building energy consumption, measurement and verification, carbon emissions, and economic evaluation. It has played an indelible role in the design strategy of low-energy, high-performance office buildings and has been a good guide in promoting China's "dual-carbon" approach. In this paper, Rhion software (Rhino 7.0) is used for building performance simulation tools, and the GH plug-in that comes with the software can be easily used for office building performance simulation and analysis. Since the targets studied in this paper are TEUI, GWP, and LCC, the Rhion software and GH plug-in are divided as follows: In the office building energy consumption section, this article uses Ladybug Tools and the Honeybee plug-in. The Honeybee plug-in is embedded with the EnergyPlus energy calculation engine to facilitate the calculation of energy consumption. For carbon emission and life cycle cost calculations, this paper uses the Python module of the GH plug-in, which utilizes programming techniques that allow for quick analysis and calculations.

3.2. Machine Learning Neural Networks

When using physical models of building performance for analysis, traditional processes typically calibrate the model to match previous data through statistical inversion strategies. To reduce such errors between the model and the observed data, this matching process is time-consuming and costly, while, at the same time, most building performance simulation software is computationally intensive [80,81]. The resulting emergence of data-driven models can significantly reduce the cost of time. Data-driven modeling represents a form of fast execution of calculations with an accuracy close to that of dynamic simulation. It helps decision-makers to quickly examine high-dimensional performance simulations and immediately derive solutions under various constraints. Therefore, the deep learning model used in this paper can effectively solve the problem of high time cost. Currently, the commonly used learning algorithms in the field of building performance prediction and optimization are RNN, LSTM, and GAN, while CNN is less used in this field. CNNs are highly adaptable in terms of local feature capture performance. It can be used in the field of building performance by constructing high-dimensional features, which can effectively learn the relationship between the nonlinear interactions among the variables affecting TEUI, GWP, and LCC. In this paper, eight data-driven models are used to analyze and optimize building performance objectives; these eight data-driven models are Backpropagation network (BP), Support Vector Machine (SVM), Genetic algorithm-based optimized BP neural network (GA-BP), BP neural network based on particle swarm optimization algorithm (PSO-BP), SVM based on particle swarm optimization algorithm (PSO-SVM), CNN(SGDM) based on different optimizers, CNN(Adam) based on different optimizers, and CNN(RMSprop) based on different optimizers.

Among them, at the CNN level, CNNs can reduce the problem of too many model parameters due to excessive dimensionality by dealing with local correlations in the input data. The key feature of CNN operations is weight sharing [82]. When the convolutional kernel scans for local features in the data, the mechanism by which the convolutional kernel extracts the data after moving a certain number of steps remains unchanged. After the constant movement of the convolution kernel, the data scanning is completed and fewer parameters are obtained. CNNs generally include a convolutional layer, an activation layer, a pooling layer, and a fully connected layer. Convolutional layers extract information from foreign data and can be categorized as row-by-row and column-by-column, depending on the direction of scanning along the input features. Input features from all individual moment points are first combined by CNN line-by-line scanning. All combined features are then learned in a time series by transposing the input data into two dimensions when importing it into the training model, which in turn transitions to column-by-column scanning. This facilitates the convolution kernel to extract features from the data to form a feature mapping map, i.e., the convolution kernel operates by regularly sweeping through the input features, making matrix element multiplicative summations of the input features within the receptive field and superimposing the amount of bias. The relevant equations are expressed below.

$$\boldsymbol{Z}^{l+1}(i,j) = [\boldsymbol{Z}^{l} \otimes \boldsymbol{w}^{l+1}](i,j) + \boldsymbol{b} = \sum_{k=1}^{K_l} \sum_{x=1}^{f} \sum_{y=1}^{f} [Z_k^l(s_0 i + x, s_0 j + y)] w_k^{l+1} \quad (1)$$

$$(i,j) \in \{0,1,\ldots L_{l+1}\} \; L_{l+1} = \frac{L_l + 2p - f}{s_0} + 1 \quad (2)$$

The summation part of Equation (1) is equivalent to solving a cross-correlation. $\boldsymbol{b}$ is the amount of deviation. $\boldsymbol{Z}^l$ and $\boldsymbol{Z}^{l+1}$ denote the convolutional input and output of layer $l + 1$. L_{l+1} is the size of $\boldsymbol{Z}_{l+1}$. $\boldsymbol{Z}(i,j)$ corresponds to the pixels of the feature map. K is the number of channels of the feature map. f, s_0, and p are convolutional layer parameters corresponding to the convolutional kernel size, convolutional step size, and number of filled layers. A schematic diagram of the convolution operation is shown in Figure 1.

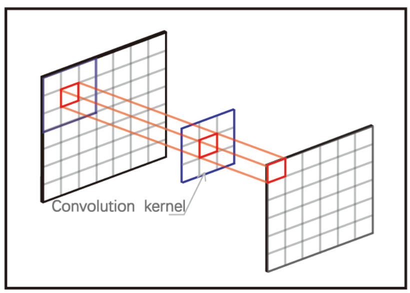
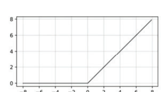
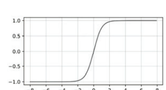
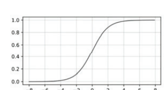
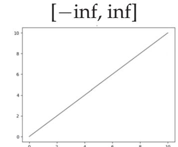


Figure 1. Schematic diagram of the convolution operation.

The feature is delivered through a nonlinear activation function that accelerates the CNN's processing of complex relationships between data. Activation functions can generally be linear or nonlinear. The output of the former is simply a weighted sum of the inputs and cannot be backpropagated. While nonlinear functions have nonlinear functions, they can also solve linear functions. The activation functions routinely used are shown in Table 1. In this paper, the ReLU function is used.

Table 1. Activation functions in CNN data-driven models.

Function	ReLU	Tanh	Sigmoid	Linear
Formula	y = max(0,x)	$y = \frac{1}{(1+e^{-x})}$	$y = \frac{e^x - e^{-x}}{e^x + e^{-x}}$	y = ax
Nature	Nonlinear	Nonlinear	Nonlinear	Linear
Range	[0, inf]	[−1, 1]	[0, 1]	[−inf, inf]
Response				

After feature extraction in the convolutional layer, the output feature map is passed to the pooling layer for feature selection and information filtering. The pooling layer contains predefined pooling functions whose function is to replace the result of a single point in the feature map with the feature map statistics of its neighboring regions. The pooling layer is inspired by the hierarchical structure within the visual cortex, which is generally represented by the model:

$$\boldsymbol{A}_k^l(i,j) = \left[\sum_{x=1}^{f} \sum_{y=1}^{f} \boldsymbol{A}_k^l(s_0 i + x, s_0 j + y)^p\right]^{\frac{1}{p}} \quad (3)$$

where the step size s_0, and pixel(*i,j*) have the same meaning as the convolutional layer. p is a pre-specified parameter. When p is equal to 1, it takes the mean value in the pooling region and is called mean pooling. When p tends to infinity, it takes an extreme value in the pooling region and is called extreme pooling. This paper is extremely pooled.

In addition, CNNs use optimizers that can change weights, learning rates, etc., to minimize the loss function. At the optimization level, the gradient descent method is the conventional method. In this, the gradient of the loss function for the parameters is operated and the parameters are updated by backpropagation on this basis. The parameter update equation is Equation (4).

$$\theta_{t+1} = \theta_t - \eta \mathbf{d}_t \tag{4}$$

where $\mathbf{d}_t$ denotes the gradient of the objective function $J(\theta)$ based on the parameter θ at time t, and η represents the learning rate.

The difficulty of the gradient descent method is in the optimal value of the learning rate. Smaller learning rates require more training, while larger learning rates cause the network to converge quickly to a suboptimal solution.

Another aspect involves the adaptive learning rate methods. The most common are RMSprop and Adam. RMSprop can solve the difficulty of AdaGrad learning rate decay. The RMSprop weight update can divide the learning rate by the square root of the squared mean of the exponential decay gradient, $R[\mathbf{d}^2]_t$. The weight update formula is Equation (5).

$$\theta_{t+1} = \theta_t - \frac{\eta}{\sqrt{R[\mathbf{d}^2]_{t+\epsilon}}}\mathbf{d}_t \tag{5}$$

The Adam optimizer retains the exponentially decaying mean of the gradient squared and the exponentially decaying mean of the gradient.

The parameter-related calculation of the Adam optimizer is given in Equation (6).

$$\theta_{t+1} = \theta_t - \frac{\eta}{\sqrt{\hat{v}_{t+\epsilon}}}\hat{m}_t \tag{6}$$

where m_t and v_t represent the estimates of the first-order and second-order moments of the gradient, respectively. $\hat{m}_t$ and $\hat{v}_t$ represent the corrected m_t and v_t. The estimated first-order and second-order moments of the gradient are shown in the following table.

At the level of data-driven model evaluation, root mean square error (*RMSE*), mean absolute error (*MAE*), and coefficient of determination (R^2) are selected as the evaluation metrics of the results in this paper. Where R^2 shows the degree of deviation between the predicted and actual values of the model, the closer R^2 is to 1 (indicating that the direction between the predicted and actual values is more similar), the better the prediction effect. MAE and RMSE reflect the predictive accuracy of the data-driven model, with smaller values corresponding to a better predictive performance. Meanwhile, the various data-driven models analyzed in the article's study, as well as the construction of the various models, were analyzed and completed via Python (version 3.11) software.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2} \tag{7}$$

$$R^2 = 1 - \frac{\sum_i(\hat{y}_i - y_i)^2}{\sum_i(\overline{y}_i - y_i)^2} \tag{8}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{9}$$

where y_i is expressed as the i actual value, $\hat{y}_i$ is expressed as the i predicted value of the model, $\overline{y}_i$ is the mean value, and n is the sample size of the data.

3.3. LHS

For data processing, this paper uses Latin Hypercube Sampling (LHS). It is a more advanced form of Monte Carlo sampling. It can divide the space of independent variable parameters into equal parts and then randomly sample on that basis. It effectively prevents aggregation of parameters and samples the entire space of variables. At the same time, the number of this sample is generally equal in number to about 5–15 times the number of parameters of the independent variable. At the level of data-driven model accuracy, to optimize its prediction performance, 2000 samples are taken for simulation in this paper to obtain the data set of the independent variable—the target variable. The specific procedure for Latin Hypercube Sampling (LHS) is as follows:

(1) The sample size M of the independent variable and the number of dimensions m are established first.
(2) Equalize the interval of the independent variable parameter X as [lb, ub]. That is, it is the maximum and minimum values of the parameters of the independent variables.
(3) The interval of the independent variable parameter X is transformed into a homogeneous region of M equal parts.
(4) Selection point samples were performed in each interval of each dimension.
(5) All the points of the interval are added together to form a vector.

3.4. MOP Algorithm

In this paper, the NSGA-II algorithm is used for multi-objective optimization of objective values (TEUI, GWP, and LCC). The algorithm is a fast non-dominated solution MOP algorithm with an elite reservation mechanism [83]. Its superior performance characteristics have been widely used in various building industry designs and green building performance evaluations. In this paper, the population size and maximum number of generations were set to 45 and 100, and the probability of variation and crossover rate were set to 0.07 and 0.90. The optimization criterion is to minimize the TEUI, GWP, and LCC objective values by adjusting the parameters of the independent variables. Its expression is:

$$F(\vec{x}) = \begin{cases} f_1 = f\left(\vec{x}, TEUI\right)_{\min} \\ f_2 = f\left(\vec{x}, GWP\right)_{\min} \\ f_3 = f\left(\vec{x}, LCC\right)_{\min} \end{cases} \tag{10}$$

3.5. Decision Analysis

In the decision analysis section, this paper uses the entropy-based Topsis method [84–93] when making decisions on the optimization scheme. The method has the following advantages: The entropy weighting method can confirm the weighting information of the target indicators by analyzing the entropy value of the target indicators of each scenario, which in turn can provide a reference for the multi-objective assessment later. Topsis analysis uses matrix extrapolation to calculate the worst and optimal solutions and then derives the distance between the objective and the first two. Finally, the closeness of each target solution to the first two ideal solutions is derived. If the indicator is close to the positive ideal solution and far from the negative ideal solution, the result is good. Finally, the above two methods are fused into one, with the entropy weighting method being used to calculate the weights and the Topsis method being used for ranking. The specific practices are as follows:

(1) Establishment of the matrix.

Use the initial data to build the matrix for m indicators and n objects.

(2) Calculate the entropy value of the target variable.

According to the importance of each indicator to the comprehensive evaluation, the information entropy is used to calculate each entropy value.

$$e_j = \frac{-1}{lnm \sum_1^m p_{ij} lnp_{ij}} \tag{11}$$

(3) The coefficient of variation in the target variable was established.

Let g_j be the coefficient of variation of target indicator j.

$$g_j = 1 - e_j \tag{12}$$

(4) Determination of entropy weights of target indicators.

Let H_j be the entropy weight of target indicator j. Normalize g_j to obtain the indicator H_j.

$$H_j = \frac{g_j}{n} - \sum_1^n d_j \tag{13}$$

(5) Analyze the distance between the result and the two ideal solutions.

$$Di^+ = \sqrt{\sum_{j=1}^n \left(z_{ij} - z_j{}^+\right)^2} \tag{14}$$

$$Di^- = \sqrt{\sum_{j=1}^n \left(z_{ij} - z_j{}^-\right)^2} \tag{15}$$

where Di^+ and Di^- denote the distance of the i evaluation object from the optimal and worst solutions, respectively.

(6) Calculation of relative progress for each target indicator.

$$\mathrm{C}_i = \frac{D_i{}^-}{D_i{}^+ + D_i{}^-} \tag{16}$$

where C_i denotes the final score for each scenario. The value is $0 \le C_i \le 1$.

3.6. Sensitivity Analysis

Sensitivity analysis refers to the change in the outcome of the target variable, as the independent variable changes when a variable is varied within a certain range. Since sensitivity analysis can respond to the degree of influence of characteristic parameters on the performance of office buildings, it plays an important role in green building performance analysis, retrofitting of existing office buildings, and evaluation of building performance models. Two sensitivity analysis methods are used in this paper: RED-FAST and DMIM analytical methods. The DMIM method is a density-based global analysis method with proven authority at the methodological level of sensitivity analysis [94]. It has two types of visualization of analysis results when results are analyzed on the independent variable−target variable data set, TOI and FOI. FOI indicates the contribution of a single independent variable parameter to the output results. TOI indicates the contribution of a single independent variable and the interaction of that variable with other variables to the output result. The RBD-FAST method introduces the RBD concept at the level of the FAST method and then goes on to solve the shortcomings of the FAST method, which has too many sample points and too many time costs. At the same time, it is a complementary FOI to DMIM [95].

3.7. Research Framework for the Thesis

The full frame content of this paper is presented in Figure 2.

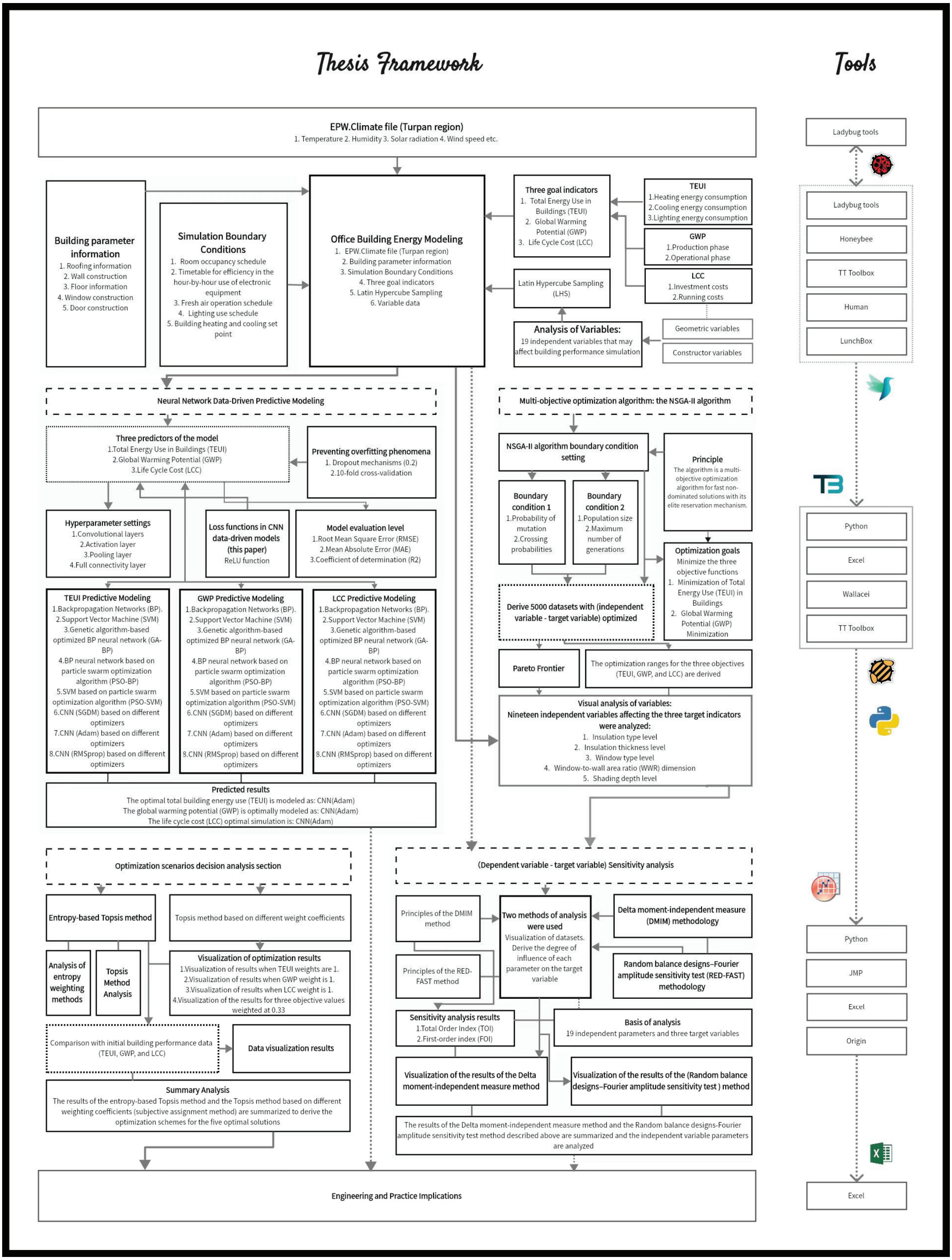


Figure 2. Article Framework Diagram.

Brief analysis: The content of the research framework of this paper is divided into the following sections. The first is building performance simulation. The independent-target variables were brought into the Rhion software to derive TEUI, GWP, and LCC. This involves bringing in the building envelope, the transparent envelope, and some other boundary conditions. The dataset was collected based on Latin Hypercube Sampling (LHS). Next, CNN data-driven model prediction, multi-objective optimization, decision analysis, and sensitivity analysis are performed based on building performance objectives (TEUI, GWP, and LCC), respectively. At the data-driven model prediction level, the article uses eight different prediction models to predict the three target values. In the multi-objective optimization phase, the article uses the NSGA-II algorithm to optimize the three objectives. In the decision analysis section, the article uses the entropy-based Topsis method and subjective empowerment to analyze the objectives. Finally, a sensitivity analysis of the variables was conducted using two methods.

4. Building Performance Simulation

4.1. Climate Analysis

The building site studied in this paper is located in the Turpan area of the Xinjiang Uygur Autonomous Region. The region is located in the eastern part of the Tien Shan Mountains and is shaped like an oval-shaped basin. It is surrounded by high mountains. The climate of the region is a continental warm temperate desert climate. In the thermal division of China, Turpan is located in the cold region. The region has hot, dry, and windy summers and cold winters. The total area of the Turpan region is 69,000 km^2 and the annual evaporation is 3100 mm, but the precipitation is only 15 mm. Temperature-wise, the area is over 37 °C for one-third of the year. Temperature extremes reach 52.2 °C in summer and −28 °C in winter. At the same time, the region is characterized by strong solar radiation, with an average daily total solar radiation rate of 16 KJ. At the level of data selection, this paper selects the CSWD literature climate data information of the Turpan area. CSWD meteorological data sources are compiled by the China Meteorological Administration (CMA), which are more in line with the meteorological data used for building design in China. These data are visualized in this paper by Ladybug Tools for climate data. Figure 3 represents typical meteorological annual radiation data for Turpan Point. Figure 4 represents additional data.

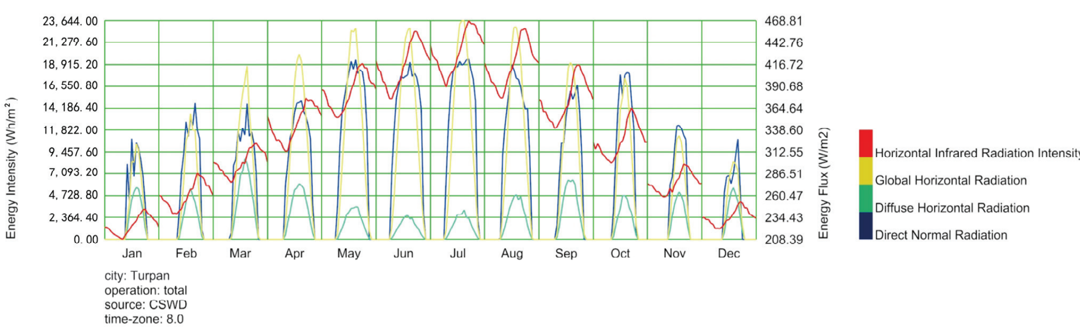


Figure 3. Climatological data for Turpan (radiation component).

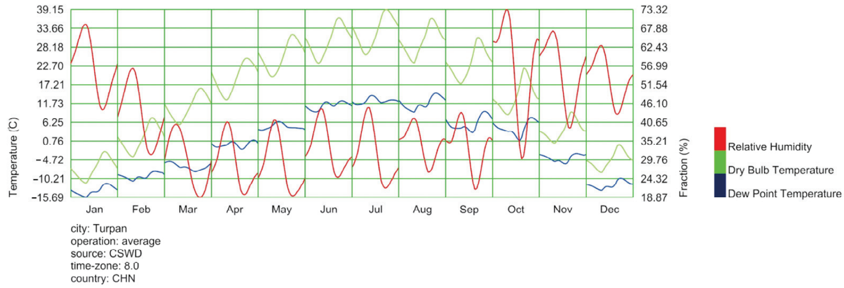


Figure 4. Climatological data for Turpan (other parts).

4.2. *Office Building Case Presentations*

In terms of location selection, the office building case selected in this paper is located in Turpan City. The building area is 4966 m^2, the number of floors is five, the height above ground is 32 m, the length is 62 m, and the width is 18 m. The building blocks are oriented east–west, with the main façade facing west, and the whole is symmetrical on the central axis. The façade of the building is in the form of a single-story glass curtain wall construction, with no snap caps on the surface of the glass curtain wall. There is a 13 m long, 4.5 m wide awning at the foyer. The east elevation of the building is framed by 70 mesh windows. The north and south elevations of the building are strips of glass curtain walls intended to provide light to the corridors. Figure 5 shows the office building portraits and models. Figure 6 shows the standard floor plan of the office building.

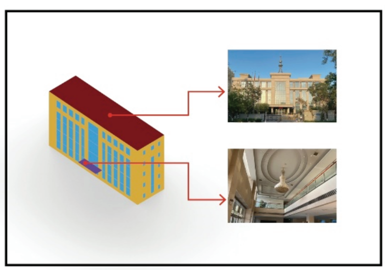


Figure 5. Office building portraits and model drawings.

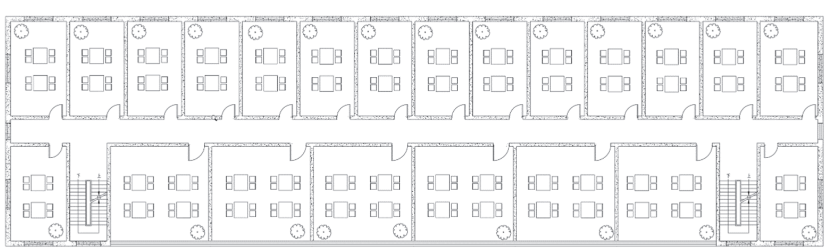


Figure 6. Building plan illustration.

4.3. *Parameter Selection*

Parametric modeling is an approach that makes use of geometric attribute variables. It enables designers to use mathematical and programming techniques to assemble to numerical models [96]. In this paper, in terms of parameter selection, 19 parameter variables that may affect the TEUI, GWP, and LCC of office buildings in Turpan are selected. It contains five building construction variables as well as 14 building geometry variables.

The type of exterior wall insulation (WIT), the type of roof insulation (RIT), and the type of windows (WT) are used as office building construction variables in this paper. According to the research, the commonly used insulation materials in the region are Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), and Polyurethane (PU) boards, among others. Therefore, this paper selects the external insulation material aspects for the above three. At the window perspective level, this paper selects five types of external windows with different thermal properties, which are ranked as follows according to the level of performance, as shown in Table 2. In terms of architectural geometric variables, this paper includes five types: they are window-to-wall area ratio (WWR_N, WWR_E, WWR_S, WWR_W), shading system louver length (DEP_N, DEP_E, DEP_S, DEP_W), number of shading system louvers (Shade count_N, Shade count_E, Shade count_S, Shade count_W), shading angle of the east and west wall louvers of the shading system (Angle_E, Angle_W), thickness of the exterior wall insulation (TW), and thickness of roof insulation (TR), as shown in Table 3. In contrast to other conventional research analyses, this study considers the heat transfer process in different dimensions of the facade and the roof. At the same time, careful differentiation of the thickness of insulation between the two types of external walls and roofs can lead to finer optimization of energy saving and carbon reduction. Meanwhile, vertical and horizontal louvers are used for east–west and north–south directions, respectively. Defining the length and number of shading systems can be explored to study the extent to which exterior building shading systems affect the performance of office buildings in the Turpan region.

Table 2. Thermal performance data for office building materials.

Categories	Names	No.	Conductivity [W/(m·K)]	Specific Heat Capacity [J/kg·K]
Insulation	EPS	0	0.037	1380
	XPS	1	0.030	1380
	PU	2	0.024	1380
Categories	**Names**	**No.**	**Conductivity [W/(m·K)]**	**SHGC**
Window	Double pane, Low-e	0	2.1	0.6
	Double pane, Low-e, argon	1	1.7	0.6
	Triple pane, Low-e	2	1.3	0.55
	Triple pane, Low-e(green)	3	0.9	0.5

Table 3. Distribution data for 19 variables.

No.	Categories	Symbol	Unit	Range
1	Wall insulation type	WIT	/	[0–2]
2	Roof insulation type	RIT	/	[0–2]
3	Window type	WT	/	[0–3]
4	Window-to-wall radio of north wall	WWR_N	/	[0–0.6]
5	Window-to-wall radio of east wall	WWR_E	/	[0–0.6]
6	Window-to-wall radio of south wall	WWR_S	/	[0–0.6]
7	Window-to-wall radio of west wall	WWR_W	/	[0–0.6]
8	North-facing louver depth	DEP_N	m	[0–1.5]
9	East-facing louver depth	DEP_E	m	[0–1.5]
10	South-facing louver depth	DEP_S	m	[0–1.5]
11	West-facing louver depth	DEP_W	m	[0–1.5]
12	Number of north-facing louvers	SC_N	/	[0–5]
13	Number of East-facing louvers	SC_E	/	[0–5]
14	Number of South-facing louvers	SC_S	/	[0–5]
15	Number of West-facing louvers	SC_W	/	[0–5]
16	East-facing louver shading angle	A_E	(°)	[0–90]
17	West-facing louver shading angle	A_W	(°)	[0–90]
18	Wall insulation thickness	TW	mm	[0–330]
19	Roof insulation thickness	TR	mm	[0–330]

4.4. Research Indicators

4.4.1. TEUI

Energy consumption is the energy consumed during the use of a building. This includes energy consumption at the building heating level, cooling level, lighting level, and equipment level. Since office buildings are fundamentally different from residential buildings in terms of use functions, their total energy consumption is much greater than the latter. The building energy consumption studied in this paper is the sum of heating energy consumption per unit area (HEUI), cooling energy consumption per unit area (CEUI), and lighting energy consumption per unit area (LEUI). Combined, these are the total energy use per unit area (TEUI). The TEUI expression is:

$$E_{total} = \frac{E_{heat} + E_{cool} + E_{light}}{A_1} \tag{17}$$

where E_{total}—Total building energy consumption (kWh/m^2); E_{heat}—Building heating energy consumption (kWh/m^2); E_{cool}—Building cooling energy consumption cooling (kWh/m^2); E_{light}—Energy consumption of building lighting (kWh/m^2); A_1—Office floor space (m^2).

4.4.2. GWP

In this paper, GWP is selected as an environmental indicator for office building performance evaluation. It can be used to screen the heat storage capacity of other gases in the atmosphere, such as CO_2, in terms of CO_2 equivalent. Therefore, this indicator was selected as the target indicator, representing the impact on the environment. In this paper, the calculation part of this GWP consists of two parts: carbon emissions during the production phase of building materials and the operational phase of the building. The formula is as follows, and the method used is the CEF calculation method. Table 4 represents the relevant parameter variables' economic costs and carbon emission factors.

$$GWP = \sum_{m=1}^{M} Q_m \times f_m + a \times \left[\frac{Q_H \cdot H}{\eta_H} \cdot f_c + \left(\frac{Q_c}{\eta_c} + E_L \right) \cdot f_e \right] \tag{18}$$

where m—type of construction material; Q_m—Quality of construction materials; f_m—CEF for construction materials; f_c—CEF for coal energy; f_e—CEF for electrical energy; a—The number of years of the survey, which is 50 years in this study.

Table 4. Construction material prices and carbon emission factor data.

Categories	Names	No.	Cost	CEF
Insulation	EPS	0	360 CNY/m^3	5.7 kgCO_2/kg
	XPS	1	450 CNY/m^3	20.1 kgCO_2/kg
	PU	2	1050 CNY/m^3	5.1 kgCO_2/kg
Window	Double pane, Low-e	0	340 CNY/m^2	92 kgCO_2/m^2
	Double pane, Low-e, argon	1	430 CNY/m^2	101 kgCO_2/m^2
	Triple pane, Low-e	2	620 CNY/m^2	130 kgCO_2/m^2
	Triple pane, Low-e (green)	3	740 CNY/m^2	141 kgCO_2/m^2
Energy	Coal	\	0.45 CNY/kg	2.62 kg/kg
	Electricity	\	0.48 CNY/kWh	0.89 kg/kWh

4.4.3. LCC

The life cycle cost is selected as the sum of the economic costs of the initial investment phase of the building and the operational phase of the building (LCC). It includes the economic cost of running the office building and the initial investment cost. It is the sum of the cost values over the entire life cycle. The life cycle for this study was chosen to be 50 years, and only the initial construction and annual energy economic costs were considered for their impact on life cycle costs. The relevant formulas are as follows:

$$LCC = \frac{DLC + \sum_{i=1}^{50}[EC \cdot R_{\mathrm{d}}(i)]}{A_{\mathrm{floor}}} \tag{19}$$

$$R_{\mathrm{d}}(i) = \frac{1 - (1 + R_{\mathrm{r}})^{-i}}{R_{\mathrm{r}}} \tag{20}$$

$$R_r = \frac{R_{\mathrm{i}} - R_{\mathrm{e}}}{1 + R_{\mathrm{e}}} \tag{21}$$

where *LCC*—Total Life Cycle Cost of Office Buildings; *DLC*—Difference in investment costs between the optimized building case and the reference building case (CNY); including the increased economic cost of the passive technology compared to the initial building; *EC*—Energy cost (CNY) in year *i*; A_{floor}—Gross floor area of office buildings (m^2); R_d(i)—Discount rate for year *i*; R_{r}—Real Rate of Interest; R_{e}—Rate of escalation of costs, = 1.2%; R_{i}—market interest rate; = 4.25%. It is assumed that this energy demand remains constant over the number of years calculated.

Where EC is the economic cost of energy for the year. The formula is as follows:

$$EC = \frac{Q_H \cdot H}{\eta_H} \cdot P_H + (\frac{Q_c}{\eta_c} + E_L) \cdot P_E \tag{22}$$

where *H*—Electricity and coal conversion factor (kg/kWh); η_H—Heating efficiency, =0.82; P_H—Local area coal prices (CNY/kg); η_c—Cooling efficiency, =3; P_E—Price of Electricity (CNY/kWh).

4.5. Office Building Performance Simulation Modeling

4.5.1. Boundary Condition Setting

Office building performance model creation: For the Turpan office building studied in this paper, the thermal performance information of the relevant building materials and the carbon emission-related indexes are brought into the GH and Honeybee plug-ins during the creation of the performance model to provide the building envelope and transparent envelope performance information. At the same time, the geometric information required to create an office building is created via the Rhion software. The two are then blended into one in Ladybug Tools. Meanwhile, this paper samples the parameters of the independent variables using the LHS method, which is a commonly used sampling method in deep neural network model prediction. It avoids the problem of overlapping samples. Among them, in terms of the original office building performance data, this paper sets the thermal performance of the enclosure structure in the cold region of Turpan by the General Specification for the "General Specification for Energy Efficiency and Renewable Energy Utilization in Buildings" (GB55015-2021 [97]). From the field study, the office building has a body shape factor of 0.21. In terms of thermal parameters of building models, the K-value of the building's exterior walls is 2.65 W/(m^2·K). The K-value of the roof is 0.88 W/(m^2·K), and the K-value of the exterior windows is 2.70 W/(m^2·K), with a SHGC of 0.30. This results in an initial TEUI of 258.76 kWh/m^2, a GWP of 116.51 kg/m^2, and an LCC of 270,192.01 CNY/m^2 for the office building (baseline model).

Aspects of setting operational parameters for office buildings: In terms of the building's energy consumption, heating temperatures, cooling temperatures, and human activity affect the results. The building performance model studied in this paper refers to the General Specification for the "General Specification for Energy Efficiency and Renewable Energy Utilization in Buildings" (GB55015-2021) (hereinafter collectively referred to as the Specification). At the level of personnel activity rate influencing factors, the personnel presence rate, number of personnel, and personnel category all have important influencing effects on the TEUI, GWP, and LCC of this office building. The building's personnel density is set at 10 m^2/person according to the code. Personnel in the room rate by the norms of the basis and then combined with the specific local work and rest time in the Turpan set, as shown in Figure 6. The room rate of personnel in the room is set accordingly with the specific local work and rest time in Turpan based on compliance with the specification, as shown in Figure 7.The cooling and heating temperatures in this paper are set concerning the temperatures in the code and combination with the local climatic characteristics of Turpan. In this paper, the indoor cooling temperature is set to 28 °C and the heating temperature is set to 18 °C. Cooling and heating schedules are set according to local working hours. The electrical equipment parameters are set at 15 W/m^2 according to the specifications. The hour-by-hour usage schedule of electrical equipment, the lighting usage schedule, and the building fresh air operation schedule are set in conjunction with specific local working hours, as shown in Figure 7.

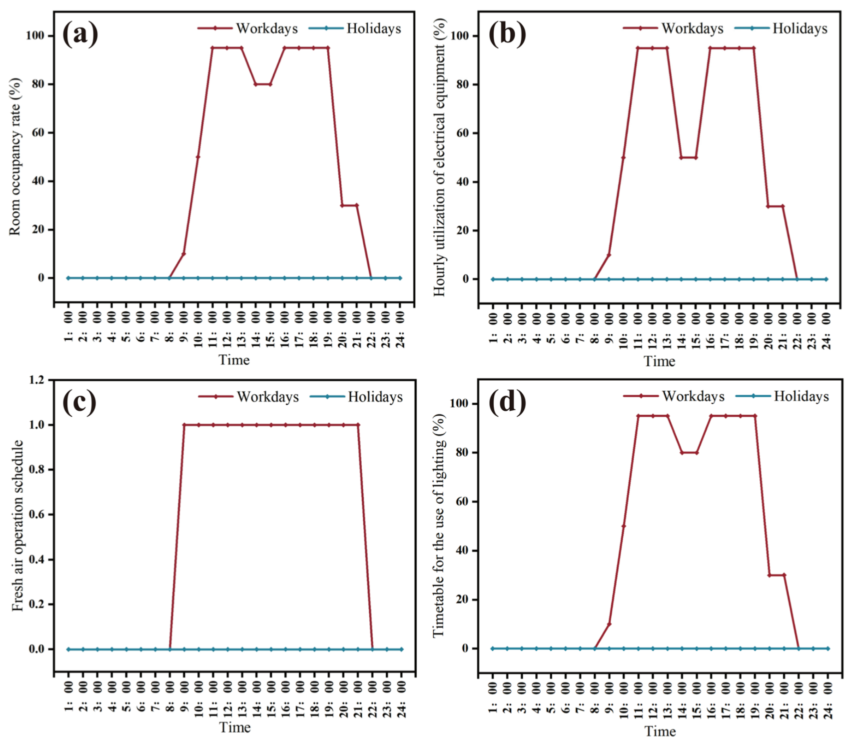


Figure 7. Building operating boundary condition settings. (**a**) Timetable of indoor occupancy rates. (**b**) Timetable for efficiency in the use of building equipment. (**c**) Building ventilation operating schedule. (**d**) Timetable for the use of lighting.

4.5.2. Other Condition Settings

Building performance data organization. In this paper, the Calibri Aggregator plug-in was chosen to statistically organize the building performance indicators (TEUI, GWP, and LCC). In addition, two widgets were connected to it: *CP Plugin*—which was mainly used as a target indicator for statistical building performance—and *CI Plugin*—which was mainly used to link the required samples. Finally, the Folder plug-in was used to save the records of the three target metrics of the building (TEUI, GWP, and LCC) to the Computer Specific Information folder. The target metrics obtained above are collected and organized and finally read into the xlsx file format for next use and analysis.

4.6. Building Performance Prediction Model Boundary Setting

After performing the independent variable-target variable dataset creation, this paper samples 2000 samples. An amount of 80% of these samples are used to train the model, and a 20% sample size is used to validate the accuracy of the model. The model consists of 19 input values (independent variable parameters) and three target values (TEUI, GWP, and LCC) with data of numerical type. After carrying out the prediction modeling, the selection of hyperparameters is also a difficult part of building a high-precision prediction model. In Deep Learning Convolutional Neural Networks (CNNs), the 2000 sample set is divided into 80% and 20% training and validation sets. To prevent the emergence of model overfitting risk, K-fold cross-validation is used in this paper for suppression. It can make the training set obtain more information and ensure the stability of the deep learning model. At the same time, outliers need to be culled. Outliers in the data that are not dealt with have no real meaning in the simulation, even though a deep learning model with higher accuracy can be obtained in the end. Therefore, the above method is used to establish a high-precision data-driven model with practical significance.

5. Results

5.1. Model Creation

Convolutional Neural Network (CNN) model creation. In this paper, three optimizers are chosen to change the weights, namely Adam, Sgdm, and RMSprop. The batch size for each model is 128. For the learning rate setting, the initial value is set to 0.01 in this paper. The input data are also standardized according to the standardization formula to eliminate the effect of the scale between the data. Meanwhile, to prevent the CNN data-driven model from encountering the overfitting phenomenon, this paper adopts the Dropout mechanism and K-fold cross-validation. The Dropout mechanism indicates that each neuron has a certain probability of being dropped, i.e., its output is 0 and the weights are not updated. In this paper, the Dropout value is set to 0.2, i.e., it means that 20% of randomly selected nodes will not be trained. Meanwhile, 7-fold cross-validation is used to improve the stability of deep learning models.

5.2. CNN Hyperparameter Settings

In CNN deep neural network models, more CNN layers lead to greater feature loss because the independent variable-target variable dataset is itself highly expressive. Therefore, this paper uses three layers for prediction. Meanwhile, the size of the convolution kernel in this paper is set to 3×3, and the step size of each move of the convolution kernel is 1. The information about the hyperparameter settings of the CNN deep neural network in this paper is shown in Table 5.

Table 5. Visualization of CNN Convolutional and Pooling Layer Settings.

Layer	Filter Size	Pool Size	No.of Filters	Stride	Padding Strategy	Activation Functions
Conv-1	3 × 3	---	32	1	0	ReLU
Pool-1	---	2 × 2	---	2	---	---
Conv-2	3 × 3	---	64	1	0	ReLU
Pool-2	---	2 × 2	---	2	---	---
Conv-3	3 × 3	---	128	1	0	ReLU
Pool-3	---	2 × 2	---	2	---	---

5.3. TEUI Forecasting Model Analysis

The training process of the TEUI convolutional neural network model for the Turpan office building is shown in Figure 8.

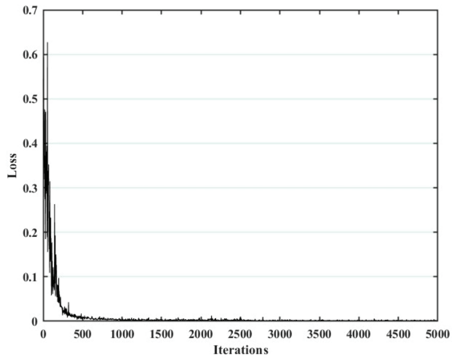


Figure 8. The CNN model training process for TEUI.

Analysis: In the case of the office building TEUI, the data information for the eight-building performance data-driven models is shown in Table 6. Also, the visualization results of R^2, RMSE, and MAE are shown in Figure 9. It is found through the figure that, among the eight models, the CNN(Adam) model has the highest correlation coefficient and the lowest RMSE and MAE. At the same time, other evaluation models have shown some advantages. The building performance modeling accuracy (R^2) sizes are in the following order: CNN(Adam), GA-BP, PSO-BP, BP, PSO-SVM, CNN(RMSprop), CNN(Sgdm), SVM. Meanwhile, the order of size in terms of RMSE evaluation metrics is as follows: CNN(Adam), PSO-BP, GA-BP, BP, PSO-SVM, CNN(RMSprop), CNN(Sgdm), SVM. Additionally, the order of magnitude in terms of MAE evaluation metrics: CNN(Adam), GA-BP, PSO-BP, BP, CNN(RMSprop), CNN(Sgdm), SVM, PSO-SVM.

Table 6. TEUI data-driven model accuracy visualization results.

Sort	Model	RMSE	MAE	R^2
1	BP	0.2522	0.1917	0.9733
2	SVM	0.9272	0.8880	0.9361
3	GA-BP	0.1986	0.1354	0.9889
4	PSO-BP	0.1963	0.1503	0.9870
5	PSO-SVM	0.2964	0.9671	0.9699
6	CNN(Sgdm)	0.4082	0.2997	0.9408
7	CNN(Adam)	0.1871	0.1254	0.9908
8	CNN(RMSprop)	0.3170	0.2541	0.9628

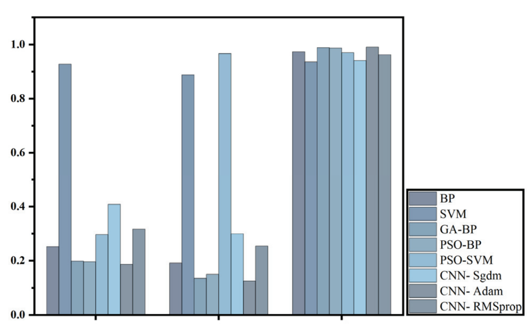


Figure 9. TEUI data-driven model accuracy visualization results.

In terms of deep learning models versus traditional regression models, CNN(Adam) reduces 0.0651, 0.7401, 0.0115, 0.0092, and 0.1093 in terms of RMSE compared to BP, SVM, GA-BP, PSO-BP, and PSO-SVM, respectively. MAE decreased by 0.0663, 0.7626, 0.01, 0.0249, and 0.8417, respectively. As for R^2, CNN(Adam) ranked the highest. The above analytical study shows that the CNN(Adam) algorithm outperforms all other data-driven models in predicting the error of the network prediction model concerning the data. It has the highest R2 score and the smallest RMSE and MAE values. This means that CNN(Adam) can be better generalized to new sample data and can be effectively used to predict data for architectural TEUI.

5.4. GWP Prediction Model Visualization Results

The training process of the GWP convolutional neural network model of the Turpan office building is shown in Figure 10.

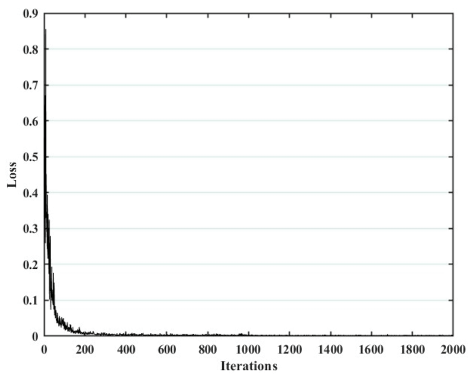


Figure 10. The CNN model training process for GWP.

Analysis: In terms of office building GWP, the data information for the eight-building performance data-driven models is shown in Table 7. Also, the visualization results of R^2, RMSE, and MAE are shown in Figure 11. It is found through the figure that, among the eight models, the CNN(Adam) model has the highest correlation coefficient and the lowest RMSE and MAE. At the same time, other evaluation models have shown some advantages. The building performance modeling accuracy (R^2) sizes are in the following order: CNN(Adam), PSO-BP, PSO-SVM, CNN(RMSprop), GA-BP, BP, CNN(Sgdm), SVM. Additionally, the order of size in terms of RMSE evaluation metrics is as follows: CNN(Adam), CNN(RMSprop), GA-BP, PSO-SVM, BP, CNN(Sgdm), SVM, PSO-BP. Finally, the order of magnitude in terms of MAE evaluation metrics is as follows: CNN(Adam), BP, CNN(Sgdm), CNN(RMSprop), SVM, PSO-BP, PSO-SVM, GA-BP.

Table 7. GWP data-driven model accuracy visualization results.

Sort	Model	RMSE	MAE	R^2
1	BP	0.1817	0.1501	0.9485
2	SVM	0.4141	0.4013	0.9029
3	GA-BP	0.1325	0.9471	0.9727
4	PSO-BP	0.8934	0.6774	0.9818
5	PSO-SVM	0.1447	0.7568	0.9797
6	CNN(Sgdm)	0.1966	0.1512	0.9436
7	CNN(Adam)	0.1263	0.1153	0.9869
8	CNN(RMSprop)	0.1292	0.2975	0.9796

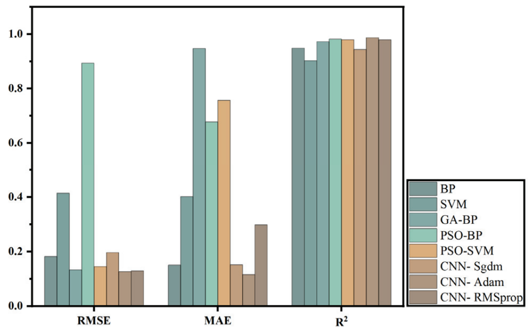


Figure 11. GWP data-driven model data schematization.

In terms of deep learning models versus traditional regression models, CNN(Adam) reduces 0.0554, 0.2878, 0.0062, 0.7671, and 0.0184 in terms of RMSE compared to BP, SVM, GA-BP, PSO-BP, and PSO-SVM, respectively. MAE decreased by 0.0348, 0.286, 0.8318, 0.5621, and 0.6415, respectively. As for R^2, CNN(Adam) ranked the highest. The above analytical study shows that the CNN(Adam) algorithm outperformed all other data-driven models in predicting the error of the network prediction model concerning the data. It had the highest R2 score and the smallest RMSE and MAE values. This means that CNN(Adam) can be better generalized to new sample data and can be effectively used to predict data for building GWP.

5.5. LCC Prediction Model Visualization Results

The training process of the LCC convolutional neural network model for the Turpan office building is shown in Figure 12.

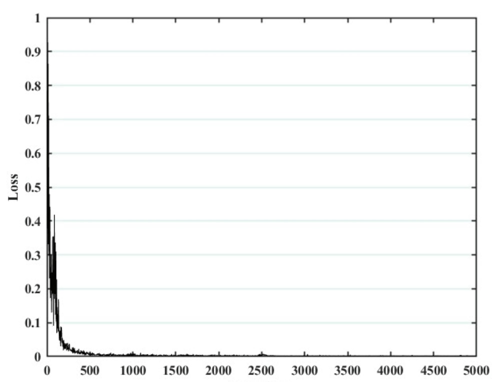


Figure 12. The CNN model training process for LCC.

Analysis: In terms of building LCC, the eight building performance models are shown in Table 8. Also, the results of R^2, RMSE, and MAE are shown in Figure 13. It is found through the figure that, among the eight models, the CNN(RMSprop) model has the highest correlation coefficient and the lowest RMSE and MAE. At the same time, other evaluation models have shown some advantages. The building performance modeling accuracy (R^2) sizes are in order: CNN(RMSprop), GA-BP, CNN(Adam), PSO-BP, BP, PSO-SVM, CNN(Sgdm), SVM. Additionally, the order of size in terms of RMSE evaluation metrics is as follows: CNN(RMSprop), GA-BP, PSO-SVM, BP, CNN(Adam), CNN(Sgdm), PSO-BP, SVM. Finally, the order of magnitude in terms of MAE evaluation metrics is as follows: CNN(RMSprop), PSO-SVM, GA-BP, BP, CNN(Adam), CNN(Sgdm), PSO-BP, SVM.

Table 8. LCC data-driven model accuracy visualization results.

Sort	Model	RMSE	MAE	R^2
1	BP	0.2387	0.1482	0.9824
2	SVM	0.8413	0.5415	0.9145
3	GA-BP	0.1945	0.1421	0.9899
4	PSO-BP	0.6756	0.5348	0.9856
5	PSO-SVM	0.1965	0.1307	0.9775
6	CNN(Sgdm)	0.6187	0.4632	0.9616
7	CNN(Adam)	0.3572	0.2639	0.9881
8	CNN(RMSprop)	0.1772	0.1295	0.9969

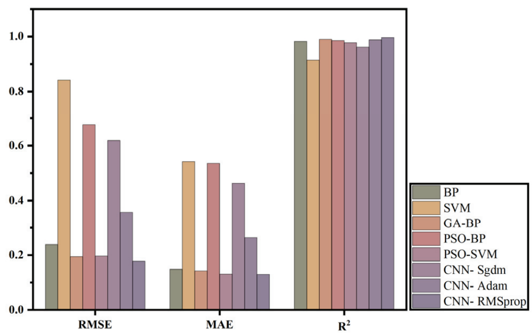


Figure 13. LCC data-driven model accuracy visualization results.

In terms of deep learning models versus traditional regression models, CNN(RMSprop) is reduced by 0.0615, 0.6641, 0.0173, 0.4984, and 0.0193 in terms of RMSE compared to BP, SVM, GA-BP, PSO-BP, and PSO-SVM, respectively. MAE is decreased by 0.0187, 0.412, 0.0126, 0.4053, and 0.0012, respectively. As for R^2, CNN(RMSprop) is ranked the highest. The above analytical study shows that the CNN(RMSprop) algorithm outperforms all other data-driven models in predicting the error of the network prediction model concerning the data. It has the highest R^2 score and the smallest RMSE and MAE values. This means that the CNN(RMSprop) can be better generalized to new sample data and can be effectively used to predict data for building LCC.

Summary: In terms of time cost, CNN prediction models can significantly reduce time cost compared to baseline models (parametric performance models created by Rhino software). In terms of energy prediction, the CNN prediction model takes only 129 s for a single run compared to 21.57 min if a traditional arithmetic model (baseline model) is used. A comprehensive comparison reveals that CNN(Adam) reduces the time cost by 90.21%. For GWP prediction, the CNN prediction model takes only 149 s to run once, while the baseline model takes 27.45 min. A comprehensive comparison reveals that CNN(Adam) reduces the time cost by 91.06%. For LCC prediction, the CNN prediction model takes only 138 s to run once, while the baseline model takes 23.29 min. A comprehensive comparison reveals that CNN(RMSprop) reduces the time cost by 90.20%, as shown in Figure 14. It can be concluded that the efficiency of the model can be greatly improved and the time cost can be saved by the method based on deep learning model prediction.

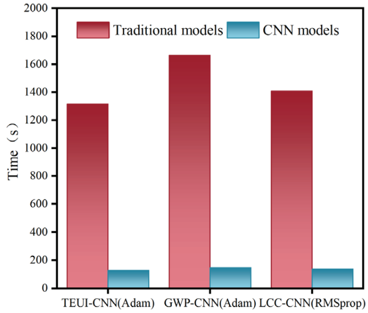


Figure 14. The plot of TEUI, GWP, and LCC data-driven models against baseline model time.

5.6. Visualization of Multi-Objective Optimization Results

5.6.1. Three Types of Objective Function Analysis

As shown in Figure 15, in this paper the NSGA-II algorithm is used for multi-objective optimization. After traversing the data for 100 generations, a sample set of 4500 is obtained. The distribution of the three target indicators (TEUI, GWP, and LCC) is shown in Figure 11. A study and analysis of the optimized solution set (independent parameter-objective variable) shows the range of distribution of the three objectives TEUI, GWP, and LCC. In terms of TEUI, the data are mainly distributed between 148.25 kWh/m^2 and 165.22 kWh/m^2. In terms of GWP, the data are mainly distributed between 67.82 kg/m^2 and 77.97 kg/m^2. In terms of LCC, the values are mainly concentrated between 178,407.20 CNY/m^2–189,508.02 CNY/m^2. The three target values for the original office building are a TEUI of 198.89 kWh/m^2, a GWP of 91.51 kg/m^2, and an LCC of 267,731.96 CNY/m^2. After the optimization of the objectives, the optimal index and the original building index are reduced by 108.53 kWh/m^2, 47.31 kg/m^2, and 84,537.83 CNY/m^2, respectively. The three target values were reduced by 41.94%, 40.61%, and 31.29%, respectively.

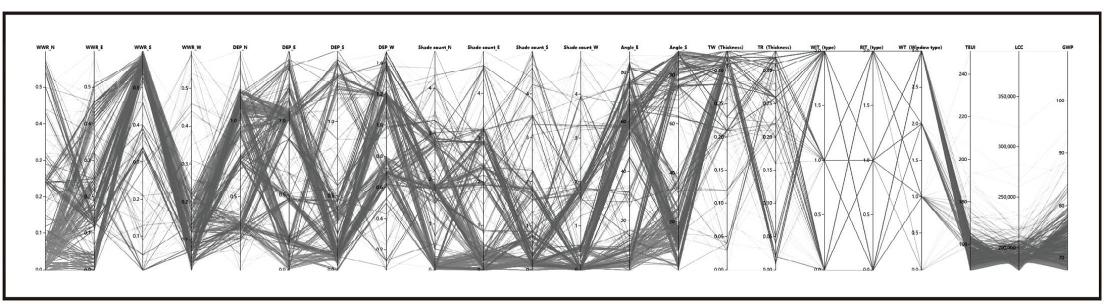


Figure 15. The plot of total data results for 4500 multi-objective optimizations.

5.6.2. Analysis of Variables

Based on the obtained 45 Pareto solutions in parallel coordinate plots, the distribution of each variable can be seen, as shown in Figure 16. In terms of insulation type, WIT is focused on EPS and PU, and RIT is focused on PU. Optimization variables show that exterior walls have a wider range of insulation options compared to roofs. This is mainly due to the large area of building coverage on the exterior walls compared to the roof. Although EPS has a poor thermal performance compared to XPS and PU. However, in the case of large office buildings with large surface areas, coupled with relatively affordable prices, EPS has a significant advantage in terms of economic cost.

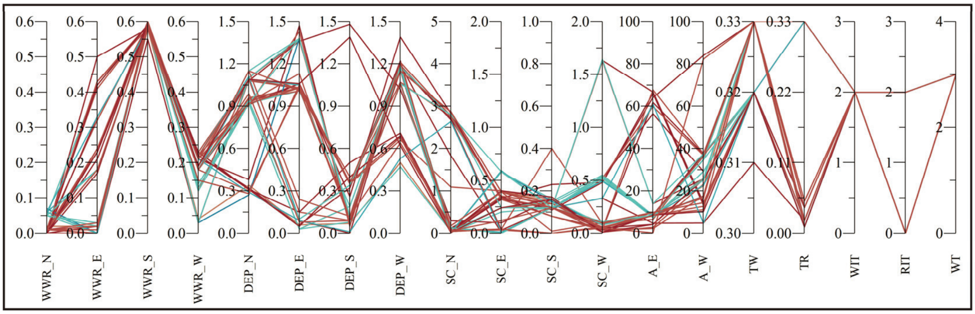


Figure 16. Distribution of variables for 45 Pareto optimization schemes.

Analysis in terms of insulation thickness. TW is mainly distributed around 0.32 and TR between 0.02 and 0.11. Analyze the reasons for its existence in a cold region like Turpan, where winters are cold and summers are hot. Since it has very strong solar radiation, take the maximum number of uses at the TW insulation level.

In terms of window types, the last option was chosen for all scenarios. The reason for this is that it has a small heat transfer coefficient, which effectively prevents heat loss in winter. It also has a relatively high SHGC, which increases the absorption of solar radiation in office buildings in winter. In addition to this, WT with good thermal performance has a profound impact on the life cycle of office buildings in cold regions like Turpan.

In terms of WWR distribution. The distributions of WWR_S and WWR_N are more concentrated compared to WWR_W and WWR_E, which are distributed around 0.55 and 0.01, respectively. This allows the building to receive more solar radiation in the winter, allowing more heat to be gained inside while avoiding heat loss. For high-latitude places like Turpan, where buildings in the region are more susceptible to western sunlight, which in turn leads to overheating indoors, WWR_W has a smaller distribution than WWR_E. Therefore reducing WWR_W minimizes the cooling energy consumption of the air conditioner in the summer and also reduces the LCC and GWP.

In terms of shade depth, DEP_S is mainly distributed between 0 and 0.3, and DEP_E is mainly distributed around 1.1; additionally, their average values are lower than those of DEP_N and DEP_W. The reason for this is that increasing the length of shading at these two levels of this office building, although it reduces the entry of hot outdoor heat into the interior during the summer months, has the negative effect of making the interior less thermally comfortable during the winter months. Meanwhile, in terms of WWR_E and WWR_W, their values are relatively widely distributed due to the long summer period in Xinjiang. West-facing shading can effectively improve indoor thermal comfort while also reducing energy consumption and economic costs.

5.7. Analysis of Entropy-Based Evaluation Models for the Topsis Method

In evaluating the 45 programs on the Pareto frontier using the entropy-based Topsis method, the target metrics are first selected. That is, TEUI, GWP, and LCC are selected in this paper. Secondly, the type of indicator is established, and the three indicators selected in this paper are all of the very small value type. That is, the smaller the value representing the Turpan office building performance capacity, the better, and the more environmentally friendly the energy-saving emission reduction adjustment ability will be In the third step, information on the various indicators for the three objectives is established, as shown in Table 9 below.

Table 9. Indicator information for the three objectives of the entropy weighting method.

Type	Total Energy Consumption (TEUI)	Global Warming Potential (GWP)	Life Cycle Costs (LCC)
Information entropy values (e)	0.955	0.954	0.962
Information utility value (d)	0.045	0.046	0.038
Weights (%)	35.10	35.63	29.27

Table 10 shows the matrix calculation information for the Topsis method. The ranking data information for each target scenario was analyzed and compiled based on the Topsis methodology. Meanwhile, Table 10 shows the top 10 highest-rated results.

Table 10. Entropy-based Topsis method program data information (Top 10).

Optimal Type	Positive Ideal Solution (D+)	Negative Ideal Solution (D−)	Composite Score	Sort
Option 1	0.368924	0.758328	0.672722	1
Option 2	0.387277	0.780325	0.668314	2
Option 3	0.352599	0.695340	0.663531	3
Option 4	0.389703	0.760765	0.661266	4
Option 5	0.375661	0.712357	0.654729	5
Option 6	0.375361	0.685431	0.646150	6
Option 7	0.474827	0.839538	0.638740	7
Option 8	0.371605	0.656131	0.638423	8
Option 9	0.371808	0.649367	0.635901	9
Option 10	0.450525	0.782468	0.634609	10

Analysis: Visualize the above table in a graph. As shown in Figure 17, the higher the square block rises, the higher the score for the program. As can be seen from the graph, option 1 scored 0.672722, which is the highest score. It has an optimal solution: TEUI is 150.23 kWh/m^2, GWP is 69.20 kg/m^2 and LCC is 185,654.18 CNY/m^2.

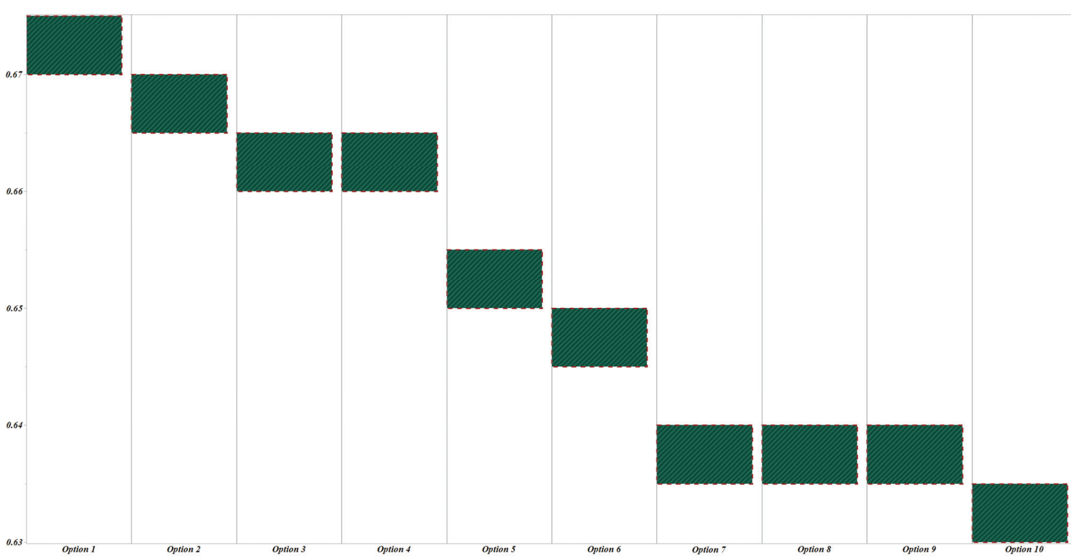


Figure 17. Graphical representation of data information for each scenario of the entropy-based Topsis method.

5.8. Evaluation Model Analysis of the Topsis Method Based on Subjective Empowerment

The program ranking scores are analyzed in this subsection by varying the weighting factors. Based on changing different weighting factors, two schemes are derived from this: The first one is to set TEUI, GWP, and LCC as preferred targets in order, with preferred targets weighted at 1 and others at 0. The second option is to assign 0.33 to each of the three indicators to visualize the study analysis.

5.8.1. The First Empowerment Scheme

Analysis: In terms of TEUI, it is shown in Table 11. The optimal solution score is 1. The corresponding optimal solutions are WIT for PU, RIT for EPS, WT for Triple pane Low-e(green), WWR_N for 0.05, WWR_E for 0.01, WWR_S for 0.59, WWR_W for 0.03, DEP_N for 1.11 m, DEP_E for 1.38 m, DEP_S for 0.12 m, DEP_W for 1.06 m, SC_N for 0, SC_E for 0, SC_S for 0, SC_W for 1, A_E for 8.52°, A_W for 25.76°, TW for 0.33 m, TR for 0.02 m, TEUI for 148.25 kWh/m^2, GWP for 67.92 kg/m^2, and LCC for 188,149.84 CNY/m^2.

Table 11. Graphical representation of the top 10 program rankings when TEUI weight information is 1.

Optimal Type	Positive Ideal Solution (D+)	Negative Ideal Solution (D−)	Composite Score	Sort
Option 1	0.000000	0.999988	1.000000	1
Option 2	0.003536	0.996452	0.996464	2
Option 3	0.011905	0.988084	0.988095	3
Option 4	0.039309	0.960679	0.960691	4
Option 5	0.043257	0.956731	0.956742	5
Option 6	0.067008	0.932981	0.932992	6
Option 7	0.074139	0.925850	0.925860	7
Option 8	0.082979	0.917009	0.917020	8
Option 9	0.110913	0.889075	0.889085	9
Option 10	0.116925	0.883064	0.883074	10

In terms of GWP, as shown in Table 12, the optimal solution score is 1. The corresponding optimal solutions are WIT for PU, RIT for PU, WT for Triple pane Low-e(green), WWR_N for 0.01, WWR_E for 0.01, WWR_S for 0.55, WWR_W for 0.03, DEP_N for 1.11 m, DEP_E for 1.37 m, DEP_S for 0.12 m, DEP_W for 1.19 m, SC_N for 2, SC_E for 0, SC_S for 0, SC_W for 2, A_E for 13.97°, A_W for 25.66°, TW for 0.32 m, TR for 0.02 m, TEUI for 148.31 kWh/m^2, GWP for 67.82 kg/m^2, and LCC for 189,508.02 CNY/m^2.

Table 12. Graphical representation of the top 10 program rankings when GWP weight information is 1.

Optimal Type	Positive Ideal Solution (D+)	Negative Ideal Solution (D−)	Composite Score	Sort
Option 1	0.000000	0.999980	1.000000	1
Option 2	0.004948	0.995032	0.995052	2
Option 3	0.009693	0.990287	0.990307	3
Option 4	0.052566	0.947414	0.947432	4
Option 5	0.072996	0.926984	0.927002	5
Option 6	0.078864	0.921117	0.921135	6
Option 7	0.101570	0.898411	0.898428	7
Option 8	0.122356	0.877624	0.877642	8
Option 9	0.135865	0.864116	0.864133	9
Option 10	0.172855	0.827125	0.827142	10

In terms of LCC, as shown in Table 13. The optimal solution score is 1. The corresponding optimal solutions are WIT for PU, RIT for EPS, WT for Triple pane Low-e(green), WWR_N for 0.01, WWR_E for 0.50, WWR_S for 0.58, WWR_W for 0.21, DEP_N for 0.38 m, DEP_E for 1.47 m, and DEP_S for 0.07 m, DEP_W is 1.19 m, SC_N is 3, SC_E is 0, SC_S is 0, SC_W is 0, A_E is 64.12°, A_W is 83.90°, TW is 0.33 m, TR is 0.02 m, TEUI is 165.22 kWh/m^2, GWP is 77.97 kg/m^2, and LCC is 178,407.20 CNY/m^2.

Table 13. Graphical representation of the top 10 program rankings when the LCC weight information is 1.

Optimal Type	Positive Ideal Solution (D+)	Negative Ideal Solution (D−)	Composite Score	Sort
Option 1	0.000000	1.000000	1.000000	1
Option 2	0.003347	0.996653	0.996653	2
Option 3	0.018799	0.981201	0.981201	3
Option 4	0.043928	0.956072	0.956072	4
Option 5	0.063234	0.936766	0.936766	5
Option 6	0.081126	0.918874	0.918874	6
Option 7	0.119132	0.880868	0.880868	7
Option 8	0.124258	0.875742	0.875742	8
Option 9	0.149042	0.850958	0.850958	9
Option 10	0.154563	0.845437	0.845437	10

5.8.2. The Second Empowerment Scheme

In this subsection, TEUI, GWP, and LCC are visualized and analyzed with weights set to 0.33, as shown in Table 14.

Table 14. Graphical representation of data information for three targets with weight information of 0.33 (Top 10).

Optimal Type	Positive Ideal Solution (D+)	Negative Ideal Solution (D−)	Composite Score	Sort
Option 1	0.390863	0.740950	0.654658	1
Option 2	0.366709	0.683724	0.650897	2
Option 3	0.411852	0.760994	0.648844	3
Option 4	0.413608	0.742166	0.642138	4
Option 5	0.394783	0.697264	0.638493	5
Option 6	0.391516	0.672434	0.632017	6
Option 7	0.382523	0.646877	0.628402	7
Option 8	0.381307	0.641183	0.627080	8
Option 9	0.506743	0.815601	0.616784	9
Option 10	0.479964	0.760820	0.613177	10

As shown in Table 14, the optimal solution score is 0.654658 under this scheme. The corresponding optimal solutions are WIT for PU, RIT for EPS, WT for Triple pane Low-e(green), WWR_N for 0.05, WWR_E for 0.02, WWR_S for 0.59, WWR_W for 0.14, DEP_N for 0.92 m, DEP_E for 0.03 m, DEP_S for 0.19 m, DEP_W is 1.18 m, SC_N is 0, SC_E is 0, SC_S is 0, SC_W is 1, A_E is 8.52°, A_W is 34.65°, TW is 0.33 m, TR is 0.01 m, TEUI is 150.23 kWh/m^2, GWP is 69.20 kg/m^2, and LCC is 185,654.18 CNY/m^2.

5.9. Comparative Analysis between Optimal Solutions

The three objectives of the Pareto frontier solution are sequentially ranked, using the entropy-based Topsis method and subjective assignment. Obtain five solutions to visualization: Topsis optimal, TEUI optimal, GWP optimal, LCC optimal, and each of the three objective value weights is 0.33, as shown in Table 15.

Table 15. Optimal Solution Objective Indicators and Distribution of Variables.

Categories	TOPSIS Optimal	TEUI Optimal	GWP Optimal	LCC Optimal	Weighting 0.33 Each
WIT	PU	PU	PU	PU	PU
RIT	EPS	EPS	PU	EPS	EPS
WT	Triple pane Low-e(green)	Triple pane Low-e(green)	Triple pane Low-e(green)	Triple pane Low-e(green)	Triple pane Low-e(green)
WWR_N	0.05	0.05	0.01	0.01	0.05
WWR_E	0.02	0.01	0.01	0.50	0.02
WWR_S	0.59	0.59	0.55	0.58	0.59
WWR_W	0.14	0.03	0.03	0.21	0.14
DEP_N	0.92	1.11	1.11	0.38	0.92
DEP_E	0.03	1.38	1.37	1.47	0.03
DEP_S	0.19	0.12	0.12	0.07	0.19
DEP_W	1.18	1.06	1.19	1.19	1.18
SC_N	0	0	2	3	0
SC_E	0	0	0	0	0
SC_S	0	0	0	0	0
SC_W	1	1	2	0	1
A_E	8.52	8.52	13.97	64.12	8.52
A_W	34.65	25.76	25.66	83.90	34.65
TW	0.33 m	0.33 m	0.32 m	0.33 m	0.33 m
TR	0.01 m	0.02 m	0.02 m	0.02 m	0.01 m
TEUI	150.23	148.25	148.31	165.22	150.23
GWP	69.20	67.92	67.82	77.97	69.20
LCC	185,654.18	188,149.84	189,508.02	178,407.20	185,654.18

As can be seen from the above table, for the entropy-based Topsis method, the TEUI is 150.23 kWh/m^2, the GWP is 69.20 kg/m^2, and the LCC is 185,654.18 CNY/m^2. In terms of optimal TEUI, the TEUI is 148.25 kWh/m^2, GWP is 67.92 kg/m^2, and LCC is 188,149.84 CNY/m^2. In terms of optimal GWP, the TEUI is 148.31 kWh/m^2, GWP is 67.82 kg/m^2, and LCC is 189,508.02 CNY/m^2. In terms of LCC optimization, TEUI is 165.22 kWh/m^2, GWP is 77.97 kg/m^2, and LCC is 178,407.20 CNY/m^2. For each of the three target value weights of 0.33 scenarios, TEUI is 150.23 kWh/m^2, GWP is 69.20 kg/m^2, and LCC is 185,654.18 CNY/m^2.

6. Article Discussion

6.1. Comparative Analysis of Data with the Original Office Building Program

6.1.1. Comparison of the Results of the Optimal Scheme of the Entropy-Based Topsis Method with the Initial Data

From Section 4.5.1, the TEUI of the original office building is 258.76 kWh/m^2, the GWP is 116.51 kg/m^2, and the LCC is 270,192.01 CNY/m^2. After comparing the optimal solution with the entropy-based Topsis method, it is shown in Figure 18. The TEUI of the office building was reduced by 108.53 kWh/m^2, the GWP by 47.31 kg/m^2, and the LCC by 84,537.83 CNY/m^2. The TEUI, GWP, and LCC were reduced by 41.94%, 40.61%, and 31.29%, respectively.

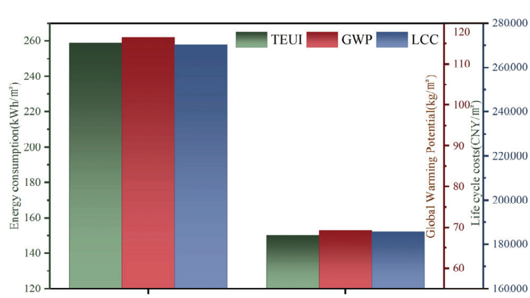


Figure 18. Comparison of the optimal entropy-based Topsis method with initial building data.

6.1.2. Comparison of the Results of the Optimal TEUI-Based Scheme with the Initial Data

In the optimal TEUI scheme, as shown in Figure 19, the optimal TEUI for office buildings is 148.25 kWh/m^2. Compared with the original building TEUI, the reduction is 110.51 kWh/m^2, which is 42.71% energy saving.

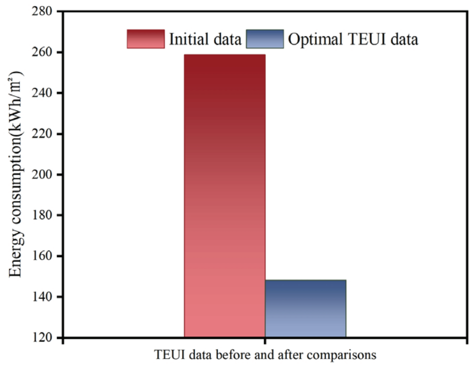


Figure 19. Comparison of TEUI optimal solution with initial building data.

6.1.3. Comparison of the Results of the Optimal GWP-Based Scheme with the Initial Data

In the optimal GWP scheme, this GWP consists of two parts, i.e., the carbon dioxide emissions during the initial phase cycle (CO_2_DLC) and the carbon dioxide emissions during the operational phase cycle (CO_2_OP) of this Turpan office building. As shown in Figure 20, the optimal GWP value of the office building is 69.20 kg/m^2, CO_2_DLC is 143,209.39 kgCO_2, and CO_2_OP is 3,247,800 kgCO_2, while the GWP of the original building is 116.51 kg/m^2, CO_2_DLC is 294,752 kgCO_2, and CO^2_OP is 5,530,748 kgCO_2. The comparison shows that GWP is reduced by 47.31 kg/m^2, CO_2_DLC is reduced by 151,542.60 kgCO_2, and CO_2_OP is reduced by 2,282,948 kgCO_2. They were reduced by 40.61%, 51.41%, and 41.28%, respectively.

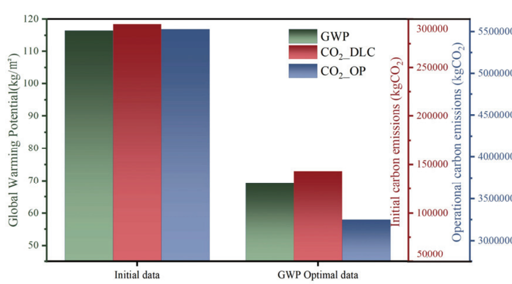


Figure 20. Comparison of GWP optimal solution with initial building data.

6.1.4. Comparison of the Results of the Optimal LCC-Based Scheme with the Initial Data

In the optimal LCC scheme, as shown in Figure 21. The LCC of this scheme is 178,407.20 CNY/m^2 and the building operating cost (EC) is 240,006 CNY. Compared to the original LCC, the LCC was reduced by 91,784.81 CNY/m^2 and the EC was reduced by 122,473 CNY. They were reduced by 33.97% and 33.79%, respectively.

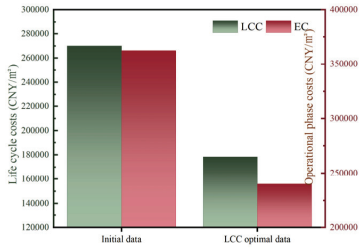


Figure 21. Comparison of LCC optimal solution with initial building data.

6.2. Visualization of Sensitivity Analysis

The Pareto frontier solution can only give the set of regional solutions within the optimal range of the three metrics, but it does not give information about the ranked situation or the importance of the characteristics of the parameters of the independent variables. Therefore, on this basis, this paper uses the sensitivity analysis strategy to define the degree of influence of the parameters of the independent variables on the target variables. After the methodology has been used to derive the degree of influence between the variables, it can be used as a basis for further screening under specific conditions and the prioritization of important parameters, which enhances the performance of the office building. At the level of sensitivity analysis carried out in this article, the article uses two different schemes, the RBD-FAST and DMIM methods.

6.2.1. RBD-FAST Methodology Analysis

In the RBD-FAST method, for the variables affecting TEUI, the top four are TR > WWR_W > WWR_E > TW. These four variables account for 43.31% of the overall, as shown in Figure 22a. For GWP, the top four influences are TR > WWR_W > WWR_E > TW. These four variables accounted for 85.96% of the total, as shown in Figure 22b. In terms of LCC, the top four influences are TR > TW > WT > SC_E, respectively. These four variables accounted for 88.75% of the total, as shown in Figure 22c.

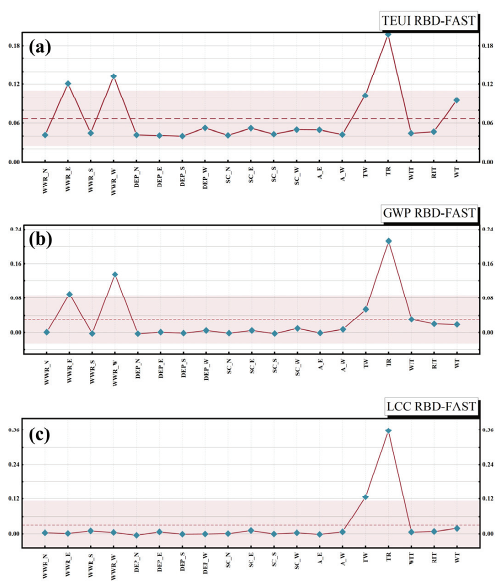


Figure 22. RBD-FAST method analysis. (**a**) TEUI results visualization. (**b**) GWP results visualization. (**c**) LCC results visualization.

6.2.2. DMIM Methodology Analysis

In the DMIM sensitivity approach, as shown in Figure 23, for TEUI, the top four TOI and FOI rankings are TR > WWR_W > WWR_E > TW and TR > TW > WWR_W > WWR_E, respectively. They represent 43.30% and 80.30% of the TOI and FOI as a whole, respectively.

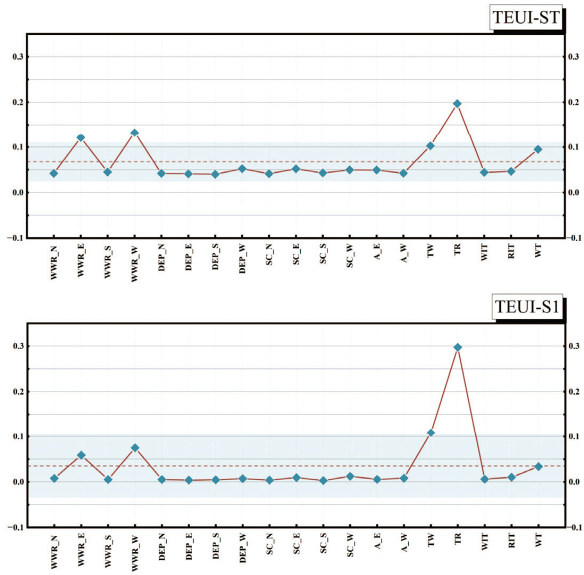


Figure 23. Visualization of the DMIM method analysis of TEUI.

For GWP, the top four TOI and FOI rankings are WWR_W > WWR_E > TR > WIT and TR > WWR_W > WWR_E > TW, respectively. These four variables accounted for 41.12% and 73.13% of the overall TOI and FOI, respectively. Figure 24 shows the results of the analytical visualization of the DMIM method for GWP.

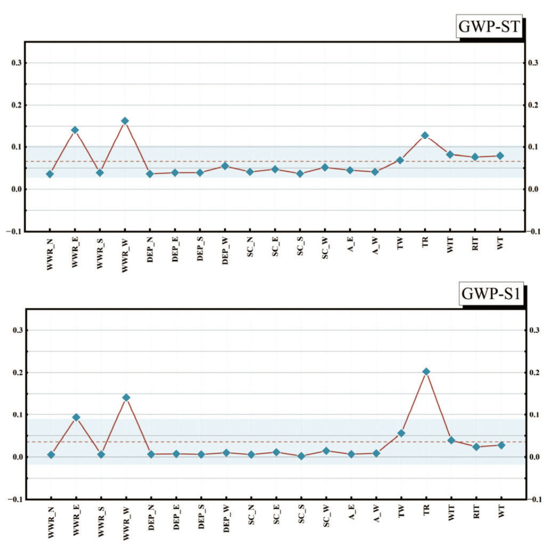


Figure 24. Visualization of the DMIM method analysis of GWP.

For LCC, the top four TOI and FOI rankings are TR > TW > WT > WWR_W and TR > TR > TW > WT > SC_E, respectively. They accounted for 34.38% and 82.25% of the overall TOI and FOI, respectively. Figure 25 shows the results of the analytical visualization of the DMIM method for LCC.

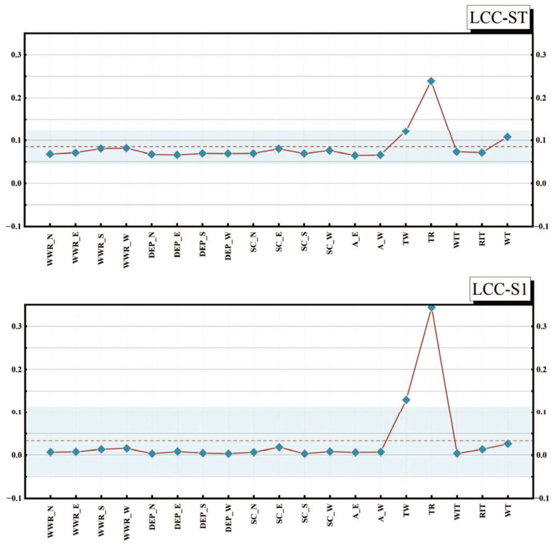


Figure 25. Visualization of the DMIM method analysis of LCC.

6.2.3. Analysis of Results

For TEUI and GWP, the big impacts are TR, WWR_W, and WWR_E. More attention should be paid to the TR aspect of the design in future building construction. The design can be carried out in such a way as to increase the TR according to the specific construction. In addition, when building a new construction or remodeling, designers should be more likely to consider the impact of WWR_W and WWR_E on the performance of office buildings. Shading not only reduces the TEUI of office buildings but also reduces carbon emissions. It is also in line with the "dual-carbon" policy that China has proposed in recent years. In terms of LCC, increasing TR with TW is an optimized form of measurement to reduce LCC. A modest increase in TR and TW will allow office buildings to reduce some of the solar radiation during the summer months. It also provides insulation in the winter months. In the long run, the impact on the performance characteristics of office buildings in the region will be far-reaching. SC_N and SC_S are ranked very close to 0 for the three target indicator impacts. Therefore, the above two independent variable parameters have little impact on the results of the study when conducting the design, and the designer can make trade-offs according to the specific scenario when making decisions.

6.3. Comparison and Linkage of Findings to Existing Research

6.3.1. At the Level of Multi-Objective Optimization

The starting point of the research content of this paper is to optimize the TEUI, GWP, and LCC of the building and analyze them using the NSGA-II algorithm, then go on to provide a guiding idea for the optimization of the building performance in extremely hot and cold regions. The results of the study show that, when optimizing the performance objectives (TEUI, GWP, and LCC), the WWR_N and WWR_S of the building are presented as minimized and maximized, respectively. This optimization can result in a building that can gain more heat in the winter while also reducing heat loss. Existing studies have found that Zhang et al. went about studying office building GWP and LCC by utilizing the NSGA-II algorithm [22]. Song et al. used the NSGA-II algorithm to optimize the LCC and HTD (hours of thermal discomfort) for residential buildings in Turpan [98]. The multi-objective optimization results of the above two scholars are consistent with this paper. That is, the distribution of WWR_N and WWR_S is the most concentrated, and WWR_N and WWR_S show the tendency of minimization and maximization in the multi-objective optimization process. It can be seen that, especially in very hot and cold regions and severe cold regions, WWR has a great influence on the building performance when optimizing the building performance in a multi-objective way. Therefore, the impact of WWR on buildings should be considered in future designs.

6.3.2. At the Level of Decision Analysis

The article uses two decision analysis methods, the entropy-based Topsis method, and the subjective empowerment Topsis method. In this case, when the entropy-based Topsis method is used, the optimization results in a reduction in the TEUI, GWP, and LCC of 41.94%, 40.61%, and 31.29%, respectively. Literatures [37,98] used the entropy-based Topsis method to go for the effect of optimization of building energy efficiency in extremely hot and cold regions and severe cold regions, respectively. In the above optimization results, in terms of building performance improvement strategies at the level of the building envelope, at the level of the building shading measures, and at the level of the building's thermal insulation performance, the method objectively evaluates and measures the optimization results to quickly and efficiently improve the building's performance potential. Thus, they can provide some advice to the designers involved in the analysis phase of future decisions.

6.3.3. At the Level of Sensitivity Analysis

The article uses two sensitivity analyses to investigate the effect of independent variable parameters on building performance goals. It was found that, for reducing the TEUI, GWP, and LCC, the optimized measure is the selection of high-performance windows. The optimization in this paper results in the use of Triple pane, Low-e(green) type windows. Secondly, increasing the WWR_S and decreasing the WWR_N and WWR_E of a building is critical to improving building performance. Literatures [37,98] are more consistent at the level of performance sensitivity analysis compared to the results derived from the optimization in this paper. It can be seen that window performance and the WWR of a building have a very significant effect on building performance, so more attention should be paid to this aspect in future research.

6.4. Limitations of Future Research

In the framework content studied in this paper, the internal heat flow direction in office buildings is not considered. Subsequent research could look at issues related to heat flow inside buildings in terms of fluid dynamics. Also, in terms of the building's internal wind environment, a good wind environment direction can improve the indoor air quality and enhance the comfort of office workers. Therefore, it can also be included in the analysis of subsequent studies. Analyzed in terms of life cycle stages, the dismantling stage can be added to the study in subsequent research. Changes in various economic cost rates over time can also affect LCC. The unexplored life cycle years of office buildings in extremely hot and cold regions can have a direct impact on GWP and LCC. In addition, the development of passive technologies has been accompanied by subtle changes in building performance, e.g., the economic costs and carbon emissions associated with improved thermal insulation and changes in high-performance windows, which in turn lead to improvements in building airtightness, are difficult to demonstrate quantitatively at the initial investment stage and will still require some realistic assessment and measurement in future research.

7. Conclusions

7.1. Applicability of the Article's Research

In the course of the research in this paper, the content of the framework is not immutable; it is malleable. For example, this article examines the energy consumption, CO_2 emissions, and economics of office buildings in Turpan only. Subsequent studies could add other performance metrics to this, such as optical performance indicators and thermal comfort indicators (PMV, UTCI, PET, SET). Additionally, research from different climate zone levels can have more options and applications. At the same time, the content of the framework studied in this paper is variable. For example, when considering a larger number of independent variable parameters and multiple performance targets, a sensitivity analysis can be performed to retain the more influential independent variable parameters. This greatly reduces the time spent on analysis, which in turn improves the efficiency of building performance. In addition to this, other MCDM methods can be added when a larger number of performance objectives needs to be considered. Analysis through multiple methods at the decision-making stage can, in turn, increase the transparency and credibility of decisions.

7.2. Article Conclusions

This paper takes the optimization of office building performance prediction in the Turpan area as the research objective. It uses TEUI, GWP, and LCC as the target indicators for performance prediction optimization analysis, and then proceeds to explore the energy-saving strategies in performance prediction optimization of office buildings in the cold region of Turpan. The conclusions of the article are divided into the following areas:

(1) This paper creates three deep neural network data-driven prediction models based on office building performance objectives (TEUI, GWP, and LCC). In this analysis, each performance metric was compared using eight separate data-driven models for prediction. Finally, in the prediction results, the optimal data-driven model in terms of TEUI is CNN(Adam), which is a deep learning model with R^2 of 0.9908, RMSE of 0.1871, and MAE of 0.1254. In terms of GWP, the optimal data-driven model is CNN(Adam), which is a deep learning model with an R^2 of 0.9869, RMSE of 0.1263, and MAE of 0.1153. In terms of LCC, the optimal data-driven model is CNN(RMSprop), which is a deep learning model with R^2 of 0.9969, RMSE of 0.1772, and MAE of 0.1295.

(2) In this paper, a multi-objective optimization of the performance objectives of office buildings in the Turpan region is carried out. The article uses the NSGA-II optimization algorithm to optimize the three objectives. The optimized three objectives were then compared against the initial data for the office building. The results of the analysis were as follows: The TEUI was reduced by 108.53 kWh/m^2 from the initial value, and its reduction was 41.94%. The GWP was reduced by 43.71 kg/m^2 from the initial value, and its reduction was 40.61%. The LCC was reduced by 84,537.83 CNY/m^2 from the initial value and its reduction was 31.29%.

(3) In the program decision part, this paper adopts the entropy-based Topsis method and subjective empowerment method for decision analysis. In the entropy-based Topsis method scheme, the three metrics of the optimal solution are TEUI of 150.23 kWh/m^2, GWP of 69.20 kg/m^2, and LCC of 185,654.18 CNY/m^2. In the subjective assignment method, the three target indicators of the optimal TEUI scheme are 148.25 kWh/m^2 for TEUI, 67.92 kg/m^2 for GWP, and 188,149.84 CNY/m^2 for LCC. The three target metrics for the optimal GWP scheme are TEUI of 148.31 kWh/m^2, GWP of 67.82 kg/m^2, and LCC of 189,508.02 CNY/m^2. The three target indicators of the optimal LCC scheme are 165.22 kWh/m^2 for TEUI, 77.97 kg/m^2 for GWP, and 178,407.20 CNY/m^2 for LCC. The target indicators under each of the three performance objectives weighted at 0.33 program are 150.23 kWh/m^2 for TEUI, 69.20 kg/m^2 for GWP, and 185,654.18 CNY/m^2 for LCC.

(4) In the sensitivity analysis section. Two methods of analysis are used in this paper: In the RBD-FAST method, the top four variables affecting TEUI are TR > WWR_W > WWR_E > TW. The top four variables affecting GWP are TR > WWR_W > WWR_E > TW. The top four variables affecting LCC are TR > TW > WT > SC_E. In the DMIM method, the top four variables affecting the TEUI are TR > WWR_W > WWR_E > TW. The top four variables affecting GWP are WWR_W > WWR_E > TR > WIT. The top four variables affecting LCC are TR > TW > WT > WWR_W.

The above findings were analyzed mainly with office buildings in extremely hot and cold regions. In future research, the building's internal thermal comfort conditions, wind environment design, and acoustic environment design can be included in the study, which will improve the completeness and comprehensiveness of office building performance research. At the same time, the theme of this paper can be extended outwards. For example, the office building performance indicators (TEUI, GWP, and LCC) studied in this paper can be applied to time series forecasting in the future [99–103]. Finally, the research in this paper can provide references and ideas for the design of building performance in other different climate zones, such as hot summer and cold winter regions, hot summer and warm winter regions, and mild regions [104–108].

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Article

Aesthetic and Thermal Suitability of Highly Glazed Spaces with Interior Roller Blinds in Najran University Buildings, Saudi Arabia

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Abstract: Highly glazed spaces are visually appealing and trendy, but effectively managing their temperature in hot arid climates remains a significant challenge. This study evaluates the effectiveness of dark-tinted double low-E glass with internal roller blinds in reducing heat gain in glazed spaces in hot arid climates and investigates architects' perspectives on these facades. It combines field measurements and a survey to assess the balance between thermal control and aesthetics in such environments. This study reveals that the current glazing significantly attenuates solar radiation ingress, evidenced by a marked indoor—outdoor temperature differential (ΔT) of approximately 9.2 °C. The mean radiant temperature registers at 1.5 °C above the indoor air temperature, which can be attributed to the glazing's propensity to absorb and retain solar heat, resulting in an inner glass surface temperature of 43 °C. The implementation of adjustable blinds has a dynamic influence on the heat transfer coefficient (HTC), effectively modulating the temperature by impeding natural convection currents. With the blinds retracted, the HTC stands at an average of 7.1 W/m^{2}K, which diminishes to 5 W/m^{2}K when the blinds are 50% closed and further reduces to 4.2 W/m^{2}K when the blinds are fully closed (100%). Survey results suggest that architects prioritise glazed facades for aesthetics (52%) while facing challenges in thermal and energy efficiency (44%). Future studies should concentrate on developing novel glazing systems that integrate solutions for visual appeal, lighting and thermal efficiency in glazed facades, particularly in hot arid climates.

Keywords: tinted glazing double low-E; interior blinds; thermal profile; hot arid climate; aesthetic appeal

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1. Introduction

From the standpoint of architectural design, the facade stands out as a crucial element in a building's ability to display its aesthetic qualities and convey its architectural identity. Meanwhile, from an engineering standpoint, building envelopes, which encompass the facade, assume a vital role in preserving indoor thermal profiles and enhancing the overall sustainability of buildings [1]. Among the critical aspects of architecture, building envelope materials play a pivotal role in shielding interior spaces from the harsh effects of outdoor environments, particularly in the context of excessive heat gain. The evolution of building facades over history is a testament to their adaptability to meet functional and climatic demands. From their humble origins, using materials such as clay, stone, wood and brick, facades have progressed to incorporate steel and glass, reflecting advancements in technology and design [2]. These changes in materials are driven not only by practical considerations but also by the pursuit of architectural beauty and aesthetics. In the thoughtful choice of materials for building facades, a crucial task is to recognise that the visual appeal of these materials holds a significance that goes beyond mere comfort [3]. Notably, exterior aesthetics often wield a more pronounced influence than their interior counterparts, captivating attention and shaping perceptions [4]. On the basis of this concept, the aesthetics of extensively glazed facades have been adopted worldwide. However, since the early days of modern architecture, concerns have been raised about their associated drawbacks, including issues such as glare, increased thermal loads and the need for external shading solutions [5]. The following review briefly outlines the aspects previously discussed in research on the factors that influence an architect's choice of a glazed facade, even when it contradicts the primary design recommendations.

1.1. Aesthetics Appeal of Glazed Facades

The ability of architectural forms to evoke a deep sense of beauty is often referred to as the 'aesthetic' function [6]. Glass, with its extensive aesthetic possibilities, has become an integral part of contemporary building facades, empowering architects' creativity [7]. This infusion of glass into architectural design highlights the convergence of form and aesthetics, where the inherent beauty of glass blends seamlessly with the architect's vision, resulting in buildings that are both visually captivating and functionally sound. This situation aligns with the enduring principles of firmitas (strength), utilitas (utility) and venustas (beauty) established by the Roman architect Vitruvius in his influential work 'De architectura' [8]. These principles continue to guide architectural considerations through the ages. Aesthetic qualities, defined as those that evoke delight and admiration, significantly contribute to an object's appeal, making it visually attractive and beautiful [4]. Buildings with extensive glazing create a visual connection between the interior and exterior while simultaneously shielding occupants from outdoor weather conditions. This aspect holds great importance for architects, who often place great emphasis on the symbolic connotations associated with different design choices [9]. An iconic historical example of a completely glazed facade is the Crystal Palace, a creation of the architect Sir Joseph Paxton, constructed in London for the Great Exhibition of 1851 [10]. The prevalence of extensively glazed buildings has become a worldwide design trend, surpassing concerns related to climate [11]. Given this trend, engaging with the ongoing scholarly discourse about the influence of glazed facades on building design, encompassing aesthetics and beyond, becomes crucial.

When contemplating facade design in hot climates, three key factors come into play: aesthetics, thermal function and their impact on a building's energy consumption [1]. Numerous studies have delved into this subject, underscoring the complexity of glazed facades within architectural design. One study underscored the need to broaden our comprehension beyond comfort and energy efficiency, urging the inclusion of an aesthetic dimension in facade and space design [12]. A study centred on the morphology of glazed facades, with a specific focus on their aesthetic aspects, determined that the glazed facade and shading are two integral components that need to harmonise seamlessly [13]. The aesthetic elements are frequently neglected in the design of energy-efficient buildings, leading to visually unappealing outcomes on numerous occasions. The recognition of the role of glazing in shaping building aesthetics and its simultaneous influence on energy consumption underscores the dual importance of employing this material in building facades [4,9,14,15]. Architects often face trade-offs between aesthetics and heat gain, particularly in hot climates. While extensive glazing may provide stunning views and aesthetics, it can also result in higher thermal loads [5]. A comprehensive review of different glazing solutions also contributes to this discourse, assessing them from multiple perspectives, including their environmental impact and aesthetic influence [16]. These studies collectively illustrate that while glazed facades are often appreciated for their visual appeal, the specific effects of various types of glazing on building aesthetics remain a subject of intricate research and debate in the context of architecture and building design, particularly in hot arid climates like that of Najran University.

The architectural exteriors of Najran University buildings, as illustrated in Figure 1, exhibit a noticeable dichotomy: opaque facades are primarily constructed using prefabricated concrete, while glazed facades predominantly feature double layers of blue–green solar-control glass materials. The choice between highly glazed facades and a multitude of smaller windows plays a significant role in shaping a building's aesthetics. However, the primary concern revolves around evaluating the thermal efficiency of the highly glazed spaces, especially in the challenging context of a hot arid climate. As one walks through the university campus buildings, a detail that becomes evident is that areas with extensive glazing are present in various locations, such as lecture halls, the library reading hall, lounges, corridors and administrative offices.

Figure 1. Exterior views of certain Najran University buildings highlighting glazed facades.

Generally, highly glazed facades not only offer a stylish and contemporary look but also allow ample natural light indoors, decreasing the need for artificial lighting during daylight hours. Moreover, they provide extensive views, creating a feeling of connectivity between indoor and outdoor areas, which collectively enhances the overall sense of well-being. The challenges associated with the use of aesthetically pleasing, highly glazed spaces in hot arid climates stem from the fact that these materials amplify the heat load within adjacent interior spaces, necessitating a significant amount of energy to maintain comfort. This condition has a profound impact on the nation's energy consumption, with Saudi Arabia reporting that the building sector is accountable for about 29% of total energy usage and more than 75% of total electricity consumption [17,18]. In this context, architectural design emerges as a crucial factor. Thoughtful and efficient design is essential for boosting energy efficiency and promoting sustainability in Saudi Arabian buildings. This study focuses on evaluating the thermal performance of highly glazed spaces at Najran University and exploring architects' viewpoints on the use of glazing. It serves as a case study, providing insights into regional architectural practices and their alignment with energy-efficient and sustainable design principles.

1.2. Solar Heat Gain through Glazing with Interior Roller Blinds

Solar heat gain is a major concern in hot arid climates, as it can lead to high indoor temperatures and increased energy consumption. Solar heat gain can be reduced in a number of ways, such as using advanced solar control glazing and installing shading devices. The amount of total solar radiation that passes through glass can be characterised in two ways. Firstly, it accounts for the heat gain caused by direct solar radiation transmission (ultraviolet [UV], visible light [VL] and infrared [IR]), represented as τ_s, and secondly, it considers the inward heat transfer, denoted as Ni, which emerges due to the temperature disparity between the air temperature and the surfaces of the glazing. The total solar heat gain that permeates through glazing is typically assessed using the solar heat gain coefficient (SHGC) defined by ASHRAE in the following Equation (1) [19]:

$$\mathrm{SHGC} = \tau_s + \mathrm{Ni} \times \alpha s \tag{1}$$

where τ_s is the direct solar transmittance of the fenestration system, Ni is the fraction of absorbed radiation that flows inward, and αs is the solar absorptance.

In hot climates, optimal glazing selection prioritises a low SHGC, and this choice is contingent upon the spectral attributes of the glass. Various glass types exhibit distinct characteristics in relation to solar radiation preferences for double low-emissivity (low-E), vacuum glazing and smart glass systems that autonomously adjust the transparency to effectively counteract heat gain [20]. Currently, low-E glass remains the most popular energy-efficient glass on the market. U-values in low-E glazing systems can be lowered through improvements made by adjusting gap thickness, altering inert gases, incorporating translucent aerogel materials and introducing multiple layers of low-E coating [21,22]. Low-E glass reflects heat and is evaluated by its U-value, with a lower U-value indicating better thermal insulation. The U-value measures heat transfer and is expressed as $W/m^2{\cdot}K$. [7]. In hot climates, low-E coatings are commonly used on the outer pane to combat high outdoor temperatures during the summer, minimising UV damage, all with minimal impacts on natural light [23]. Observations indicate that buildings incorporating hard-coat low-E double glazing can achieve energy savings of approximately 9% to 14% in daily air-conditioner usage [24,25]. In brief, advancements in glazing are set to offer better choices for designing building facades, with a particular emphasis on minimising heat gain and enhancing visual comfort and the aesthetic appeal of facades [1].

The shortcomings of unshaded glass facades have long been recognised in the field of sustainable architecture for their impact on thermal discomfort [5]. Despite the use of advanced glazing, a certain amount of direct solar radiation can still infiltrate a building. Consequently, the strategic incorporation of shading devices is vital in achieving optimal control over solar heat gain. External shading is typically the most effective solar control method, but it may be less preferred due to factors such as cost, aesthetics, maintenance, structural constraints and wind load concerns [26]. The adoption of external window shading can conflict with architects' desires for transparent glass buildings [5]. However, in desert environments, interior blinds are a prudent option due to their immunity to external dust accumulation. Internal shading devices can affect the thermal performance of glazing by disrupting the natural convective airflow and reducing the exchange of long-wave radiation heat between the glazing and the indoor area. In addition to decreasing thermal radiation from the window surface, blinds act as a thermal barrier for individuals near the window [13,27–29]. Numerous studies have explored the advantages and considerations of utilising interior roller blinds as shading solutions in hot climates, as cited in References [30–33]. This study specifically examines the utilisation of top-down interior roller opaque blinds in spaces throughout Najran University.

As referenced in the review, the widespread adoption of glazing in building facades, driven by aesthetic and other considerations, has posed challenges in preserving optimal thermal comfort within buildings. In response, this study seeks to address the following research questions: Can architects achieve aesthetically appealing buildings by using highly glazed facades while maintaining the visibility of the external glass surface in a hot arid climate by employing thermally insulated glass and internal curtains? To what extent do these interventions effectively shield the indoor environment from excessive heat gain?

The research objectives are threefold:

- To assess the thermal performance of the thermally insulated glazed facades in the buildings of Najran University, located in the hot arid climate of Saudi Arabia;
- To evaluate the effectiveness of interior roller blinds in reducing solar heat gain in highly glazed spaces in a hot arid climate;
- To explore architects' perceptions of glazing in building facades.

2. Materials and Methods

Recognising the divide between engineering's detailed performance analysis and architecture's artistic elements, the author utilised a mixed-methods approach to thoroughly investigate glazing in hot arid climates. Field tests yielded specific thermal measurements, complemented by architects' surveys that shed light on the artistic and experiential aspects of glazing. This fusion of quantitative and qualitative approaches provides a broader perspective on glazing's effect on building design and the experiences of industry professionals.

2.1. Local Climate

Najran, located in southwestern Saudi Arabia, is positioned at the geographic coordinates of 17.62° north and 44.42° east. Figure 2 shows that under the Saudi Building Code (SBC-601), Najran falls within Zone 1, defined as a hot arid area [34]. This classification aligns with ASHRAE's climate zone 1B, which is categorised as hot and dry.

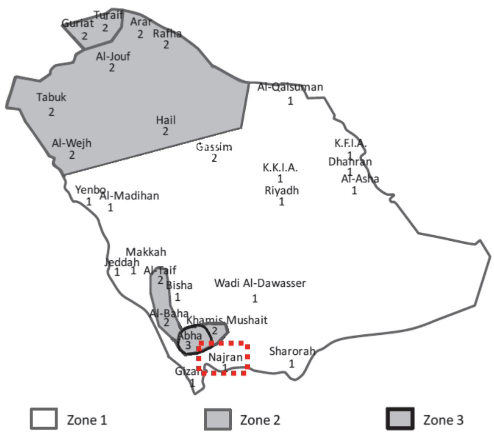

Figure 2. Classification of Najran as Zone 1 (hot arid) under SBC-601 [34].

Figure 3 offers a comprehensive overview of the fluctuations in solar radiation and air temperature throughout the year in Najran, revealing a distinct seasonal pattern. Both direct normal irradiance (DNI) and global horizontal irradiance (GHI) show a gradual increase from January, reaching their peaks around June, with GHI reaching approximately 600 W/m^2 and then decreasing towards December. This solar radiation trend closely corresponds to the variation in air temperature, which also rises to its highest levels during the summer, with maximum temperatures surpassing 40 °C or even higher. In contrast, the average low temperatures in winter hover around 15 °C. The annual average temperature is approximately 29 °C, with only minor variations. A distinctive characteristic of Najran's desert climate is the pronounced disparity between daytime and nighttime temperatures, reflecting the typical thermal dynamics of desert environments.

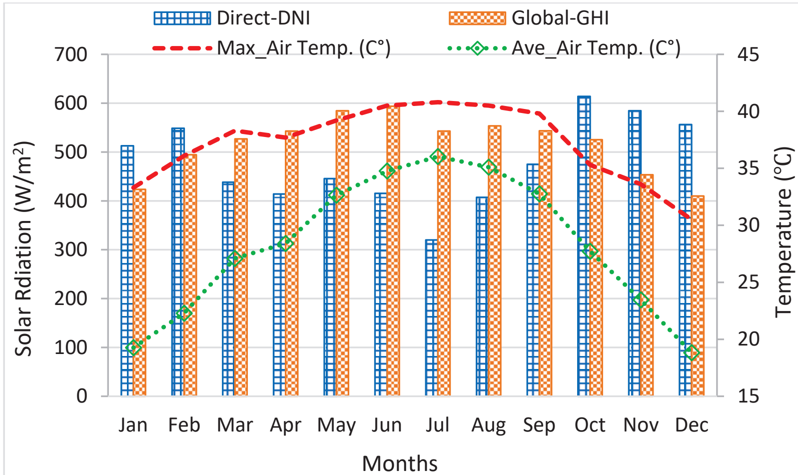

Figure 3. Monthly and yearly fluctuations in solar irradiance and air temperature. (Source: author, derived from NU weather station data, 2013–2016).

2.2. Case Study Definition and Instrumentation

The College of Engineering building at Najran University, presented in Figure 4—which provides a view of the building's layout and facade—is a three-storey structure with external dimensions of 202 m × 132 m. Its architectural design includes several fully glazed spaces, such as lecture halls, lounges, corridors and atriums. The specific highly glazed space under investigation is situated on the third floor of this building. The building features a roofing system comprising multiple layers, including a gravel stone layer, thermal insulation consisting of polystyrene, lightweight concrete and a concrete slab.

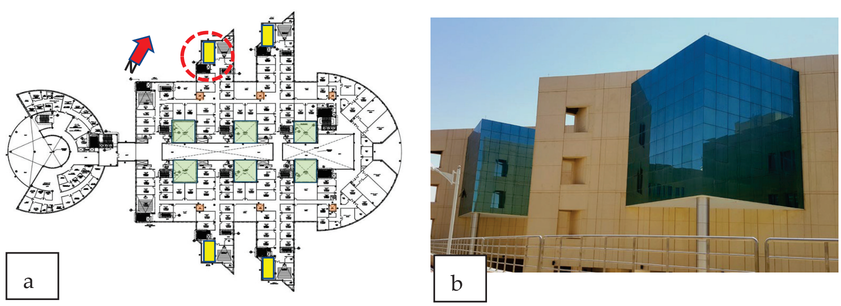

Figure 4. Visualisation of the measured lecture hall. (**a**) Plan of the third floor of the College of Engineering highlighting the lecture hall, (**b**) west-facade view of the lecture hall.

The lecture hall's external walls feature double-glazed facades, where each unit is composed of an outer pane made from 6 mm blue–green tinted glass with a low-E coating. This outer pane is paired with a 6 mm clear glass inner pane, creating a 12 mm air cavity between them. Figure 5 illustrates a cross section of the glazing system employed in the fully glazed spaces in Najran University buildings. The following is the theoretical basis for this glazing configuration:

(a) Double low-E tinted glazing consists of two glass layers separated by an air gap and hermetically sealed along their perimeter. The thicknesses are as follows: 6 mm tinted glass with low-E coating facing the cavity, a 12 mm air gap and 6 mm clear glass;

(b) The blue–green heavy tint of the glass further diminishes glare and solar heat gain by absorbing and reflecting a portion of the incoming solar energy;
(c) Interior roller blinds, which are constructed from light-grey PVC opaque material, regulate the amount of light and heat entering the space;
(d) The glazed facades are designed to be exposed to the outside view without any external shading. This design choice is made to ensure the facades remain visually appealing.

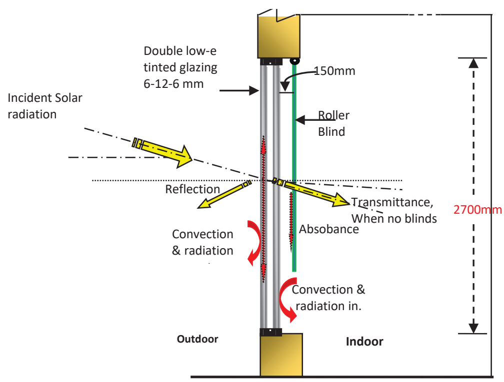

Figure 5. Schematic of glazing configuration and solar radiation interaction.

This configuration serves a crucial function in mitigating the effects of solar radiation, significantly reducing heat transfer from the external glazing surfaces to the interior. This reduction is achieved through a combination of mechanisms, including the reflection of a portion of the solar radiation, absorption of energy within the tinted glass and roller blinds, and the restriction of convection and radiation heat transfer through the air gap and low-E coatings. Table 1 provides information on the optical properties of the glazing material supplied by Saudi American Glass (SAG), with data sourced from the General Management of Projects, Maintenance, and Facilities at Najran University.

Table 1. Optical characteristics of SAG glazing installed in the College of Engineering building (Source: NU, General management of projects, maintenance and facilities).

Description		Air Filled	VL %			SHGC %	U-Value Summer W/m²K
Coating	Substrate		Tv	Reflectance			
				Out	In		
SS-08-	Blue Green	6 mm/12 mm/6 mm	6	32	49	0.15	2.42

Data collection for this study was conducted from 1 to 18 June 2023, focusing on a lecture hall strategically positioned to receive direct solar radiation from both the southwest and northwest directions. Detailed indoor environmental data were gathered using three LSI-R-Log data loggers equipped with eight sensors. Outdoor environmental conditions were monitored through a rooftop weather station at the college. These instruments simultaneously recorded various parameters, including indoor and outdoor air temperatures, inner surface glazing temperature, air velocity, heat flux and horizontal global solar radiation (Figure 6 and Table 2). The sensors were positioned at the room's centre, approximately 1.0 m above the floor, and mounted on two tripods. Data loggers were programmed to continuously record readings at 5 and 10 min intervals over a 24 h period. Manual temperature readings were periodically taken using both a standard thermometer and an IR thermometer to enhance data accuracy. This study explores different roller blind configurations, including those fully closed, partially open and fully open (Figure 7).

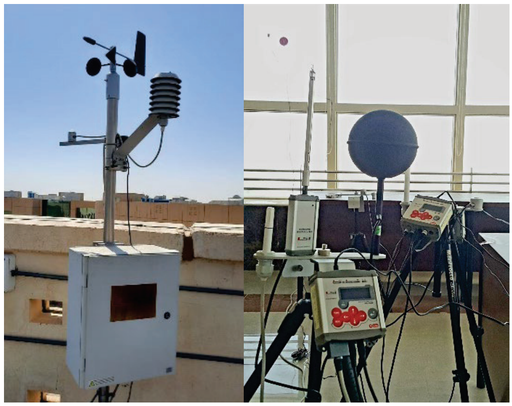

Figure 6. Data loggers for indoor and outdoor environments (LSI-R-Log and LSI-E-Log Weather Station).

Table 2. Technical specifications of the sensors used in the investigation.

Instruments	Measuring Range		Resolution
Three LSI-R-Log, data loggers	Surface temperature	−40 °C to +80 °C	±0.01 °C
	Air temperature	−40 °C to +80 °C	±0.01 °C
	Glob temperature	−40 °C to +80 °C	0.01 °C
	Heat flux	−2000 ÷ +2000 W/m^2	50 µV/W/m^{-2}
	Air speed	0.01 ÷ 20 m/s	0.01 m/s
	Lux	Human eye response (CIE)	3%, Uncertainty
LSI-E-Log, data logger—outdoor	Air temperature	−50 ÷ 70 °C	0.1 °C (@0 °C)
	Air speed and direction	0 to 75 m/s	0.07 m/s
	Pyranometer	0 to 2000 W/m^2	10 ÷ 15 µV/W/m^2

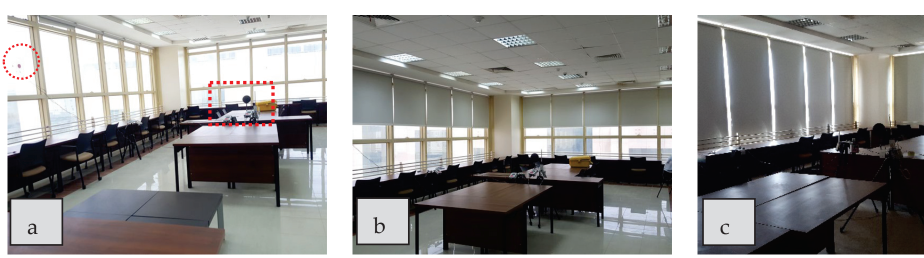

Figure 7. Arrangement for indoor measurements: (**a**) uncovered glazing measurement, (**b**) 50% closure of roller blinds, (**c**) full closure of roller blinds.

2.3. *Architects' Perceptions of Glazing in Building Facades*

This section delves into the insights of architects who are staff or alumni of Najran University who have direct experience of the university's buildings. This study examines their professional assessments regarding the aesthetic appeal, functional and climatic suitability of glazed facades in buildings in hot arid climates. An online survey provided a structured quantitative framework for these architects to rate the importance of glazing attributes on a scale from 1 (least important) to 5 (most important). The gathered data, presented in percentages, offer an aggregate perspective on the value placed on each aspect of glazing.

3. Results and Discussion

In this section, results and discussions are presented, detailing experimental conditions and evaluating the thermal performance of glazing materials, as well as the impact of interior roller blind configurations on the indoor environment. Additionally, the effects of these factors on lighting quality and environmental outcomes are explored. Finally, architects' perspectives on the aesthetic, functional, and environmental impacts of glazing in hot arid climates are examined, emphasizing the balance between aesthetic appeal and thermal efficiency in architectural designs.

3.1. Schedule of Measurements

The data collection period extended over 18 days, with each case corresponding to different ratios of manually controlled roller blinds (0%, 50% and 100% closed) observed for 6 days each. Figure 8 illustrates the average hourly values recorded for the whole days of various outdoor parameters, including outdoor air temperatures, air speed and global solar radiation associated with indoor air temperature, recorded from 1 to 18 June 2023. The data show variations in outdoor air temperature over the period. These fluctuations will be accounted for when assessing the thermal performance of the space under varying roller blind configurations. For precise analysis, the study concentrates on specific days with similar outdoor conditions: 10 and 11 June for the 100% closed blinds scenario, 14 to 17 June for the 50% closure and 6 to 9 June for the scenario without blinds (0% closed).

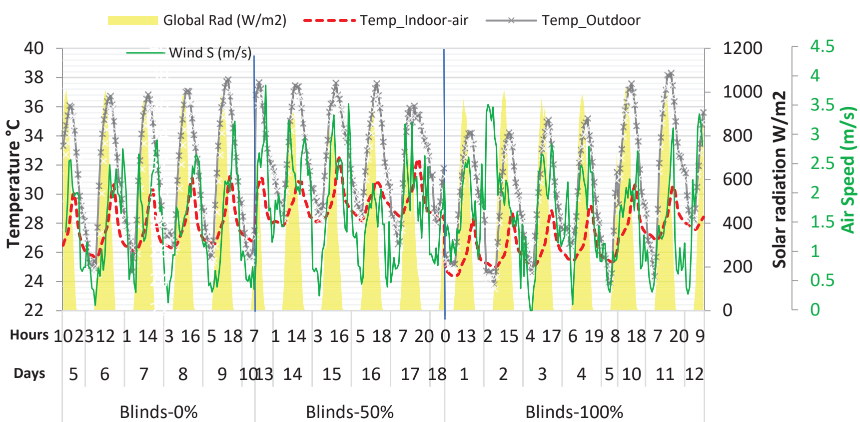

Figure 8. Schedule of measurements of all cases from 1 to 18 June 2023. Temperature against solar radiation and outdoor air speed is given.

3.2. Glazing's Thermal Performance

In unoccupied spaces where air conditioning is not in operation, as in the investigated lecture hall, the primary consideration should be glazing performance rather than indoor thermal comfort. This section of the assessment evaluates the efficiency of the selected glazing in Najran University buildings, specifically in managing heat gain, focusing on the measured solar heat gain, which is essentially the heat added to a space by the solar radiation transmitted through the glazing and absorbed by various surfaces.

The data in Figure 9 present two different measurements over a 24 h period, illustrating the relationship between the temperature differential across the glazing (ΔT) and the corresponding heat flux, which offers insights into the glazing's capability to reduce solar heat gain. The ΔT line fluctuates over time, showing positive values for most of the day and reaching a peak at approximately 9.2 °C, suggesting that the glazing helps maintain a lower indoor temperature compared with the outdoors. In contrast, the heat flux values are negative throughout, indicating an inward conduction of heat. The most pronounced inward heat flux, at −105 W/m^2, coincides with the maximum ΔT, reflecting the substantial heat absorption by the heavily tinted glazing. This absorption is in line with the glazing's low SHGC of 0.15, which is significantly lower than that of standard commercial double glazing with SHGC values between 0.31 and 0.84 [35]. While the low SHGC suggests reduced solar heat transmission, the notable inward heat flux, particularly during periods of intense solar radiation, points to considerable heat transfer into the building. This data is crucial for understanding the thermal performance of the glazing on the facade of the College of Engineering building. However, the figure demonstrates a time shift between ΔT and heat flux values, attributed to a pronounced increase in inward heat flux when the glazed facade faces solar radiation around 3 pm. This condition leads to a surge in indoor temperature, which, in turn, reduces the ΔT, illustrating the dynamic interaction between heat flux and indoor thermal conditions. In a hot arid climate, buildings often use thermal mass to help stabilise indoor temperatures. The results suggest that the building has a good thermal mass that helps keep the indoor temperature lower than the outdoors even with significant heat flux through the glazing.

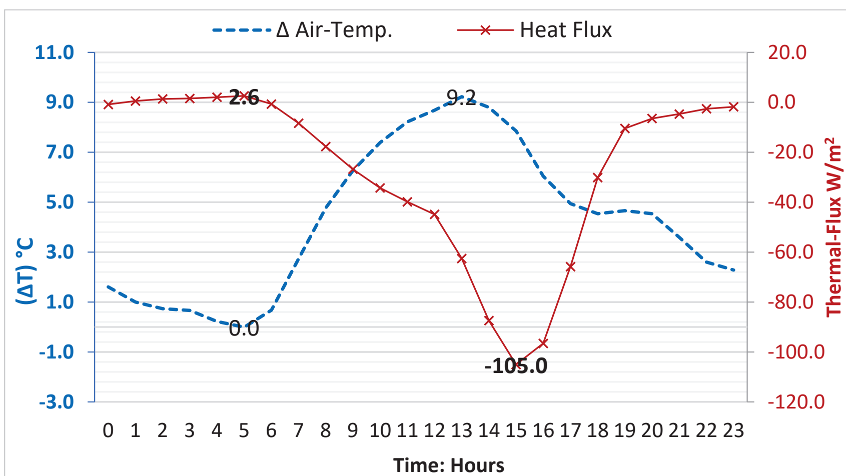

Figure 9. Steady state of solar heat gain, the heat added to a space by the sun's radiation measured by (T2-T1) along with heat flux through glazing.

The relationship between solar radiation and the indoor thermal profile in the lecture hall is depicted in Figure 10. As solar irradiance increases, reaching its peak at approximately 1000 W/m^2 at noon, the outdoor temperature, marked by the red dashed line, rises accordingly, which is expected because of the direct solar heating of outdoor surfaces and air. Indoor air temperature rises from roughly 26 °C at 6 am to 30.5 °C at 4 pm, when the outdoor air temperature is 36.2 °C. The MRT, inferred from the globe temperature, exhibits more variability, ascending from 26 °C at 6 am to a peak of 32 °C at 4 pm, which suggests a radiant heat impact on the space. This effect is further accentuated by the inner glass temperature, which rises to approximately 43 °C at 4 pm when direct solar radiation strikes the west facade of the investigated lecture hall. This temperature is notably higher than both the indoor air and globe temperatures. This peak indicates substantial solar heat absorption by the glazing, contributing to the radiant heat within the lecture hall. The glazing, which absorbs solar radiation, becomes a radiative heater itself, elevating the MRT and, by extension, the perceived temperature by occupants. The radiant temperature difference, at its peak, is around 1.5 °C between the globe and indoor air temperatures, highlighting the net radiant heat exchange influencing the indoor thermal profile. This effect would need to be considered in air-conditioning operations to ensure students' comfort, as the actual air temperature may not fully represent the thermal sensation experienced due to radiant heat exchange.

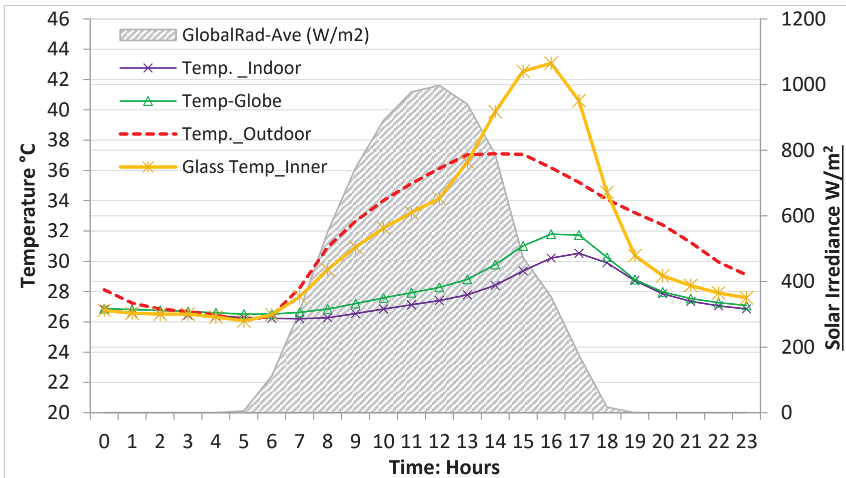

Figure 10. Correlation between indoor thermal profiles and external environmental conditions.

Figure 10 reveals a discernible temporal disconnection between indoor and outdoor temperature fluctuations, underscoring the building's thermal management capabilities. At 1 pm, the peak of outdoor temperature is 37 °C, whereas by 5 pm, the indoor temperature ascends to a moderate 30.5 °C despite a decline in the outdoor temperature to 35.2 °C. The observed thermal delay in the indoor environment can be attributed to the synergistic effects of direct solar radiation on the glazing when the sun shifts towards the western facade, coupled with the building's thermal inertia. This inertia enables the structure to function as a thermal buffer, gradually absorbing heat and then slowly releasing it over time. This finding indicates that the glazing strategically mitigates heat transfer, effectively decoupling the indoor climate from external temperature spikes, thus enhancing occupant comfort and reducing the demand on cooling systems.

3.3. Interior Shading Effectiveness

As previously mentioned, the glazing in the examined space demonstrates a notably low SHGC of 0.15, effectively impeding 85% of the solar radiation from penetrating the interior space. This high level of solar control is achieved through a combination of reflection, absorption within the glazing itself and the transmission of long-wave IR radiation, which contributes significantly to the reduction of solar heat gain. The addition of interior blinds offers an extra layer of thermal regulation, markedly influencing the heat transfer dynamics by modifying convective heat exchange at the glazing's inner surface. The impact of the blinds on the building's thermal performance is quantitatively assessed by calculating the HTC, a measure that is instrumental in evaluating the efficacy of temperature regulation within the space. A lower HTC signifies superior insulative properties, correlating with enhanced energy conservation and occupant comfort.

$$h = \frac{q}{\Delta T} (\mathrm{W/m^2/K}) \tag{2}$$

where q is the heat flux (W/m^2) and ΔT is the difference in temperature between the glazing surface and air within the space (K). Equation (2) is commonly referred to as Newton's law of cooling [36].

This HTC has been meticulously computed and is illustrated in Figure 11, showcasing the thermal profiles for three specific scenarios: the absence of blinds, 50% closed blinds and completely closed blinds. These scenarios present a comprehensive view of how varying levels of shading contribute to the interior thermal environment, ultimately guiding strategic decisions for passive cooling and energy efficiency enhancements in building design. As depicted in the figure, the HTC is reduced when the blinds are either partially or fully open, demonstrating the blinds' role in impeding heat ingress, primarily by reducing convective heat transfer and curtailing the influx of solar radiation. Notably, the HTC does not remain static, even with the blinds' position held constant, underscoring the influence of external variables such as fluctuations in outdoor temperature or the solar trajectory. This finding indicates that blinds serve as an adjustable barrier to heat transfer. A lower HTC reflects better insulation properties, leading to improved energy efficiency and enhanced comfort for occupants. The findings are summarised as follows:

- When the blinds are completely open (0%), the HTC values start at around 6 W/m^{2}K in the early morning and reach peaks close to 8 W/m^{2}K, coinciding with the times of elevated outdoor temperatures. The average daytime HTC in this scenario is 7.1 W/m^{2}K;
- When the blinds are 50% closed, the HTC exhibits a noticeable reduction, peaking at approximately 5.6 W/m^{2}K. This reduction suggests a moderate decrease in heat transfer, likely due to the blinds' partial shading effect. The average daytime HTC here is 5 W/m^{2}K;
- In the scenario where the blinds are fully closed (100%), despite higher outdoor air temperatures compared with that in other scenarios, the HTC drops significantly, thereby indicating the blinds' efficiency in insulating the interior from external heat. In this case, the HTC values typically range from 3 W/m^{2}K to 5 W/m^{2}K, indicating the most effective insulation from the blinds. The average daytime HTC in this setting is 4.2 W/m^{2}K.

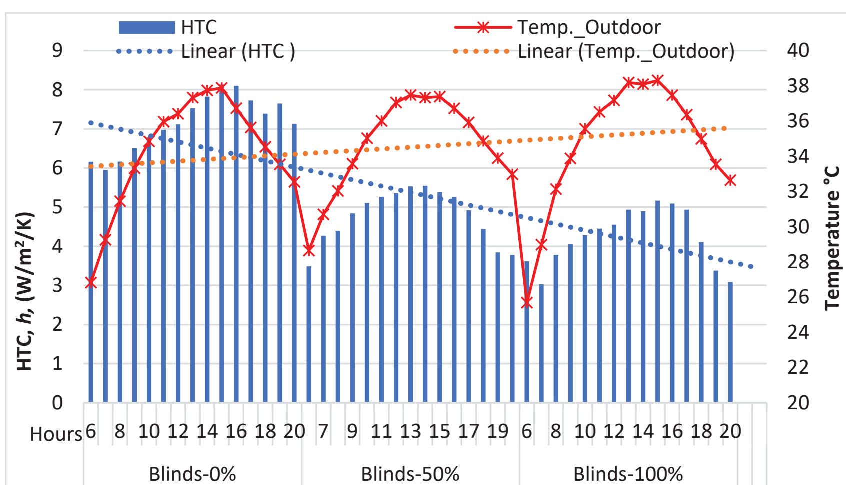

Figure 11. Impact of interior roller blinds on HTC and correlation with diurnal outdoor temperature variations.

Figure 12 corroborates the observation that blinds play a role in modulating indoor thermal dynamics. With the blinds fully retracted (0%), the inner surface of the glass registers a temperature of 43.1 °C at 3 pm, coupled with an elevated air speed when compared with other scenarios, which aligns with the increased HTC values. The temperature gradient between the hot glass surface and the relatively cooler air farther away causes air movement. Closing the blinds by 50% results in a noticeable dip in the glass surface temperature, peaking at 42 °C, and the HTC, reaching 5.6 W/m^{2}K. Notably, when the blinds are completely closed (100%), the glass surface temperature rises unexpectedly, peaking at 47.8 °C at 4 pm. This finding suggests that while the blinds mitigate direct solar radiation, the air confined between the blinds and the glass may amplify the glass temperature. Despite this condition, the HTC declines significantly, which underscores the blinds' effectiveness in insulating the space from external thermal variations.

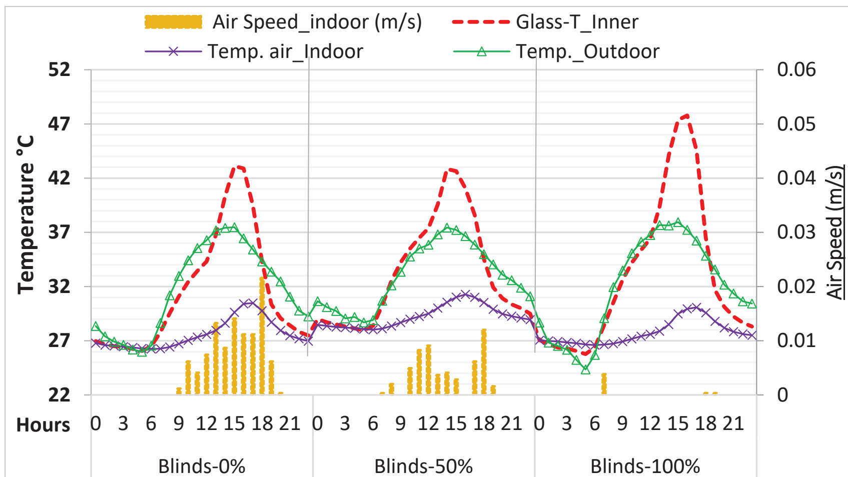

Figure 12. Impact of blinds on glass surface temperatures and indoor heat transfer dynamics.

3.4. Further Discussion on Lighting and Environmental Impacts

Previous studies [37,38] explored daylight illumination in the space under investigation. However, Figure 13, depicting lux measurements in the centre of the lecture hall, reveals the impact of heavily tinted, low-E coated double-glazing on light transmission and indoor illumination. On days with the blinds fully open, the lux levels reach up to 150 lux, a moderate intensity due to the tinting and low-E coating, which manage solar radiation and reduce potential glare. Interestingly, the indoor air temperature peaks are aligned with the lux peaks, suggesting that despite the tinting and low-E coating, a noticeable heat gain that affects the indoor climate remains. When the blinds are drawn to 50%, the lux levels decrease significantly, indicating less light penetration and a corresponding moderate reduction in the indoor air temperature peaks, which illustrates the combined thermal control properties of the blinds and the glazing. With the blinds fully closed, the lux measurements drop below 50 lux, which contributes to a further stabilisation of the indoor air temperature, underscoring the synergy between the glazing's properties and the blinds in regulating both light and heat, which is essential for maintaining a comfortable indoor environment.

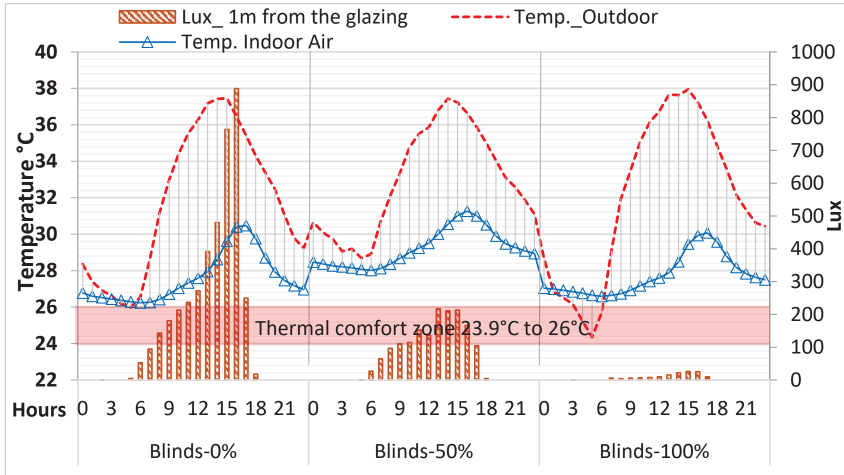

Figure 13. Light and temperature control using blinds, assessing VT and solar heat gain.

In redesigning the lecture hall for optimal performance, a key focus should be on improving the light-to-solar gain (LSG) ratio. This ratio measures the ability of glazing materials to offer adequate VL while reducing solar heat gain [16]. The current glazing of the investigated lecture hall, characterised by a low SHGC, suggests the potential improvement of VL transmittance (VT). Selecting glazing with a higher VT but still retaining a low SHGC is crucial to enhance the LSG ratio. Furthermore, incorporating dynamic shading systems can provide tailored control over light and heat, adapting to changes in solar exposure. Implementing advanced insulated glazing with dynamic smart films, such as PDLC film, could dynamically respond to varying solar radiation intensities, thereby efficiently distributing daylight in the absence of direct solar radiation and simultaneously reducing direct solar gain.

Overall, the glazing installed in the building significantly limits solar radiation entry, evidenced by the up to 9.2 °C temperature difference between the indoors and the outdoors. Specifically, Figure 13 highlights that without blinds, indoor temperatures soar to 30.4 °C by 5 pm, exceeding the Saudi Building Code's (SBC) comfort ceiling of 26 °C. This scenario indicates that while the current design curtails some cooling needs, there is potential for further enhancements. Integrating daylighting optimisation and passive design principles in line with SBC standards is vital to achieve a more effective balance between maintaining comfortable temperatures and conserving energy. Such improvements will not only enhance thermal comfort but also contribute to environmental protection by lowering CO_2 emissions, advancing sustainability efforts at Najran University.

3.5. Architects' Perceptions of Glazing in Najran University Buildings

This section analyses the perspectives of 35 architects regarding the aesthetic, functional and environmental implications of glazing in building designs at Najran University. Figure 14 shows a clear preference for functionality among the architects, with a striking 71% of responses indicating that it is the most important criterion (level 5). This strong emphasis on functionality likely stems from the architects' recognition of the critical role of glazing in the practical aspects of a building's performance, such as natural lighting, insulation and overall environmental interaction. Aesthetic appeal is the second most valued criterion, with more than half of the respondents (52%) giving it the highest level of importance. This finding suggests that architects consider the visual impact of glazing to be nearly as crucial as its functional role. The importance of aesthetics highlights the architects' focus on the design and appearance of building facades, which contribute significantly to the overall architectural expression and the way a building is perceived. Energy efficiency also receives considerable attention, with 44% of responses ranking it the most important criterion. Its close rating to aesthetic appeal suggests that energy-efficient design is nearly as prioritised as the visual aspects, reflecting an integrated approach to aesthetic and sustainable design practices. Cost-effectiveness has a relatively balanced spread across levels 3, 4 and 5, indicating a moderate importance.

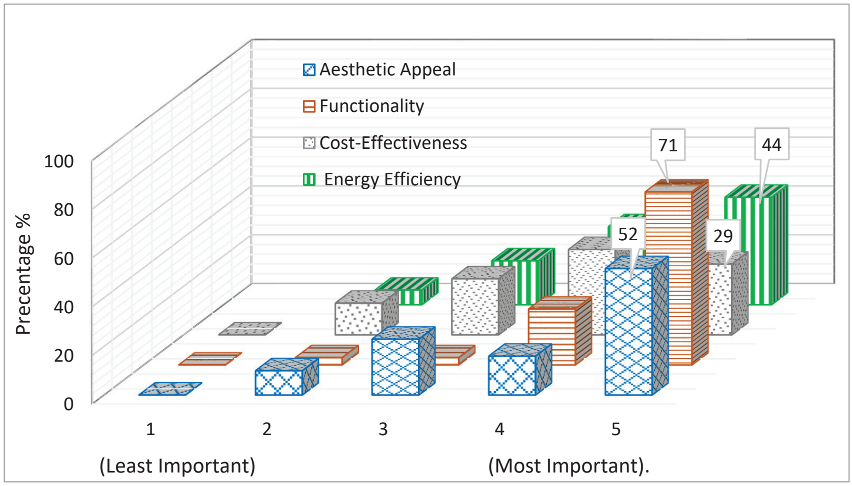

Figure 14. Architects' prioritisation of criteria in glazed building facades at Najran University.

Figure 15 provides insights into the perceptions of the effectiveness of glazing in addressing specific concerns related to building facades at Najran University. The data are categorised into three distinct queries. The first query, assessing the effectiveness of Najran University's glazed facades in addressing the hot arid climate, shows a notable distribution across the scale, but with the highest concentration of responses in the mid to high importance range, suggesting that many respondents see glazing as fairly effective in mitigating harsh climatic conditions. The second query evaluates the impact of glazed facades on indoor comfort levels. A significant majority (73%) rated this as the most important. This overwhelming response indicates a strong consensus among architects that glazed facades play a crucial role in influencing the comfort levels within the buildings, likely due to their ability to control light and heat transmission. The third and final query concerns the importance of thermal insulation in glass facades. It is considered by 61% of the respondents to be the most important, marking it at level 5. This high percentage underscores a widespread recognition of the critical role of thermal insulation in enhancing the performance of glazed facades. Concerning the effectiveness of Najran University's glazed facades in addressing the hot arid climate, only 24% of respondents ranked it as having the highest level of effectiveness. This finding signifies a critical viewpoint, indicating that although the glazed facades, as evidenced in the earlier thermal discussion, may be operating adequately, their overall effectiveness in such a challenging climate is not entirely satisfactory, demanding further attention.

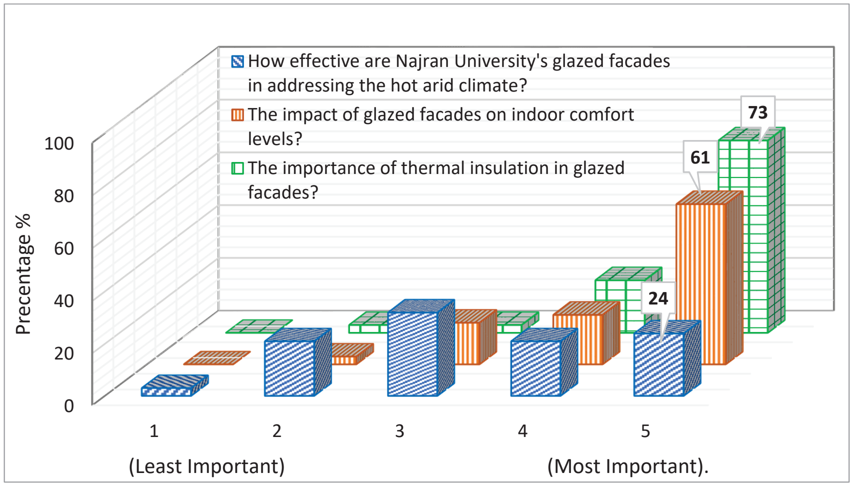

Figure 15. Evaluating the role of glazed facades in climate adaptation at Najran University.

Overall, the results suggest that while aesthetics are valued, the practical aspects of functionality are of paramount concern. Moreover, architects recognise the crucial influence of glazed facades on the comfort levels in buildings and the essential role of thermal insulation in enhancing facade efficacy. This finding could reflect a trend in architectural design, prioritising sustainable and efficient building practices without compromising on the visual appeal of the buildings.

3.6. Limitations and Uncertainties

With measurements taken over a period of 18 days, variations in outdoor weather conditions can introduce variability into the data. This variability makes it challenging to establish a controlled baseline for comparison. A pretest-posttest design that does not account for identical outdoor weather conditions can yield skewed results, affecting the reliability of the conclusions about the blinds' effectiveness and the glazing's thermal performance. A careful selection of days for comparison is essential to mitigate this limitation. Days with similar weather conditions were chosen to ensure that the data reflect the performance of the glazing and blinds rather than the fluctuations in the external environment. This approach allows for a more accurate assessment of the glazing's properties and the impact of the internal blinds on indoor temperature conditions, leading to more reliable conclusions.

The air in both the investigated space and the adjoining corridor exhibits temperature disparities, leading to variations in density. Gaps around the door allow for uncontrolled air leakage, contributing to this phenomenon. The warmer air in the lecture hall generates a minor pressure differential close to the door, facilitating air movement and leading to a marginal heat loss from the lecture hall. This thermal infiltration around the door can lead to a decrease in the indoor air temperature of the non-conditioned space being studied, altering the temperature differential. This change affects the performance metrics and outcomes of the investigated facade system. Therefore, accounting for the impact of infiltration towards adjacent spaces is important when assessing the glazed facade's ability to control heat gain in future studies. Furthermore, the influence of adjacent air-conditioned areas could skew the results of the effects of the glazing and interior roller blinds in the investigated space. While acknowledging the limitation of not measuring the heat flux between adjacent spaces and the lecture hall, a crucial detail to highlight is that the partition walls are 20 cm thick concrete walls, and one of these two walls is adjacent to bathrooms equipped with mechanical ventilation, which reduces thermal exchange through these boundaries. The presence of substantial physical barriers and a consistently closed door significantly reduces the thermal exchange. This condition is a limitation due to the lack of sensors and could be covered in future studies.

4. Conclusions

This study conducts field measurements to assess the thermal performance of aesthetically driven glazed facades in a hot arid climate, exposing an architectural paradox that lies in the conflict between achieving aesthetically pleasing glazed facades and the need for energy efficiency in such climates. The findings can help architects and engineers in enhancing building aesthetics and sustainability while prioritising occupant well-being, aligning with Najran University's vision for a sustainable campus environment.

The following are the key conclusions from the on-site thermal measurements:

- The existing glazing, with a low SHGC of 0.15, effectively reduces solar radiation transmission, as indicated by lower indoor temperatures compared with the outdoors, with a peak temperature difference of about 9.2 °C;
- The glazing significantly absorbs solar heat, raising the inner glass temperature to 43 °C and acting as a radiative heater. As a result, the MRT is increased by 1.5 °C compared with indoor air temperatures, suggesting an impact on the indoor thermal profile despite the glazing's effectiveness;
- The adjustable blinds have a notable impact on the HTC, effectively regulating temperature by obstructing the natural convection currents, which are usually affected by the temperature of the glass surface;
- With blinds fully open (0%), the HTC averages 7.1 W/m^2K during the day. When the blinds are closed 50%, the HTC decreases to a 5 W/m^2K daytime average. Fully closed blinds (100%) significantly reduce HTC to an average of 4.2 W/m^2K during the day, demonstrating their efficiency in thermal insulation;
- Despite the glazing's heavy tint and blind usage, a correlation between indoor light levels and temperatures is observed, indicating daylight's contribution to thermal load. This condition highlights the need to optimise the glazing's VT to improve the LSG ratio. Employing real-time responsive shading systems and daylighting simulation tools for predictive modelling could further enhance environmental control in spaces.

The study's survey reveals architects' preference for glazed facades, with a majority prioritising functionality (71%) and aesthetics (52%). In contrast to the emphasis on visuals, challenges such as energy efficiency (44%) are delicately weighed. Notably, 73% of architects underscore the significance of thermal insulation associated with glass facades, highlighting the need for a comprehensive approach to address both visual and thermal aspects. Regarding Najran University's glazed facades and their effectiveness in the hot arid climate, only 24% of respondents rated them as highly effective. This percentage suggests a critical perspective, indicating that the overall effectiveness of glazed facades in this challenging climate demands further attention despite their satisfactory performance in specific aspects exhibited in the thermal performance results.

Future studies can explore different related directions. The use of adaptive shading systems, such as automated blinds or dynamic glass, is recommended to respond effectively to varying outdoor conditions, thus balancing heat gain control and daylight utilisation. An integrated design approach, considering both aesthetics and functionality, is essential. This approach should involve collaboration among architects, engineers, and sustainability experts from the early stages of design, ensuring a harmonious blend of form and function.

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

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Abbreviations

DNI	Direct normal irradiance, W/m^2
GHI	Global horizontal irradiance, W/m^2
HTC, (h)	Heat transfer coefficient, W/m^2K
IR	Infrared
Low-E	Low-emissivity
LSG	Light to solar gain, %
MRT	Mean radiant temperature, °C
q	Heat flux (W/m^2)
SAG	Saudi American Glass
SHGC	Solar heat gain coefficient, %
UV	Ultraviolet
VL	Visible light
αs	Solar absorptance
τs	Direct solar transmittance

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Article

Mitigating Overheating Risks for Modern Flats in London Due to Climate Change

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Abstract: With the increase in global temperatures, a significant threat of overheating has been reported due to more frequent and severe heatwaves in the UK housing stock. This research analyzes dwellings' physical attributes through overheating assessments and their adaptation for modern flats in London in the current (2022) and anticipated (2050) weather. According to preliminary research, Southeast and London in England, mid-terraced, and flats (especially built post 2012), among other archetypes, were discovered to be the most susceptible to overheating in the UK. This study employed a case study of a 2015 modern flat located in a high-risk overheating zone in London to understand the building's overheating exposure. A range of Dynamic Thermal Simulations (DTS) was conducted using EnergyPlus with reference to case studies in order to assess the performance of passive cooling mitigation strategies (PCMS) on peak summer days (15 July) as well as during the summer against CIBSE Guide A and ASHARE 55. Reduced window area and LoE triple glazing were identified as excellent mitigation prototypes, in which solar gains through exterior glazing were reduced by 85.5% due to triple glazing. Zone sensible cooling was reduced by 52%, which minimized CO_2 emissions. It was also identified that the final retrofit model passed CIBSE Guide A by achieving a temperature threshold of 20 °C to 25 °C during the summer months, whereas it failed to accomplish the ASHARE 55 criteria (20–24 °C). The outcome of this study justifies the necessity of tested PCMS and advises UK policymakers on how to foster resilient housing plans to overcome overheating issues.

Keywords: overheating; climate change; passive cooling mitigation strategy; modern flat; EnergyPlus; thermal comfort; London

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1. Introduction

Since the UK government is scaling up its efforts towards net zero, resilient higher adaptation goals should be implemented against heatwaves. The UK's average surface temperature has increased by 1.2 °C since the pre-industrial era (1850–1900) [1]. As per UKCP18, which is largely in connection with prior predictions of UKCP09 [2], by the end of the 21st century, the UK climate will continue to warm, and the sea levels will continue to increase. Given the current weather, there is a moderate concern in the Midlands and Wales, and the risk is particularly high in the Southeast of England, where London is the hotspot. There is currently little risk to Scotland, Northern Ireland, and Northern England [3].

A dwelling exceeding 24 °C of OT can disrupt sleep quality and cause discomfort. CIBSE TM59 recommends that peak bedroom temperatures should not exceed a threshold of 26 °C [4], which can be referred to as overheating. Practically, the air temperature is utilized to assess overheating by measuring humidity, absence of airflow, radiant heat, and duration of heat exposure for the region [5]. These periods of unusually hot weather in the summer are classified as heatwaves [6].

The UK witnessed record-breaking heat on 18 and 19 July 2022, with temperatures over 40 °C in London. As per Zachariah [7], these days were announced as red alerts (heatwaves), so rare with a 1 in 100 chance that they were statistically impossible before the Industrial Revolution. The Level 4 heat-health alert "national emergency" was declared by the UK Health Security Agency. The extreme heat caused an increase in hospital admissions, numerous fires, and serious disruptions in public transit [8]. If efforts are not made to tackle global warming, parts of the UK could theoretically experience an average temperature of 40 °C in July 2050, as predicted by the Met Office [9]. But then, there will also be individual weather events like today, where heatwaves could reach 45 °C, or even become closer to 50 °C, in 2050 [9].

According to the statistics of UK housing stock and its energy performance, in 2020, 46% of the stock had the highest EPC band A to C, as opposed to 14% in 2010, whereas only 11% of the stock was categorized in band E to G in 2020, which was 39% in 2010, as shown in Figure 1 [10]. Therefore, it can be concluded that during the last decade, the energy performance of UK dwellings has significantly improved due to the utilization of sustainable building elements and HVAC systems, which led to higher EPC bands.

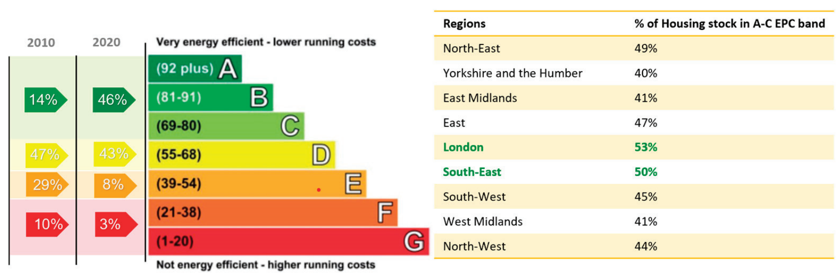


Figure 1. The increase in energy efficiency of UK housing stock between 2010 and 2020 [10].

According to the census of 2021 [11], households with the highest median energy efficiency score were identified in London (53%) and the Southeast (50%) compared to all other regions in England. London has a lower number of homes with F or G bands and the highest number of homes with an EER (energy efficiency ratio) of A or B. This indicates that one of the most overheating-prone regions (London) experiences a high level of internal heat gains during the summer despite having the highest EPC ratings due to climate change and location. Consequently, adaptive strategies and mitigation measures should be implemented to alleviate the discomfort of the occupants.

In terms of internal heat gain, the old dwellings somewhat perform better compared to modern structures due to the lower air infiltration rate employed, as per Approved Document Part F-Ventilation [12]. But overheating episodes were still reported in old constructions. A substantial amount of secondary data was discovered highlighting retrofit overheating mitigation measures for traditional housing stock (1900–2000) that effectively improved thermal comfort. However, limited data were found for high-EPC-rated modern flats (constructed after 2012) in terms of overheating adaptation. They are greatly vulnerable to overheating due to their high level of airtightness [12].

The aim of this study is to assess the overheating conditions in modern flats with the EPC bands A, B, and C in London and test relevant PCMS for the current climate and a 2050s 90% high-emission weather scenario during summer, with an emphasis on the extreme summer month of July. This is achieved by developing dynamic thermal modelling (DTM) of a modern flat and examining the extent of improvement in internal thermal comfort against CIBSE Guide A and ASHARE 55, 2017 by performing sensitivity analysis on various PCMS. The discovered set of PCMS may become a toolkit for experts (retrofit consultants, manufacturers, architects, designers, etc.), which can be executed from the design stage as well as employed in the retrofitting of UK housing stock. The following objectives are formulated to accomplish the aim:

- to discover and analyze existing literature on UK housing stock in terms of overheating exposure during the summer due to climate change and its mitigating solutions,
- to determine the OT exceeding the habitable temperature (25 °C) and examine PCMS,

- to achieve energy-efficient combinations of PCMS for UK domestic dwellings that will eliminate overheating risks in the present and future climatic probabilities.

2. Context and Background Knowledge

This climate change scenario and its percussions in the future in terms of overheating exposure in the UK housing stock were discussed. British standards providing an internal housing threshold temperature for overheating analysis were identified. Major factors responsible for internal heat gains were explained thoroughly. The examined PCMS were reviewed from the secondary literature. Highly durable and efficient PCMS were recognized and further evaluated in this study.

The research gap was distinguished from the analysis of current literature, which facilitated the authors' construction of methodology.

2.1. Climate Change Causes Overheating in the UK Housing Stock

The UK's Climate Change Risk Assessment (CCRA3) took into account emission scenarios as of mid-2021. The emission scenario RCP2.6 targets keeping global temperatures below 2 °C, while RCP6.0 fits within the present policy compatibility, showing a 4 °C increase at the end of the 21st century [9,13]. Adopting COP26 concepts into practice globally, RCP2.6 might be accomplished by 2100. Climate Action Tracker, however, voiced reservations about how realistic it would be to achieve the COP26 targets of reducing emissions by 2030, thereby placing a burden on the carbon budget for 1.5 °C [14]. The UK building regulations and policies have addressed climate change by prioritizing adaptation to colder winters while paying minimal attention to overheating problems in modern structures.

According to official statistics from the UK Valuation Office Agency [15], terraced houses represent 26.3% of all housing stock in England and Wales, followed by semi-detached houses (23.8%) and flats (23.2%). The research, which concentrates on areas vulnerable to overheating, indicates that flats comprise the majority of housing stock in London (55%), while the Southeast region has a more evenly distributed mixture of terraced houses (24%), flats (23%), and semi-detached houses (21%) [15]. The size, layout, and construction of a house affect the ways it reacts to heat. Typical UK archetypes are shown in Figure 2, each with unique sizes and geometric characteristics that influence overheating [3].

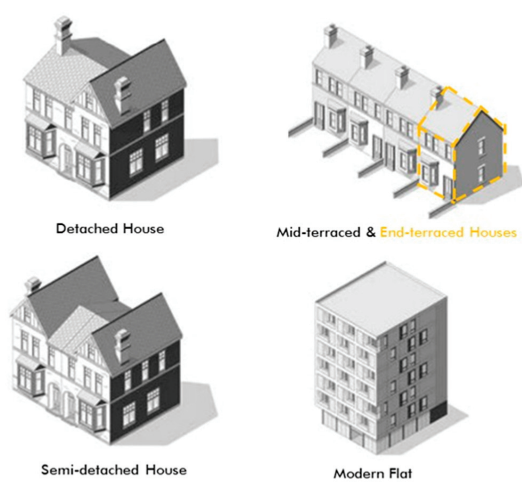


Figure 2. Classification of the Housing Stock, UK (created by author through Adobe Photoshop); derived from [3].

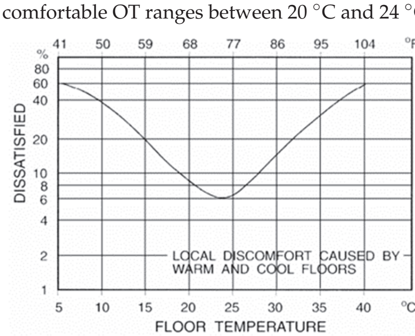
A qualitative study and experimental results on categorized housing stock demonstrate that the threat of overheating differs by house type. Due to their wider floor space, detached houses have the lowest risk, followed by semi-detached and end-terraced houses [3]. Mid-terraced houses suffer a larger risk because of their smaller size, while contemporary flats are the most vulnerable. Modern apartments with full-height glass and restricted ventilation alternatives are aggravated by the excessive air tightness imposed by Approved Document Part F [12], particularly in those built after 2000. Top floors are especially prone to overheating since hot air rises quicker than cool air and has less possibility for cross-ventilation owing to their limited windows [3]. The study focuses on modern apartments due to their predominance in London (55%), possibly providing mitigation prototypes for experts to address overheating problems in 55% of London's flats and 23.2% of dwellings (flats) in England and Wales overall.

Based on the English Housing Survey 2020–2021 [16], 8% of English homes experienced excessive heat in at least one room, with a 40% rise in overheating in living areas and bedrooms since 2018, once anticipated for the 2050s [17]. Flats and little houses in London and the Southeast were particularly vulnerable. Only 2% of English houses recorded utilizing air conditioning, whereas 50% utilized portable fans [18]. Due to hot, impure urban areas, increased air conditioner usage in the UK strains electricity supply and burdens the impoverished with prices. Furthermore, the discharge of heat waste from air coolers exacerbates the consequences of urban heat islands [19,20].

2.2. British Standards for Comparative Overheating Analysis

Different definitions of overheating are presently used to evaluate a property's overheating risk in the UK, during both new construction and retrofitting. Table 1 shows the comparison of UK standards in relation to overheating.

Table 1. Comparison of UK standards in terms of overheating.

<table>
<tr><th>Standard</th><th>Synopsis</th><th>Concise Explanation</th><th>Scope</th></tr>
<tr><td>SAP Appendix P [21]</td><td>Assessment of a dwelling with an overheating risk in the summer. Does not provide cooling needs, does not affect SAP rating or CO_2 emissions, and is non-integral</td><td>Assessment method for a Threshold Temperature: 20.5–22.0 °C low risk, 22.0–23.5 °C medium risk, ≥23.5 °C high risk</td><td>To evaluate and compare dwelling (both existing and new) energy performance</td></tr>
<tr><td>ASHRAE 55 [22]</td><td>Describes thermal comfort to explain acceptable levels of internal thermal temperature for occupants</td><td>Based on occupant activities, clothing insulation levels, ventilation, air speed, humidity, acceptable air temperature change, and OTs are identified. Optimal comfortable OT ranges between 20 °C and 24 °C.


DB utilizes EnergyPlus report outputs, which use ASHARE 55-2010 to validate occupant thermal comfort with reference to outside temperature</td><td>To identify appropriate thermal comfort levels for occupants under a wide range of conditions</td></tr>
</table>

Table 1. *Cont.*

Standard	Synopsis	Concise Explanation	Scope
CIBSE Guide A [23]	Provides benchmark summer temperatures and overheating criteria	The adaptive approach to comfort, CIBSE, considers a range of OTs in which acceptable indoor conditions are related to outside conditions	To assist in the identification of various factors of overheating and guidance for mitigation
CIBSE TM59 [4]	Standard methodology to predict overheating risks for domestic building designs (new build or major refurbishment)	Two requirements are listed in CIBSE TM59: Criteria A for living rooms, kitchens, and bedrooms is as follows: During the months of May to September, the percentage of occupied hours where the operating temperature is 1 Kelvin or higher than the comfort temperature should not exceed 3%. Criteria B for bedrooms only: The OT in a bedroom from 10 p.m. to 7 a.m. should not exceed 26 °C for more than 1% of the annual hours to offer comfort (CIBSE indicates "guarantee comfort"). Overall, 33 or more hours over 26 °C are reported as a failure since 1% of the yearly hours between 10 p.m. and 7 a.m. for bedrooms is 32 h. The acceptable summer indoor design operating temperature for non-air-conditioned dwellings is 25 °C.	Dynamic thermal modelling of new and old residential structures under various conditions
CIBSE TM52 BS EN 15251: 2007 (European Standard) [24]	Indoor environmental parameters for building energy performance design and assessment address internal air quality, thermal environment, lighting, and acoustics. Provides guidelines for indoor conditions where occupant's comfort would not be compromised in the name of energy savings	Acceptable temperature range for free-running buildings and of PMV for mechanically ventilated buildings. Acceptable temperature of category I lies within ± 2 K, so the optimum temperature is considered between 24 °C and 2 °C	To recommend stable and adaptive criteria for thermal comfort assessment of all types of buildings

CIBSE Guide A and the ASHARE 55 method are utilized to predict OT, as the EnergyPlus dataset already possesses this benchmark within the software.

2.3. Accountable Factors for Overheating

The authors divided overheating factors into three parts: subjective heating sources, sociological factors, and the elements of dwelling that disrupt indoor air quality as shown in Figure 3.

2.3.1. External Air Temperature

The "Urban Heat Island Effect" (UHIE) is caused by variables such as industrial activity, big structures, and minimal green space, resulting in greater temperatures in highly populated metropolitan regions such as London [19]. Even in less densely populated urban zones with some vegetation, temperatures may still be roughly 2 °C higher than in rural areas, making night-time cooling difficult.

2.3.2. Internal Heat Gains

Human metabolism produces heat based on the type of activity and is proportionate to the amount of air inhaled (breathing). A sedentary adult not performing physical activity, for example, is expected to produce 58 W of heat per square meter of the skin's surface, or one metabolic unit (met) [25]. The lighting, electrical equipment, and services (boiler, thermostat, computer, gas stove, refrigerator) utilized through electricity are also converted into heat.

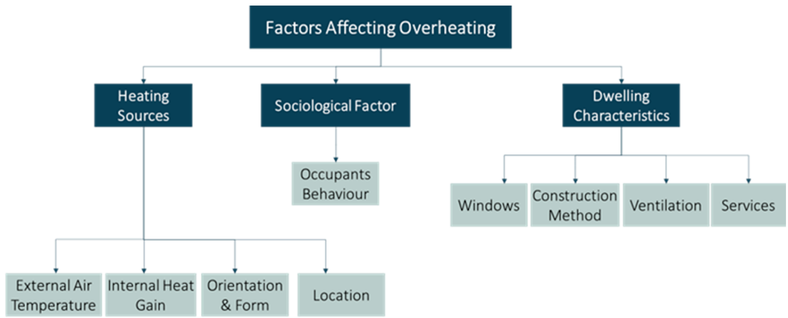


Figure 3. Overheating causing factors.

2.3.3. Orientation and Form

The ARUP panel [3] discovered that living areas facing west are the most likely to overheat, subsequently followed by those facing south, east, and north. In England, both ancient and modern mid-terraced structures frequently overlook orientation in design and construction, making certain properties more prone to overheating [5]. Apartments may have one side that is more prone to overheating than the other.

The Good Homes Alliance (GHA) [26] discovered 84 incidents of overheated residences using a survey that included environmental health officers, housing providers, residents, and consultants. In total, 59 of the 84 instances were flats (23 converted and 36 purpose built), mostly pre-1919 or post-2000 construction, implying that purpose-built flats in the UK tend to be more prone to overheating than those of other categories (Figure 4).

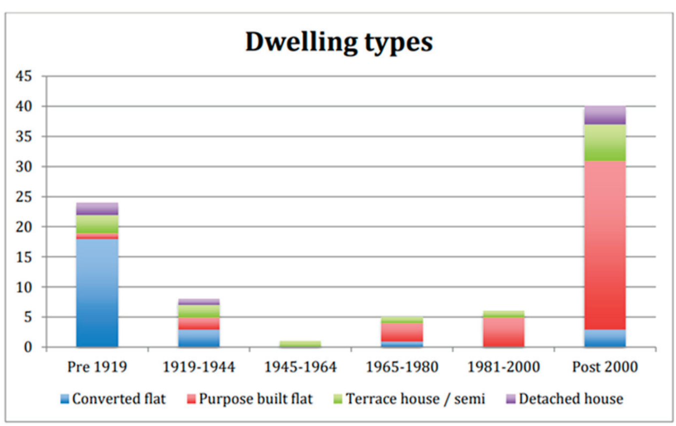


Figure 4. Classification of 84 Dwelling types suffering from overheating [26].

2.3.4. Location

People in urban areas like London may be reluctant to open windows due to extreme air pollution, noise, and security [5]. Among 58 dwellings, the highest number of overheated dwellings (32) was located in the urban areas, followed by 19 and 7 dwellings in suburbs and rural areas, as shown in Figure 5.

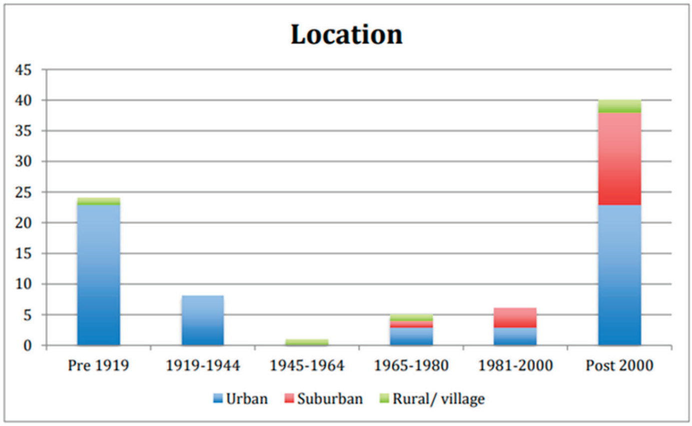


Figure 5. Distribution of 84 dwellings experiencing overheating as per location [26].

2.3.5. Windows

Any glazing with a large surface area accumulates solar gain, except north-facing windows. Homes in the UK usually lack window shading, which can result in excessive solar gain [27]. The heat from the radiation that is not reflected by blinds or curtains enters the room and heats the air in the room. Without window shade, solar energy is internally absorbed, and the heat is then gradually released back into the air of the space [5].

2.3.6. Construction Method

According to the English Housing Survey (EHS) [16], occupants in homes with insulated cavity walls and steel, concrete, or wooden frames have higher overheating issues compared to those in solid, uninsulated structures. Overheating rates in timber and steel frame structures are 18% and 17%, respectively [16]. Wall insulation, on the other hand, can minimize overheating in detached, end-terrace, and semi-detached houses with large outer wall areas, but has little effect on flats and mid-terrace structures with fewer external walls, according to ARUP's sensitivity assessments [3]. The efficacy of wall insulation differs based on location and climate, with that in Manchester being more effective than that in London. According to GHA's findings [26], uninsulated solid brickwork or stone masonry structures have the greatest overheating levels (31 homes out of 84), as opposed to insulated cavity brick/block and dwellings made of concrete, wood, SIPs, or steel (Figure 6).

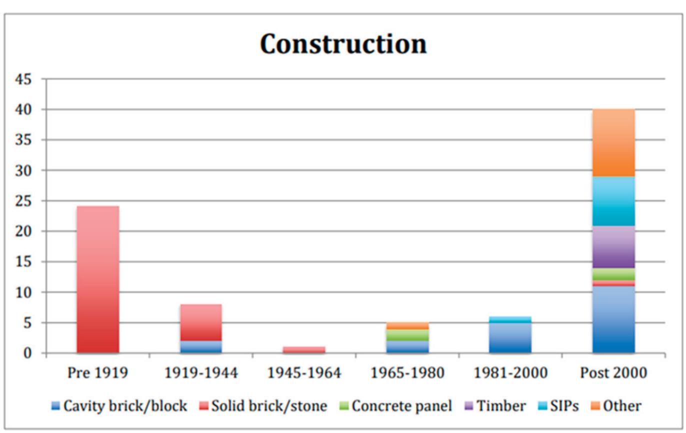


Figure 6. Construction types causing overheating [26].

According to Fosas et al. [28], insulation can contribute up to 5% of the overall overheating response in the UK homes, and increasing insulation levels may not always result in lower interior temperatures when window operation is restricted for safety purposes.

ARUP [3] and Fosas et al. [28] concluded that the influence of insulation on overheating is less significant when compared to glazing ratio, climate, location, building orientation, shading, and ventilation. External insulation serves an insignificant role in resolving overheating, particularly in new apartments, but when paired with other variables, it can help minimize the problem.

2.3.7. Ventilation

UK Part L building regulations [29] implied air permeability to be less than 10 $m^3/(h.m^2)$ at 50 Pa for domestic housing stock, highlighting the significance of regulated ventilation [30]. Mechanical ventilation with heat recovery (MVHR) is prevalent and required when a household's infiltration rate is less than 5 $m^3/(h.m^2)$; however, problems might emerge due to insufficient setup, training, and monitoring [31]. But it is widely used in Passivhaus and other well-insulated dwellings [32]. Surprisingly, Figure 7 shows that 42 homes with overheating rely on natural ventilation, demonstrating that simply opening windows is not sufficient. To reduce overheating, effective ventilation systems must incorporate design aspects such as window type, size, orientation, g-value, and night purge cooling capacities. Furthermore, post-2000 houses with specialized mechanical ventilation systems, as shown in Figure 7 [26], suffer heat-related concerns owing to installation, maintenance, or user control issues.

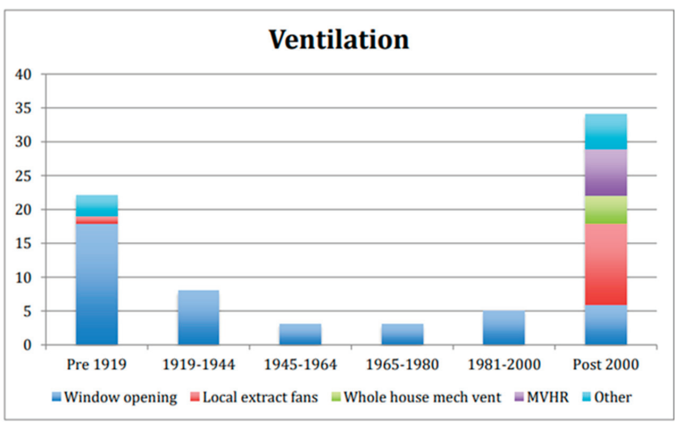


Figure 7. Overheating problems occurring in means of ventilation systems [26].

2.3.8. Services

It was crucial to take additional heat gains from community pipes into account when estimating the risk of overheating in flats that have a communal heating system. The usage of communal heating systems raised overheating risks due to heat loss from inadequate DHW pipes that are distributed through flats and corridors [3]. Uncontrollable underfloor heating that is malfunctioning may also cause major concern. Service voids for ventilation and pipes for drainage, electricity, water, and gas should be addressed to lower overheating.

2.3.9. Occupant Behavior

Houses with higher occupancy rates, such as those with elderly, disabled, or unemployed residents, were more susceptible to overheating because they were "in use" for an increased number of hours on a daily basis. Occupant activity can both increase and decrease the danger of overheating. Examples include window opening patterns, appliance use, and spatial layout. The use of heat-rejecting equipment often might potentially cause overheating. The risk of heat gain is higher when a bedroom is located in a hotter zone of the house, such as a south-facing space with glass windows. Bedrooms have lower thresholds for warming than living rooms [33].

2.4. Passive Cooling and Overheating Mitigation Strategies

Effective window design solutions are discussed to prevent internal heat gains from windows. Ventilation strategies and construction methods are highlighted, along with an additional non-passive method (Figure 8).

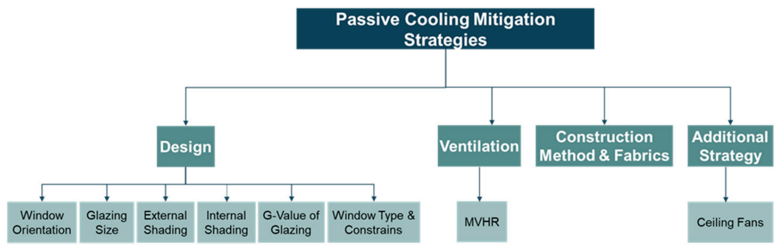


Figure 8. Accentuated parameters as mitigation strategies.

2.4.1. Window Orientation

In order to optimize solar benefits in winter and reduce overheating in summer, buildings should preferably be positioned north–south with maximum window coverage on the north façade to achieve daylight and a 15–25% glass area on the south façade. Orienting a residence north–south is not always practical. When developing openings for houses with an east–west orientation, extra attention should be paid to glazing areas and shading devices to address lower-angle sun radiation, which is usual at the start and end of the day in summer. Shading solutions like overhangs, louvres, external blinds, or shutters should be employed [34].

Approved Document O [35] has provided Window to Floor Ratios (WFR) for high and moderate overheating risk regions in the UK. Rooms of dwellings with and without cross-ventilation should not exceed the maximum glazing areas mentioned in Tables 2 and 3 below.

2.4.2. Glazing Size

Achieving excellent daylighting should be balanced against glazing size and placement. Vertical windows from floor to ceiling lose heat and create gains while being inefficient in increasing daylighting. For the same amount of window area, horizontal glazing offers more daylighting (Figure 9). With a larger sill height, it is also simpler to maximize the openable surfaces for passive cooling on horizontal windows [34].

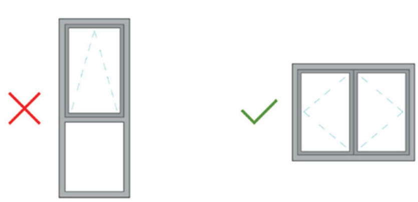


Figure 9. Glazing aspect and openable areas [34].

Table 2. Limiting solar gains for parts of buildings with cross-ventilation [35].

	High Risk Location		**Moderate Risk Location**	
Largest glazed façade Orientalin	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	37	18	37
East	18	37	18	37
South	15	22	15	30
West	18	37	11	22

Table 3. Limiting solar gains for parts of buildings without cross-ventilation [35].

	High Risk Location		**Moderate Risk Location**	
Largest glazed façade Orientalin	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	26	18	26
East	11	18	18	26
South	11	11	15	15
West	11	18	11	11

2.4.3. Window Type and Constraints

The free-flowing, openable surface is determined by the window's size and opening technique. Tilted and top-hung windows have significantly smaller opening areas than side-hung windows, whereas inward-opening windows allow for exterior shutters and insect netting [34]. Porritt et al. [36] discovered that bottom-hinged windows decrease overheating by 11%, while top-hinged and side-hinged alternatives minimize it by 19% and 26%, respectively (Figure 10).

Figure 10. Types of windows [36].

2.4.4. External Shading

Overhangs and brise soleil are most suitable for south-facing windows to protect them from the high-level summer sun while not blocking the weak winter sun [34]. But, since the sun has a comparatively low altitude as it moves to the northwest in the mid- to late afternoon of summer, applying the same method to a west elevation would be less effective [37]. Moreover, the fixed shade or overhang should subtend a 60° angle to the bottom border of the glass, as shown in Figure 11 [34], where it is employed on the south windows. Vertical louvers and shutters are more suitable for northwest windows [37]. Deployable shading, like shutters, blinds, or awnings, is efficient where fixed shading is inapplicable. Automatic operation can be added where the shading device and window are not accessible [34].

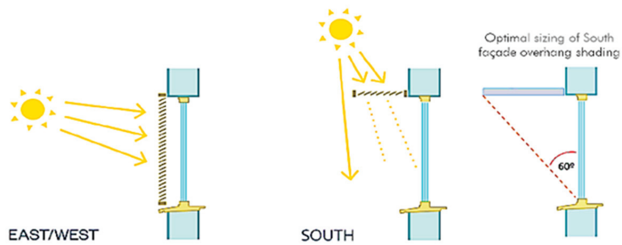


Figure 11. Shading strategies as per orientation [35] (created by author through Adobe Photoshop).

2.4.5. Internal Shading

If external shading is unattainable, internal shading can be considered, but it is less efficient. While internal shading can only limit solar gain by a maximum of 40%, external shading can lower it by 80–100% [34]. Depending on the behavior of the occupants, internal shading may limit cross-ventilation. For best results, it is worth placing white or reflective blinds behind the window, which would reflect the sun's radiation back out through the glass.

2.4.6. g-Value of Glazing

Solar gain can be minimized by glazing types with a lower g-value. The reduction in overheating risk needs to be balanced against the reduced winter sun light. A lower g-value also influences the quality of the vistas and the amount of daylighting throughout the year [34]. Adaptation of lower g-value glazing, particularly for overheating-prone locations, can be an efficient strategy.

2.4.7. Ventilation

Homes in the UK typically have 0.5 air changes per hour (ACH); however, mechanical systems may raise that number by 25–50%. With conventional systems, it is difficult to double ventilation to 1 ACH. No mechanical system can achieve this without being specifically constructed. Purge ventilation is at least four times as high or eight times the average, but it demands wide-opening windows. Sustainable ventilation should be passive and not rely on fuel. Therefore, the best passive ventilation technique would be night purge ventilation, since it achieves cooling overnight during the summer.

2.4.8. MVHR

When it is warm both indoors and outside, a smarter MVHR system detects it and activate "Summer Bypass Mode" [38]. These filters enter the fresh air and exhale warm, humid air. Yet, even in the boost mode, a typical Passivhaus MVHR system only generates approximately 0.5 ACH, providing barely any cooling, no more than opening windows [34]. A larger MVHR unit for more cooling is not practical due to restrictions imposed by larger duct diameters, higher unit costs, high energy consumption, and operational noise. Summer bypass is not mentioned in the UK BRs document F-Ventilation [12]. Consequently, the author would not be employing the MVHR unit as a modification tool.

2.4.9. Construction Methods and Fabric Interactions to Prevent Overheating

Lee and Steemers [39] evaluated the overheating of a historic mid-terraced house in London under four contexts (insulated/uninsulated cavity masonry, insulated/uninsulated timber frame masonry) with natural ventilation and internal blinds. Insulated timber framing performed worse than cavity masonry; insulation made overheating worse in a south-facing bedroom that was only used at night. Although solar blinds and opening windows reduced temperatures, they were not practical owing to security issues. According to Gupta and Cregg [40] research, exterior insulation was the most efficient, whereas internal insulation was the least effective and likely to cause severe heat gains. Thus, combining PCMS with effective external insulation would prevent overheating.

2.4.10. Additional Strategy: Ceiling Fans

Although ceiling fans do not attain factual cooling, they can result in a perceived temperature decline of 2–3 °C and are hence useful in sustaining comfort levels where a low degree of overheating is recorded [3]. Designers should install fans at 2.5 m or more of ceiling height for a suitable amount of airflow [5].

2.5. Discussion of Combined PCMS and Their Results as Per Climate Change

Dynamic thermal simulations (DTS) were performed by several researchers, including Wright and Venskunas [27], Morten [41], and Li et al. [42]. They studied the possible influence of future warming temperatures on overheating in conventional English dwellings. They examined potential mitigation strategies under high- and medium-emission scenarios from the present, 2030s, 2050s, and 2080s. External sun shade and natural ventilation, particularly at night, were the most effective overheating mitigation techniques, lowering overheating by around 50%. Morten [41] underlined the importance of outside drapes and automated shutters in mitigating future climate change. External shutters were shown to be the most effective method, followed by low g-value windows in living areas by ARUP's Bouhi et al. [3], but ceiling fans were an equally beneficial low-energy method compared to active cooling. Li et al.'s [42] simulation results revealed that solar control devices reduced median degree hours by 54%, external shutters, low g-value windows, and night purge ventilation decreased heat gain by 96%, 86%, and 89%, respectively, while internal curtains and roller blinds lowered heat gain by 57% and 50%, respectively.

Figure 12 highlights the ranking of PCMS as per longevity and efficacy after thoroughly analyzing the secondary literature. The blue tick measures were applied and tested on the dynamic thermal model of a selected case study (a modern flat in London), while the yellow tick measures already existed in the base model.

Scenario	Assessment of longevity	Longevity (1-10)	Efficacy (1-10)
Reduced glazing area (Window to Floor ratio WFR)	Durable in all conditions	10	10
Fixed external shading (overhang- horizontal south, Louvres- verticle- east & west)	Durable in all conditions	10	9
External shutters	Average durability, Needs occupants action when installed without automatic controls & reduces winter heat gain	8	10
Internal blinds	Subjected to automated control or residents action. Automation might malfunction and occupants may be reluctant to use it due to blockage of outer views	4	8
Low g-value glazing (Solar control coat)	Highly robust but reduces winter heat gain	10	7
Night-purge ventilation	Highly efficient but subjected to occupants action and restrictive usage due to noise, privacy and security reasons	4	9
Reflective paint on walls	Subjected to insulation type and thickness	10	4
Reflective paint on roof	Subjected to insulation type and thickness	10	6
External wall insulation	Highly effective when combined with efficient passive cooling interventions	10	4
Internal wall insulation	Somewhat durable when combined with efficient passive cooling interventions	10	2
External loft insulation	Moderately durable when combined with efficient passive cooling interventions	10	3
Ceiling fan	High longevity but non-passive measure and consume electricity	4	9

8 to 10
4 to 7
1 to 3

Figure 12. Synopsis of longevity and efficacy of mitigation strategies.

3. Methodology

3.1. Research Method

In this research, literature data collection was completed in a sequential multi-phase design approach by initially analyzing the problem of overheating in the UK housing stock due to climate change using the qualitative method, then identifying statistical data for the affected UK archetypes (apartments and mid-terraced houses) using the quantitative method, and finally emphasizing British overheating benchmarks along with factors causing overheating and its mitigation solutions using the qualitative method. To encompass a practical evaluation of the performance of the PCMS under overheating events, a range of dynamic thermal simulations (DTS) were performed using the EnergyPlus interface.

A substantial amount of secondary data was discovered highlighting retrofit overheating mitigation measures for old construction (1900s–2000s), which effectively improved thermal comfort. However, limited data were found mentioning mitigation steps for modern structures (constructed after 2010), especially those with a high EPC band, because they are greatly vulnerable to overheating due to their high level of airtightness. Since the ratio of modern purpose-built flats is the highest amongst other archetypes in London, it was worth evaluating for overheating risks. Moreover, London exclusively occupies 55% of flats among other archetypes and is a peak region experiencing overheating problems. Therefore, this study focuses on identifying mitigation solutions for modern flats in London.

To accomplish the aim, a case study of a modern flat from London (natural setting) was conducted to understand overheating exposure in current and 2050s UK weather in summer. The simulations were performed quantitatively by studying the actual conditions of the flat during the summer via a descriptive and evaluative research design. Effective strategies obtained from the simulation results became a prototype for the overheating-prone zones (London and Southeast) that can be implemented in the high-EPC UK housing stock. The methodological steps to attain the aim were divided into two phases, as shown in Figure 13.

Phase 1 (Overheating Analysis): The selected case study of a modern flat was assumably 3D-modelled in DB and monitored at each design step, incorporating location, weather, zones, occupancy hours, building fabric, and the HVAC system. Construction systems (U-values for walls, floors, doors, and windows) were employed as per the UK Building Regulations 2010 (Approved Document Part L [16]). Both the current and 2050 weather conditions were used to determine the flat's risks (number of hours over 25 °C).

Phase 2 (Performance of Retrofit Mitigation Strategies): The emphasis was placed on highly susceptible rooms (living rooms and bedrooms) in this phase. The OT for the base model was identified through thermal simulations. PCMS (refer to Figure 13) were applied step by step, compared, and examined in terms of internal thermal comfort under both climatic probabilities: the present and 2050. Lastly, the toolkit of the most efficient PCMS was discovered, which eliminated overheating in susceptible rooms by decreasing the number of hours exceeding 25 °C.

3.2. DesignBuilder (DB)

DB [43] was employed to perform thermal simulations with the EnergyPlus simulation engine, allowing advanced DTS at sub-hourly timesteps. This assessed the effect of integrated PCMS in different zones, such as living rooms, bedrooms, etc., on overheating, as well as tested solar gains on surfaces and their surface temperatures, internal temperature distribution, and passive performance [43]. DB is extensively used for the evaluation of building energy performance for both commercial and research purposes in the UK, and room level is used to measure temperatures.

Future Weather Data

To execute building simulations in terms of future climate change, percentiles provide a technique to explain various probability assumptions [43]. The worst-case scenario in a high emission might be above the 90th percentile, while the best-case scenario in a low emission might be the 10th percentile. For instance, if the 90th percentile prediction forecasts a 6 °C temperature increase by 2050, then there is a 90% chance that the real temperature increase will be lesser. The mean value is represented by the 50th percentile projection, which indicates an equal possibility of the temperature climbing above or below this range [44,45]. CIBSE offers the following emission scenarios for use in dynamic building simulations:

- 2020s: High emissions scenario (10th, 50th, 90th percentile),
- 2050s: Medium: 10th, 50th, 90th,
- 2050s: High: 10th, 50th, 90th.

DB provides thermal comfort by simulating results through operative temperature, which represents a thermal comfort index to assess occupant perceptions. These internal temperatures are achieved in accordance with the outside dry-bulb temperature (ODBT). In interpretation, the internal temperature changes as the ODBT fluctuates. Therefore, the average current climate's and 2050′s outside dry-bulb temperatures in DB are adopted with medium (50%) and high (90%) weather scenarios (Figure 14) shown in Table 4 to analyze overheating conditions.

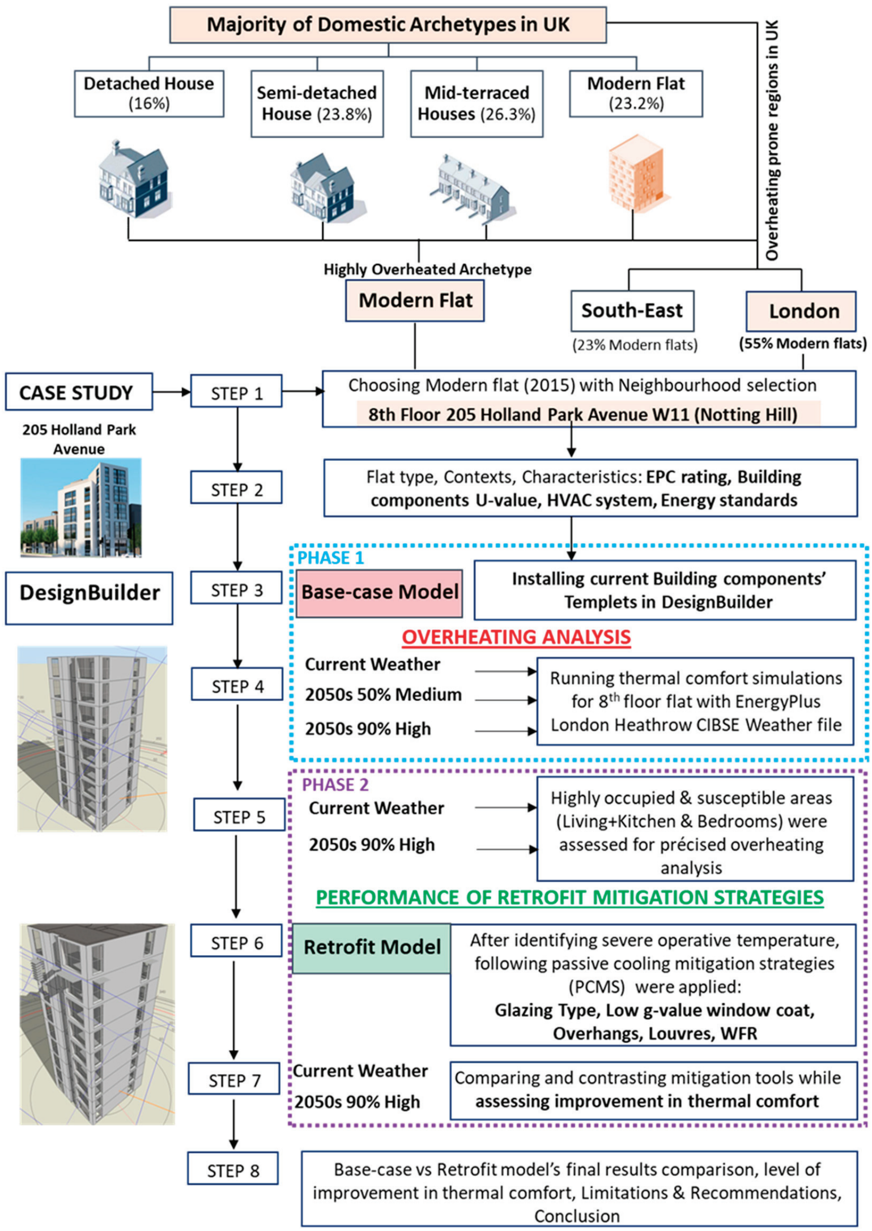


Figure 13. Research Framework.

Table 4. Overheating threshold of climate projections for London; derived from [27,40].

Current Climate	2050 Medium 50% Probability	2050 Medium 90% Probability
27.0–28.2 °C	27.3–29.7 °C	28.2–31.2 °C

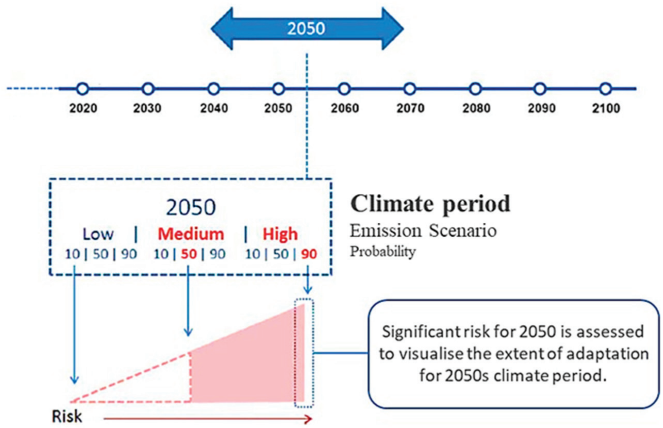


Figure 14. The probabilistic range tested for 2050s climate period illustrates significant risk; derived from [40].

Wright and Venskunas [27] generated a chart highlighting a high-emission (90%) scenario for 14 regions in the UK as per 2018 RCP 8.5 compared to UKCP09 and UKCP18. With reference to this chart, the 2050s' DSY was assumed to be a medium (50%)-emission scenario that increased by 1 °C and a high (90%)-emission scenario that increased by 2 °C according to UKCP18, as shown in Figure 15. The ODBT for the current climate was 28 °C in DB. Hence, in order to conduct overheating simulations in the 2050s in DB, according to the Wright and Venskunas [27] temperature fluctuation graph (Figure 15), ODBT was raised by 1 °C by assuming 29 °C for the 50th percentile medium-emission scenario. Similarly, a 30 °C ODBT was assumed for the 90th percentile high-emission scenario by raising the temperature by 2 °C.

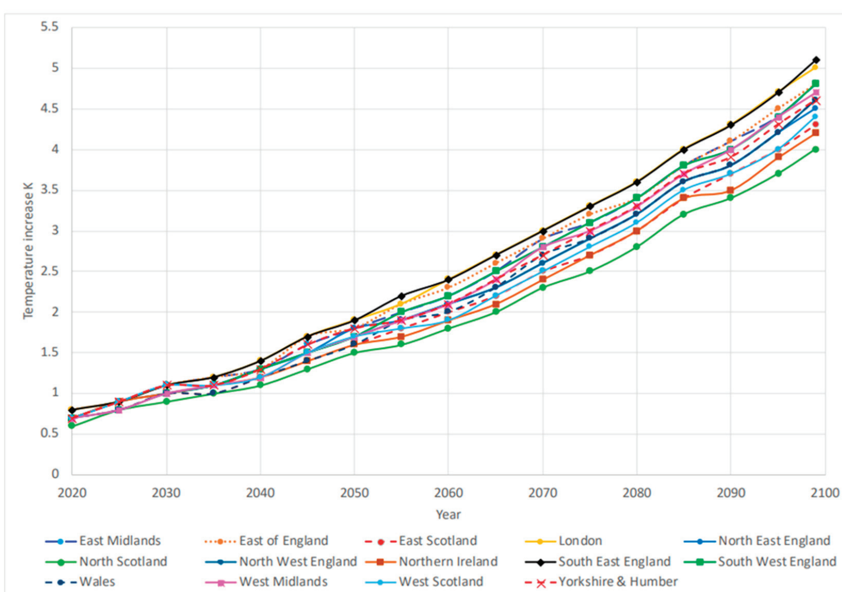


Figure 15. Temperature fluctuations from 1981-2000 baseline, for 2018 RCP 8.5, according to scenario UKCP09 and UKCP18 high-emission scenarios for 14 regions of UK [27].

4. Case Study

To reduce overheating caused by heat waves, the UK government released overheating mitigation Approved Document Part O [35]. The majority of British dwellings were categorized in document Part O [35] as having a moderate risk of overheating, with several high-risk regions, notably central and suburban London. The document imposed stronger regulations in high-risk areas. In order to collect extensive information and understand the ways in which the building components and HVAC systems were adopted in UK modern flats, an apartment on Holland Park Avenue, London W11 constructed in 2015 with an EPC rating of B was selected as a case study. The postcode (W11) is characterized as a high-risk zone in London (refer to Appendix C, Table C1 from Approved Document Part O [35]). DTM was developed with the guidance of this case study to acquire realistic and plausible simulation outputs in DB.

The property is located near central London at the junction of Holland Park and Holland Road in the urban area (Figure 16) and exposed to the A3220 primary road with a roundabout intersection [46]. As per the Road Traffic Statistics UK [47], A3220 is a Class A principal road in an urban area, which can be noisy and overcrowded. It can be indicated that people living there may not be able to open their windows due to loud noise and security reasons. The dense, solid structures near the flat may release heat, warm up the area by a few degrees, especially at night, and create UHIE.

Figure 16. Aerial view of 205 Holland Park Avenue [48].

The apartments on all floors were identical in design and layout. A southwest-cornered eighth-floor flat was chosen as a case study because the top floors are highly prone to overheating, as derived from the literature review [3]. The reasons for selecting this flat were its location, orientation of the living and kitchen (southwest) with a higher glazing ratio, 2015 construction, B-EPC rating, and building fabric and HVAC systems adapted from the new UK Energy Standards of 2010 and partly 2013 [49].

Part L1 2013 principles were also implemented after the property's inauguration in April 2013, which was expected to deliver a 25% improvement in energy efficiency compared to Part L1 2010. The development exceeds the requirements of the London Plan 2011 target by approximately 4% and those of the Part L 2010 target by approximately 29% [49]. This indicates that the property might be susceptible to overheating due to tighter energy standards with a 3 $m^3/h.m^2$ air-infiltration rate, which may not allow air penetration. The base case model was created in DB by adopting similar element specifications from Tables 5 and 6, and the planning layout from Figure 17 to accomplish the aim of the study.

Table 5. Apartment characteristics [49].

Address	Holland Park Avenue, London W11
County	Great London
Construction completion	2015
EPC rating	B (87)
Property type	Mixed-use development: 5 linked pavilions, 4–10 stories, 41 residential apartments
Selected apartment	8th floor, 2-bedroom flat
Apartment orientation	Southwest-facing living room with modern kitchen. Provision of 2 bathrooms
Floor to ceiling height (m)	3
Apartment floor area (m^2)	97.8
Heating system	Combined heat and power (CHP) with underfloor heating
Air permeability	q50 = 3 m^3/h.m^2
Ventilation system	Mechanical extract ventilation (MEV)—extract fans in the open kitchen and bathrooms
Demographics	Rental apartments allowed 4–5 occupants for a 2-bedroom suite
Energy standards	2010 UK building regulations, partially adopted part L1 2013

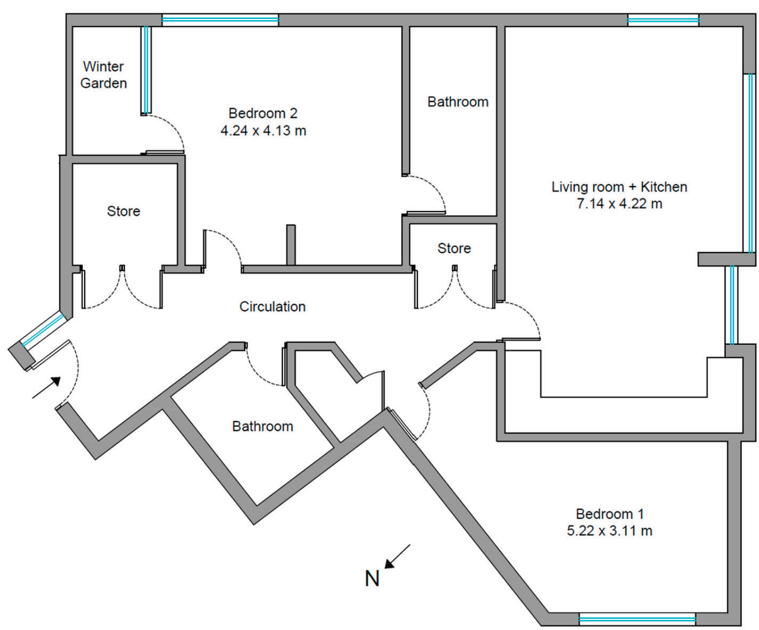


Figure 17. Eighth floor plan (drafted by the author); derived from [46].

Table 6. U-values of building components [49].

Building Components	U-Value (W/(m^2.K))
External Wall	0.20
Floor	0.19
Roof	0.15
Windows (Double glazed)	1.78
Doors	1.50

Phase 1: Base Case Model Configurations in DB

The property of the case study was located in a 4.5-mile radius of central London and 13 miles from London Heathrow Airport. Therefore, London Heathrow was chosen in the location template of DB for a precise evaluation, as shown in Figure 18. The base case model was developed as per the assumptions from the case study, which is shown in Figures 16 and 19.

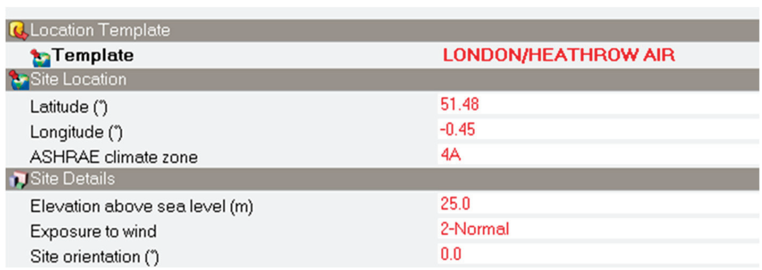
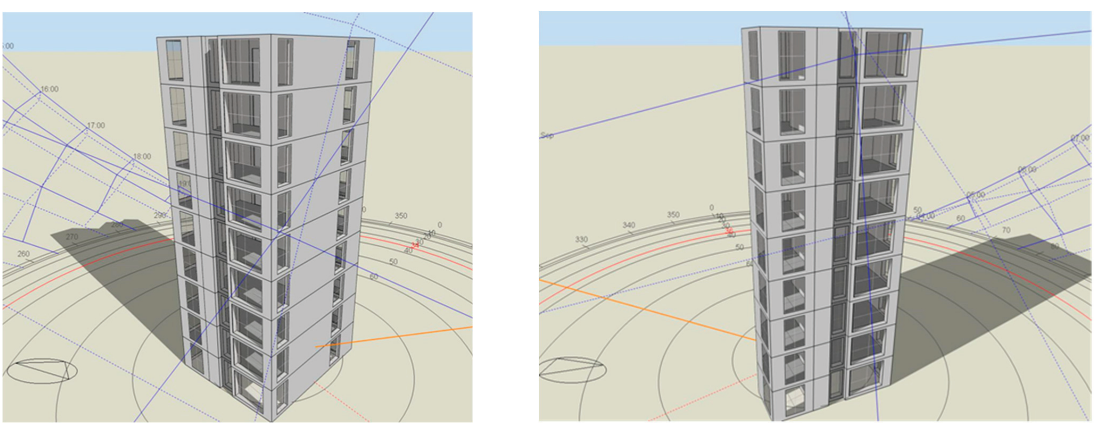


Figure 18. Location Template.



(**a**) (**b**)

Figure 19. DesignBuilder Base Model of a flat assumed from case study: (**a**) view from the southwest; (**b**) view from the southeast.

According to the UK housing standards [50], the occupancy rate of a domestic dwelling with two bedrooms varies from two to four members. It is assumed that the flat is occupied by three people, including a single parent with a child. Therefore, the building is presumed to be occupied for 20 h (2 p.m.–11 a.m.) on working days and 22 h on weekends, as shown in Table 7.

Table 7. Flat occupancy details.

Occupants	Occupants Living Pattern	Occupancy Ratio
Pensioners	A pensioner couple at home most of the day	08.00–20.00 Living room
		22.00–06.00 Bedroom 1
Single Parent	A working adult with a child going to school	14.00–18.00 Living room
		20.00–06.00 Bedroom 2

Since the electronic appliance also contributes to internal heat gains, the equipment schedule was added in DB to keep the overheating assessment accuracy intact. It was assumed that Bedroom 1 and the living room have televisions and are utilized for 5 h (Monday to Saturday) (Table 8). Kitchen appliances come under the catering schedule. It is believed to be operated for 5 h every day. The activity template was selected according to internal area's utilization of CIBSE TM59, as shown in Figure 20. A substantial amount of daylighting was shown inside the flat at different times on 15 July 2022, according to the sun path (Figure 21).

Table 8. Activity Template set in DB.

Space	Floor Area	Occupancy (People/m^2)	Activity (m)	Summer Clothing (clo)	Equipment (W/m^2)	Schedule of Equipment
Living room, Kitchen	29	0.0188	1	0.65	TV 3.55	TV 5 h (Mon to Sat)
					Stove, Oven, Microwave 30	Catering 5 h (Mon to Sun)
Bedroom 1	16.23	0.0229	1	0.55	3.55	5 h (Mon to Sat)
Bedroom 2	17.46	0.0229	1	0.55	-	
Circulation	12	0.0155	0.9	0.65	-	

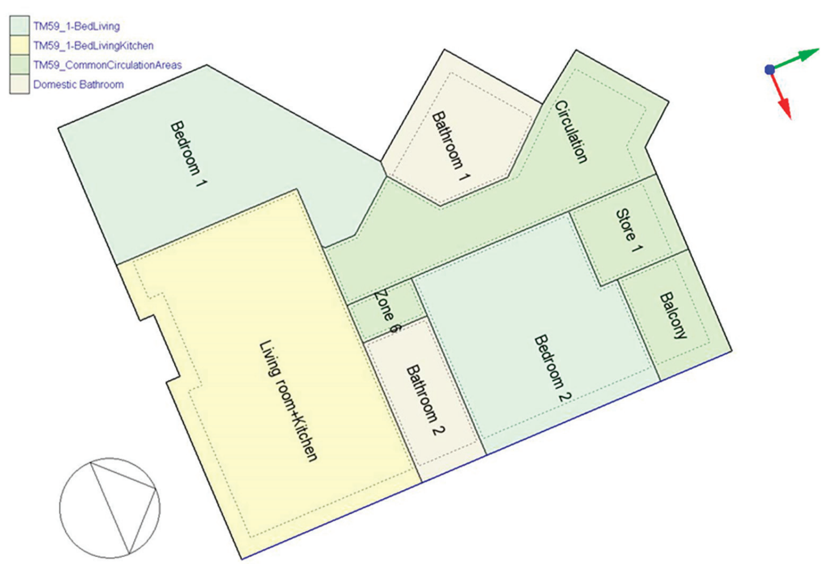


Figure 20. Base model of an 8th floor flat with the activity template.

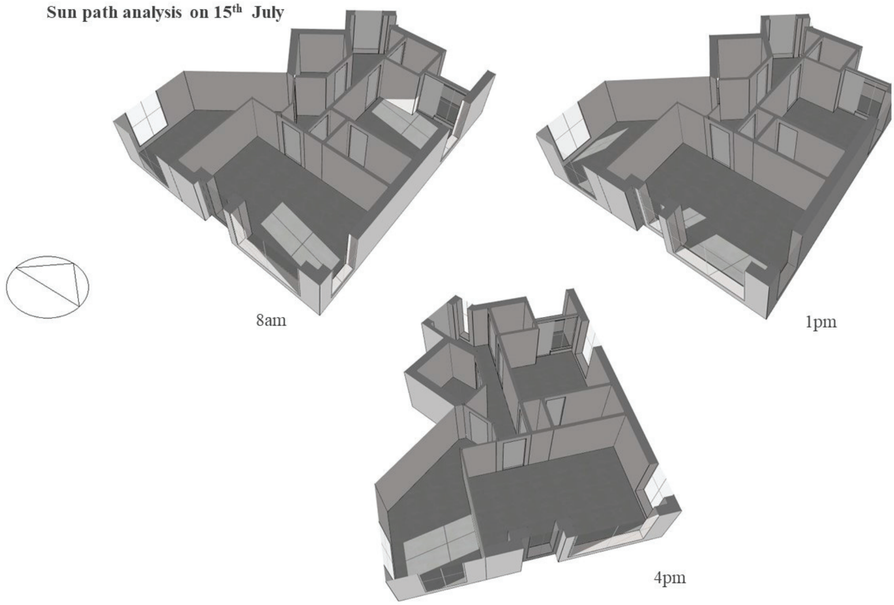


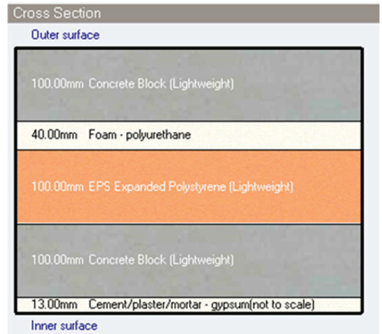
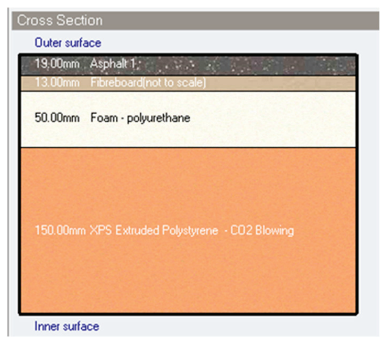
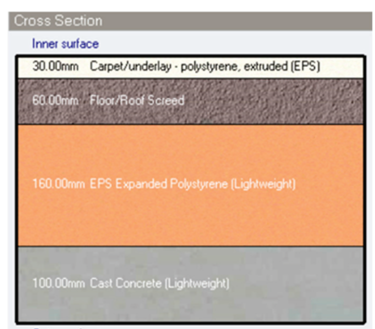
Figure 21. 8th Floor Base model in DesignBuilder: internal 3D layout with sun path analysis at different times on 15th July.

The energy-efficient building construction components are illustrated in Table 9 as a lightweight structure with U-values from Table 6.

Double-glazed windows were chosen for the base model as per Table 5. Overall, a 25% glazing with a top-hung outward opening was presumed (refer to Figure 10) (an approximately 70% openable ratio), which may provide some cross-ventilation when opened. While the surrounding area of the property was overcrowded with vehicles and people, a 25% openable glazing and a 75% fixed glazing (which cannot be operated by occupants) may moderately reduce noise pollution. Therefore, night purge ventilation can be recommended as one of the passive cooling solutions.

Moreover, a southwest façade with a 46% window-to-floor ratio (WFR) was assumed as per the case study as shown in Table 10. This was approximately twice the ratio presented in Part O [35]. Therefore, acceptable WFR was proposed after considering Part O guidelines (Tables 2 and 3) without compromising the daylight factor because low daylight may affect wellbeing. The reduced window sizes may be considered a mitigation strategy if required. Table 10 shows the window sizes installed in the base model.

Table 9. Construction Template.

<table>
<tr><th></th><th>Construction Layers</th><th>U-Value ($W/m^2.K$)</th></tr>
<tr><td>External walls</td><td>
</td><td>0.20</td></tr>
<tr><td>Flat roof</td><td>
</td><td>0.15</td></tr>
<tr><td>Floor</td><td>
</td><td>0.19</td></tr>
<tr><td>Glazing
(Double-Glazed windows)</td><td>UPVC window frame</td><td>1.80</td></tr>
</table>

Part L 2010 ventilation system was selected in the HVAC template (Figure 22), meeting the high-level requirements of building regulations Part L1 2010 and 2013 (Table 5). The air infiltration rate of mechanical ventilation was kept at 3 ACH. The heating system was kept as default, and mechanical cooling for summer was scheduled for May to September for 4 h from mid-day (12.00–16.00 h) and kept off during winter as shown in Figure 23.

Table 10. Window design details of Base model with proposed WFR.

Model Zones	Window Size (m)	Floor Area (m^2)	Orientation	Window to Floor Ratio (WFR) in %	Acceptable WFR as Per Part 'O'
Living room	2.5 × 3	29	SW	46%	22%
	2.5 × 1		SE		
Kitchen	2.5 × 1.30		SW		
Bedroom 1	2.5 × 1.50	16.23	SW	46%	25%
	2.5 × 1.50		NW		
Bedroom 2	2.5 × 1.50	17.46	SE	35%	27%
Bedroom 2 (Balcony)	2.5 × 1.15		NE		

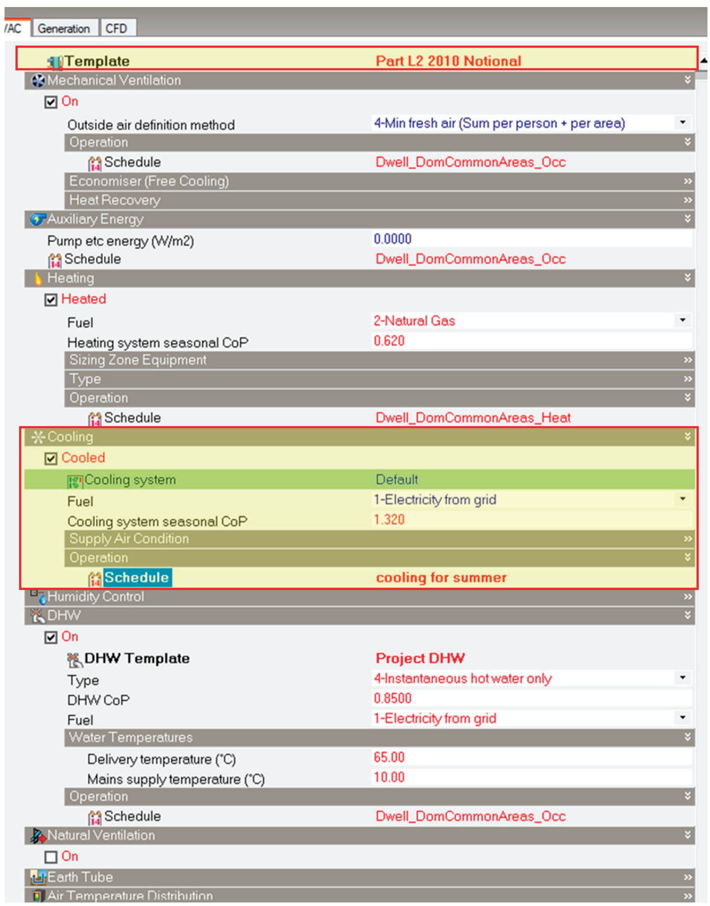
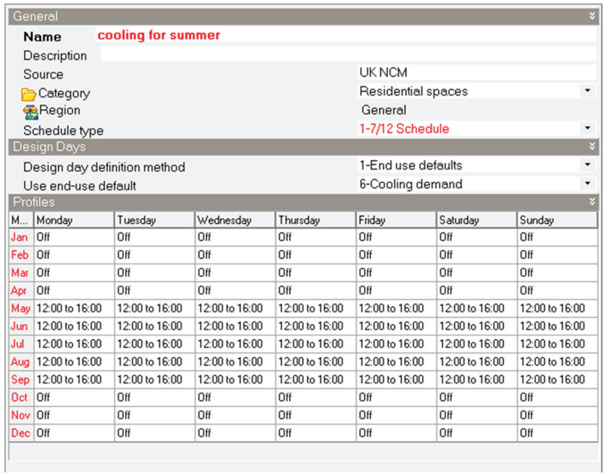


Figure 22. HVAC Template.



General

Name	cooling for summer
Description	
Source	UK NCM
Category	Residential spaces
Region	General
Schedule type	1-7/12 Schedule

Design Days

Design day definition method	1-End use defaults
Use end-use default	6-Cooling demand

Profiles

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	Off	Off	Off	Off	Off	Off	Off
Mar	Off	Off	Off	Off	Off	Off	Off
Apr	Off	Off	Off	Off	Off	Off	Off
May	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00
Jun	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00
Jul	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00
Aug	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00
Sep	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00	12:00 to 16:00
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 23. Schedule for summer cooling according to property design.

5. Results

5.1. Phase 1: Base Model (Flat 8) Overheating Analysis (15th July)

5.1.1. Current Climate

A range of DTS was conducted for the peak summer day (15 July) to analyze overheating conditions with reference to heatwave occurrences. When ODBT reached its highest level of 28.20 °C at 14:00 h, the OT began to rise despite providing mechanical cooling. The house retained a temperature between 26.51 °C and 31.34 °C for the whole day, and the temperature was at 30.17–31.34 °C for 2 h (12.00–14.00 h). This condition is dangerous for the wellbeing of the occupants because they were spending 20 h a day inside. Domestic dwelling should maintain a 21–25 °C habitable temperature as per CIBSE Guide A [23] and ASHARE-55 [22] during the summertime.

The primary factor identified for internal overheating was solar gains through exterior windows because they can directly penetrate through the external glazing, while the other factors, namely walls, ceilings, floors, partitions, and general lighting at night, were negligible. The solar gains in Flat 8 started to increase OT from 5.00–6.00 h in the morning by 3.04 kW until 18.00 h in the evening. Moreover, energy consumption for zone sensible cooling began at 6.00 h and reached its peak during mid-day, consuming 5.96–5.57 kW from 12.00 to 14.00 h.

5.1.2. 2050s Climate

- 50% medium-emission scenario

A 29 °C ODBT was added for the 2050s 50th percentile medium-emission scenario, shown in Figure 24, which is 1 °C higher than the current climate. The house remained between 27.74 °C and 31.16 °C for the whole day, and 30.13 °C and 1.16 °C OT were recorded for 2 h (10.00–12.00 h), similar to the current climate, but here, the flat experienced a larger frequency of 27.89–28.72 °C OT throughout the day, which was 1.3 °C lower for the 2022 climate.

- 90% high-emission scenario

A 30 °C ODBT was added for the 90th percentile (%) high-emission scenario in DB (2 °C higher than 2022). The overheating analysis for this scenario was similar to the 50% medium-emission scenario, with only 0.20–0.30 °C fluctuations. Therefore, in further study, the performance of PCMS was evaluated for a 90% high-emission scenario.

For a precise overheating assessment, OT will be analyzed for highly susceptible areas (living rooms and bedrooms) for both climates in further study because these rooms have massive glazing areas and a higher occupancy ratio.

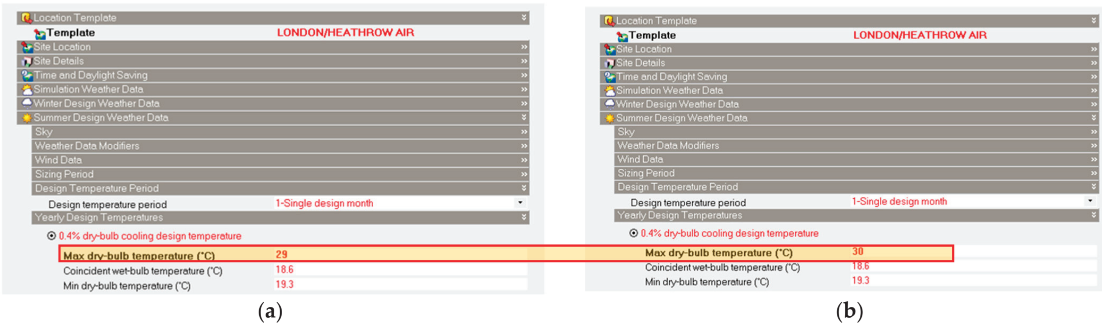


Figure 24. Outside dry bulb temperature for 2050s climate; (**a**) 50% medium-emission scenario, (**b**) 90% medium-emission scenario.

5.2. Phase 2: Overheating Analysis of the Living and Kitchen and Bedrooms (15 July)

5.2.1. Current Climate

Compared to the whole flat, the living room and kitchen had the highest internal heat gains due to massive window coverage in the southwest (WFR: 46; refer to Table 10), which was clearly reflected in the simulation results. A range of 28.66–29.89 °C of OT (1 °C higher than the whole flat's OT) was reported throughout the day because of solar gains through exterior windows. Similarly, Bedroom 1, also oriented in the southwest (WFR: 46%) with most coverage in the west, showed peak heat gains of 30.13 °C OT at 18:00 h, ranging from 28.77 °C to 30.13 °C all day long. While Bedroom 2, located in the southeast (WFR: 35%), experienced lower heat gains (27.66–29.81 °C all day) in comparison but higher according to CIBSE Guide A and ASHARE 55 (24–25 °C).

5.2.2. 2050s 90% High-Emission Scenario

Starting from 8.00 h and lasting until 16.00 h, the living room and kitchen experienced severe OT of 29.59–33.24 °C. Similarly, Bedrooms 1 and 2 suffered from a dangerous environment where OT ranged from 28.72 °C to 30.80 °C and 28.95 °C to 31.83 °C, respectively. The frequency of more than 30 °C of internal temperature was noticeably higher in the 2050s (a 90% higher scenario) compared to 2022.

5.3. Phase 2: Retrofit Model-Performance of PCMS

Since all the rooms reported severe temperatures of 28–33 °C for both climates, no single tool can mitigate overheating, but the combination of durable and effective PCMS may eliminate overheating. Methods of PCMS were applied, compared, and analyzed.

The following PCMS were employed in the living room, kitchen, and Bedroom 1 and 2 areas as per orientation and necessity:

1. Triple glazing installation.
2. Low g-value window coating.
3. 1 m overhangs.
4. Louvers.
5. Windowto-floor ratio (WFR): The ratio of glazing (windows, skylights, etc.) divided by the total floor area of a particular room. Ideal WFR should be adapted as per Approved Document O (refer to Tables 2 and 3) to limit solar gains for parts of buildings to accommodate thermal comfort in the summer.

Double-glazed windows were replaced by triple-glazed low-emissivity (LoE) 13 mm air-filled glazing with a U-value of 1.10 W/m^2.K. A solar control LoE coating was applied to the outermost plane of the window. High-reflective LoE transmittance shade (internal blinds) was also provided in the internal facade of the opening, as shown in Figure 25, which can be operated by occupants as per their comfort and needs.

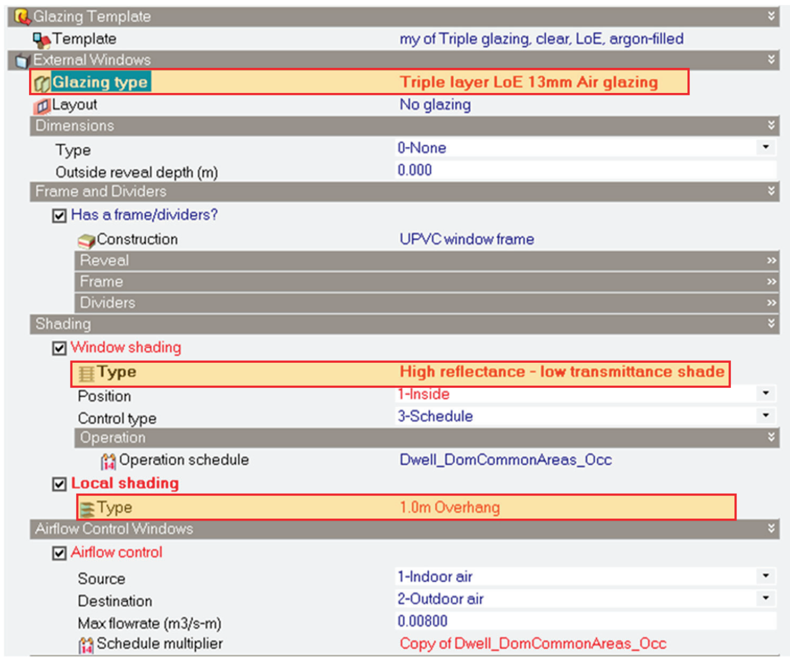


Figure 25. Modified opening template.

5.3.1. Current Climate: Performance of 1 to 4 PCMS

- Living room and kitchen:

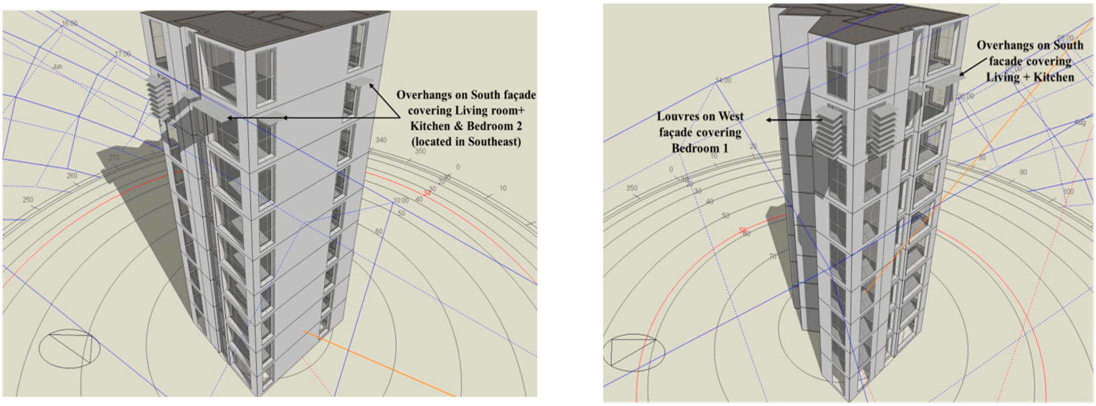
As the overhang shading was ideal for the south façade because of the high-angle sun, 1 m projected overhangs (refer to Figure 26 were provided on the glazing, which was covering the living room and kitchen in the southwest. After the adaptation of the above-mentioned PCMS, the thermal comfort in the living and kitchen areas was significantly improved, with the peak OT reduced by 1 °C from 29.89 °C to 28.67 °C at 10.00 h compared to the base model. However, the range of 27.00 °C to 28.67 °C OT was still not the habitable temperature threshold for the occupants, and other PCMS should be studied. The solar gains through exterior glazing were reduced by 96.5% (0.07 kW at 12:00 h in the retrofit model, which was 2 kW in the base model at 12:00 h).

- Bedroom 1:

Since Bedroom 1 was oriented in the west, 1 m externally projected louvres with an eight-blade configuration were provided, as shown in Figure 26b. The extreme OT was remarkably reduced by 1.4 °C, from 30.13 °C at 18:00 h in the base model to 28.74 °C in the retrofit model. One of the reasons for the thermal improvement was the massive reduction in solar gains from exterior windows.

- Bedroom 2:

The orientation of Bedroom 2 glazing was southeast, so 1 m of projected overhang was provided, which improved thermal comfort in the retrofit model by dropping 1 °C from the base model (from 29.81 °C to 28.84 °C at 10.00 h).



(**a**) (**b**)

Figure 26. Shading device implementation to Flat 8: (**a**) 1 m projected overhangs applied on southeast windows covering living room, kitchen and Bedroom 2, (**b**) louvers applied on west windows covering Bedroom 1.

5.3.2. 2050s 90% High-Emission Scenario: Performance of 1 to 4 PCMS

After applying 1 to 4 PCMS to the retrofit model under the 2050s 90% high climate scenario, the model showed a noteworthy 2–3 °C reduction in the internal rooms. The model was experiencing a 29.59–33.24 °C OT in the living room and the kitchen from 8:00 to 16:00 h, which was lowered approximately by 3 °C and dropped to 28–29 °C. Likewise, thermal comfort in Bedrooms 1 and 2 was improved by 2 °C.

To conclude, significant improvement was reported in the retrofit model containing 1-4 PCMS, which was operated solely through openings. Since the rooms did not achieve temperature thresholds as per CIBSE Guide A and ASHARE 55, other guaranteed overheating mitigation tools, such as the window-to-floor ratio (WFR), will be combined by adopting an acceptable WFR as per Table 11. The final OT obtained will be compared with the habitable temperature threshold (24–25 °C).

Table 11. Window size comparison for the Base model and the retrofit (Green) model.

Model Zones	Window Size (m) (Base Model)	Proposed Window Size (m) as per Acceptable WFR (Retrofit Model)	Floor Area (m^2)	Orientation	Window to Floor Ratio (WFR) in %	Acceptable WFR as per Part 'O'
Living room	2.5 × 3	2 × 1.50	29	SW	46%	22%
	2.5 × 1	1.5 × 1		SE		
Kitchen	2.5 × 1.33	2 × 1		SW		
Bedroom 1	2.5 × 1.50	2 × 1	16.23	SW	46%	25%
	2.5 × 1.50	2 × 1		NW		
Bedroom 2	2.5 × 1.50	2 × 1.30	17.46	SE	35%	27%
Bedroom 2 (Balcony)	2.5 × 1.15	2 × 1		NE		

- Window to Floor Ratio (WFR)

Modified sizes were provided for windows in the final retrofit model. Table 10 demonstrates proposed window sizes according to acceptable WFR, highlighted in green for the retrofit model. The final retrofit model is shown in Figure 27, where window sizes can be compared from the flats on different floors.

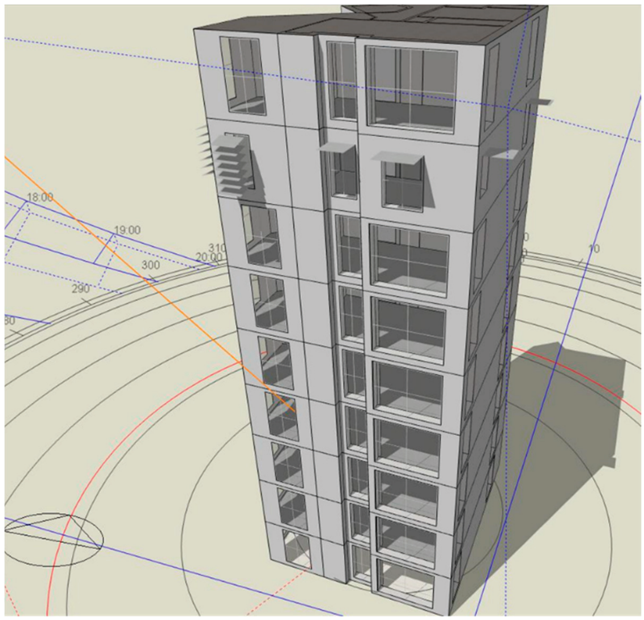


Figure 27. Final retrofit model (8th floor) after installing proposed windows sizes.

5.4. Final Retrofit Model Performance (Living, Kitchen and Bedrooms) on 15 July

5.4.1. Current Climate

The OT in the living room and kitchen was reduced by 0.7 °C from 28.72 °C to 28.0 °C, and daytime thermal comfort was improved after installing the proposed window sizes. Similarly, in Bedrooms 1 and 2, the thermal comfort was improved by OT reducing 1 °C throughout the day.

Table 12 highlights the comparison of temperature drops for all the rooms from the base model to the final retrofit model after applying all the mitigation measures for both climates. To conclude, OT was significantly reduced in all the rooms in the final retrofit model, with the living room and kitchen dropping 1.7 °C, Bedroom 1 dropping the most at 2.4 °C, and Bedroom 2 dropping 2 °C.

Table 12. Comparison of OT from the Base model to the retrofit model.

Operative Temperatures (OT) after Implementing PCMS: 15 July 2022						
	Base Model OT	**Retrofit Model OT after Implementing 1 to 4 PCMS**	**Drop in OT**	**OT after Applying Acceptable WFR**	**Drop in OT**	**Total Drop in OT**
Living room + Kitchen	28.2–29.9 °C	27.0–28.6 °C	1 °C	26.3–28.0 °C	0.7 °C	**1.7 °C**
Bedroom 1	27.7– 30.1 °C	26.8–28.7 °C	1.4 °C	26.2–27.8 °C	1 °C	**2.4 °C**
Bedroom 2	27.1–29.8 °C	26.7–28.2 °C	1 °C	26.2–27.9 °C	1 °C	**2 °C**

5.4.2. 2050s 90% High-Emission Scenario

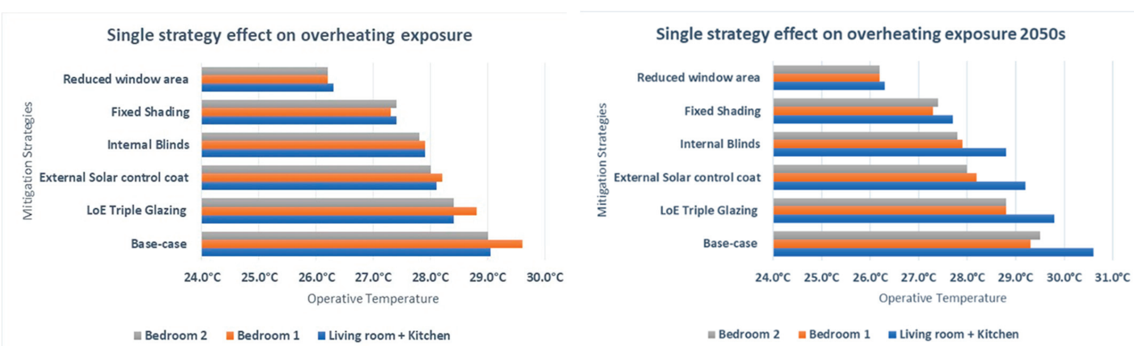
In the final retrofit model of 2050, the OT was further reduced by 1.6 °C in the living room and kitchen and by 1 °C and 1.7 °C in Bedrooms 1 and 2, respectively.

All the PCMS performed exceptionally well for 2050′s 90% high-emission scenario compared to the current climate since the OT dropped by 4.6 °C in total in the living room and kitchen, whereas it merely dropped by 1.7 °C in 2022, as compared in Table 13. Similarly, more degrees were dropped in Bedrooms 1 and 2 in 2050 compared to 2022. Therefore, it indicates that the set of PCMS will perform remarkably well in future climates to minimize internal heat gains.

Table 13. Comparison of overall reduction in OT in 2050 and current climate.

	Operative Temperatures (OT) after Implementing PCMS: 15 July 2050						2022
	Base Model OT	**Retrofit Model OT after Implementing 1 to 4 PCMS**	**Drop in OT**	**OT after Applying Acceptable WFR**	**Drop in OT**	**Total Drop in OT 2050**	**Total Drop in OT 2022**
Living room + Kitchen	27.4–33.24 °C	26.5–29.7 °C	3 °C	26.3–28.1 °C	1.6 °C	**4.6 °C**	**1.7 °C**
Bedroom 1	28.0–30.8 °C	26.7–28.9 °C	2 °C	26.3–28.0 °C	1 °C	**3 °C**	**2.4 °C**
Bedroom 2	27.1–31.8 °C	26.3–29.7 °C	2 °C	26.4–8.0 °C	1.7 °C	**3.7 °C**	**2 °C**

In terms of single PCMS performance, the window-to-floor ratio (WFR) attained the largest temperature fall, as depicted in Figure 28. In 2022, the living room and the kitchen experienced a 1 °C improvement, while in 2050, they improved by 1.6 °C. The second-best technique, LoE triple glazing, reduced temperatures by around 0.5 °C and 1 °C for the climates of 2022 and 2050, respectively. It also considerably increased the thermal comfort in Bedrooms 1 and 2. When combined, other methods like fixed shading, internal blinds, and sun control coating decreased temperatures by around 0.5–0.7 °C for 2022 and by 1–1.8 °C for 2050 in all rooms.



(**a**) (**b**)

Figure 28. Comparison of individual PCMS performance: (**a**) in current climate; (**b**) in 2050s climate.

5.5. Phase 2: Final Retrofit Model Performance (Flat 8) on 15th July

After applying 1 to 5 PCMS, the whole Block 8 (eighth floor flat) dropped 4 °C overall, ranging from 26.75 °C to 31.34 °C in the base model to falling under 26.24 °C to 27.67 °C in the final retrofit model on 15 July. Moreover, solar gains through exterior glazing were reduced by 85.5% (now 0.55 kW at 10:00 h, which was 3.79 kW in the base model). Similarly, energy consumed by zone sensible cooling was decreased by 52% (in the final retrofit model, 2.85 kW at mid-day compared to 5.96 kW in the base model).

5.6. Final Retrofit Model: Performance of Flat 8 throughout the Summer (May to September)

Overheating was experienced throughout the summer, not only during the summer peak month (July). The OT exceeded 25 °C to 28 °C, started in June, and continued like that until September.

The simulation results showed that the OT was ranging from 22 °C to 28 °C in the base model from May to September, remarkably decreasing by 2 °C and falling to 20 °C to 25.9 °C in the final retrofit model because of the implementation of PCMS. Therefore, it can be identified that the flat achieved OT below 24 °C throughout the summer (except in July and August, where OT ranged between 25 °C and 26 °C). According to CIBSE Guide A, it did not attain the ASHARE 55 comfort temperature threshold (20–24 °C) as shown in Figure 29. Therefore, it can be validated that after implementing 1–5 PCMS, the final retrofit model achieved standardized internal thermal comfort in the summer according to the UK overheating benchmark (CIBSE Guide A).

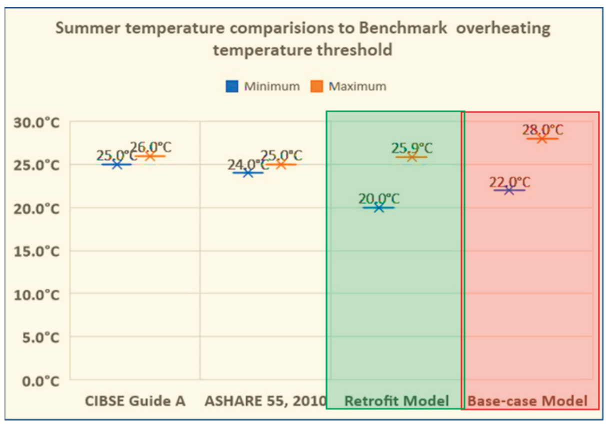


Figure 29. Comparison of Base and Retrofit Temperature thresholds to benchmark standards.

6. Discussion

This study contributed major improvements to the knowledge regarding overheating exposure in contemporary British flats and their PCMS. The necessity of tackling the principal drivers of overheating is one of the key findings that construction professionals and policymakers may benefit from. This entails using proper window designs that consider aspects such as glazing type, window-to-floor ratio (WFR), low g-value glass, and shading devices to reduce internal heat gains. Notably, the use of retrofit window solutions resulted in a 52% decrease in energy usage for zone sensitive cooling, resulting in considerable cost savings and lower CO_2 emissions.

Given the scarcity of the literature on overheating issues in modern high-EPC-rated flats and their PCMS, the findings of this study clearly delivered critical knowledge of overheating contributors with a practical examination that improves internal thermal comfort by approximately 66% during summer-inclusive heatwave occurrences in the present. All PCMS excelled in terms of future climatic probability, improving internal thermal comfort by 92%.

The recommendations from the research and probable future research areas that would be worthwhile to study could be summed up as follows:

- Since living rooms and bedrooms still have a 26–28 °C OT despite the adaptation of PCMS for 2050's 90% high weather scenario, a table/ceiling fan operating for 2–3 h does not consume huge amounts of electricity compared to air conditioning but aids in cool air circulation by reducing 2 °C to 3 °C of OT, which should be employed in the near future.

- Strategies that require no occupant involvement can facilitate more consistency (fixed objects, automatic controls) for future scenarios.
- The study will be further expanded by assessing indoor air quality against outdoor air pollutants like NO_2 and PM_5, the concentrations of which are higher in urban surroundings in the context of London.
- To gather a factual assessment of overheating episodes in terms of occupant comfort and responsive behaviour, a survey should be conducted among the occupants living in overheating-prone regions. It may provide in-depth knowledge of sociological aspects that can be combined with secondary literature findings and simulation results.
- The current study encompasses overheating mitigation strategies through window design and technologies. A detailed DTS can be performed to reduce energy consumption and CO_2.

Limitations

Although night purge ventilation is an excellent measure to let fresh, cold air in, the outside temperature should be lower than inside.

There were a few constraints in the DB software that restricted the retrofit model from obtaining the temperature threshold of ASHARE 55.

- External shutters were one of the best PCMS; similarly, solar re-elective external paint was an option on walls and roofs (refer to Figure 12). DB did not facilitate such applications. Moreover, types of windows (side-hung, top-hung, sliding, casement windows, etc.) were not included in the DB, in which retrofitting fixed windows (discussed in Section 2.4) to side-hung windows would have assisted in improving thermal comfort by proposing 2 h of night purge ventilation during extreme summer months. These solutions may have helped the author achieve the temperature threshold of ASHARE 55 (24–25 °C) for the final retrofit model.
- Results can provide estimated knowledge of the performance of PCMS. For example, to attain maximum benefit from reducing internal heat gains, overhangs should be provided to cut down on solar radiation on the south façade, as the sun angle is significantly high. But, in DB, shading devices can be applied according to the spaces (for example, a living room, a bedroom, etc.), not the orientation, which limits the potential for accuracy.

7. Conclusions

The background study incorporated overheating issues during the summer in UK housing stock due to climate change. Particularly apartments and mid-terraced homes are highly susceptible to overheating, with the southeast and London identified as overheating-prone regions. Modern apartments with excellent EPC ratings are overlooked by researchers in terms of overheating and adaptation tools, while similar literature was discovered in large amounts for older mid-terraced, detached, and semi-detached houses. Overheating events have expanded in modern apartments as a result of increased airtightness in housing as per the new UK Building Regulations.

To address heatwaves, this study primarily assessed overheating and adaptation strategies during peak summer months and heatwave occurrence months for susceptible areas (living areas and bedrooms) along with the whole summer (May–September) against CIBSE Guide A and ASHARE 55. A flat at Holland Park Avenue W11 was analyzed as a case study to understand the building components and HVAC systems that fulfilled Steps 1 and 2 as per Figure 13. To accomplish Phase 1 (Steps 3 and 4), DTM was developed as a base case model in DB to perform overheating analysis for 2022 and 2050. OT was found to be 5 °C higher in Flat 8 compared to CIBSE (25–26 °C) in 2022 and 6 °C in the 2050 climate. Since the flat was occupied for 20 to 22 h a day by an elderly couple and a single parent, this condition was threatening to the occupants. After initiating Phase 2 (Step 5), since the flat had 46% of the glazing area in living areas and Bedroom 1 and 35% in Bedroom 2, OT was 1–2 °C greater in rooms compared to the other areas of the flat. Solar gains through windows were the primary responsible source, so the authors adopted a window design approach to minimize overheating issues. The following PCMS were simulated in DB (Step 6):

1. Triple glazing installation.
2. Low g-value window coating.
3. 1m overhangs.
4. Louvers.
5. Window to floor ratio (WFR).

After the implementation of 1 to 4 PCMS, solar gains through windows were remarkably reduced by 96.5%, but relatively high OT (27 °C to 28.6 °C) was still reported in all rooms. Therefore, the fifth PCMS was applied by incorporating modified, smaller-sized windows (refer to Table 10). As a result, the window to floor ratio outperformed all the other PCMS, followed by LoE triple glazing. However, the OT for the final retrofit model ranged from 26.2 °C to 28.0 °C on 15th July, but it still lacked the ability to achieve habitable OT as per CIBSE (25–26 °C) or ASHARE 55 (24–25 °C).

The improvement in indoor environment of the final retrofit model was remarkable after employing all PCMS compared to the base model, as it dropped overall from 1.7 °C to 2.4 °C in the 2022 climate and from 3.0 °C to 4.6 °C in 2050 in all rooms.

A major reason for high OT despite applying PCMS was the selection of the peak summer month (15 July) to address heatwaves. The other reason was the high-risk overheating location (London). Simulation results proved the hypothesis that London is the most susceptible region for overheating in the UK due to climate change. The final retrofit model achieved an average of 20–25.9 °C OT as per CIBSE Guide A for all summer months.

Reduced window area and LoE triple glazing were identified as the most excellent PCMS. The performance of all strategies was 60% better in the 2050s climate compared to the 2022s climate, which also decreased energy consumption for both climates by 52%, resulting in lower CO_2 emissions. Thus, positive simulation results for 1 to 5 PCMS completed Phase 2 by accomplishing the aim of the study. If these PCMS were adopted in the current flats (50% of total housing stock) of London of southeast England and (23% of total housing stock), it would guarantee an improvement in thermal comfort. It is also applicable to any type of housing stock experiencing overheating issues in the UK.

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Abbreviations

ACH	Air Changes per Hour
ASHARE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCC	Climate Change Committee
CCRA3	UK's 3rd Climate Change Risk Assessment
CIBSE	Chartered Institution of Building Services Engineers
DB	DesignBuilder
DCLG	Department for Communities and Local Government SAP- Standard Assessment Procedure
DEFRA	Department for Environment, Food & Rural Affairs
DLUHC	Department for Levelling Up, Housing and Communities
Dynamic thermal modelling (DTM)	A process of building modelling that forecasts the internal conditions and energy requirements of a building at short time intervals utilizing weather data and building attributes.
Dynamic thermal simulation (DTS)	employs a 3D model of a building to simulate its thermal performance hour by hour.
EPC	Energy Performance Certificate
EER	Energy Efficiency Ratio
EHS	English Housing Survey
GHA	Good Homes Alliance
g-value	a measure of solar heat (infrared radiation) permitted in through a particular part of a building.
HOC	House of Commons
Low-E (LoE)	An extent of emissivity, the attributes of a material to radiate thermal energy. Low-E glazing is a thin, practically colorless metallic coating that absorbs a short-wave heat radiation while still allowing most of the natural light to pass freely through the window.
OT	Operative Temperature
PCMS	Passive cooling mitigation strategy
TM59	Design methodology for the assessment of overheating risk in homes (2017)
TM52	The limits of thermal comfort: Avoiding overheating in European buildings
UKGBC	United Kingdom Green Building Council
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UHIE	Urban Heat Island Effect

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buildings

Article

Multi-Objective Optimization and Sensitivity Analysis of Building Envelopes and Solar Panels Using Intelligent Algorithms

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Abstract: The global drive for sustainable development and carbon neutrality has heightened the need for energy-efficient buildings. Photovoltaic buildings, which aim to reduce energy consumption and carbon emissions, play a crucial role in this effort. However, the potential of the building envelope for electricity generation is often underutilized. This study introduces an efficient hybrid method that integrates Particle Swarm Optimization (PSO), Support Vector Machine (SVM), Non-dominated Sorting Genetic Algorithm II (NSGA-II), and the weighted Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method. This integrated approach was used to optimize the external envelope structure and photovoltaic components, leading to significant reductions: overall energy consumption decreased by 41% (from 105 kWh/m^2 to 63 kWh/m^2), carbon emissions by 34% (from 13,307 tCO_2eq to 8817 tCO_2eq), and retrofit and operating costs by 20% (from CNY 13.12 million to CNY 10.53 million) over a 25-year period. Sensitivity analysis further revealed that the window-to-wall ratio and photovoltaic windows play crucial roles in these outcomes, highlighting their potential to enhance building energy performance. These results confirm the feasibility of achieving substantial energy savings and emission reductions through this optimized design approach.

Keywords: multi-objective optimization; building energy consumption; photovoltaic modules; sensitivity analysis

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1. Introduction

1.1. Background

Energy conservation and carbon reduction have become a global consensus, with countries taking significant actions to combat climate change and reduce emissions. This trend is driven by international agreements like the Paris Agreement, which require nations to limit global warming and reduce greenhouse gas emissions. Policies such as the European Union's Green Deal, China's carbon-neutrality goal, and the United States' Clean Energy Plan promote renewable energy, improve efficiency standards, and reduce fossil fuel use. Additionally, technological innovations in renewable energy, smart grids, energy storage, and efficiency improvements have made these goals more feasible and economical, significantly reducing carbon emissions. About 30% of the world's energy consumption and 37% of CO_2 emissions are attributed to buildings, making them significant contributors to global warming [1]. According to data from the China Building Energy Consumption Research Report (2020) [2], in 2018, energy consumption per unit area of public buildings in China exceeded that of urban and rural buildings by 58% and 66%, respectively, highlighting the substantial potential for consumption and emission reduction in public buildings.

1.2. The Key Factor Influencing Energy Consumption

Optimizing key factors influencing energy consumption in public buildings is crucial for achieving reductions. The building envelope structure, responsible for over 70% of a building's life cycle energy consumption, mainly due to heat loss, sees air conditioning and heating systems as the main contributors [3,4]. Scholars have addressed building energy consumption by incorporating thermal insulation materials. Compared with no insulation material, this approach can save 21.52% of heat load, 3.78% of total load, and 25.34% of total cost per unit area [5]. Optimal phase-change material thickness can achieve energy savings of up to 41.61% [6]. The application of infrared reflective wall paint can reduce heat losses by 18% to 22% [7]. Compared to regular glass, thermochromic windows have the potential to save 5% to 84.7% in heating and cooling energy demand [8,9]. Compared to ordinary insulating glass (OIG), the energy-saving rates of triple silver low-e insulating glass (TSIG) range from 8.82% to 63.65% in five climate zones [10].

1.3. Application of Intelligent Algorithms in Building Energy Efficiency, as Well as Multi-Objective Optimization

In addition, during the design phase, numerical simulations can adjust and optimize variables to reduce energy consumption [11]. However, when there are many design factors, or when the building model is large, the simulation calculations can be time-consuming. Therefore, scholars combine a small number of simulations with algorithms such as Artificial Neural Networks (ANN), Random Forest (RF), and Bayesian Optimization XGBoost (BO-XGBoost) to establish datasets for optimizing design parameters and energy-consumption targets [12–15]. Integrating machine-learning optimization methods not only reduces simulation time but also predicts and analyzes building energy consumption [16]. With the development of multi-objective optimization techniques, optimization objectives involve building materials and operational phase carbon emissions, thermal comfort, and other factors. Chen et al. optimized the energy consumption, illumination, and thermal comfort of the atrium in a teaching building using NSGA-II and machine-learning methods [17]. Wang et al. used multi-objective optimization to improve the design of passive houses in Shandong Province, achieving overall improvements of 25.5% in annual energy demand and 21.6% in summer discomfort hours [18].

1.4. Application of Photovoltaic Technology in Building Energy Efficiency

Once the building envelope structures reach maximum optimization, scholars employ photovoltaic (PV) components to further reduce energy consumption. These components are integrated into architectural elements such as windows, curtain walls, and sunshades, utilizing the building's exterior surfaces for photovoltaic power generation, thus supplying electricity to the building while mitigating solar radiation. Li et al. investigated bifacial photovoltaic sunshades (BIPV) in Shenzhen and found they have higher electrical conversion efficiency than traditional monofacial ones [19]. Risa Ito et al. studied a self-regulating photovoltaic louvre window system, demonstrating that an optimized angle of photovoltaic louvres significantly reduces a building's heating and cooling loads [20]. Research by Alba Ramos et al. demonstrates that Btransparent BIPV reduced energy demand by 6.9% and improved energy balance by 21%, while opaque BIPV improved energy balance by 38.3% [21]. Gamal explored the effectiveness of implementing BIPV systems in Dubai, finding that high-rise office buildings with BIPV systems experience a reduction in heating and cooling energy consumption by 13.2% to 32.8% [22]. Luo et al. achieved near-zero energy consumption by considering factors such as energy consumption, thermal comfort, carbon emissions, and economy. Their model optimized the performance parameters of the building envelope [23]. Goia et al. optimized the design of exterior PV shading devices for Nordic office buildings, improving energy efficiency and daylight autonomy by adjusting the number of louvers, tilt angle, and position through multi-objective optimization [24]. Allouhi et al. employed genetic algorithms and TOPSIS for the economic and environmental optimization of photovoltaic capacity in commercial buildings in Morocco [25]. Katsaprakakis and Zidianakis demonstrate that a hybrid system with solar collectors, thermal storage, and a biomass heater can cover 100% of a school building's annual heating load in Crete, with solar contributing over 45% and a production cost of EUR 0.15/kWhth [26]. These studies demonstrate that multi-objective optimization plays a crucial role in enhancing the performance of BIPV systems and achieving economic and environmental goals.

In summary, current research primarily focuses on optimizing building envelope structures or applying photovoltaic components to areas such as roofs and sunshades. However, these studies have not fully harnessed the electricity-generating potential of building envelope structures nor considered the combined impact of photovoltaic windows and panels on building energy consumption, overlooking the mutual influence between photovoltaic components and envelope structures.

1.5. Research Objectives and Main Contributions

Therefore, this paper proposes a multi-objective optimization method for a full building envelope photovoltaic system, employing an optimization approach based on PSO-SVM-NSGA-II. The optimization aims to minimize building costs, energy consumption, and carbon emissions while maximizing renewable energy generation. Additionally, the study utilizes the Sobol method for global sensitivity analysis of the envelope and photovoltaic component parameters. This analysis provides a detailed understanding of how optimization variables affect the optimization objectives. Variables with high sensitivity indices are further analyzed locally, offering valuable insights for the optimization of public building renovations. The proposed multi-objective optimization method has the potential to guide energy-efficient renovations in public buildings, assisting decision-makers in balancing costs, energy consumption, and carbon emissions to achieve optimal building efficiency. Furthermore, by employing global sensitivity analysis and local analysis, our research offers key parameters and effective strategies for optimizing the design of building envelope structures and photovoltaic components, ultimately enhancing the performance of photovoltaic systems across diverse building environments.

The subsequent structure of the paper is as follows: The second section explains the theoretical methods, the third section describes the case study, the fourth section presents the research results and analysis, the fifth section discusses the findings, and the sixth section concludes the study.

2. Theoretical Approach

2.1. Research Framework

In practical problems, there are often multiple conflicting objectives or requirements, and single-objective optimization cannot meet all these demands. Multi-objective optimization not only considers the optimal solution for a single objective but also finds a balance between multiple objectives. This allows decision-makers to weigh different objectives according to specific situations. This paper uses the window-to-wall ratio, photovoltaic components, insulation materials and thickness, and air conditioning design temperature as optimization variables, with comprehensive building energy consumption, building materials and operational phase carbon emissions, and retrofit as objective functions. Based on the PSO-SVM-NSGA-II multi-objective optimization algorithm, the parameters of the envelope and photovoltaic components are optimized. The Pareto solutions, which are the sets of optimal variable values, are obtained, and the entropy-weighted TOPSIS method is used to select the optimal parameter values that minimize the objective functions.

The research framework is shown in Figure 1. CVBEC stands for combined building energy consumption, BMOPCE stands for building materials and operational phase carbon emissions, and ROC stands for retrofit and operating costs where the objective function is first established, and the objective function formulas are established for the combined value of building energy consumption, building materials and operational phase carbon emissions, and retrofit and operating costs, and the envelope and PV module variables are selected as the optimization variables. Then use SketchUp to create a 3D model of the building and import it into OpenStudio to define the thermal zone and PV settings. Subsequently, EnergyPlus is employed to incorporate the building's fundamental operational data. To expedite the simulation process after establishing the input parameters, the robust parametric tool JEPlus is utilized to perform batch simulations of EnergyPlus input files. Using Latin Hypercube Sampling (LHS), 300 samples of optimized variables are generated. The resulting simulation data—comprising building energy consumption and renewable energy generation—serve as the dataset for the Particle Swarm Optimization-Support Vector Machine (PSO-SVM) algorithm.

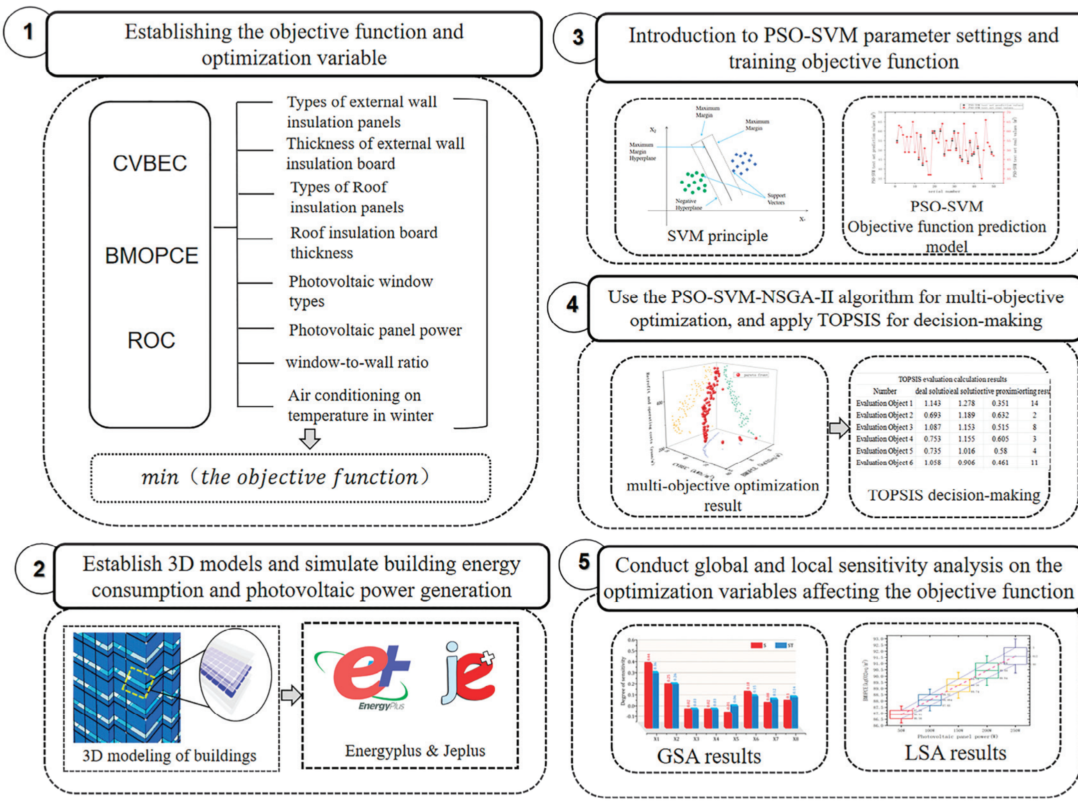

Figure 1. Research framework diagram.

The building carbon emission and building retrofit and operating costs were calculated according to the objective function formula in Section 1.3 and saved as a dataset together with the combined value of building energy consumption. After that, the dataset is imported into Matlab R2022a for PSO-SVM algorithm training and testing, and the obtained prediction model is verified with the original building energy consumption data, to verify that the available PSO-SVM is able to make fast and accurate predictions for the three objective functions. Finally, the verified PSO-SVM is used as the objective function of the multi-objective optimization problem, and the NSGA-II optimization algorithm is used to calculate the population crowding degree, and the optimal solution is obtained after continuous crossover and mutation.

Finally, the Pareto optimal solution is saved, reasonable weights are assigned to each objective according to the building design requirements, and finally the TOPSIS method is used to rank the optimal solutions based on the positive and negative ideal solution distances, and the optimal solutions are decided based on the ranking of the solutions.

2.1.1. Multi-Objective Optimization Approach

The current multi-objective optimization tools mainly fall into two categories: built-in optimization tools within simulation software and intelligent algorithms. Each has its advantages and disadvantages. Energy simulation software with built-in optimization tools, such as Transient System Simulation Tool (TRNSYS) with its optimization tool Generic Optimization (GenOpt), can perform parameter optimization and multi-objective optimization [27]. Hybrid Optimization Model for Electric Renewables (HOMER) comes with its optimization engine, supporting economic optimization, reliability analysis, and more [28]. While these software tools are relatively user-friendly and eliminate the need for coding, they require traversing all simulation processes, significantly increasing the simulation run time.

On the other hand, intelligent algorithms, such as Genetic Algorithm (GA), Multi-Objective Particle Swarm Optimization (MOPSO), and Grey Wolf Optimization (GWO) Algorithm, coupled with Artificial Neural Networks (ANN), Random Forest (RF), and Bayesian Optimization XGBoost (BO-XGBoost), utilize predictive models to find the optimal solution, thereby reducing the amount of simulation needed and speeding up the optimization process. These algorithms have distinct characteristics: GA, in global search, often requires a large number of iterations to converge to the optimal solution, leading to long computation times [29]. MOPSO is prone to getting trapped in local optima and exhibits unstable convergence speed [30]. GWO, using a single intelligent algorithm, may lack population diversity, leading to incomplete coverage of the search space and affecting global search capability [31].

The Particle Swarm Optimization-Support Vector Machine-Non-dominated Sorting Genetic Algorithm II (PSO-SVM-NSGA-II) combination leverages Particle Swarm Optimization (PSO) for global search capability, Support Vector Machine (SVM) for local search and classification, and non-dominated Sorting Genetic Algorithm II (NSGA-II) for multi-objective optimization. This combination enhances search efficiency and optimization capability. This method can effectively reduce computation time, especially in large-scale and complex problems, making it a standout choice. Therefore, this study selects PSO-SVM-NSGA-II as the algorithm for multi-objective optimization.

2.1.2. NSGA-II

NSGA-II (Non-dominated Sorting Genetic Algorithm II) is a multi-objective optimization algorithm that uses a genetic algorithm to find a set of Pareto optimal solutions for a particular problem [32–34]. This algorithm employs non-dominated sorting and crowding distance sorting methods to maintain diversity in the population and uses crossover and mutation operations to generate the next generation of individuals, ultimately producing a set of Pareto optimal solutions.

Viewing NSGA-II from the perspective of natural selection and ecosystems: in an ecosystem, various species occupy different niches and coexist through competition and cooperation. NSGA-II simulates this niche allocation mechanism by using non-dominated sorting and crowding distance calculation to ensure diversity and even distribution of solutions within the population. Natural selection is a core mechanism in ecosystems, where more adaptable species are selected to reproduce. NSGA-II employs a tournament-selection method, choosing stronger individuals for reproduction based on non-dominated sorting and crowding distance-sorting results. In biological evolution, genetic recombination and mutation are crucial mechanisms for species to adapt to environmental changes. NSGA-II simulates genetic recombination and mutation through crossover and mutation operations, generating new individuals and increasing population diversity. Through these steps, the NSGA-II algorithm effectively searches for solutions to multi-objective optimization problems, identifying a set of Pareto optimal solutions. This provides decision-makers with a range of options to achieve the best trade-off among different objectives.

2.1.3. PSO-SVM

Since it was first proposed by Vapnik and Chervonenkis in 1995, SVM algorithms have been widely used in various disciplines [35]. SVM is a powerful supervised machine-learning method that introduces a kernel function that can deal with nonlinear classification and regression problems and higher dimensional data and has better robustness in the case of large sample data spacing [36]. Particle Swarm Algorithm (PSO) can find the optimal hyperparameters for SVM by randomly generating a swarm of particles, where each particle represents a set of kernel function parameters and penalty parameters of the SVM model. The training set accuracy of these particles is compared, and the parameter values are optimally selected. The method of introducing a particle swarm can improve the SVM model's precision and accuracy [37]. This study mainly utilizes the PSO-SVM method for the prediction of each target value, due to the characteristics of the principle of PSO-SVM itself, its requirements for the number of data samples are not high, only a small amount of data can achieve good results, reducing the time of simulation operations.

2.2. Objective Functions Construct

2.2.1. Comprehensive Value of Building Energy Consumption

The "GB/T 51350-2019 Technical Standard for Near-Zero Energy Buildings" of China recommends that the Comprehensive Value of Building Energy Consumption (CVBEC) be used as the measurement indicator for building energy consumption. This indicator reflects not only the energy consumption of equipment during the building's usage period but also the impact of renewable energy generation on operational energy consumption [38]. Therefore, the CVBEC from this standard is selected as the metric for measuring energy consumption in this paper. The scope of the energy-consumption measurement defined in this paper includes heating energy consumption, lighting energy consumption, and the capacity of the building's renewable energy system. The comprehensive value of building energy consumption is defined as the difference between the building's total energy consumption and renewable energy generation. The CVBEC is calculated using Formulas (1)–(4).

$$\text{CVBEC} = E_E - \frac{\sum E_r \times f_i}{A} \tag{1}$$

$$E_E = \frac{E_h \times f_i + +E_i \times f_i + E_e \times f_i + E_c \times f_i}{A} \tag{2}$$

$$E_c = \frac{Q_C}{COP_c} \tag{3}$$

$$E_h = \frac{Q_h}{COP_h} \tag{4}$$

where CVBEC is the combined value of building energy consumption; E_E stands for the energy consumption of building lighting, heating, and cooling, while E_r represents the annual renewable energy-generation capacity of the building; A is the building area; f_i is the energy-conversion coefficient; E_h is the annual energy consumption of heating system; E_i is the annual energy consumption of the lighting system; COP_c is the comprehensive efficiency of the cooling system; COP_h is the combined efficiency of the heating system.

2.2.2. Building Materials and Operational Phase Carbon Emissions

The operation process is accounted for as the largest proportion of the building's lifecycle, averaging 67%, followed by the production phase, which averages 31% [39]. The carbon emissions from the dismantling process are relatively low, averaging 2%. Therefore, only the carbon emissions from the production phase of insulation board materials and PV modules, as well as the carbon emissions from the building's operation phase, are calculated as the optimization objectives to construct the carbon emission objective function. Referring to relevant standards and literature, the carbon emissions of building materials and the operation phase are shown in Equations (5) and (6):

$$C_{sc} = \left(\sum_{i=1}^{n} M_i EF_i\right) \quad (5)$$

$$C_{yx,e} = \left(\sum_{i=1}^{n} EY_{yx,i} \times EY_{e,i} - \sum_{i=1}^{n} ERY_{yx,j} \times EY_{e,i}\right) \times L_b \quad (6)$$

C_{sc} is the carbon emission ($kgCO_2eq$), the M_i is the consumption of the first major building material, and EF_i is the carbon emission factor of the first major building material ($kgCO_2eq$/unit of building material used). The carbon emission in the operation stage mainly involves the carbon emission from energy consumption. $C_{yx,e}$ is the carbon emission in the operation stage ($kgCO_2eq$), and $EY_{yx,i}$ is the annual consumption of Energy Type i (kg/year or kWh/year or J/year) during the operation phase. $EY_{e,i}$ is the carbon-emission factor of Energy Class i. The carbon-emission factor for electricity, derived from the average carbon emission factor of the national grid, is 0.5839 [40]. Additionally, the annual electricity generation of Class j renewable energy $ERY_{yx,j}$ in the operation stage, along with the lifetime of the PV module L_b, further affects these emissions.

2.2.3. Retrofit and Operating Costs

The process of building retrofitting incurs retrofitting costs by improving the performance of the envelope and laying technologies such as photovoltaics, and the high cost of building retrofitting affects the implementability of the program, so the retrofitting cost is used as one of the objective functions. The cost-calculation method of the retrofit program is shown in Equations (7)–(9):

$$RC = C_{con} + \sum_{n=1}^{25} \left(C_{op}\right)_k \times (i+1)^{-k} \quad (7)$$

$$C_{con} = (A_l \times d_l \times P_{l,i}) + \left(A_r \times d_r \times P_{r,j}\right) + \left(A_w \times P_{pv,w}\right) + \left(A_{pv,n} \times P_{pv,n}\right) \quad (8)$$

$$\left(C_{op}\right)_k = EC_y \times P \times (1+e)^k \quad (9)$$

where RC represents renovation costs, encompassing external wall insulation costs, roof insulation costs, and photovoltaic component costs. These costs include material expenses, labor costs, and transportation fees. C_{con} is the cost of building materials, while the A_l, A_r, and A_w denote the areas of external walls, roofs, and windows respectively, and $A_{pv,n}$ denotes the laying area of different PV modules, all in m^2. d_l and d_r denote the thickness of the insulation layer of the roof and the external wall, respectively, and the unit is m. The thickness of the insulation layer of the roof and the external wall, respectively, is $P_{l,i}$, and $P_{r,j}$, and $P_{pv,n}$ denote the unit price of insulation for different exterior walls, roofs, PV exterior windows, and PV modules, respectively, in units of yuan/m^2, yuan/m^2, yuan/block, and yuan/block, respectively. $\left(C_{op}\right)_k$ is the 1st-year operating cost, EC_y is the energy consumption of the air conditioner in 1 year, P is the unit price of electricity, e is the growth rate of energy cost, i is the real interest rate, $i = (1+i_k)/(1+f)^{-1}$, and i_k is the nominal interest rate for the k-th year.

2.2.4. Multi-Objective Decision-Making Methods

Multi-objective optimization methods generate multiple solutions, requiring decision-making methods to select the most optimal solution among them. TOPSIS is used to comprehensively consider multiple decision criteria, rank alternative solutions by comparing their similarity with ideal and negative ideal solutions, and obtain the unique optimal solution. Therefore, this article uses TOPSIS as the decision method. Its basic principles include the following steps: constructing a decision matrix, normalizing, determining weights, calculating positive and negative ideal solutions, calculating similarity, and ranking. Using the TOPSIS method involves assigning weights and ranking optimization objectives. The specific steps are as follows: first, normalize and reverse the performance indicators based on their positive and negative directions, and then assign a weight coefficient of 0–1 to the objective function according to the characteristics and actual needs of the case [41].

2.2.5. Sobol Sensitivity-Analysis Method

The objective function in this paper is a complex nonlinear model, which is more applicable using the Sobol method, which determines the sensitivity of a mathematical model by determining how much the input variables affect the output variables through the principle of variance. In this paper, the Sobol analysis selects a first-order index and a total-order index [42,43].

The formula for the Sobol sensitivity index:

First-order sensitivity index

$$S_i = \frac{V_i}{V} \tag{10}$$

Total-order sensitivity index

$$S_{Ti} = \frac{1}{V}\left(V_i + \sum_{j \neq i}^{n} V_{ij} + \cdots + V_{1,2,\cdots,n.}\right) \tag{11}$$

where first-order sensitivity index S_i represents the contribution of the change in the parameter X_i to the change in the variance of the whole model, which is used to quantitatively describe the parameters. S_{Ti} is the sum of the sensitivity indices of each order.

3. Case Analysis

3.1. Parameter Settings for Building Simulation

3.1.1. Case-Building Prototypes

The Ordos Maternal and Child Health Hospital in Ordos City, Inner Mongolia Autonomous Region, is selected as the simulation object, with a building area of 10,713 m^2 and a floor height of 51 m. Ordos City is located in the severe cold climate zone C. The hospital is a combined outpatient and inpatient building, with outpatient clinics and medical technology rooms on Floors 1–6, and wards on Floors 7–12. Based on research findings, building design data and energy-consumption information were obtained, including building-energy consumption and equipment operation schedules. The building is heated in the winter by multi-unit air conditioners. The original building’s exterior walls consist of 250 mm-thick hollow block walls and 70 mm exterior phenolic foam boards, with an exterior wall-heat transfer coefficient of 0.46. The roof is made of reinforced concrete roof panels, with a 12 mm cement mortar, 100 mm phenolic foam board, and 6 mm waterproof material, with a roof heat-transfer coefficient of 0.46. The external windows feature broken bridge aluminum alloy window frames and insulating glass 6+12A+6, with a heat transfer coefficient $\leq$ 2.9. According to relevant regulations for hospital building design and research, the building simulation is configured with the foundation settings as shown in Table 1.

Table 1. Basic settings.

Parameters	Value
Density of personnel	8 m^2/person
Number of times ventilated	2/h
Lighting power	8 W/m^2
Heat dissipation by personnel	134 W/person

3.1.2. Energy-Plus Modeling

Create a 3D model of the building using SketchUp2017 software, define the thermal zones, and integrate PV modules using OpenStudio. Utilize EnergyPlus to simulate the building's energy consumption and PV capacity characteristics, adhering to the guidelines outlined in the "Energy Saving Design Standards for Public Buildings" (GB50189) of China [44]. The optimization variables are selected as shown in Table 2. Detailed parameters for monocrystalline silicon PV panels were configured in EnergyPlus using Photovoltaic Performance: Equivalent One-Diode. Parameters for CdTe PV windows were set using the Sandia performance model to predict PV power generation, with a photovoltaic conversion efficiency of 18% for the photovoltaic windows and 19% for the PV panels. According to the Energy-Saving Design Standard for Public Buildings (GB50189-2015) of China, the optimization variables are defined as presented in Table 3. The variation in the heat-transfer coefficient among different types of photovoltaic windows depends on the thickness of the glass, where a higher heat-transfer coefficient corresponds to thicker glass. The PV installation covers 90% of the exterior wall and roof area. Through the research, six types of translucent photovoltaic glass and six types of photovoltaic panels commonly used in the market are selected, and combined with the supplier's offer and product description, the information of photovoltaic simulation is obtained specifically as shown in Tables 2 and 4. Figure 2 is a schematic diagram of a photovoltaic window. The semi-transparent cadmium telluride photovoltaic window consists of amorphous silicon thin-film cells made of cadmium telluride material, glass, and a junction box. The building simulation IDF file includes the envelope structure details, operational conditions, and PV module specifications, configured and accessed via JEPlus—a parametric simulation software built upon EnergyPlus. JEPlus enables robust parameterization of optimization variables, allowing for the generation of 300 simulation datasets by utilizing Latin Hypercube Sampling (LHS) methods to sample the optimization variables. These datasets serve as inputs for the PSO-SVM prediction model.

Table 2. Optimization variables.

Optimization Variables	Range of Values
Types of external wall insulation panels	1–4 (see Tables 2 and 3)
Thickness of external wall insulation board	0.07; 0.08; 0.09; 0.1; 0.11; 0.12; 0.13; 0.4; 0.15
Types of roof insulation panels	1–4 (see Tables 2 and 3)
Roof insulation board thickness	0.07; 0.08; 0.09; 0.1; 0.11; 0.12; 0.13; 0.4; 0.15
Photovoltaic window types	1–6 (see Tables 2 and 3)
Photovoltaic panel power	50; 100; 150; 200; 250; 300
Window-to-wall ratio	0.2; 0.25; 0.3; 0.35; 0.4
Air conditioning on temperature in winter	18;19;20

Table 3. Enclosure and PV module details.

Categorization	Price of Item	Carbon Footprint	Heat Transfer Coefficient	Generated Electrical Energy	Transmittance
	yuan/m^2	kgCO$_2$/m^2	W/m^{2}K	W	%
EPS board 1	872	3955	0.033	/	/
XPS board 2	598	6027	0.030	/	/
PU board 3	1256	5141	0.024	/	/
RW board 4	380	7800	0.044	/	/
Photovoltaic glass 1	1500	779.36	2.7	/	0.6
Photovoltaic glass 2	1500	779.36	2.7	/	0.7
Photovoltaic glass 3	1700	779.36	2.5	/	0.6
Photovoltaic glass 4	1700	779.36	2.5	/	0.7
Photovoltaic glass 5	1900	779.36	2.3	/	0.6
Photovoltaic glass 6	1900	779.36	2.3	/	0.7
Photovoltaic panel 1	83	1400	/	5 W	/

Table 3. *Cont.*

Categorization	Price of Item yuan/m^2	Carbon Footprint $kgCO_2/m^2$	Heat Transfer Coefficient W/m^2K	Generated Electrical Energy W	Transmittance %
Photovoltaic panel 2	143	1400	/	100 W	/
Photovoltaic panels 3	198	1400	/	150 W	/
Photovoltaic panels 4	255	1400	/	200 W	/
Photovoltaic panels 5	318	1400	/	250 W	/
Photovoltaic panels 6	375	1400	/	300 W	/

Table 4. PV simulation information.

Relevant Parameters	Maximum Output Power P/W	Cell Conversion Efficiency n/%	Open Circuit Voltage U/V	Short-Circuit Current I/A	Optimum Operating Current Im/A	Optimum Operating Voltage Vm/V	Sizes mm × mm
Translucent Photovoltaic Glass 1, 3, 5	42	18%	122.7	0.48	0.43	98.7	1200 × 750
Translucent photovoltaic glass 2, 4, 6	40	18%	121.1	0.46	0.42	97.9	1200 × 750
Photovoltaic panel 1	50	19%	22.02	3.02	2.7	17.82	670 × 530
Photovoltaic panel 2	100	19%	23.05	6.44	5.29	17.98	1200 × 550
Photovoltaic panels 3	150	19%	20.52	9.53	8.25	18	1320 × 670
Photovoltaic panels 4	200	19%	21.5	10.93	9.79	18	1580 × 808
Photovoltaic panels 5	250	19%	22.5	12.73	11.88	18	1380 × 990
Photovoltaic panels 6	300	19%	22.5	15.8	14.73	18.5	1640 × 992

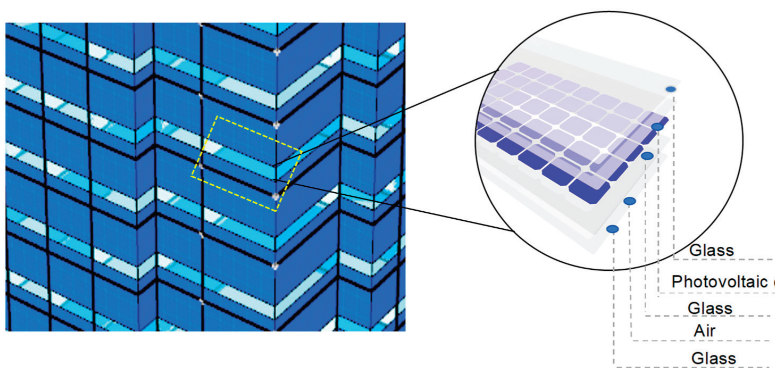

Figure 2. Schematic diagram of a photovoltaic window.

3.2. Lighting Intelligent Control Parameters

To explore the impact of photovoltaic windows on lighting energy consumption, the continuous dimming control mode is employed in EnergyPlus V8.7. According to the “Standard for Architectural Lighting Design”, GB50034-2013 [45], the illuminance at the center of the room at a height of 0.75 m is used as a control point. The illuminance at this control point determines whether artificial lighting needs to be turned on. If the illuminance exceeds 300 lux, the lamps and lanterns remain off. When the illuminance falls below 300 lux, the output power of the lamps and lanterns gradually increases until the ratio of the maximum power output reaches 1. The control principle of continuous dimming is illustrated in Figure 3.

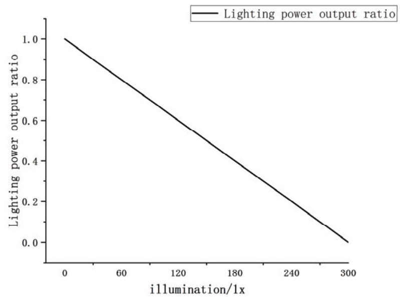

Figure 3. Control principle diagram of continuous dimming.

3.3. Optimization of Variable Constraints and Objective Function Establishment

3.3.1. Optimization Variables

The constraints of the multi-objective optimization model are based on the values taken within the requirements for the design of the external envelope in GB50189-2015 Design Standard for Energy Efficiency of Public Buildings of China and GB 50176-2016 Thermal Code for Civil Buildings [44,46]. It is specifically expressed as:

$$\text{s.t}\begin{cases} 0.2 \le x_1 \le 0.4 \\ 50 \le x_2 \le 300 \\ 1 \le x_3 \le 4 \\ 1 \le x_4 \le 6 \\ 1 \le x_5 \le 4 \\ 18 \le x_6 \le 20 \\ 0.07 \le x_7 \le 0.15 \\ 0.07 \le x_8 \le 0.15 \end{cases} \tag{12}$$

x_1 is the window-to-wall ratio, x_2 is the power of photovoltaic panels, and x_3 is the four types of roof insulation board type-specific parameters are shown in Tables 2 and 3, the x_4 is the six types of PV window types with specific parameters shown in Tables 2 and 3, the x_5 is the four types of external wall insulation boards, and x_6 for different design heating temperatures. x_7 is the thickness of the roof insulation board, and x_8 is the thickness of the external wall insulation board.

3.3.2. Objective Function

In order to explicitly study the nonlinear relationship between the building envelope and PV system and the comprehensive value of building-energy consumption, building materials and operational phase carbon emissions, and building retrofit and operating costs, the PSO-SVM algorithm is used in this study as a prediction model for the objective function of the genetic algorithm. Comprehensive Value of Building Energy Consumption (G1), building materials and operational-phase carbon emissions (G2), and retrofit and operating costs (G3) are shown in Equation:

$$\begin{cases} f1 = minG_1(psosvmregression(X_1 \ldots\ldots X_n)) \\ f2 = minG_2(psosvmregression(X_1 \ldots\ldots X_n)) \\ f3 = minG_3(psosvmregression(X_1 \ldots\ldots X_n)) \end{cases} \tag{13}$$

3.4. Benchmark Model Validation

Based on the monitoring data of the property center for 2022–2023 (1 year), the comparison between the original building and the simulation results is shown in Table 5. The discrepancies between the simulation results and the actual results for the combined values of the building's energy consumption, carbon emissions from construction materials and operational phases, and economic costs are 0.5%, 0.4%, and 0.4%, respectively. Therefore, the results of the construction simulation using the simulated building are accurate and reliable.

Table 5. Model validation.

Goal	Heating Energy Consumption (kWh)	Cooling Energy Consumption (kWh)	Lighting Energy Consumption (kWh)
Analog value	678,940	154,179	224,460
Actual value	676,034	153,265	223,458
Inaccuracies	0.5%	0.4%	0.4%

3.5. PSO-SVM Function-Prediction Modeling

The 300 sets of simulation data generated by JEPlus V2.1 were divided into training and testing sets, with 80% allocated to the training set and 20% to the testing set. As shown in Figure 4, the R^2 values of the test set, predicted using PSO-SVM for comprehensive building energy consumption, building materials and operational phase carbon emissions, and retrofits, are 0.978, 0.987, and 0.986, respectively. The RMSE values for the test set are 0.012, 0.038, and 0.043, respectively. With all R^2 values exceeding 0.97 and all RMSE values below 0.09, the PSO-SVM model demonstrates robust predictive capability for comprehensive building values, carbon emissions from building materials and the operational phase, and renovation costs. This substantiates the feasibility of constructing PSO-SVM models for multi-objective optimization.

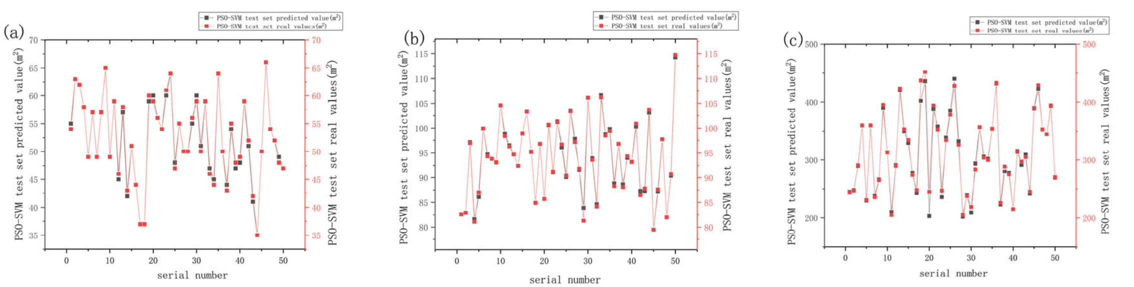

Figure 4. Comparison of predicted and real value data. (**a**) Comprehensive value of building energy consumption; (**b**) Building materials and operational phase carbon emissions; (**c**) Retrofit and operating costs.

3.6. Implementation of the PSO-SVM-NSGA-II Algorithm

First, a population of 100 solutions is randomly generated, with each individual containing the SVM parameters. During the iterative optimization process, Particle Swarm Optimization (PSO) is used to update the SVM hyperparameters of the individuals. The SVM model is trained to evaluate the objective function values, and non-dominated sorting is performed based on these values. New generations are created through selection, crossover, and mutation using crowding distance comparison.

In this optimization setup, there are three objective functions (n_{obj} = 3), the initial population size is set to 100 (n_{pop}), and the maximum number of iterations is set to 100. The crossover probability is 0.8 (p_c), with 80% of the individuals undergoing crossover, and the mutation probability is set to 0.05 (μ). The lower bounds for the constraint variables are varmin = [0.2, 50, 7, 1, 7, 18, 0.07, 0.07], and the upper bounds are varmax = [0.4, 300, 10, 6, 10, 20, 0.15, 0.15], with the step size derived from these bounds. The PSO parameters include a local search coefficient c_1 set to 1.5, a global search coefficient c_2 set to 1.7, the maximum number of generations maxgen set to 100, the population size sizepop set to 10, an acceleration coefficient k set to 0.6, and inertia weights w_V and w_P both set to 1. The SVM cross-validation parameter v is set to 5, with the SVM parameters c and g ranging from 0.1 to 100.

Therefore, this study selects PSO-SVM-NSGA-II as the algorithm for multi-objective optimization due to its effective combination of global search, local search, and multi-objective optimization capabilities, which significantly enhance search efficiency and optimization performance, especially for large-scale and complex problems.

4. Findings and Analysis

4.1. Multi-Objective Optimization Results and Analysis

After 100 iterations, the NSGA-II algorithm converged and ultimately obtained 100 sets of Pareto optimal solutions. Use the weighted TOPSIS method to assign weights and rank the optimization objectives based on the obtained Pareto solution set. After comprehensive consideration, the weight allocation is as follows: the comprehensive value of the building is 1/3, the cost of the building renovation is 1/3, and the building materials and operational phase carbon emissions of the building are 1/3.

The Pareto solution set from the final generation is illustrated in Figure 5a, with scatter plots for building energy consumption versus renovation cost, energy consumption versus carbon emissions, and carbon emissions versus renovation cost depicted in Figure 5b–d, respectively. In the three-dimensional scatter plot 5(a), the comprehensive building energy consumption values in the Pareto solution range from 53–73 kWh/m^2, building materials and operational phase carbon emissions span from 83–93 kgCO$_2$eq/m^2, and renovation costs vary between 220–514 yuan/m^2.

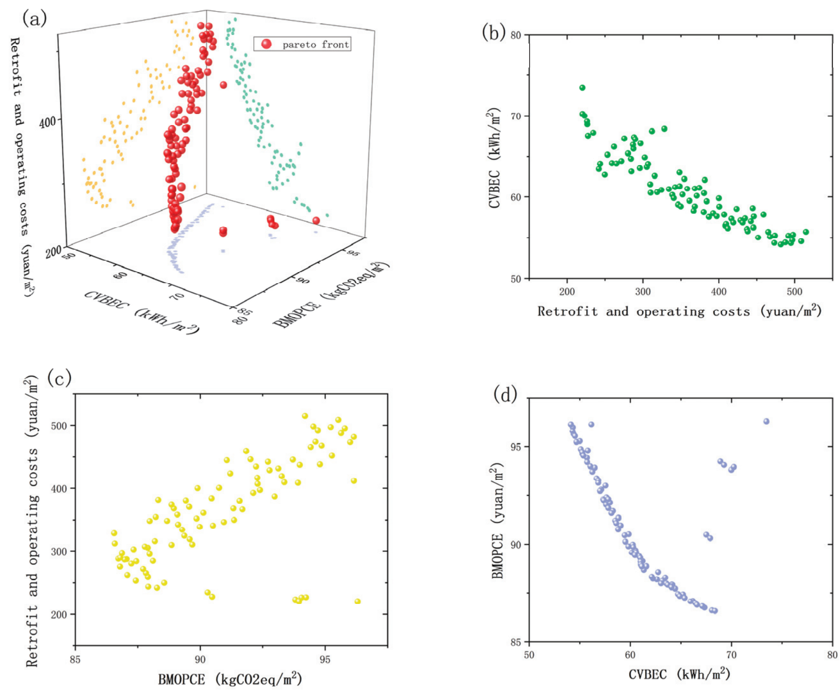

Figure 5. The three-objective-function Pareto solution set: (**a**) General diagram of the Pareto solution set (**b**) Scatter plot of retrofit and operating costs and CVBEC (**c**) Scatter plot of building materials and operational phase carbon emissions and retrofit and operating costs (**d**) Scatter plot of CVBEC and building materials and operational phase carbon emissions.

Based on the distance and comprehensive score between each evaluation indicator and the positive and negative ideal solutions, Scheme 62 achieved the highest comprehensive score of 0.6739. The final values for the optimization variables are as follows: a window-to-wall ratio of 0.2, a photovoltaic panel power of 50 W, a double-layer photovoltaic Glass 2 for the photovoltaic window, a winter heating control temperature of 18.4 degrees Celsius, a 70 mm-thick XPS board for roof insulation, and a 90 mm-thick PU board for external wall insulation. This scheme results in a comprehensive energy consumption value of 63 kWh/m^2, building materials and operational phase carbon emissions of 88 $kgCO_2eq/m^2$, and a retrofit of 228 $yuan/m^2$.

Based on the results of the optimal solution, the annual energy consumption for air conditioning and lighting is reduced to 63 kWh/m^2, which is 41% lower compared to the original building of 105 kWh/m^2. The standard calculation for the PV life cycle is 25 years. The carbon emissions for 25 years of operation are calculated based on the annual operational energy consumption and the carbon emission factor of the Inner Mongolia power grid. The carbon emissions from the production phase of the retrofit materials are determined using the carbon emission factors of monocrystalline silicon PV modules and cadmium telluride PV modules, as referenced in the relevant literature [47,48]. The initial investment for the retrofit is CNY 2.27 million, and the use of photovoltaic modules saves about CNY 210,000 of operating costs per year, with a payback period of about 11 years, as shown in Table 6.

Table 6. Comparison between the optimized target and the original target.

Goals		Original Target	Optimized Target	Overall Trends	
Comprehensive value of building energy Consumption		105 kWh/m^2	63 kWh/m^2	−41%	
Building materials and operational phase carbon emissions	Building materials carbon emissions	182 tCO_2eq	297 tCO_2eq	−115 tCO_2eq	−34%
	Operational phase carbon emissions	13,125 tCO_2eq	8520 tCO_2eq	4605 tCO_2eq	
Retrofit and operating costs	Retrofit costs	0	2.27 million yuan	−2.27 million yuan	−20%
	operating costs	13.12 million yuan	8.25 million yuan	4,870,000 yuan	

4.2. Global Sensitivity

In this study, the PSO-SVM algorithm was employed as a surrogate model to predict three objectives in MATLAB, with the prediction results illustrated in Figure 6. The Sobol method was utilized for the global sensitivity analysis of the predictive model. In Figures 2 and 3, blue bars indicate the first-order indices (S), while red bars represent the total-order indices (ST). The first-order indices, or main effects, and the total-order indices, or total effects, reveal the impact of variable interactions. The influencing factors, denoted as X1, X2, X3, X4, X5, X6, X7, and X8, correspond to the window-to-wall ratio, photovoltaic panel power, roof insulation type, photovoltaic window type, external wall insulation board type, winter indoor air conditioning temperature, roof insulation thickness, and external wall insulation thickness, respectively.

Overall, the first-order index reveals that the window-to-wall ratio has the most substantial impact on comprehensive building energy consumption, whereas photovoltaic panel power significantly influences building materials and operational-phase carbon emissions. Regarding retrofits, the type of photovoltaic window has the greatest total impact, followed by the window-to-wall ratio and photovoltaic panel power. The least significant factors are the winter air conditioning temperature and the thickness and type of wall and roof insulation layers.

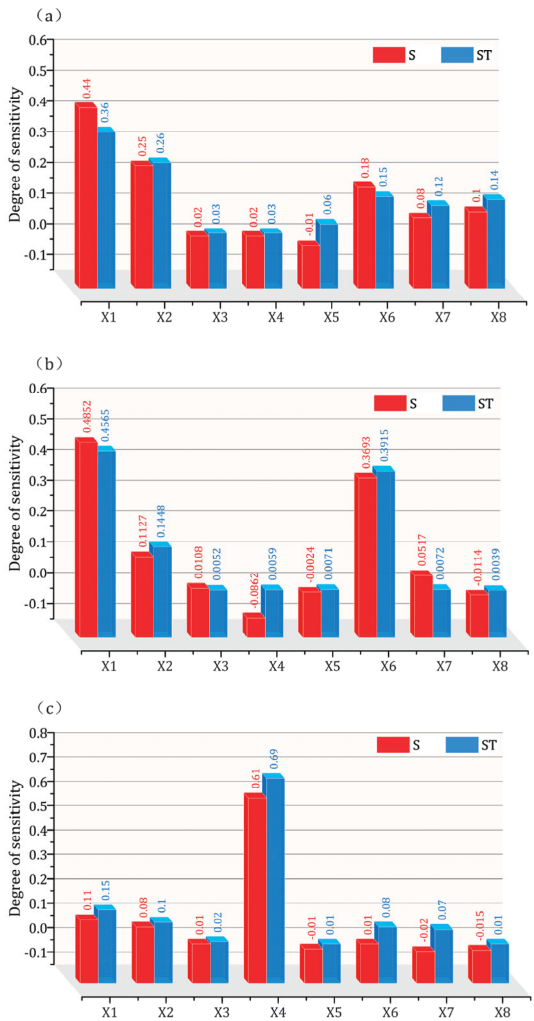

Figure 6. Sensitivity Analysis of Parameter Variables. (**a**) Comprehensive value of building energy consumption; (**b**) Building materials and operational phase carbon emissions; (**c**) Retrofit and operating costs.

According to Figure 6a, the main effect of the window-to-wall ratio on comprehensive building energy consumption reaches as high as 0.45. This high-impact value underscores the pivotal role of the window-to-wall ratio in the building energy system. A high window-to-wall ratio results in a smaller area for photovoltaic panels, thereby increasing thermal loads and, consequently, the overall building energy consumption. Conversely, the type of photovoltaic window, as well as the thickness of the wall and roof insulation, is inversely related to comprehensive building energy consumption. An increase in the thermal transmittance coefficient of photovoltaic windows and the thickness of wall and roof insulation layers leads to a reduction in comprehensive building energy consumption.

Regarding building materials and operational-phase carbon emissions, as shown in Figure 6b, the window-to-wall ratio and winter heating design temperature are the two most influential factors, with influence values of 0.45 and 0.39, respectively. Increased design temperatures lead to higher carbon emissions from electricity. The next most significant factor is the photovoltaic panel power; every 50 W increase in photovoltaic panel power increases the panel thickness by 2 mm, resulting in higher carbon emissions from the panels.

For retrofits, as shown in Figure 6c, different photovoltaic window types have varying effects on transparency and thermal transmittance. Higher transparency and lower thermal transmittance photovoltaic windows are more expensive, making them the main factor affecting retrofits, with an influence as high as 0.61. The thickness and type of wall and roof insulation layers are inversely related to building costs; as thickness increases, insulation costs also rise, but the overall impact on costs is minimal, less than 0.1.

The total-order indices indicate that the ranking of the eight variables in terms of their first-order and total-order indices for the comprehensive value of building energy consumption, building materials and retrofit stage carbon emissions, and retrofit and operating costs are consistent. This consistency suggests that the ranking of variables in terms of their primary and overall influence is aligned. The overall influence of a variable primarily stems from its interactions with other variables rather than from its individual main effect, indicating that its impact is moderated or enhanced by other variables. In the context of overall building energy consumption, the main effect of photovoltaic panel power is 20% higher than its total effect, indicating that the influence of photovoltaic panel power is primarily direct. This means that when other variables remain constant, the impact of this variable on the output is substantial and is less affected by other variables.

4.3. Localized Sensitivity

The primary determinants influencing comprehensive building energy consumption, costs, and carbon emissions are revealed by the first-order and total-order indices of global sensitivity. These determinants include the window-to-wall ratio, type of photovoltaic window, and power of photovoltaic panels. The objective function is impacted by the interaction of these factors. To thoroughly analyze the relationship between the optimization variables and the objective function, further investigation is necessary. Additionally, it is crucial to examine in detail the relationship between the transmittance of photovoltaic windows and lighting energy consumption. Indoor lighting conditions are directly affected by the transmittance of photovoltaic windows, thereby impacting the usage of the lighting system. Conducting a detailed analysis of the relationship between transmittance and lighting energy consumption allows for a more comprehensive evaluation of the role of photovoltaic windows in overall building energy consumption.

4.3.1. Impact of PV Panels with Different Power Generation and Window-to-Wall Ratio on the Comprehensive Value of Building Energy Consumption

To more intuitively illustrate the characteristics of the influence of PV panel power on the comprehensive value of building energy consumption, the PV panel power and window-wall ratio are used to classify the range of values. The results of the calculations are then plotted in a point-line diagram, as shown in Figure 7. The laying area of photovoltaic panels is affected by the panel's power. For instance, a 300 W photovoltaic panel requires a larger monolithic area. Consequently, in buildings with the same area, larger power generation leads to relatively reduced panel laying. Overall, the renewable power generation of PV panels exhibits an inverse relationship with the window-to-wall ratio. In the window-to-wall ratio range of 0.2–0.4, the annual renewable power generation of PV panels ranging from 50–300 W is approximately reduced by 16%. Additionally, within this same window-to-wall ratio range, PV panels with power ratings between 50 W and 300 W lead to a reduction in carbon emissions by approximately 2% to 4%.

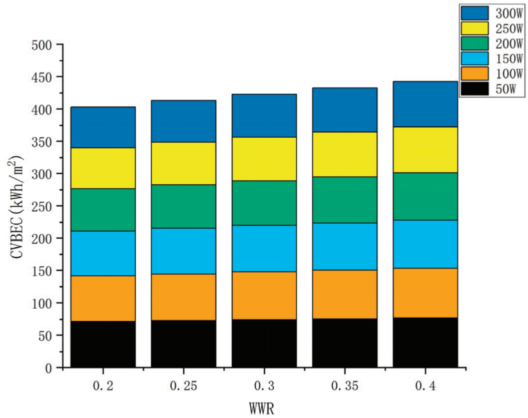

Figure 7. Impact of PV panel power on the comprehensive value of building energy consumption.

4.3.2. Impact of Different PV Window-to-Wall Ratios on Retrofit and Operating Costs

Photovoltaic windows are typically more expensive than traditional windows due to their photovoltaic conversion function. A higher window-to-wall ratio increases the window area in a building, thus increasing the overall cost of the building. It can be observed from the cost prices that Photovoltaic Windows 1 and 2 have the same unit price but different light transmittance, and the same applies to Photovoltaic Windows 3, 4, 5, and 6. Therefore, the six types of photovoltaic windows are divided into three categories. As shown in Figure 8, the cost of photovoltaic windows is directly proportional to the window-to-wall ratio. In the window-to-wall ratio range of 0.2 to 0.4, the cost of using Photovoltaic Windows 1 and 2 ranges from CNY 204 to 408/m^2, while the cost of using Photovoltaic Windows 3 and 4 ranges from CNY 216 to 432/m^2, and the cost of using Photovoltaic Windows 5 and 6 ranges from CNY 228 to 456/m^2. The retrofit increases as the thermal transmittance of the photovoltaic windows decreases.

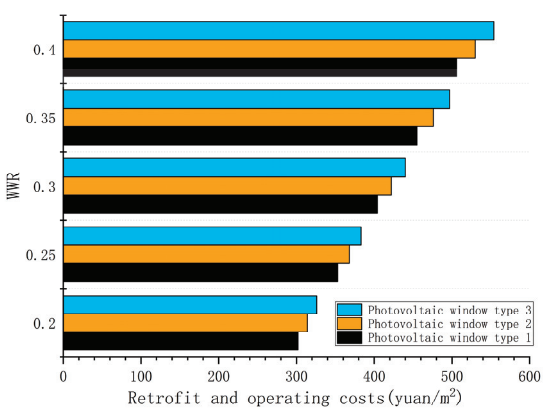

Figure 8. Effect of PV window type on retrofit and operating costs.

4.3.3. Effect of Different Power PV Panels to Window-to-Wall Ratio on BMOPCE

Figure 9 demonstrates that the power-generation capacity of photovoltaic panels has a pronounced positive effect on reducing carbon emissions. The manufacturing process of cadmium telluride photovoltaic panels is relatively streamlined and energy-efficient, involving fewer steps and lower energy consumption. In contrast, the production process of monocrystalline silicon photovoltaic panels is more complex, involving high-temperature treatment and multiple production steps, resulting in nearly twice the carbon emissions per square meter compared to cadmium telluride. Due to the low cost of monocrystalline silicon, many buildings use monocrystalline silicon photovoltaic panels. For every additional 50 W of monocrystalline silicon photovoltaic panels, the thickness of the panels increases by 2 mm, and carbon emissions increase by 1.48 $kgCO_2eq/m^2$.

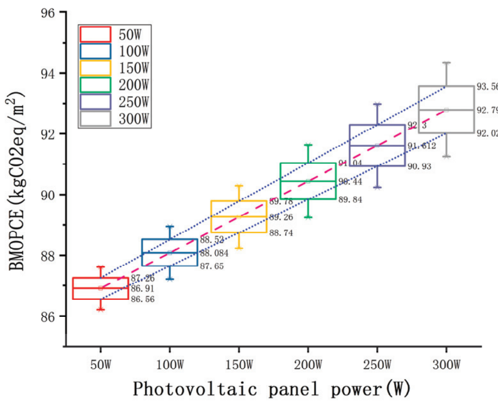

Figure 9. Impact of PV panel power on building materials and operational phase carbon emissions.

4.3.4. Impact of PV Window Transmittance and Window-to-Wall Ratio on Lighting Energy Consumption

In the context of using photovoltaic windows, this study analyzes the comparison of two types of light transmittance according to the transmittance limit specified in China's Energy-Saving Design Standard for Public Buildings (GB50189-2015). As shown in Figure 10, the transmittance of photovoltaic windows affects lighting energy consumption, although the impact is generally small. For a window-to-wall ratio between 0.2 and 0.4, a photovoltaic window with a transmittance of 0.7 reduces lighting energy consumption by approximately 2% compared to a window with a transmittance of 0.6. Additionally, regardless of the PV window transmittance, a window-to-wall ratio of 0.4 reduces lighting energy consumption by about 7% overall compared to a ratio of 0.2.

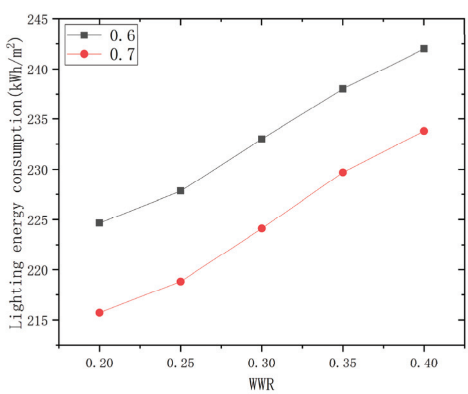

Figure 10. Effect of solar spectrum-averaged transmittance on lighting energy consumption.

4.4. Summary of This Section

In the previous sections, the results and analysis of multi-objective optimization, global sensitivity, and local sensitivity were presented. Table 7 briefly summarizes these results. In the local sensitivity analysis, the significant impact of photovoltaic (PV) panel power and window-to-wall ratio on building energy consumption and carbon emissions was highlighted. The findings shown in Figure 7 indicate that as the window-to-wall ratio decreases (from 0.4 to 0.2), the annual renewable power generation of PV panels (ranging from 50 W to 300 W) decreases by approximately 16%. This study supports the conclusions of Reffat et al. on the optimization of photovoltaic building design, who found that increasing the areas of PV on buildings by using facades due to limited roof areas can enhance power generation [49]. Our findings extend this by showing that adjusting the window-to-wall ratio can also increase PV area and consequently impact renewable power generation.

Table 7. Summary of findings.

Objective Function	Multi-Objective Optimisation Results		Global Sensitivity Level (ST)	Key Findings on Local Sensitivity
	Original Target	Optimized Target		
CVBEC	105 kWh/m^2	63 kWh/m^2	X1 > X2 > X6 > X8 > X7 > X5 > X3 = X4	As the window-to-wall ratio decreases (from 0.4 to 0.2), the annual renewable power generation of PV panels (ranging from 50 W to 300 W) decreases by approximately 16%.
BMOPCE	13,307 tCO_2eq	8547 tCO_2eq	X1 > X6 > X2 > X7 > X5 > X4 > X3 > X8	In the window-to-wall ratio range of 0.2 to 0.4, the cost of photovoltaic windows ranges from 204 to 456 yuan/m^2.
ROC	13.12 million yuan	10.52 million yuan	X4 > X1 > X2 > X6 > X7 > X3 > X8 = X5	Each additional 50 W of monocrystalline silicon panels increases thickness by 2 mm and carbon emissions by 1.48 $kgCO_2eq/m^2$

Additionally, the cost analysis of different types of photovoltaic windows (see Figure 8) indicates that due to the higher cost of photovoltaic windows compared to conventional ones, a higher window-to-wall ratio leads to an increase in overall building costs. Md Muin Uddin et al. concluded in their study on the optimization of photovoltaic building design that CdTe combined BIPV windows can save approximately 30–61% of electricity consumption compared to conventional window systems [50]. However, they emphasized that their analysis of cadmium telluride's photovoltaic power generation did not include an economic analysis. Our study expands on this aspect, providing designers with more comprehensive reference data. Additionally, Dong et al. has demonstrated that PV systems can effectively reduce carbon emissions, positively contributing to the environment. However, they did not consider the carbon emissions during the production stage of photovoltaic modules, which this paper investigates in depth [51].

5. Discussion

The study demonstrates significant energy, carbon, and cost reductions through building envelope optimization and PV integration for a specific case. However, the applicability of these findings to other building types, locations, and climates is uncertain, and the potential for generalization and limitations should be discussed.

(1) Applicability and limitations for different building types

The optimization methods and PV integration strategies used in this study can be applied to residential buildings. However, the energy consumption patterns and PV system performance may differ due to variations in occupancy, usage patterns, and building design. Commercial buildings often have larger energy demands and different operational schedules compared to residential buildings. The potential for energy savings and carbon emission reductions might vary, necessitating customized optimization strategies.

(2) Geographic and Climatic Considerations

The effectiveness of PV systems is highly dependent on geographic location. Regions with higher solar irradiance will benefit more from PV integration. Conversely, areas with lower solar exposure might see diminished returns, requiring additional energy-saving measures. Climate significantly impacts building energy consumption. In colder climates, the heating demand is higher, while in hotter climates, cooling demand dominates. The optimization strategies must account for these differences to ensure effective energy performance across various climates. Seasonal changes in sunlight and temperature can affect the performance of PV systems and building energy needs. The study's findings should be evaluated for their seasonal adaptability to ensure year-round efficiency.

(3) Case Studies and Simulations for Different Scenarios

To enhance the generalizability of the results, it is important to conduct additional case studies and simulations across varied scenarios. This includes testing optimization strategies on buildings with different architectural styles and materials, simulating in regions with diverse solar irradiance and climates to evaluate PV performance, and performing seasonal simulations to ensure consistent benefits throughout the year.

The study shows potential for energy savings and carbon reduction through optimized building envelopes and PV integration. However, validating these findings across various building types, locations, and climates is needed. Further case studies and simulations will improve the generalizability and support broader applications in sustainable building designs.

6. Conclusions

(1) Using the PSO-SVM-NSGA-II multi-objective optimization algorithm, which combines Particle Swarm Optimization (PSO) for tuning SVM hyperparameters based on social behavior patterns, and Support Vector Machine (SVM) for training data samples obtained from EnergyPlus simulations. Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used for identifying the best trade-offs between multiple objectives. This integrated approach effectively optimizes the building envelope and photovoltaic components to reduce energy consumption and carbon emissions. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to select the final solution. This integrated approach was used to optimize the external envelope structure and photovoltaic components, leading to significant reductions: overall energy consumption decreased by 41% (from 105 kWh/m^2 to 63 kWh/m^2), carbon emissions by 34% (from 13,307 tCO_2eq to 8817 tCO_2eq), and retrofit and operating costs by 20% (from CNY 13.12 million to CNY 10.53 million) over a 25-year period.

(2) The Global-sensitivity analysis was conducted using PSO-SVM as a surrogate model. The window-to-wall ratio (X1) has the most substantial impact on the comprehensive value of building energy consumption, with a main effect value of 0.45. A higher window-to-wall ratio increases thermal loads and overall energy consumption due to a smaller area available for photovoltaic panels. Photovoltaic panel power (X2) significantly influences building materials and operational phase-carbon emissions during the building's materials and operational phases, primarily due to increased panel thickness with higher power ratings. For retrofit and operating costs, the type of photovoltaic window (X4) is the most influential factor, with an impact value of 0.61. Higher transparency and lower thermal transmittance photovoltaic windows, although more expensive, reduce thermal loads and energy consumption.

(3) Local sensitivity analysis was conducted for variables with higher sensitivity to each objective. As the window-to-wall ratio decreases (from 0.4 to 0.2), the annual renewable power generation of PV panels (ranging from 50 W to 300 W) decreases by approximately 16%. Photovoltaic windows are typically more expensive than

traditional windows, and their cost is directly proportional to the window-to-wall ratio. In the window-to-wall ratio range of 0.2 to 0.4, the cost of photovoltaic windows ranges from CNY 204 to 456/m^2. Photovoltaic windows are categorized into three types based on unit price and light transmittance, with higher transmittance and lower thermal transmittance resulting in higher costs. Photovoltaic power had a significant positive impact on building material carbon emissions. Cadmium telluride photovoltaic panels emit less carbon than monocrystalline silicon panels, despite the latter being cheaper. Each additional 50 W of monocrystalline silicon panels increases thickness by 2 mm and carbon emissions by 1.48 kgCO_2eq/m^2; and between a window-wall ratio of 0.2 and 0.4, using a photovoltaic window with 0.7 light transmittance reduced lighting energy consumption by about 2% compared to a photovoltaic window with 0.6 light transmittance.

The findings of this study contribute to achieving energy savings and carbon reduction in building design and retrofitting. Based on the optimization results, architects and engineers can adopt efficient building envelopes and photovoltaic window configurations to minimize energy consumption and carbon emissions. This approach is applicable not only to new constructions but also to renovation projects, ensuring long-term energy savings and cost reductions. Governments should provide financial incentives and subsidies, such as tax breaks and grants, to promote the adoption of photovoltaic technology and optimized building envelopes.

Future research should conduct multi-scenario simulations in different geographic locations and climate conditions to validate the general applicability of the optimization solutions, and continuously monitor advancements in photovoltaic technology and building materials to assess their impact on the optimization results. In practice, optimized strategies based on research findings should be implemented, with field tests conducted to verify their effectiveness. By collaborating with policymakers and industry organizations, supportive policies can be developed, and challenges encountered during implementation can be addressed, ultimately promoting sustainable development in the building industry.

Author Contributions: N.Z.: Supervision, Resources, Writing—review and editing. J.Z.: Conceptualization, Methodology, Project administration, Software, Writing—original draft, Funding acquisition, Investigation. Y.D.: Visualization, Conceptualization, Software. C.D.: Supervision, Resources, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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

Nomenclature

CVBEC	Comprehensive value of building energy consumption
BMOPCE	Building materials and operational phase carbon emissions
ROC	Retrofit and operating costs
PSO-SVM	Particle Swarm Optimization-Support Vector Machine
NSGA-II	Non-dominated Sorting Genetic Algorithm II
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
PSO-SVM-NSGA-II	Particle Swarm Optimization-Support Vector Machine-Non-dominated Sorting Genetic Algorithm II
tCO_2eq	Tonnes of CO_2 equivalent

CO_2	Carbon Dioxide
XPS	Extruded Polystyrene
EPS	Expanded Polystyrene
PU	Polyurethane
RW	Rock Wool
PV	Photovoltaic
BIPV	Building integrated photovoltaic

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Article

Transformers for Energy Forecast

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Abstract: Forecasting energy consumption models allow for improvements in building performance and reduce energy consumption. Energy efficiency has become a pressing concern in recent years due to the increasing energy demand and concerns over climate change. This paper addresses the energy consumption forecast as a crucial ingredient in the technology to optimize building system operations and identifies energy efficiency upgrades. The work proposes a modified multi-head transformer model focused on multi-variable time series through a learnable weighting feature attention matrix to combine all input variables and forecast building energy consumption properly. The proposed multivariate transformer-based model is compared with two other recurrent neural network models, showing a robust performance while exhibiting a lower mean absolute percentage error. Overall, this paper highlights the superior performance of the modified transformer-based model for the energy consumption forecast in a multivariate step, allowing it to be incorporated in future forecasting tasks, allowing for the tracing of future energy consumption scenarios according to the current building usage, playing a significant role in creating a more sustainable and energy-efficient building usage.

Keywords: transformers; time-series forecast

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1. Introduction

Building energy efficiency has become increasingly important as climate change and energy security concerns have grown [1]. Building energy usage accounts for significant global energy consumption and greenhouse gas emissions. Improving building energy efficiency is a crucial strategy for reducing energy consumption and mitigating climate change.

One emerging technology that can potentially improve building energy efficiency is energy forecast models, trained from live data from sensors and other sources [2].

Energy forecasts can be used to improve building energy efficiency in several ways. One approach is to optimize the operation of building systems, such as heating, ventilation, and air conditioning (HVAC) systems [3] according to the current demand.

By forecasting and analyzing the building's energy performance, operators can identify ways to reduce energy consumption while still maintaining comfort and safety. Another approach is to use the forecast models to identify and prioritize energy efficiency upgrades [4].

Developing an effective energy forecast model requires heterogeneous sensor data to unveil hidden building usage patterns. The Figure 1 diagram shows how building sensor data combined with additional data and machine-learning models allow all available data to represent the building energy consumption pattern.

In addition to improving the building energy efficiency, forecasting energy consumption allows operators to identify ways to optimize the structure for different use cases by simulating different scenarios.

The energy forecast model is based on modifying the multi-attention transformer model by including a learnable weighting feature attention matrix to address the building energy efficiency. The model is leveraged by analyzing live sensor data from the Institute for Systems and Computer Engineering, Technology and Science (INESC TEC)

Research Building, consisting of computer research labs, auditoriums and support facilities, alternating more than 700 researchers, staff and other personnel.

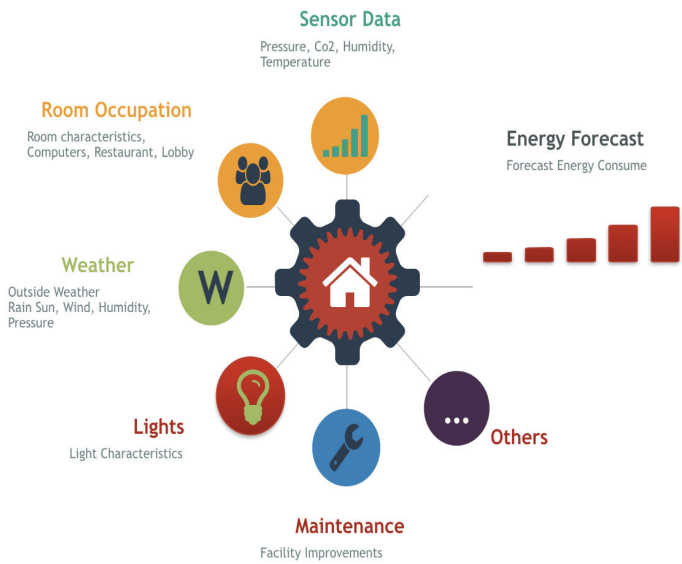


Figure 1. Energy Consumption Forecast.

The objective is to forecast the energy consumption for the next 10 days, allowing the application of effective mitigation procedures regarding energy waste and quickly assessing how these mitigation procedures impact the actual energy consumption.

With this in mind, this research work is organized into sections, with Section 2 presenting a comprehensive study on forecast models works, focused on energy forecast and maintenance; Section 3 showing the principal methodology to be followed and techniques to be employed; Section 4 containing the data analysis and forecast modeling; Section 5 containing the results discussion; and the conclusion in Section 6.

2. Literature Review

Building energy forecast models are an excellent tool for understanding and mitigating infrastructure efficiency in many fields. They allow for the creation of several data scenarios to foresee the impact on energy consumption and evaluate the impact of building usage modifications.

Maintenance decision-making and sustainable energy are the main concerns of [5], by employing the forecasting of electrical energy consumption in equipment maintenance by means of an artificial neural network (ANN) and particle swarm optimization (PSO). With the same objective, [6] employs fully data-driven analysis and modeling by first analyzing the linear correlation between the outdoor environmental parameters with the actual measured energy consumption data and then employing the use of the backpropagation artificial neural network (BP-ANN) to forecast energy consumption, allowing the reduction of the low-carbon operation and maintenance for the building HVAC systems.

The issue of CO_2 emissions poses a significant challenge to building efficiency. In the study conducted by [7], the research delves into both the advantages and limitations of conventional energy consumption mitigation methods. Notably, the study emphasizes the potential of integrating 2D GIS and 3DGIS (CityGML) [8] with energy prediction approaches. This combination considers frequent interventions at the building scale, applicability throughout the building's life cycle and the conventional energy consumption forecasting process.

In the work of [9], the emphasis is placed on the significance of forecasting energy usage in building energy planning, management and optimization. The review acknowledges the potential of deep learning approaches in effectively handling vast quantities of data, extracting relevant features and enhancing modeling capabilities for nonlinear phenomena.

The use of LSTM and GRU for energy forecasting was the subject of study for [10]. LSTM combinations with CNN were proposed by [11] for the same purpose. The CNN-LSTM proposed model employs a CNN to extract complex non-linear features combined with a LSTM to handle long-term dependencies through modeling temporal information in the time-series data.

LSTM, Bi-LSTM and GRU are employed in [12] to perform occupancy prediction in buildings with different space types. Another example related to intelligent vehicle systems can be found in [13], where the authors evaluated the performance of different architectures, including LSTM, to predict vehicle stop activity based on vehicular time-series data.

In a similar way, [14] exploits CNN–LSTM models for household energy consumption, with a particular emphasis on data normalization. The transformers for time series are also a subject of interest in [15], proposing Autoformer, a novel architecture with an auto-correlation mechanism based on the series periodicity, which conducts the dependencies discovery and representation aggregation at the sub-series level, outperforming self-attention in both efficiency and accuracy.

Although energy forecasting models mostly target foreseen target variables, they can be employed to define maintenance operations, allowing for the mitigation of the operational cost in building or manufacturing facilities [16].

The current time-series forecast models have several limitations, namely, in exploring all the available information in a meaningful way, harming the forecasting of a longer period of time. This concern makes it vital for developing models that use all information in a multivariate way and captures very long patterns useful in a correct energy consumption forecast.

3. Methodology

The main objective of this work is to employ a modified multi-variable transformer to forecast energy building consumption for the next 10-day period (250 h).

To establish a comparison baseline, multistep LSTM/GRU models are also employed and trained with the same data. The overall description of the proposed and evaluated models is below.

3.1. Baseline Models

lstm [17] is a type of rnn suitable for time-series forecasting. It is designed to address the vanishing gradient problem in traditional rnns that occurs when the gradients used to update the network weights become very small when propagating through many time steps, harming the learning of long-term dependencies.

The lstm models consist of a series of lstm cells (Figure 2), with the number of cells as a hyperparameter. Each of these cells contains three gates (input, forget and output) that control the flow of information through the cells. The weight of these gates is learned during the training process. Each cell stores information over time, and a hidden state allows it to pass information between cell chains in the network.

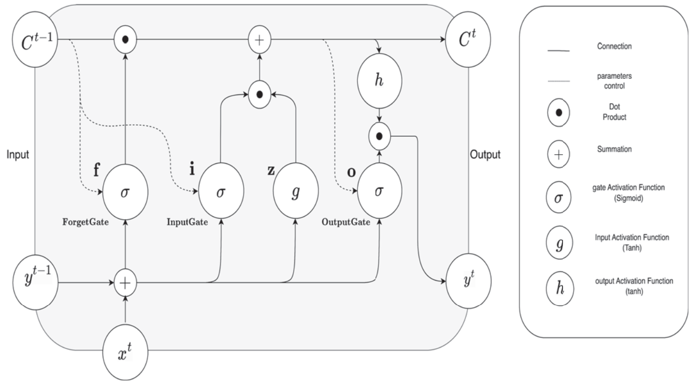


Figure 2. LSTM cell block.

The equations for the long short-term memory (LSTM) model are as follows:

$$\begin{aligned}
\text{Input Gate:} \quad & i_t = \sigma(W_{xi}x_t + W_{hi}h_{t-1} + W_{ci}c_{t-1} + b_i) \\
\text{Forget Gate:} \quad & f_t = \sigma(W_{xf}x_t + W_{hf}h_{t-1} + W_{cf}c_{t-1} + b_f) \\
\text{Cell State Update:} \quad & \tilde{c}_t = \tanh(W_{xc}x_t + W_{hc}h_{t-1} + b_c) \\
\text{Cell State:} \quad & c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t \\
\text{Output Gate:} \quad & o_t = \sigma(W_{xo}x_t + W_{ho}h_{t-1} + W_{co}c_t + b_o) \\
\text{Hidden State:} \quad & h_t = o_t \odot \tanh(c_t)
\end{aligned}$$

where

i_t represents the input gate activation at time step t,
f_t represents the forget gate activation at time step t,
$\tilde{c}_t$ represents the candidate cell state at time step t,
c_t represents the cell state at time step t,
o_t represents the output gate activation at time step t,
h_t represents the hidden state (output) at time step t,
x_t represents the input at time step t,
h_{t-1} represents the hidden state at the previous time step $(t-1)$,
c_{t-1} represents the cell state at the previous time step $(t-1)$,
σ represents the sigmoid activation function,
$\odot$ represents the element-wise multiplication (Hadamard product).

These equations describe the operations performed by an LSTM cell to update and pass information through time steps in a recurrent neural network architecture.

The memory cell is updated based on the input, forget, and output gates, while the hidden state is updated based on the memory cell and the output gate. In summary, LSTM has these particular hyperparameters: the number of LSTM layers that determine the network depth; the number of LSTM units, allowing for the definition of the size of the hidden state and memory cell, controlling the network ability to store information.

GRU [18] is also a type of RNN widely used in time-series forecasting. It addresses the same problem as lstm through a simpler architecture, described in Figure 3.

The GRU cell also contains a hidden state, which is used to pass information between cells in the network. Unlike LSTM, GRU only has one memory cell, which is updated using the reset and update gates. Both models commonly employ a Dropout technique [19] to prevent overfitting and adaptable learning rate usage, such as Adam [20] or SGD [21].

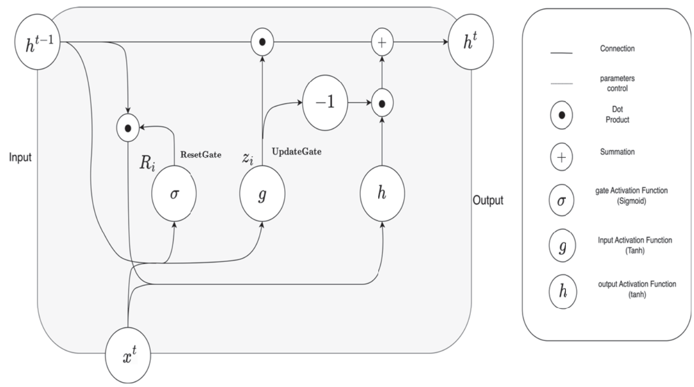


Figure 3. GRU cell block.

The equations for the gated recurrent unit (GRU) model are as follows:
Update Gate:

$$z_t = \sigma(W_{xz}x_t + W_{hz}h_{t-1} + b_z)$$

Reset Gate:

$$r_t = \sigma(W_{xr}x_t + W_{hr}h_{t-1} + b_r)$$

Candidate Hidden State:

$$\tilde{h}_t = \tanh(W_{xh}x_t + W_{hh}(r_t \odot h_{t-1}) + b_h)$$

Hidden State Update:

$$h_t = (1 - z_t) \odot h_{t-1} + z_t \odot \tilde{h}_t$$

where

z_t represents the update gate activation at time step t,
r_t represents the reset gate activation at time step t,
$\tilde{h}_t$ represents the candidate hidden state at time step t,
h_t represents the hidden state (output) at time step t,
x_t represents the input at time step t,
h_{t-1} represents the hidden state at the previous time step $(t-1)$,
W represents weight matrices,
b represents bias vectors,
σ represents the sigmoid activation function,
$\odot$ represents the element-wise multiplication (Hadamard product).

These equations describe the operations performed by a GRU cell to update and pass information through time steps in a recurrent neural network architecture.

Overall, LSTM and GRU architectures are both effective for time-series forecasting, and the choice between the two will depend on the specific requirements of the task at hand. In general, LSTM is a better choice for tasks requiring capturing long-term dependencies, while GRU may be more appropriate for tasks requiring faster training times or datasets with shorter-term dependencies. Although many variations of LSTM and GRU were proposed to improve forecasting capabilities, such as a bidirectional LSTM [22], by utilizing information from both sides, or a bidirectional GRU [23] with the same purposes, the main fundamental architecture is used.

3.2. Proposed Transformer Multistep

The transformers model [24] employs the use of an encoder–decoder scheme formed by a set of stacked self-attention in combination with point-wise layers to map the input sequence $(x_i, \ldots, x_n)$ to a series of continuous representations $z = (z_1, \ldots, z_n)$. For a given z, it generates a set of output symbols $(y_i, \ldots, y_m)$ at each time, in an auto-regressive manner, using the previously generated forecast points as additional inputs.

The sequence data points are transformed into discrete tokens, converted into a numeric token representation and fed into the input embedding layer to map the sequence element into a continuous learnable vector.

Because the proposed transformer model does not contain any recurrence or convolution blocks to insert information regarding the relative position of the input tokens among the input sequence, a piece of positional encoding information is inserted into the embedding layer that corresponds to a cosine and sine relative function representation, generating two separate vectors from the even $p_e(m, 2n)$ and odd $p_e(m, 2n+1)$ sequence time steps, embedding the positional information based on https://github.com/oliverguhr/transformer-time-series-prediction, accessed on 30 May 2023).

The embedding vector is defined by the dimension D and the positional embedding $p_e(m, 2n)$ with the even elements of the positional vector P for a given input X in each time step represented in $p_e(m, 2n)$, resulting in Equation (1):

$$p_e(m, 2n) = \sin m^{[-2n \log(1000)/D]} \tag{1}$$

Regarding the odd element representation, each positional embedding $p_e(m, 2n+1)$ is expressed in Equation (2).

$$p_e(m, 2n+1) = \cos m^{[-2n \log(1000)/D]} \tag{2}$$

The final positional encoded P vector aggregates both the even and pairs positional encoding, resulting in a final embedding vector with $X + P$ dimensions.

Concerning the encoding, layers are formed by a stack of N_l. This hyperparameter corresponds to the number of stacked identical layers. Each layer is formed by a multi-head self-attention mechanism combined with the positional-wise fully connected feed-forward network. Each sub-layer employs a residual connection followed by a layer normalization, with the output expressed in Equation (3).

$$Output = LayerNorm(y) + SubLayer(y)) \tag{3}$$

All sub-layers and embedding layers inside the model generate an output dimension D equal to model size d_{model} considering the input features $inputfeature$. In this case, the optimal value was found to be $250 \times inputfeature$ to encompass the full 10-day forecast period.

The decoder is very similar to the encoder. However, it adds a third sub-layer to perform multi-head attention over the output of the stacked encoders and two sub-layers, using similar residual connections as the encoder and adjacent layer normalization. Similarly, the number of decoder layers is a hyperparameter to be determined. The final decoder stack embedding output is compensated by one position, allowing the avoidance of current positions being mixed with subsequent ones when using squared subsequent masking.

The input queries Q, keys K and values V of dimension d_v are subject to the scaled dot product of the keys with all given keys, normalized by the dimension of keys d_k as $\sqrt{d_k}$, to overcome the monotonous magnitude growth with the increase of the d dimension, leading to gradient vanish (Figure 4). The final attention matrix A that encapsulates the packed Q, K, V is obtained using a softmax to gather the weights of the values, being represented in Equation (4)

$$A(Q, K, V) = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)V \tag{4}$$

Figure 4 shows how Queries Q, Keys K and Values V are combined in an incremental dot product, passing by the scaling layer, optional masking layer, softmax and final matrix multiplication to form the attention matrix A.

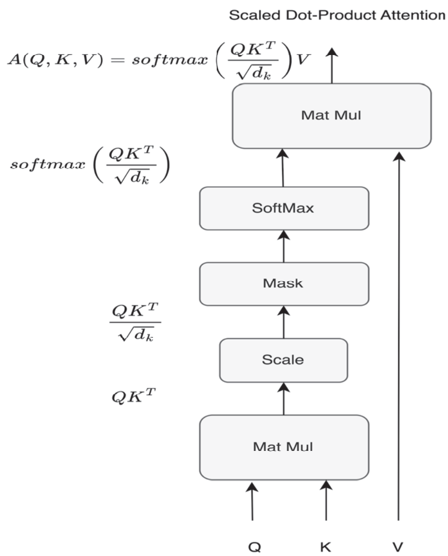


Figure 4. Scaled dot product attention scheme.

The train of transformers allows us to effectively construct an attention matrix formed by queries Q, keys K and value V.

Transformers models can contain single or multi-attention heads, with a single head putting all focus in a single location, aggregating all contributions to a location with the same weight. The main drawback of single-attention heads is that they lead to averaging the contributions to a local representation.

Alternatively, multi-head attention (Figure 5 allows the modeling of several representations from different locations simultaneously, allowing the capture of information from several sparse locations with different weights, expressed in Equation (5). For each of the projected queries d_k, d_k and d_v, attention is performed in parallel, resulting in d_v dimensional value representations, and the final heads h becoming concatenated into a single attention output.

The final Equation (5) for multi-head attention can be expressed as

$$MultiHead(Q,K,V) = Concat(h_1, h_2, \ldots, h_n)W^O \tag{5}$$

with h_n being the number of attention heads and n being the projections matrices, with each head represented as $head_i = Attention(QW_i^Q, KW_i^K, V_i^W)$, containing Q queries and K keys as a result of the dot product, and the projections matrices that correspond to parameters matrices $W_i^Q \in \mathbb{R}^{D\times d_k}, W_i^K \in \mathbb{R}^{D\times d_k}$ and $W_i^V \in \mathbb{R}^{D\times d_v}$. Following this operation, the outputs are concatenated and multiplied by the weighting matrix W^O, corresponding to a squared matrix obtained from $R^{hdv} \times D$ [24].

The proposed multistep transformers with the modified attention heads and input embedding follow the diagram of Figure 6, which is largely based on [24]. However, with a modification on the multi-attention heads and how the inputs X are combined, we use a correspondent embedding through a learnable weight attention matrix instead of a dedicated embedding for each input feature. The final proposed input aggregated embedding is expressed in Equation (6).

$$\epsilon_t = \sum_{j=1}^{n} m_{X_t}^{(j)} \epsilon_t^{(j}$$ (6)

where $\hat{\epsilon}_t$ corresponds to the linear transformer feature input, m_{X_t} is the leaned matrix weight regarding the combination of each of the input transformed features at time t towards the final embedding $\hat{\epsilon}_t$ at instant t.

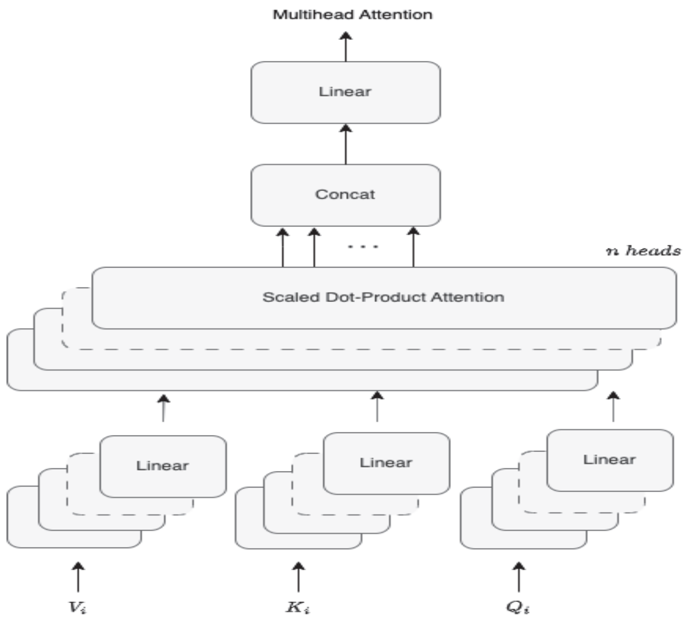


Figure 5. Multihead attention scheme.

The proposed multistep multi-head transformer model is represented in Figure 6, with inputs X_1 to X_n at instant $m-k$, corresponding to the different input features at a particular period of time, combined in an attention head A_m from Equation (6) for each considered instant, following by the aggregated embedding and the combination of the positional encoding and transformer block to form the full encoder stage. The decoder stage employs the transformer decoder block, the forecast layer and the dense for each target future value.

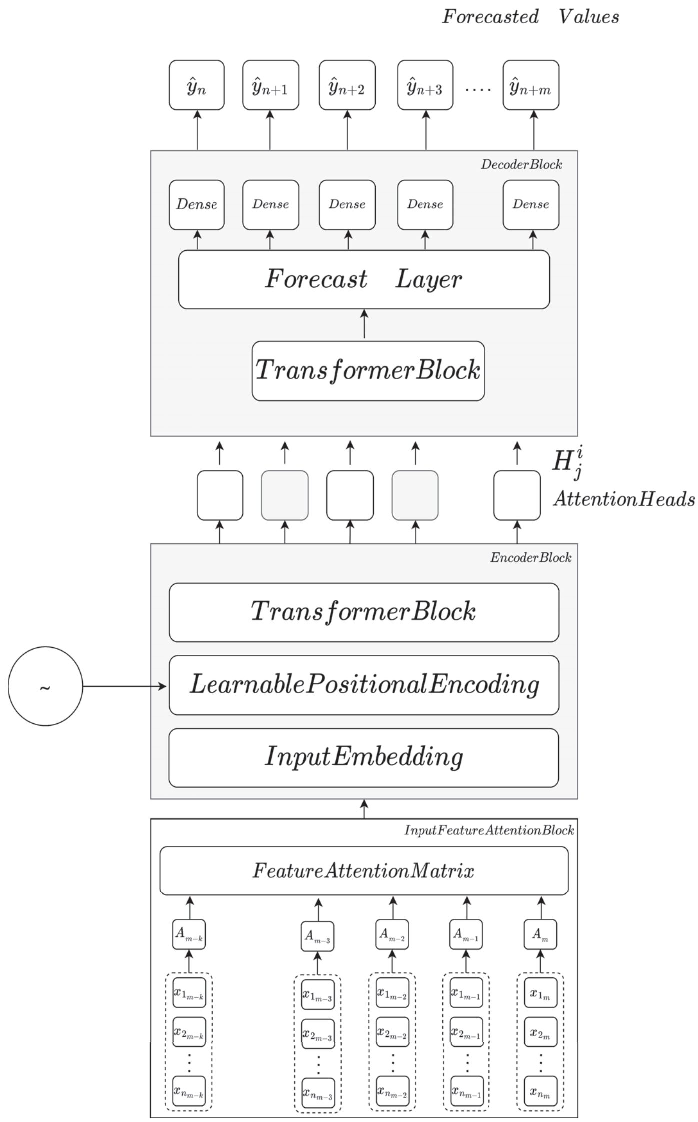


Figure 6. Transformer Proposed Model.

4. Setup And Forecasting

To evaluate the performance of the proposed multivariate transformer, two comparison baselines, LSTM and GRU, were trained on the same data with the same objective. For easy modeling, the redundant sensors are averaged into a single one per room to construct the feature regarding each room measurement.

4.1. Models

To evaluate the performance of the proposed transformer and baseline models, after training, the models infer over 250 points of historical data (test input that corresponds to 10 days) and forecast another 250 hourly future points (corresponds to the 10 day period ahead). For training, 70% of the data starting from day 1 are set for training, the subsequent 10% chunks for validation and 20% for testing purposes.

In more detail, the proposed transformer blocks follow the arrangement of Figure 6 with an aggregation of the multivariate input features using Equation (6).

The LSTM and GRU models use 250 units cells to forecast the same period length, described in Figure 7.

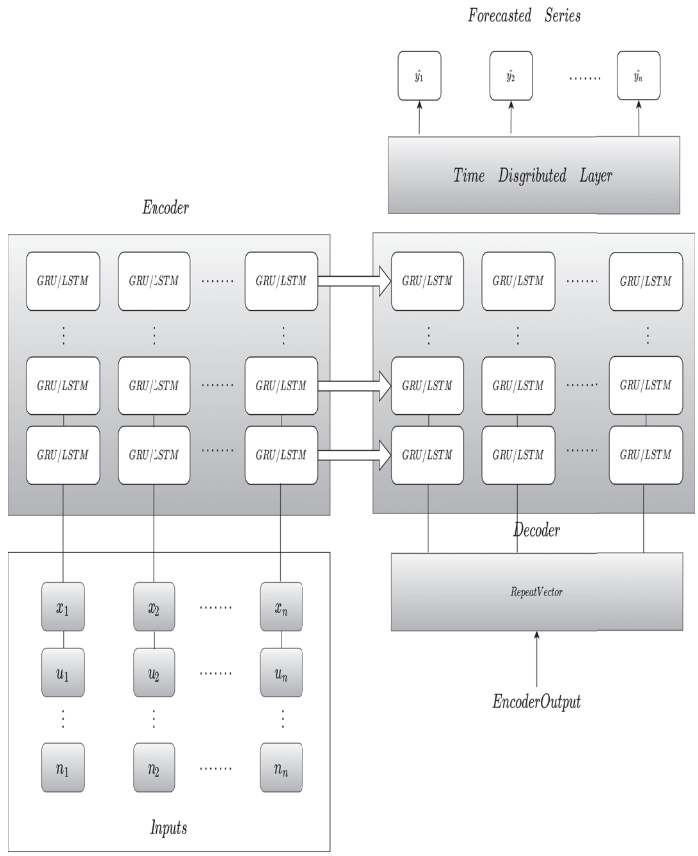


Figure 7. LSTM and GRU time-series forecast model.

Considering the multistep forecast, an additional repeat vector layer and time-distributed dense layer are added to the architecture.

4.2. Evaluation Metrics

The trained models were evaluated using MSE and MAPE on each time period Δ_t. The forecasted value $\hat{y}_i$ subtracted from the actual one y_i and divided by y_i and normalized by the set of samples N, is expressed as

$$\text{MAPE}(y, \hat{y}) = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_i - \hat{y}_y}{y_i}\right|. \tag{7}$$

MSE considers the average of the squared errors between the real value y_i and the predicted $\hat{y}_i$ in a given N set of samples, expressed as

$$\text{MSE}(y, \hat{y}) = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2. \tag{8}$$

4.3. Dataset

To construct a model capable of forecasting energy consumption, the first task is to analyze the data produced by several sensors during one year. The activities conducted at the building are mainly research regarding computer science and electrical engineering and support services, composed of research labs, human resources, auditoriums, restaurants and other common building infrastructure. The building comprises two blocks of four floors encompassing several room characteristics, such as computer labs, meeting auditoriums, restaurants and service spaces.

Each of the individual rooms contains a set of sensors to measure environmental variables and energy consumption through a dedicated sensor network. The deployed sensors on each room perform a combined measurement of **humidity**; **temperature**; **Co2** concentration, **pressure**, expressed in Pascals; and local energy consumption, for a total of 144 sensors.

The dataset includes the following:

- Real-time historical data from the INESC TEC building.
- Encompassing two-year time span.
- Totaling 8760 × 2 sample points (2 years).

4.4. Data Analysis

Regarding the data in analysis, the mentioned dataset comprises the building rooms' ambient sensory and corresponding energy consumption gathered during a year. The variables in the dataset contain the interior temperature in degrees Celsius °C, relative humidity in percentage %, air pressure expressed in Pascals *PPa* and room energy consumption as a target variable gathered in 15-min intervals throughout the year, aggregated in hour means. The analysis is restricted to only one year of data for a more concise analysis.

Concerning the energy consumption, Figure 8 presents the average energy consumption per room considering the day period and weekday.

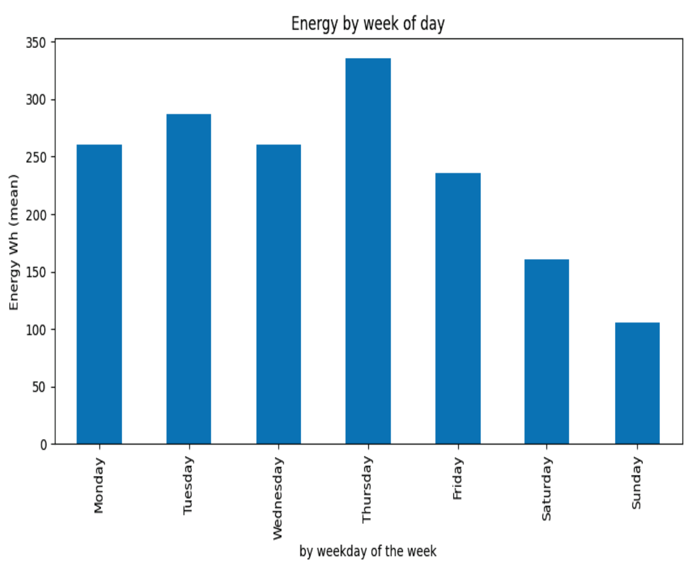


Figure 8. *Cont*.

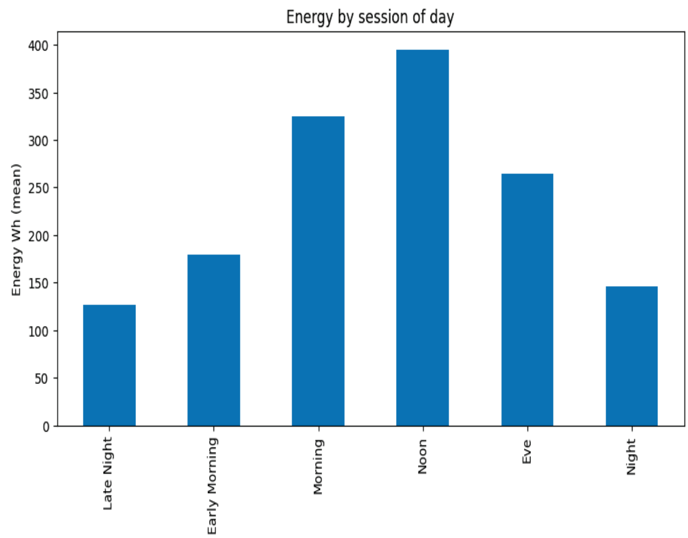


Figure 8. Average room consumption per weekday and season.

Figure 8 clearly highlights that weekends account for lower consumption, and the morning and noon periods account for a large part of the total building consumption, corroborated by the fact that it is a computer science research lab. However, it is clear that Thursday accounts for a peak in average room consumption, with Friday showing a clear descent in energy consumption.

Regarding the energy consumption among the building's main floors and sections, Figure 9 aggregates the average consumption per floor.

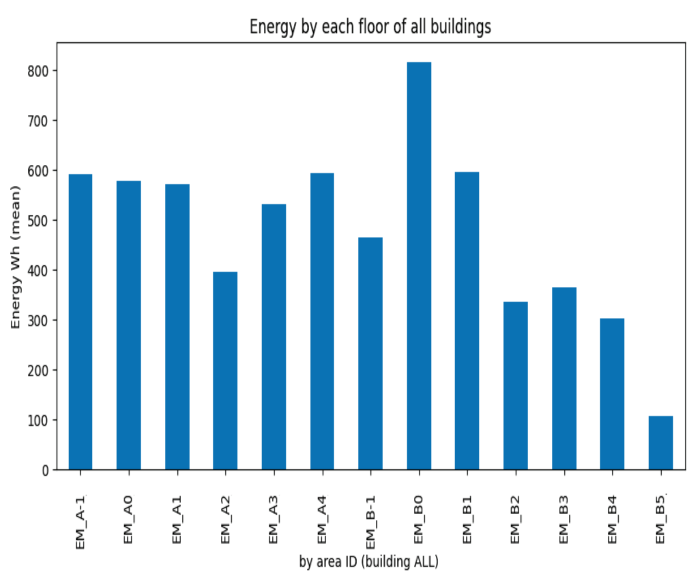


Figure 9. Average consumption per building floor (*A* or *B* means the building block and the number of the floor).

From Figure 9, it is possible to identify a clear outlier, namely, floor B0, which corresponds to the location of the restaurant and cafeteria of the building, where large energy kitchen appliances are present. In the opposite direction, floor B5 accounts for the lowest average energy consumption, correlated by the fact that this floor only contains small building auxiliary devices. The restaurant information can be corroborated by Figure 10.

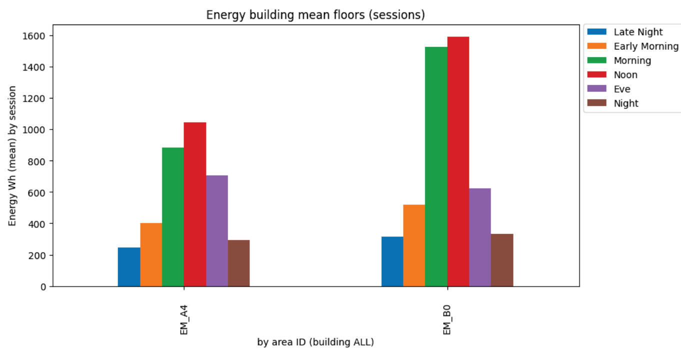


Figure 10. Average session consumption per building floor compared to lower floor consumption.

Figure 10 exhibits that floor B0 has a higher energy peak in the morning and at noon compared to the second largest floor consumption (A4), corresponding to the services floor. The consumption on floor B0 intersects with the most agitated period of the restaurant at lunchtime.

Figure 11 shows the mean building consumption by month, with clear evidence that the August months account for a lower consumption due to vacations and the winter months for a substantial increase in consumption due to lighting and heating.

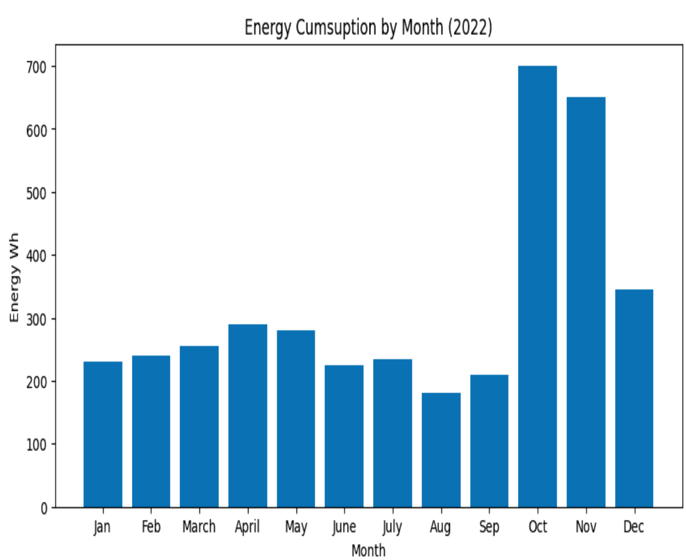


Figure 11. Energy consumption (mean) by month—the year 2022.

Regarding environment variable sensors, Figure 12 shows the box-plot distribution of the ambient variables by room.

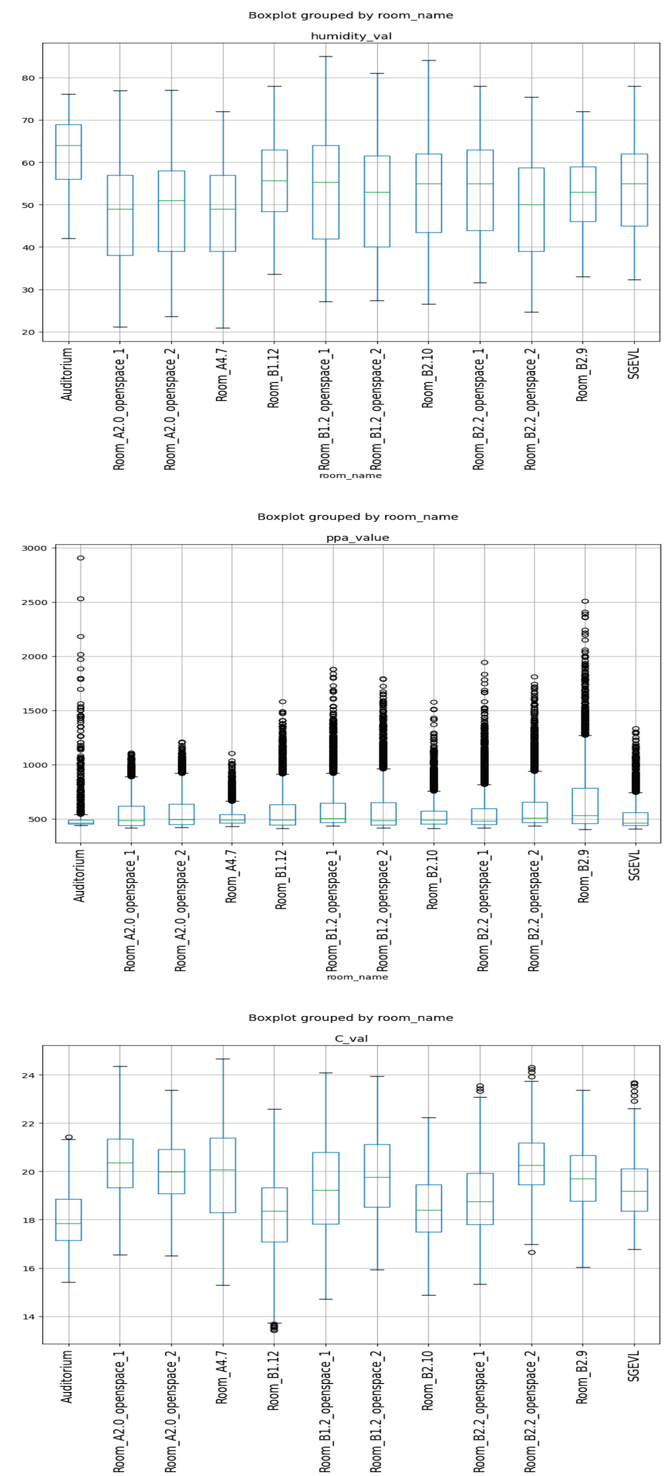


Figure 12. Box-plot of ambient variables by room.

From Figure 12 there is clear evidence that auditoriums present higher humidity levels due to less usage and exposure to the sun. Considering these large auditoriums are located on the lower floor, they present with higher humidity due to a lower temperature (Figure 13), a well-known ambient variable phenomenon.

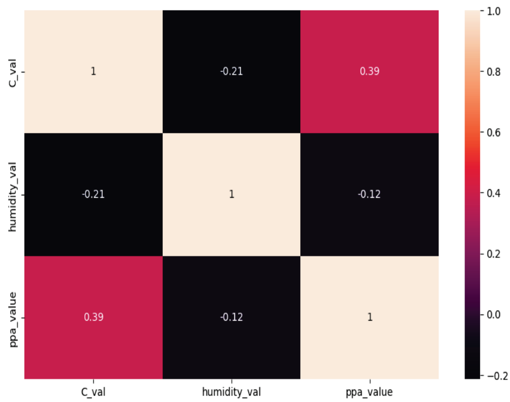


Figure 13. Variable correlation.

4.5. Time-Series Analysis and Pre-Processing

To accurately forecast energy consumption, it is relevant to determine the presence of seasonality, trends and the presence of abnormal values.

ACF corresponds to the correlation between a time series with a lagged version of itself, up to 50 lags, starting at a lag of 0 and having the maximum correlation at this period of time. It allows us to determine if a time series corresponds to white noise/random, the degree of the relation of a given observation regarding its adjacent observation and determine the order of the time series. Additionally, PACF allows the inclusion or exclusion of indirect correlations in the ACF calculation. Figure 14 summarizes the main time-series correlation (considered only 10 lags). The blue area depicts the 95% confidence interval, meaning that anything within the blue area is statistically close to zero, and anything outside the blue area is statistically non-zero with regard to the target variable, **EnergyWh**, the ACF and PACF in Figure 14, and derived features such as weekday (Monday to Sunday), day period ('Late Night', 'Early Morning', 'Morning', 'Noon', 'Eve', 'Night'), and season of the year (spring, summer, autumn, winter).

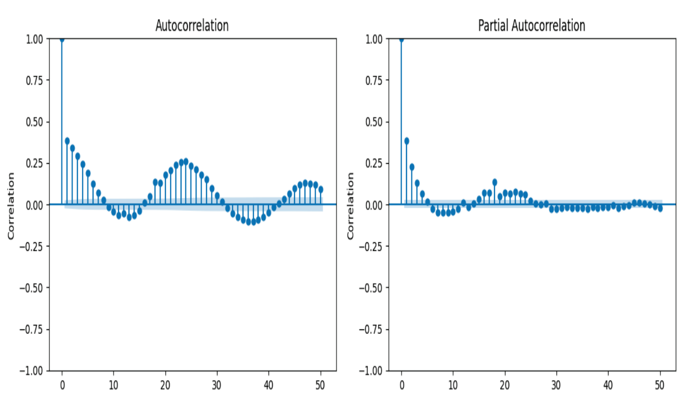


Figure 14. ACF and PACF.

Shows that for most lags, the auto-correlation is significantly non-zero for all lags. Therefore, the time series is not random, presenting some degree of seasonal patterns.

In order for models to converge properly, the dataset is pre-processed to find outliers or erroneous measures that may harm the training of the models, replacing those values with the mean of the previous and next values $X_i = \frac{1}{2}(x_{i-1} + x_{i+1})$. Furthermore, the data were normalized with respect to min–max to be fed to models, and the reverse process was made to recover the target forecasted value.

5. Results

Several combinations of hyperparameters were used to train and evaluate the three models effectively. All models were trained during 100 epochs in a 2 $\times$ Intel Xeon Gold 2.5 Ghz with 20 cores each, totaling 384 GB RAM, fitted with 2 Teslas v100 with 32 Gb each and 2 GTX 2080 with 11 Gb each. A 5 k-CV was employed to determine the set of the best hyperparameters for each configuration and to evaluate the model in the test set.

In order to compare different time-series forecasts, MAPE was employed, since it is a scale-independent measurement, and our time series does not cross zero, so the undefined problem is circumvented.

The final transformer model architecture took approximately 20 h of training, with an average of 1000 s on each epoch, approximately 1.6 times higher than LSTM and 1.9 than GRU, with the final convergence curves represented in Figure 15.

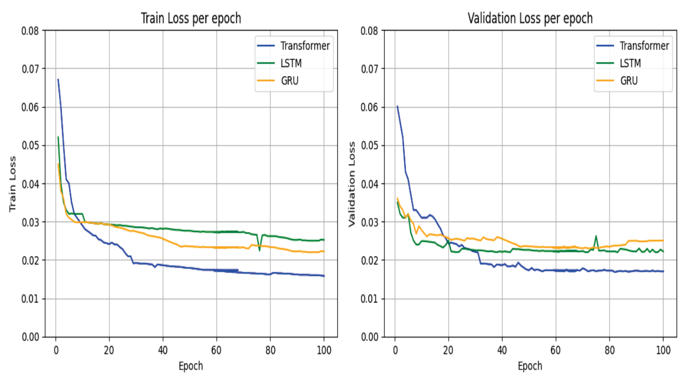


Figure 15. Convergence curves of all evaluate models (training and validation).

From Figure 15, it is evident that GRU models presented some degree of overfitting, compared with LSTM and the transformer proposed model. The transformer model shows a more stable convergence during the set of epochs, mainly due to a larger complexity when compared with other RNN models.

After curated debugging and hyperparameter tuning, the transformer with six heads stacked with six identical encoders obtained the best result (Table 1), with a dropout max of $dropout = 0.2$.

The decoder block employs the use of a linear transformation of the input data into the same number of $in_{features} = features_{size} = 250 \times n$ and $out_{feature} = 1$, corresponding to the forecast of 10 days (250 h).

The loss was the $L2$-norm, employing SGD with a $gamma = 0.98$, a learning rate of $lr = 0.005$ and $step_size = 10$ using a batch the size of 16. The transformer's total number of parameters was 16,330,827, with a look-back window of 34.

Regarding LSTM, the optimal number of nodes is 256 nodes per layer (Table 1), using a dropout of 0.2, a decay rate 0.99, with a look-back window of 32, employing Adam optimization with a learning rate/step size of $lr = 0.005$, with $\beta_1 = 0.9$ and $\beta_2 = 0.99$, using a $L2$-loss with a batch size of 16.

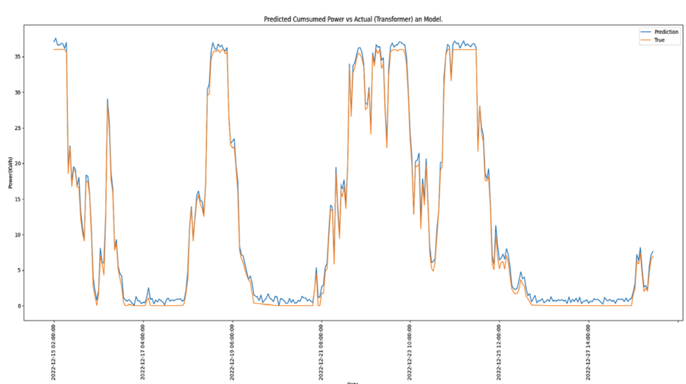
Regarding GRU, the optimal number of nodes is 200, 128 nodes per layer, a dropout of 0.2, Xavier weight initialization, decay rate 0.99, with a look-back window of 26, employing Adam optimization with a learning rate/step size of $lr = 0.005$, with $\beta_1 = 0.9$ and $\beta_2 = 0.99$, using a $L2$-loss with a batch size of 16.

Table 1 summarizes the results obtained in all the evaluated models using the test input samples (MAPE and MSE).

Table 1. Results on the models variations (normalized).

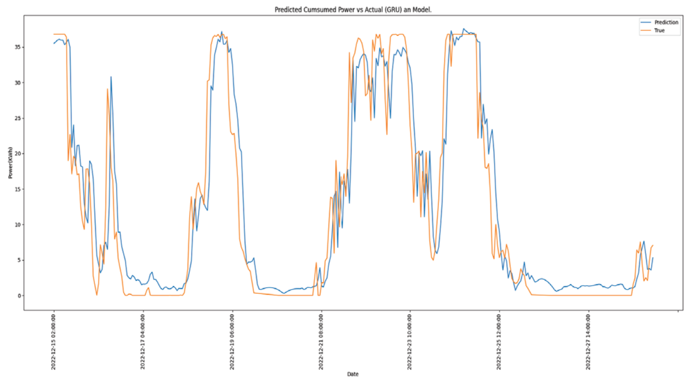
		LSTM			
N Cells	**N Nodes**	**Window**	**Parameters**	**MAPE**	**MSE**
400	128	32	18M	18.11%	15.43%
300	128	32	16M	16.34%	13.35%
200	256	32	13M	17.41%	14.45%
300	256	32	14M	14.26%	11.65%
200	128	24	12M	12.42%	10.02%
250	256	32	14M	**10.02**%	7.04%
		GRU			
N Cells	**N Nodes**	**Window**	**Parameters**	**MAPE**	**MSE**
400	128	32	14M	23.56%	21.43%
300	128	32	13M	15.98%	12.54%
200	256	32	12M	13.93%	11.56%
300	256	12	13M	15.34%	12.76%
200	128	26	11M,	**11.66**%	09.43%
250	128	32	12M	13.59%	10.49%
		Transformer			
Heads	**Enc/Deco**	**Window**	**Parameters**	**MAPE**	**MSE**
10	10/10	32	24M	12.33%	10.61%
10	6/6	32	14M	11.25%	9.75%
10	5/5	32	13M	10.43%	8.27%
6	10/10	32	20M	10.24%	8.11%
6	6/6	32	16M	**7.09**%	5.42%
5	5/5	32	13M	8.36%	6.62%

Figure 16 presents a side-to-side comparison of the top performer models against the ground-true values in the test set.

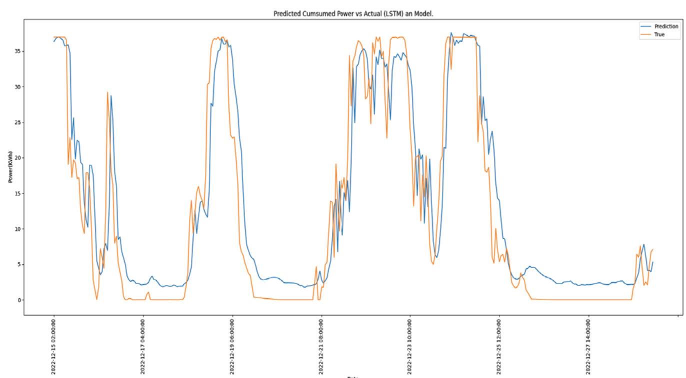


(**a**)

Figure 16. *Cont.*



(**b**)



(**c**)

Figure 16. The forecast of energy consumption for each best-performing model. (**a**) Transformer. (**b**) LSTM. (**c**) GRU.

Choosing an input window is crucial for achieving optimal performance. It is important to analyze the input data to identify any seasonal patterns thoroughly, and the input sequence size should include these personalities or trends. In this case study, a look-back window of 32 to forecast 250 points ahead with six heads, both in the encoder and the decoder, resulted in the best overall performance on the proposed transformer model. In the transformer models, an input window lower than 250 time steps led to suboptimal results. This corresponds to a suboptimal selection of input-target sequences that do not capture relevant time-series patterns useful for the model to forecast future energy values correctly.

This study aimed to assess the performance of multi-head attention-based transformers for the energy consumption forecast and compare the performance with LSTM and GRU-based models.

Transformers have proven to be highly suitable for multivariate time-series forecasting using large data samples and the correct use of the input window. The multi-head attention mechanism increases the performance, particularly in tasks involving multi-step forecasting. Implementing such models is widely applicable across various sectors, including energy forecasting, where they can aid in establishing mitigation policies to reduce operational costs and address challenges related to climate management. Additionally, they can be beneficial for modeling building maintenance and predictive control for HVAC systems [16,25], bringing operational benefits.

However, further changes and improvements are necessary to enhance the model's efficiency and robustness to ensure greater competence in real-world data-driven models for different sectors.

6. Conclusions

Energy forecasting is crucial for building characterization, which often manifest unpredictable energy consumption patterns that are not captured by models, leading to a degradation of their performance. Deep learning approaches, on the contrary, allow for a model of non-linear dependencies and capture relevant information to perform forecasts.

In this article, a modification of a multi-head multivariable transformer model is proposed for building an energy consumption forecast, complemented by a comprehensive performance comparison with common RNN models, such as GRU and LSTM and a real-time building energy and environment collected dataset. MSE and MAPE were used to evaluate the models. The performance of the multivariate transformer model using a multi-head attention mechanism and modified input embedding is almost 3.2 p.p. better than the best-trained baselines.

The construction of a richer dataset must follow the guidelines of the ROBOD project [26], which encompasses many sensors, HVAC, building occupancy and WiFi traffic, among others.

The main drawback of the multi-head attention transformer concerns its complexity and training time and the limited set of training features. Thus, training in a more rich dataset such as the Building Data Genome Project 2 [27] or the Global Occupant Behaviour database [28] would enable us to further validate the proposed forecast model with more variables, allowing us to foresee potentialities in the use of transformers in the current energy forecast, providing accurate energy consumption forecasts.

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Abbreviations

The following abbreviations are used in this manuscript:

NLP	Natural language
CNN	Convolution neural networks
ViT	Visual transformers
AUC	Area under the curve
MLP	Multi layer perceptron
BERT	Bidirectional encoder representation of transformers
DT	Digital twin
GRU	Gated recurrent unit
LSTM	Long short term memory

RNN	Recurrent neural network
SGD	Stochastic gradient descent
MSE	Mean-squared error
MAPE	Mean absolute percentage error
ACF	Auto-correlation function
PACF	Partial auto-correlation function

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buildings

Article

Assessment of Households' Perceptions of Health Co-Benefits in Relation to the Willingness to Undertake Energy Retrofits in Barcelona

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Abstract: Energy retrofits have, so far, been studied from the perspective of economic benefits that undertaking energy retrofit brings. They have also been of interest in the pursuit of reducing carbon emissions. However, few have studied the perception of health co-benefits of energy retrofits. Therefore, this paper seeks to shed light on how the residents' perception of their health affects their decision to undertake an energetic retrofit. The focus of this article is to determine how residents perceive their health and their willingness to undertake energy retrofits to improve their health in the municipality of Barcelona. The methods used were in-depth interviews with experts and face-to-face and surveys conducted online. The results were analysed using descriptive, segmental, and unconditional logistic regression. We also analysed if awareness of the health co-benefits of retrofits corresponded with the respondent's housing conditions, socio-demographics, and willingness to energy retrofit their homes. A total of 127 participants were included, of which 6.3% listed health co-benefit improvements as an influencing factor in undertaking an energy retrofit. The survey findings show that the less educated households are less aware of the health co-benefits of energy retrofits. These findings reveal the need to re-evaluate the current energy and housing policies.

Keywords: health co-benefits; indoor comfort; energy retrofit; cross-sectional survey

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1. Introduction

According to the United Nations Environmental Programme, the construction industry consumes 40% of the world's raw materials and 36% of CO_2 emissions in Europe [1]. The increase in carbon in the atmosphere contributes to rising temperatures, which requires higher energy consumption to preserve comfort in buildings placed in hot climates. This generates a repetitive cycle that contributes to global warming. Regarding local energy consumption, the residential sector accounts for 30% of the total in Barcelona municipality [2]. In a residential building, the building envelope plays a determining role in the impact of indoor conditions, such as thermal comfort, which may have an underestimated impact on the health conditions of its residents. Barcelona, however, is aggravated by poor housing conditions due to the age of the housing stock (80% of the housing stock predates 1979, when the first regulation requiring thermal insulation was passed) [3] and the inadequate implementation of insulation.

Directive (EU) 2010 (Energy Performance of Building Directive-EPBD) [4] introduced the imposition of Energy Performance Certificates (EPCs) to certify existing buildings and has been updated in 2018 and 2023. This recent recast introduced terms, such as energy poverty [5]. In Spain, however, the general transposition of this directive has not yet been fully implemented, as there is no clear persuasion of the benefits that efficient housing or the retrofitting of existing housing can bring.

Several studies have tried to quantify the co-benefits related to energy efficiency in retrofitted dwellings, the costs related to health services and medicines, and the temporary labour costs related to work losses. For example, Ortiz, J. and Salom, J. [6] investigated the economic impact of energy retrofit in residential buildings in Spain, through a cost–benefit analysis. The most significant contribution of such research consisted of estimating the return on investment, considering, on the one hand, the investment cost, and on the other, energy savings, avoided labour costs, and public health expenditures. By including such positive externalities, it is possible to reduce energy retrofit payback periods by almost half. An important limitation of this research is that the gradient between the cost of medicines and labour costs is taken from a public sector perspective; however, people also spend from their own resources, making it impossible to give a real economic value to this aspect. Furthermore, in order to characterise dwellings that cannot guarantee comfortable conditions in winter, the definition of energy poverty is based on the definition that total energy costs should not exceed 10%.

Martin Jakob [7] has proposed a methodology that quantifies the marginal costs of energy efficiency investment in the residential sector in Switzerland (e.g., benefit from avoided costs of generation and distribution of space heating when improving wall insulation and window systems). The cost–benefit analysis addresses key issues such as improved living comfort, indoor air quality, and protection against external noise. However, such research is unable to explain the economic effects of other environmental conditions (i.e., cold temperatures in winter, high temperatures in summer, damp and fungal problems) because it lacks epidemiological analyses for the respective diseases. The present research takes into account the factors contributing to the increased perception of co-benefits. The study carried out by Dell' Anna et al. [8] investigates, through contingent valuation and Bidding Game (BG), the health benefits related to retrofitting interventions in residential buildings in Turin. Its findings suggest that people are willing to pay (WTP) an amount of EUR 7541 on average, coming from improved comfort conditions and reduced negative health impacts. These investment amounts allow for the installation of various energy efficiency measures, such as the replacement of the boiler and windows/façade insulation. In short, we refer to the people WTP based on improving the architectural conditions of the dwelling. The present study tries to go a step further by considering, in addition, environmental factors, explicitness in health conditions, and the level of sensitivity in the perception of the recipients of these benefits. Baron A. [9] studied the change in perceived thermal comfort after implementing a neighbourhood-scale energy retrofit in Santa Coloma (Barcelona). However, it was limited to the winter period, relegating the fact that summer produces thermal stress aggravated by heatwaves in the Mediterranean area. Biere Arenas, R. et al. [10] used a survey and identified that perceived financial benefits (e.g., energy savings) and co-benefits (e.g., comfort and health) of efficient homes are contingent on the socio-demographic characteristics of the population. Older and higher-income people appreciate more co-benefits, such as health, comfort, and environmental conservation, but younger and lower-income people value economic aspects more. Certainly, in the same direction as the contributions, it is necessary to cite Marmolejo et al. [11]. Based on the hypothesis that "current living conditions influence perceived co-benefits", it was possible to explain, to some extent, whether these conditions affect the perception of co-benefits; however, the issue of health was made explicit in a general way, without breaking it down into the different vectors associated with the environmental conditions of housing, such as high temperatures in summer, cold temperatures in winter, dampness problems, low levels of air quality, and high levels of noise.

As can be seen in Table 1, a number of methodologies have been employed to study the impacts on benefits and co-benefits, focusing, however, on economic theories [6–8,12–15] (e.g., replacement costs, avoided costs, hedonic pricing, contingent valuation). However, these valuations have been criticised by arguments referring to the "*commodification of services*" [16] or aspects involving the value of life in countries with different income levels. Few have employed a methodology in which co-benefits are studied at the level of people's perceptions [9–11], but none have studied them merely at the level of health co-benefits by focusing on perceptions of health and their impact on undertaking energy retrofits.

Given that the importance of the issue of the effectiveness of EPCs is limited [17,18] in encouraging residents to commit to retrofitting their homes, there is a great need to understand the perception of the residents while facing the challenge of prioritising the financial savings of retrofitting their homes. The argument for energy savings, mainly in winter, is overshadowed in Mediterranean areas, such as Barcelona. For this reason, the objectives of this article were (a) to assess whether residents are aware of the influence that energy-efficient housing conditions have on their health; (b) assess the extent to which the population is willing to undertake energy retrofits once they are confirmed that there is a link between housing conditions and health; and (c) identify the perceptions that residents have on their health. All of the specific objectives listed can be compressed into a general one: determine whether health co-benefits influence residents' decision-making to undertake energy retrofitting. The novelty in this research lies in the fact that to date, although these health co-benefits have been increased in the number of studies published in the scientific literature in relation to greenhouse gas emission reductions and urban environmental health [19–22], no investigation has assessed residents' perceptions about health co-benefits and their impact on undertaking energy retrofits.

This paper also explores whether occupants' perceptions can contribute to undertaking energy retrofitting through passive design strategies, such as integral insulation in external walls and windows, when they are informed about health improvement.

Table 1. Selected indicators and methodology of different co-benefits.

Supporting Literature	Impact Subcategory	Causes	Physical Indicator	Method Used
Vandentorren et al. (2003) [9] France	High interior temperatures	Heat waves Living in a penthouse Lack of thermal insulation	Additional deaths Respiratory diseases Cardiovascular diseases	A case study in four different areas in France (where the heat wave was strongest)
Kampa and Castanas (2008) [10]	Indoor air quality	Particulate matter (PM10 and PM2.5). Nitrogen dioxide (NO_2). Sulfur dioxide (SO_2) emissions of Sox and NOx CO_2 and ozone (O_3)	Mortality Respiratory problems (asthma and chronic bronchitis) Cardiovascular problems Lung cancer	Avoided costs approach Contingent valuation method Willingness to pay (WTP)
Ortiz, J. and Salom, J. (2016) [6] Spain	Cold temperatures in winter	Age of the dwelling Existence and characteristics of the heating system Price of energy (heating)	Self-perceived health Respiratory diseases (asthma and chronic bronchitis) Cardiovascular diseases Mortality and morbidity	Characterise the housing stock in Spain Characterise dwellings that do not guarantee comfort conditions in winter Describe people's health
Chapman et al. (2003) [11] United States	Condensations (dampness and fungus)	Warm climates	Irritation, allergies, infections, and asthma	Meta-analysis
Bjørner, T. (2004) [12] Denmark Copenhague	Noise exposure	Road and air traffic Ambient noise above 55 dB	Cardiovascular diseases Cognitive impairment in children Sleep disturbance Tinnitus Increased mortality Irritation or anger	Contingent valuation and questionnaire Willingness to pay (WTP)

Table 1. *Cont.*

Supporting Literature	Impact Subcategory	Causes	Physical Indicator	Method Used
Martin Jakob (2004) [7] Swiss. Residential sector	Thermal comfort	n.a.	n.a.	* Avoided cost approach * Cost–benefit analysis
Barón Rodríguez, A. (2017) [13] Spain	Co-benefits Thermal comfort	n.a.	n.a.	* Survey * Descriptive statistical analysis
Biere Arenas, R. et al. (2023). [14] Barcelonés	Pecuniary benefits Co-benefits	n.a.	n.a.	* Survey * Multivariate analysis of results * Principal components
Marmolejo et al. (2020) [15] Spain	Co-benefits Thermal comfort	n.a.	n.a.	* Survey * Descriptive statistical analysis * Regression model
Larger scale; exterior housing				
Arellano, B. Et al. (2022) [23] Spain. Barcelona	Heat island	* Torrid temperatures	* Respiratory diseases * Cardiovascular diseases * Morbidity and mortality	* Individualised analysis for the four weather stations * Linear ordinary least squares regression (OLS)

Note: n.a. is "not applicable" Source: Prepared by the authors using the review by Ürge–Vorsatz et al. [24] and several authors.

2. Research Methodology

The methodology for conducting an assessment of residents' health perception consists of (1) methods and materials, where data collection is further elaborated; (2) a brief statistical analysis is performed to identify residents' health perception and awareness of the impact of housing conditions on health; and (3) finally, in the conclusions, guidelines for policy implementation are provided and limitations are highlighted, and the research methodology flowchart is shown in Figure 1. Lastly, the potential influencing factors of occupants' perception status are identified.

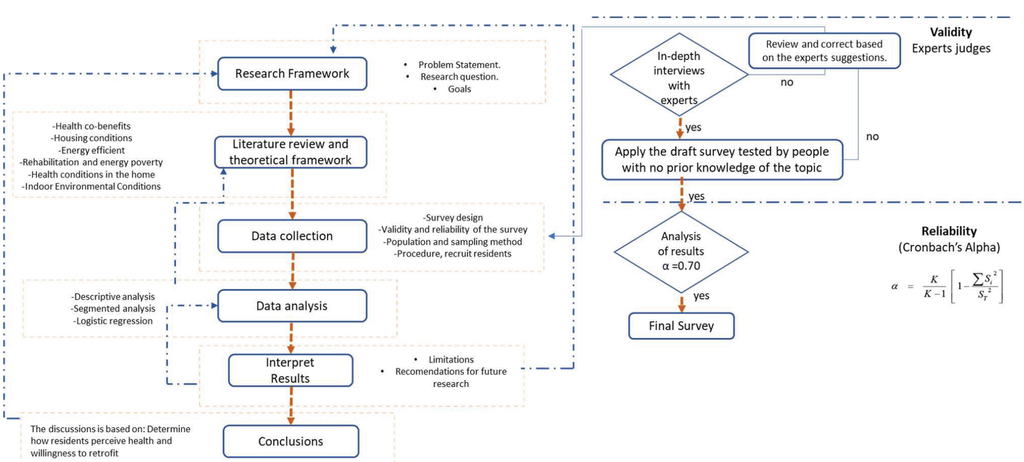


Figure 1. Flowchart of the research methodology.

3. Method and Materials

The methods used in this study can be divided into two sections: data collection methods and analysis methods.

3.1. Survey Design

A semi-structured questionnaire was developed following an extensive review of the scientific literature on health co-benefits. During the preliminary elaboration, some experts were interviewed (Table 2). The opinions and comments were incorporated into the revised questionnaire. The survey is based on the standardised questionnaire ASHRAE Standard 55:2017 [25] and ISO 10551:2019 [26] consisting of 15 questions on perception of health, thermal comfort, and willingness to undertake energy retrofits and 13 questions on housing conditions and characteristics. The socio-demographic information of the respondents was inquired at the end of the interview with 10 questions. In total, the questionnaire contained 38 questions.

Table 2. In-depth interviews with experts.

No	In-Depth Interview Topic	Interviewee	Date, Roll, and Affiliation
1	Introduction to co-benefits and cost-effectiveness assessment	Federico Dell'Anna	31 April 2022 Research Professor—Polytechnic University of Turin
Summary: To understand different methods to quantify the co-benefits of improved building efficiency.			
2	Review of previous surveys	Tian Weijia	21 December 2022 Research Professor—Tongji University
Summary: Review the advance and critique of the method and analysis of the prior epidemiological survey, Health Survey of Catalonia—ESCA in Spanish—2022.			
3	Review of survey draft	Deng Linshuang	23 February 2023 Post-Doctor Researcher–Tongji University
Summary: Categorise the five topics in the survey based on the hypothesis and research question.			
4	Review of survey draft	Joana Aina Ortiz Ferra	23 February 2023 Deputy Head of Thermal Energy and Building Performance—Fundació Institut de Recerca en l'Energia de Catalunya (IREC)
Summary: Apply the survey based on the ASHRAE 55 standard that measures comfort.			
5	Review of survey draft	Belen Onecha Perez	24 February 2023 Research Professor—Polytechnic University of Catalonia

Summary: feedback related to the characteristics of the dwelling conditions, such as the orientation of the main façade and heat-producing systems. Source: own elaboration.

The main indoor comfort parameters considered were thermal, acoustics, dampness, and indoor air quality (IAQ), but no direct subjective assessment methods for lighting were considered. The questionnaire also included basic diagrams where respondents indicated the location of the building, the main orientation of the façade, whether the windows or walls had external insulation, and the type of window and carpentry. Also, if any questions were not obvious, they were explained when taking the survey. The questions were mostly divided into qualitative questions with closed questions, Likert scale (7-point) multiple choice, single choice, matrix questions, and open questions. The sample questionnaire and technical details in Table 3 are structured as follows.

Housing Conditions: This section analyses the condition of the dwelling, starting from the year of construction according to the first and subsequent thermal insulation building regulations, and whether or not they have external insulation (walls and windows). Residents are also required to indicate their estimated electricity and gas bills, as well as whether they have heating and air conditioning in their homes.

Indoor comfort conditions in the dwelling. In this section, residents should express how satisfied they are with the indoor comfort, determined by the five environmental factors previously described: outdoor noise, indoor air quality, dampness and leaks, thermal comfort in summer, and thermal comfort in winter. In addition, residents have an open option to indicate any other problems with their dwelling.

Self-perception of health. In this section, an attempt is made to study residents' self-perception of their health, respiratory diseases, cardiovascular diseases, and mental illnesses, and there is a sub-section on the level of knowledge and understanding of perceptions of health co-benefits concerning housing conditions in general.

Willingness to undertake energy retrofits. The penultimate section explores the level of willingness to undertake energy retrofits to improve their health, and what factors are the main influences in making such a decision. It includes an open-ended multiple-choice question to express the difficulties in undertaking an energy retrofit.

Socio-demographic conditions. The last section looks at income levels, professions, age ranges, the dwelling tenure type, and a question where residents indicate whether, in the last twelve months, they have had any arrears on their mortgage, rent, or utility bills, to establish whether energy poverty exists.

Table 3. Technical details and structure of the survey.

Qualitative Study Technical Sheet		**Structure of the Survey Request**	**Answer Format**	**Statistical Reliability (Cronbach's Alpha)**
Research scope	Barcelona municipality	1.1 Which floor do you live on?	Closed, multiple choice	n.a.
Type of study	Primary qualitative descriptive and segmented study	1.2 Typology of your apartment	Closed, single option	n.a.
Research technique	Face-to-face and online surveys	1.3 Main orientation of your apartment	Closed, multiple choice	n.a.
Data collection instrument	A survey using ten closed-response Likert-scale questions, five closed-response single-choice questions, eight closed-response multiple-choice questions, three open-response free-text questions, and two matrix questions	1.4 Period of construction of your apartment	Closed, multiple choice	n.a.
Type of sample survey	Consecutive and stratified by sex and socio-professional in order to be accessible and representative of the study group	1.5 How much, on average, is your monthly electricity bill?	Open, free option	n.a.
Survey sample size	A total of 127 valid cases have been collected in the 10 districts of Barcelona, Spain, with a response rate of 9% from the neighbourhood associations	1.6 How much, on average, is your monthly gas bill?	Open, free option	n.a.
Survey error level	A total of 7% for global data in the assumed simple random sampling at a 90% confidence level, and p-q-0.5	1.7. Does your dwelling have external wall insulation?	Closed, single option	n.a.
Data collection period	25 March 2023 to 31 July 2023	1.8 Specify whether your exterior window glasses are original or whether you have upgraded them.	Matrix option	n.a.

Table 3. *Cont.*

Qualitative Study Technical Sheet		Structure of the Survey Request	Answer Format	Statistical Reliability (Cronbach's Alpha)
Research	EnerValor 2 research project	1.9 Specify whether your window frames are original or whether you have upgraded them.	Matrix option	n.a.
		1.10 Do you have a heating system in your apartment?	Closed, single option	n.a.
		1.11 What type of heating system is installed in your apartment?	Closed, multiple-choice	n.a.
		1.12 Do you have air conditioning installed in your apartment?	Closed, single option	n.a.
		2.1 How satisfied are you with the level of external street noise?	Closed, Likert scale	0.489
		2.2 How satisfied are you with the indoor air quality in your apartment?	Closed, Likert scale	0.721
		2.3 How satisfied are you with dampness problems, such as leaks or condensation?	Closed, Likert scale	0.524
		2.4 How do you perceive thermal comfort in summer?	Closed, Likert scale	0.401
		2.5 How do you perceive thermal comfort in winter?	Closed, Likert scale	0.462
		2.6 Please indicate any other problems in your apartment.	Free text	n.a.
		3.1 What would you say your general health is like?	Closed, Likert scale	n.a.
		3.2 Have you had any cardiovascular disease?	Closed multiple choice	n.a.
		3.3 Have you ever had a respiratory illness?	Closed multiple choice	n.a.
		3.4 Housing conditions have an impact on cardio/respiratory diseases?	Closed, Likert scale	0.821
		3.5 Housing conditions have an impact on mental health? (depression, etc.)	Closed, Likert scale	0.876
		3.6 Do housing conditions have an impact on your health?	Closed, Likert scale	0.861
		4.1 Are you willing to undertake energy retrofit in your apartment?	Closed, Likert scale	n.a.
		4.2 Which of these aspects of your dwelling would you be willing to...	Closed, single option	n.a.
		4.3 If you were to carry out an energy retrofit, which would you. . .	Closed, multiple choice	n.a.
		4.4 What makes it difficult for you to carry out an energy retrofit?	Closed, multiple choice	n.a.

Note: n.a. is "not applicable" Source: own elaboration.

3.2. Validity and Reliability of the Survey

The validity of the survey is concerned with the accuracy of the questions. This depends on formulating questions that actually measure what they are supposed to measure. Thus, the survey was discussed with various experts in the fields of architecture, energy efficiency, and health. A draft survey was tested on a restricted sample of experts, which had observations up to thirteen times, and was then tested by people with no prior knowledge of architecture (six relevant people chosen) to identify and resolve any complications with technical terms. Reliability refers to the internal consistency of the survey; that is, for questions using the Likert scale, Cronbach's alpha was used. Questions with multiple choices or closed single choices were discarded. The average test was conducted according to its structural groups where the perception of thermal comfort was 0.741, indicating an acceptable level of reliability, and awareness was 0.928, indicating that the questions are consistent.

On the other hand, points 3.1 and 4.1 are clearly not indicators of a common underlying factor. Alpha and any other consistency approaches are, therefore, inappropriate.

3.3. Population and Sample

The study was carried out in the municipality of Barcelona, Catalonia, in the north-east of Spain, where, according to the National Institute of Statistics (INE in Spanish), there are 671,177 households (population size) [27]. Within this group, there are two types of buildings: single-family housing and multi-family housing. The required sample size, n, was generated as $n = z^2Npq/e^2\ (N-1)\ z^2pq$, where n is the sample size sought, N is the size of the research scope = 671,177, z is 1.645 (with a confidence level of 90%) with a margin of error of 7%, and p-q is 50%. The result of the sample size is 138. In this paper, 127 residents agreed to participate in valid surveys. Therefore, given the limitations, the sample is not representative of each district but of the municipality of Barcelona as a whole. The sample was stratified by sex, which was representative of the distributions determined according to the latest statistical census of the city. Eligible respondents were residents for at least one year living in the city who were over the age of 18. Only one eligible member of each household was selected to complete the survey. The sample was compared with the characteristics of the total population, which showed similar distributions across genders (Table 4).

Table 4. Demographic information of the sample versus the total target population.

Items	Study Participants (N, %)	Target Population (%)
Barcelona municipality	127	1.63 million (in 2022)
Gender		
Male	54 (42.5%)	47.59%
Female	73 (57.5%)	52.41%

Source: own elaboration based on information from the National Institute of Statistics (INE in Spanish) data.

The distribution of the sample to make it as representative as possible was carried out following the socio-professional distribution in Barcelona [28]. On this basis, and based on the hypothesis that the level of health literacy is related to education and income level, neighbourhoods were selected according to the following criteria: (1) neighbourhoods with divergent socio-professional levels; (2) neighbourhoods with the highest number of tourists and rentals (Barrio Gótico, Raval, El Born, La Barceloneta, and Sant Pere) were discarded, as they are in the end of the agglomeration close to the historic centre where the percentage of temporary rentals is very high at 65.10% (Barcelona City Council. Oficina Municipal de Dades. Barcelona 2020 Socio-demographic Survey). Therefore, the distribution of the survey was mainly performed in the following neighbourhoods:

High income: Sarrià and Sant Gervasi;

Medium income: La Sagrera, Sants, and Sant Antoni;

Low income: Trinitat Vella, C. Meridiana, Roquetes, La Verneda and La Pau, and Bèsos.

These neighbourhoods are taken as the starting point; however, because the sample was partly online, the participation of residents in neighbourhoods other than those mentioned above was taken into account to a lesser extent.

3.4. Data Collection

Data were collected with a four-month survey conducted from March to July 2023. Participants were recruited through neighbourhood associations in each neighbourhood and community institution (e.g., civic centres, "Casals"). They responded to the paper through face-to-face interactions. Then, to increase the number of participants, a "snowball sampling" procedure was used. A QR code with the link to the questionnaire was used for people who could not be interviewed face-to-face. Participants were included as long as they were adults and residents of Barcelona municipality for at least one year. They were given 10–15 min to complete the survey anonymously. The questionnaire script was based on the Health Survey of Catalonia (ESCA 2022) (source: Plan estadístico de Cataluña, Departamento de Salud (ESCA)) and the ASHRAE 55 standard that measures the level of comfort in a building. A total of 18 institutions were visited, and a total of 127 residents agreed to participate (valid responses), of which 69% were paper responses through face-to-face interactions and 31% were online responses through the Qualtrics platform (QR codes with their own URLs were distributed through mailboxes or delivered personally to potential participants or through the associations' websites) (L'associació de veïns i veïnes del barri de Sants. Página web: https://www.centresocialdesants.org/ (accessed on 24 August 2023)).

3.5. Survey Improvement and Respondents Recruiting

Six people were selected for an in-depth questionnaire to determine if there were any specific fields/topics that were not yet covered that were relevant to include in the survey (Table 5). Therefore, these interviews were pilot-tested on the draft survey, where the inputs of the six random individuals without previous expertise were introduced to obtain the final design of the survey. The six people were chosen based on having no prior knowledge of the topic, relationships, or role in their neighbourhood. Thus, three Spanish women (n = 3), two Spanish men (n = 2), and one British nationalised Spaniard (n = 1) were accepted (Table 4). The first part of the interviews was carried out in parks, on the street, and, on a few occasions, in workplaces open to the public (e.g., flower shops), in three neighbourhoods depending on the socio-professional level: high, medium, and low (Ciutat Meridiana, Sant Antoni, and Sant Gervasi). Once we had identified the people and introduced ourselves as researchers, the following open questions were used: Are you a resident of Barcelona municipality for at least one year? Once the interviewee answered positively, we proceeded to carry out the questionnaire. The second part was carried out through the neighbourhood associations (AAVVs in Spanish). Multiple calls were made and e-mails were sent to all associations registered in the Federation of Neighbourhood Associations of Barcelona (favB) (source: FAVB Federación de Asociaciones Vecinales de Barcelona. Available online: https://www.favb.cat/entitats (accessed on 28 September 2023)), and seven AAVVs received a positive response. As expected, the associations with the greatest housing problems and low/middle income were the ones willing to participate. The third part was carried out by means of visits to the "Casals" and "Civic Centres" of certain neighbourhoods, where it was explained that a research project was being carried out, and we asked if we could go to an event or neighbourhood meeting to carry out the questionnaire together with the neighbours who were there.

Table 5. Profile of the five residents and their main contributions.

Idem	Features	Inputs
KE-1	Woman; 44 years old; Spanish; architect and professor. A resident of the Sant Gervasi neighbourhood; an expert in insulation and thermal materials.	Point 1.3. The east and west façade is added. Point 1.9. The iron carpentry is changed to steel. Point 6.8. It is specified that it is net per month.
KE-2	Female; 37 years old; Spanish. Deputy Director of Thermal Energy and Building Performance.	Design comfort questions are based on the ASHRAE 55 standard.
KE-3	Female; 21 years old; Spanish; law student.	Point 6.2. Ownership regime. A section is added with others to specify children who are living in the parents' house and do not own or rent. In addition, persons living in a concession of the use of the building.
KE-4	Male; 35 years old; Spanish. Neighbour and president of the AAVV Verneda. He has lived in the neighbourhood all his life.	Understanding technical terms to simplify them and other problems with housing such as asbestos, aluminosis, or leaks.
KE-5	Male; 38 years old; British. Comedian; 29 years in Spain. Resident of Sant Antoni.	Points 3.4, 3.5, and 3.6. Replace "The conditions of your dwelling . . ." with "the conditions of the dwelling in general...".
KE-6	Male; 45 years old; Spanish. Engineer. Resident of Parc Vall d'Hebron.	Point 1.10. The term "aerothermal" heat pump is changed to just "heat pump".

Source: own elaboration.

4. Statistical Analysis

Responses from both paper and online surveys were archived as a dataset in spreadsheet format. Only relevant variables were included for statistical analysis using the statistical package IBM SPSS Statistics version 29. First, all datasets were analysed with descriptive statistics to examine the distribution and identify outliers. Segmented analysis was also employed. Next, inferential statistical analysis was performed to compare variables using logistic regressions and reach a robust conclusion.

In addition, unconditional logistic regression analysis was conducted to assess associations of demographic variables, perceptions (from 1 = strongly disagree to 7 = strongly agree), and practice factors (independent variables) with respondents' perceptions of health co-benefits related to housing conditions (dependent variable, coded as missing = 0, and presence = 1).

5. Results and Discussion

5.1. Descriptive Analysis

5.1.1. Socio-Demographic Characteristics

Of the total number of participants surveyed, women accounted for 57.5% and men accounted for 42.5%, respectively. In terms of age distribution, the most prevalent group of residents surveyed was the 45–65 age group, specifically 52%, and 26.8% of residents were aged 25–34 and 9.4% were aged 65 and over. The sample covered various educational and occupational levels, with more than half of the respondents (52.0%) claiming to have completed university studies. A total of 26% had a bachelor's degree or technical studies, 10.2% claimed to have completed primary studies, and 11.8% claimed to have completed secondary studies. In terms of occupation, the most prevalent group (74.0%) is working. This is followed by 14.2% who are retired people (it should be noted that this percentage is higher than the percentage of people over 65 (9.4%) in the survey because Spain has an early retirement system, so it is possible to retire before this age); 7.1% who are unemployed (a figure very similar to the unemployment rate as of July 2023 of 6.92% according to the National Statistics Institute, INE); and 4.7% who do housework, are students, and others.

The average net monthly family income is almost even (29.1%) for the two groups and is between EUR 1001 to 2000 and EUR 2001 to 3500. Likewise, 27.6% made EUR 3500 per month. Only 12.6% do not exceed EUR 1000 per household.

In relation to housing tenure, 66.9% are owners and 30.7% are tenants. Only (2.4%) live in another type of housing tenure, such as, for instance, cession of use. Also, within the "other" group, it should be noted that there were participants who lived in the home of a relative or were young adults who had not yet become independent.

With respect to energy poverty, i.e., households in arrears due to financial difficulties, the question was divided into five groups (Figure 2), where the most prevalent group (7.9%) was utility expenses, specifically gas and electricity (not including property tax nor rubbish collection fee) followed by water (6.3%) (it is worth mentioning that a specific group is taken for water with respect to the others, such as electricity and gas, due to the fact that since 2014, a measure of not cutting off the water supply to any user was approved). Interestingly, the groups of mortgage loans and deferred purchases or other loans are evenly matched, with 3.9% being overdue one or more times. Although rent arrears only account for 3.1%, this relatively low percentage can be explained by the fact that arrears can lead to an eviction claim or interest generated by late payment.

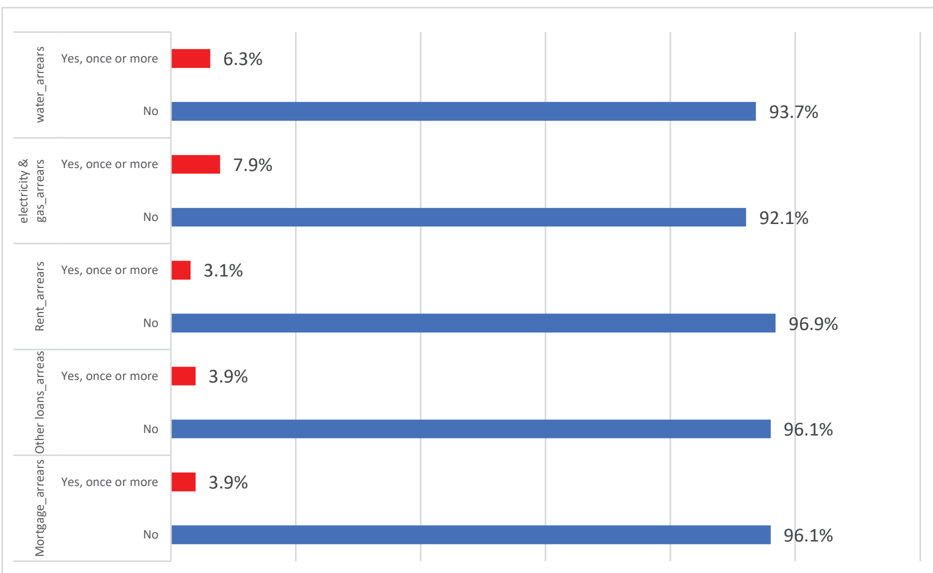


Figure 2. Arrears of a bill due to financial difficulties.

5.1.2. Housing Conditions and Attributes

By analysing the profile of housing conditions and attributes, it is observed that the predominant typology in Barcelona is the multi-family dwelling (83.5%), as opposed to the single-family dwelling with only 16.5%. In addition, in multi-family dwellings, which encompasses different types of floors, almost a third of respondents live on intermediate floors of the building (73.11%), with 14.29% in attics, 7.56% on the ground floor, and 5.04% in mezzanines. It is important to typify these types of floors because the scope of the study will focus exclusively on the exterior facades, which will be seen in the impact of the energy efficiency of the exterior walls and windows and whether or not they have good thermal insulation.

Regarding the orientation of the main façade of the dwelling, 54.3% of apartments face south and west, which is a convenient configuration for sun exposure during winter, although it may represent overheating during summer.

Regarding the period of construction, most of the dwellings (68.5%) were built before 1979, when the first Spanish construction code included minimum insulation requirements for buildings so that if they have not been retrofitted; they are in a state of "energy ruin". On the one hand, it can be seen that 18.1% of apartments were built in the period from 1980 to 2007 when the technical code was (including more restrictive thermal insulation) put into effect. On the other hand, only 9.4% of apartments were built after 2007, which took into account the energy-saving criteria of the newest construction code.

The group of the renovation of external windows in Figure 3 encompasses different types of materials: joinery (aluminium or PVC, wood), types of glazing (single and double glazing), and the type of renovation used (original, renovated by the owner himself or renovated by the previous owner).

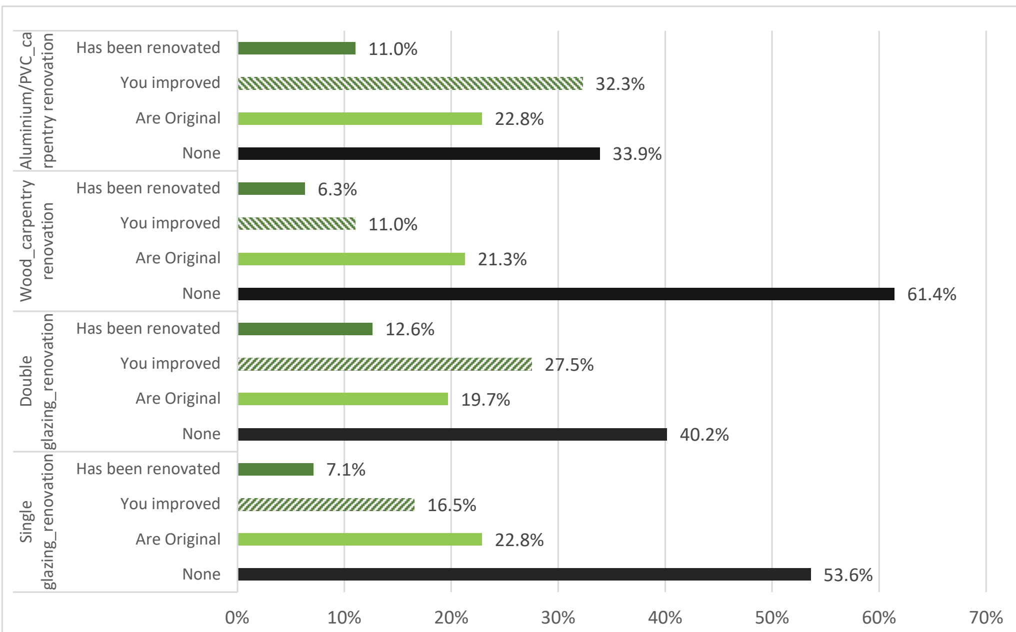


Figure 3. Percentage of exterior windows according to type of renovation.

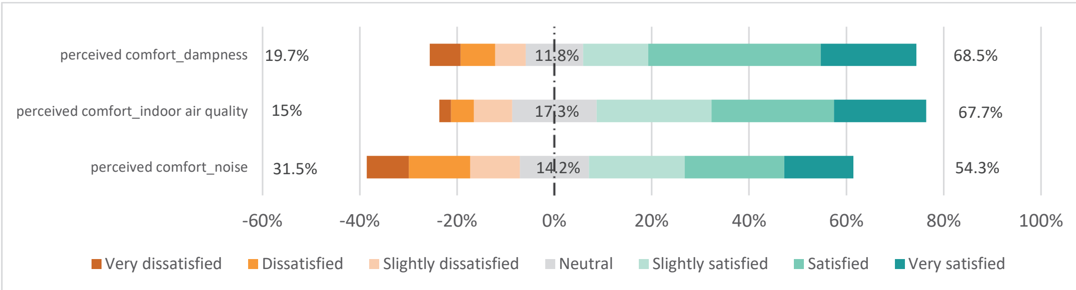
Sorting by material, it can be seen that the two largest groups are "aluminium joinery" (66.1%) and "double glazing" (59.8%), followed by "wooden joinery" (38.6%) and "single glazing" (46.5%), respectively.

As can be seen, the sum of the glazing typology and the joinery make up more than one hundred percent. This is because some residents claimed to have more than one type of glazing or joinery on the main external façade.

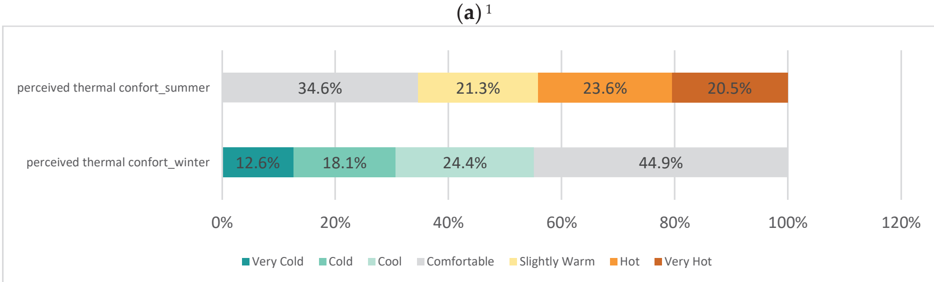
5.1.3. Perception of Indoor Comfort Conditions

Residents' perception of their homes is based on the context of the climatic conditions of Barcelona municipality, which has a "warm subtropical Mediterranean/dry summer" climate in the Köppen–Geiger climate classification.

Figure 4a shows the perception of indoor comfort conditions in the dwelling. In the first quadrant, the clear climatic factor of environmental quality focuses on satisfaction with the indoor air level, outdoor noise from the street, dampness, and leaks.



(**a**) [1]



(**b**)

Figure 4. (**a**) Percentage of perceived indoor comfort. Own elaboration. (**b**) Percentage of perceived thermal environment. Note: without relying on mechanical systems, such as heating or air-conditioning being turned on. (a) [1]: Due to limitations in the text editing software, in mathematical contexts, the intended representation of hyphens (-) is a minus sign (−).

The responses were summarised by counting the number of responses to each question at each of the defined scale levels to provide a graphical summary of the results (Figure 4a). Approximately one-third (31.5%) reported that they are not satisfied with the external street noise, and this paper only focuses on the comprehensive renovation of the external walls and windows (see limitations).

Regarding dampness and leaks, 19.7% indicated that they are dissatisfied and that there is some kind of leakage. For example, the lack of adequate water tightness causes the water that infiltrates the interior through filtration to peel off the walls and produce saltpetre stains and mould.

Similarly, 15% said they are dissatisfied with the indoor air quality in their home, but this should be taken with caution, as many elements are undetectable to smell and micro-organisms present in indoor air (see limitations).

Figure 4b shows the perceived thermal comfort. In one corner, the perceived thermal comfort in summer is shown, and in the other corner, the perceived thermal comfort in winter is shown. Knowing that heating and cooling systems are used to counteract construction deficiencies and acclimatise the dwelling, in the questions related to thermal comfort, it was explained that they should indicate their level of perception in summer/winter without considering the heating or cooling systems to be on.

It is worth noting that approximately two-thirds (65.4%) stated that they perceive thermal discomfort in summer, as opposed to winter (55.1%). This finding is interesting since due to climate change, summers have increased their length and have several heat waves. In addition, the period of the questionnaire (from the end of winter to mid-summer) could significantly influence the answers.

5.1.4. Self-Perception of Health

According to Figure 5, participants were asked about their self-perceived health. The majority (78.7%) reported that they are in good health, as opposed to 4.7% who said that their overall health is poor.

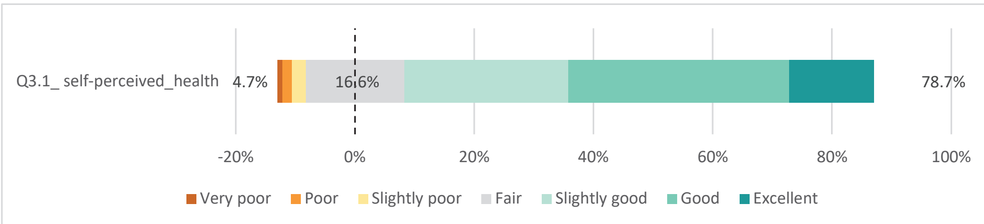


Figure 5. Percentage of residents' self-perceived health. Own elaboration. Note: Due to limitations in the text editing software, in mathematical contexts, the intended representation of hyphens (-) is a minus sign (−).

It should be noted that the format used may have biased some sensitive questions, such as the self-perception of health (see limitations). Therefore, one of the advantages of using both methods (face-to-face and online surveys) is that one neutralises the other, i.e., when respondents answered online, due to the anonymity, they felt freer to answer, as some diseases are still considered taboo and they prefer not to disclose them face-to-face.

However, when asked if they had had any cardiovascular disease, 78.7% said they had no disease, in contrast to 15.7% who had high blood pressure, 2.4% who had myocardial infarction, and 3.1% who had other ailments. It is worth noting that other cardiovascular diseases include arrhythmia, etc.

Regarding respiratory diseases 80.3% of respondents reported that they do not have any disease. On the other hand, within the 19.7% who have a respiratory disease, there is a tie with (8.7%) those who stated that they have chronic allergy and asthma or chronic bronchitis. On the other hand, and to a lesser extent, 0.8% have Chronic Obstructive Pulmonary Disease (COPD), and 1.6% have other diseases, including, for example, cancer.

5.1.5. Awareness of the Health Co-Benefits of Housing Conditions

Figure 6 summarises respondents' perceptions of health co-benefits about building quality in different health sectors: general health, cardio-respiratory diseases, and mental illness. In general, residents showed levels of agreement, but with some degree of confusion. For example, with the statement "Housing conditions (meaning the architectural-constructive quality of housing) have an impact on your health", two-thirds (66.9%) of the participants agreed, but 26% disagreed, which is a significant percentage.

In reference to the level of agreement with the statement "Housing conditions, in general, have an impact on the fact that I may suffer from some mental illnesses (depression, anxiety, nervousness, etc.)", about one-third (32.3%) disagreed, which was the highest percentage among the three aspects studied.

In the group of cardio-respiratory diseases with the statement "Housing conditions in general impact on the fact that I may suffer from some cardio-respiratory diseases, premature death, etc..", 28.3% indicated that they disagreed with this statement, while 11% said they were neutral.

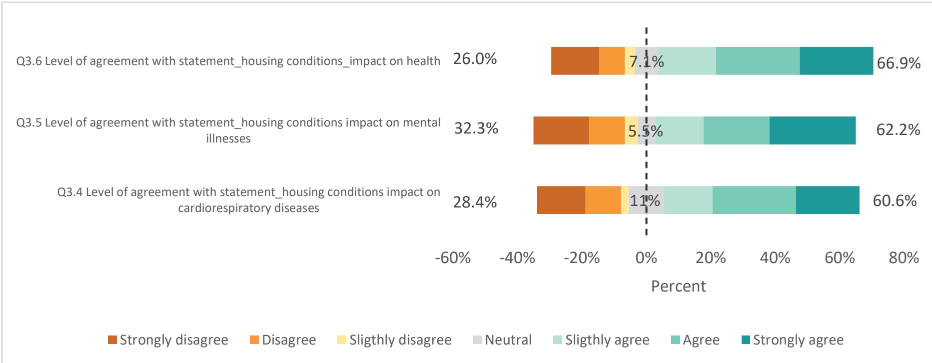


Figure 6. Percentage of awareness of the fact that housing conditions have an impact on health.

5.1.6. Willingness to Undertake an Energy Retrofit

With regard to the question, "How willing are you to undertake energy retrofits of your home in order to improve your health?" Residents showed interest, and 65.4% agreed to undertake energy retrofits, leaving the economic issue aside; however, 19.7% indicated that they were unwilling to undertake energy retrofits because their house is new or was recently retrofitted, and 15% were neutral (Figure 7).

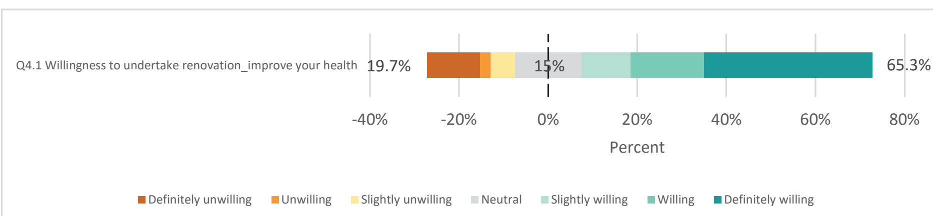


Figure 7. Percentage of residents willing to undertake energy retrofits. Own elaboration.

Regarding, the question "In the case that you were willing to carry out an energy retrofit, which of the following factors are the main ones that influence your decision?" six statements were given: "Increasing the value of the dwelling, environmental protection, reducing the energy bill, improving my health, improving in thermal comfort and all the above". Almost one-third of respondents (32.3%) selected all of the above options. If we disaggregate further, in second place, as expected, is the economic factor (25.2%). Respondents indicated that they would retrofit their homes if it reduced energy costs, while relatively few (18.9%) admitted that they would like improvements in thermal comfort and environmental protection (8.7%), and improving their health was in last place (6.3%). Therefore, although most people are aware of the co-benefits (such as thermal comfort and health), it seems that the economy still takes prominence when undertaking retrofitting. The health co-benefits are not an influencing factor that impacts residents' decision-making to undertake an energy retrofit.

Regarding the barriers to carrying out an energy retrofit, the largest problem is the "lack of financial aid or subsidies" (45.7% of the total), followed by 13.4% who "live in rented accommodation" and would not be interested in retrofitting because they feel they are in a temporary space. Finally, 11.8% stated "recovering the investment in the long term" and "lack of information on subsidies".

5.2. Segmented Analysis

- *Relationship between awareness of health co-benefits and educational attainment*

Segmented analyses were conducted first to examine the associations between each independent variable (socio-demographic) and the dependent variable (participants' perceptions of health co-benefits). Due to the number of samples and for the sake of a quick understanding, the Likert scales of the variables are re-escalated into two groups: the first group (strongly disagree to neutral) and the second (slightly agree to strongly agree).

Looking at the results, there is a clear trend towards a lack of knowledge that "housing conditions impact on health", with more than three-quarters (76.9%) of residents with primary education and more than half (53.3%) with secondary education. Such a lack of awareness decreases significantly among respondents holding technical studies and postgraduate or university degrees (22.7%) (Figure 8).

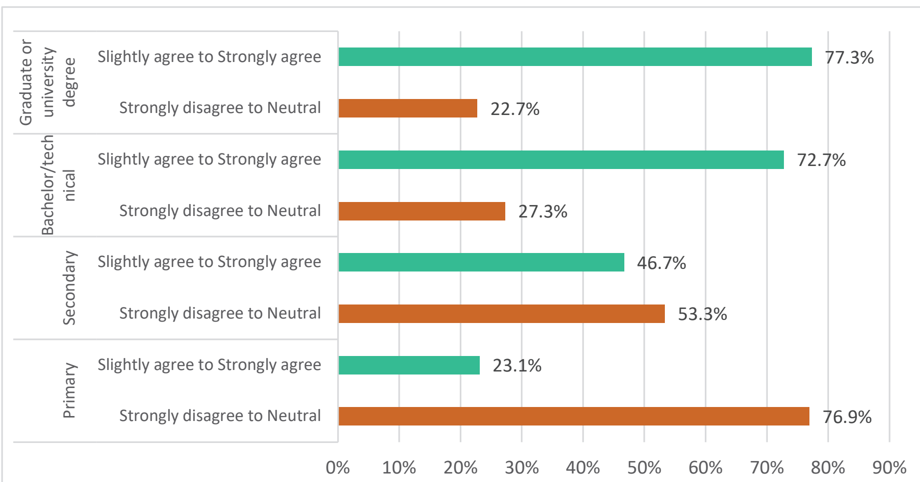


Figure 8. Percentage of the level of agreement with the statement "housing conditions have an impact on health".

- *Explanatory model for awareness*

The correlation between awareness of the effect of housing conditions on health and educational attainment is studied using a set of bivariate regressions. For this purpose, other control variables of socio-demographic factors, such as "Age", "Gender", "Family monthly average income", and "Neighbourhoods", have been controlled, but none of them turned out to be statistically significant, possibly because of the modest sample size. As seen in Figure 9, according to the results, the model is able to explain the awareness of the participants by 12%.

Model Summary

Step	-2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
1	145,586 [a]	0.116	0.161

[a] Estimation has been terminated at iteration number 4 because the parameter estimates have changed by less than 0.001.

(**a**)

Classification Table [a]

Observed			Predicted: q3.6_levelofagreement_statement_housingconditions_health_si — Strongly disagree to Neutral	Predicted: q3.6_levelofagreement_statement_housingconditions_health_si — Slightly agree to Strongly agree	Percentage Correct
Step 1	q3.6_levelofagreement_statement_housingconditions_health_si	Strongly disagree to Neutral	18	24	42.9
		Slightly agree to Strongly agree	10	75	88.2
	Overall Percentage				73.2

a. The cut value is 0.500

(**b**)

Variables in the Equation

		B	S.E.	Wald	df	Sig.	OR
Step 1a	Q6.6_Education level	0.750	0.200	14.108	1	0.000	2.117
	Constant	−1.627	0.644	6.384	1	0.012	0.197

a. Dependent variable: awareness
OR: odds ratio; SE: standard error; df: degree of freedom

(**c**)

Figure 9. (**a**) Summary of the regression model to explain residents' awareness about "housing conditions have an impact on health". (**b**) League table to explain residents' awareness about "housing conditions have an impact on health". (**c**) Coefficients in the regression model to explain residents' awareness about "housing conditions have an impact on health".

The model educational attainment is significant at almost 99% (OR = 2.11; 95% CI: 0.99). +Education = +Awareness.

- *Relationship between respiratory diseases and dampness*

In this analysis, respiratory diseases are the dependent variable and dampness is the independent variable. For this purpose, dummy variables have been established, i.e., whether people perceive that they have respiratory diseases (asthma, bronchitis, chronic allergy, etc., and a value of 1 is adopted) or do not have respiratory diseases (a value of 0 is adopted). Furthermore, perceived dampness used a Likert scale where 1 is very dissatisfied with dampness and 7 is very satisfied.

According to Figure 10, the results show that perceived dampness is significant and correlates negatively with respiratory diseases, i.e., the more dissatisfied with perceived dampness the participants are, the higher the significance of having respiratory diseases. However, it is rather weak (R^2 0.05). By contrast, other control variables such as education, family income, and age have been used; however, they have not entered the model, as they appeared statistically non-significant.

For this model, indoor air quality has been discarded, as there was multicollinearity between the former and the dampness variable. The Pearson correlation method (0.575), therefore, confirms the correlation between these two variables.

+Dissatisfaction Dampness = +Respiratory Illnesses.

Model Summary

Step	-2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
1	120,078 [a]	0.045	0.072

[a] Estimation terminated at iteration number 4 because parameter estimates changed by less than 0.001.

(**a**)

Classification Table [a]

Observed			Predicted q3.3respiratory_diseases_si No	Predicted q3.3respiratory_diseases_si No	Percentage Correct
Step 1	q3.3respiratory_diseases_si	No	102	0	100.0
		Yes	25	0	0.0
	Overall Percentage				80.3

[a] The cut value is 0.500.

(**b**)

Variables in the Equation

		B	S.E.	Wald	df	Sig.	OR
Step 1 [a]	Q2.3_perceived_dampness	−0.291	0.119	5.930	1	0.015	0.748
	Constant	−0.020	0.585	0.001	1	0.972	0.980

a. Dependent variable: respiratory diseases
OR: odds ratio; SE: standard error; df: degree of freedom

(**c**)

Figure 10. (**a**). Summary of the regression model to explain people's perception of whether they have respiratory diseases. (**b**). League table to explain people's perception of whether they have respiratory diseases. (**c**). Coefficients in the regression model to explain people's perception of whether they have respiratory diseases.

- *Relationship between willingness to undertake energy retrofits and housing conditions*

For this purpose, we used the control of the factors or attributes of the dwelling, including "heating", "A/C", "external walls insulation", "external windows insulation", "façade main orientation", "year of construction", and "type of dwelling", and socio-economic variables, including "Age", "Regimen", "Education level", "gender", and "family average income", and dummy variables by neighbourhood (high, medium, and low income) were also controlled.

The dummy variable for the neighbourhood was recategorised into three categories (a high-income neighbourhood with a value of 1 and other neighbourhoods with a value of 0); (a medium-income neighbourhood with a value of 1 and other neighbourhoods with a value of 0); (a low-income neighbourhood with a value of 1 and other neighbourhoods with a value of 0). Then, dummy variables were established to examine the dependent variable, i.e., the answers obtained by the Likert scale were grouped with values from 1 to 7, where if you are more willing to undertake a reform to improve your health, a value of 1 is adopted, or if you are less willing to undertake a reform to improve your health, a value of 0 is adopted. According to the results (R^2 0.047), (Figure 11) the model shows that it is able to explain the willingness to undertake energy retrofits of the participants by only 5%.

Model Summary

Step	-2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
1	157,743 [a]	0.047	0.065
2	152,020 [a]	0.089	0.123

[a] Estimation terminated at iteration number 4 because parameter estimates changed by less than 0.001.

(**a**)

Classification Table [a]

Observed			Predicted: q4.1_willingnesstoundertakenrenovation_si Unwilling	Predicted: q4.1_willingnesstoundertakenrenovation_si Willing	Percentage Correct
Step 1	q4.1_willingnesstoundertakenrenovation_si	Unwilling	0	44	0.0
		Willing	0	83	100.0
	Overall Percentage				65.4
Step 2	q4.1_willingnesstoundertakenrenovation_si	Unwilling	7	37	15.9
		Willing	3	80	96.4
	Overall Percentage				68.5

a. The cut value is 0.500

(**b**)

Variables in the Equation

		B	S.E.	Wald	df	Sig.	OR
Step 1 [a]	q1.7_exteriorwindow_insulation_si	−0.937	0.382	6.002	1	0.014	2.552
	Constant	0.143	0.268	0.285	1	0.593	1.154
Step 2 [b]	q1.7_exteriorwalls_insulation_si	−1.073	0.466	5.303	1	0.021	0.342
	q1.7_exteriorwindow_insulation_si	−1.410	0.460	9.394	1	0.002	4.094
	Constant	0.331	0.284	1.362	1	0.243	1.393

a. Dependent variable: willingness to undertake a renovation. b. Dependent variable: willingness to undertake a renovation included two probabilities
OR: odds ratio; SE: standard error; df: degree of freedom

(**c**)

Figure 11. (**a**) Summary of the regression model to explain willingness to undertake energy retrofits. (**b**) League table to explain readiness to undertake energy retrofits. (**c**) Coefficients in the regression model for willingness to undertake energy retrofits.

According to the housing conditions, the insulation of exterior windows is significant in 99% of cases, i.e., residents who have no or little insulation in exterior windows are more willing to renovate. Furthermore, in the second step, it is noted that the insulation of external walls influences the model with the expected negative sign. Consequently, the more exterior wall insulation, the lower the probability of undertaking energy retrofits.

−External Windows Insulation = +Willingness to Undertake a Retrofit.

−External Walls Insulation= +Willingness to Undertake a Retrofit.

- *Relationship between cardiovascular diseases and neighbourhood (income)*

Cardiovascular disease was also studied as a predictor variable, where it was coded as 0 = does not have cardiovascular disease or 1 = does have cardiovascular disease.

Figure 12 shows the results are interesting because they highlight two aspects. First, age is significant at 99%, i.e., the higher the age, the higher the probability of cardiovascular disease. Second, the low-income neighbourhood is significant at 96%, meaning that neighbourhoods with lower economic capacity have a higher probability of cardiovascular disease. The model has an R^2 of 0.117.

+Age = +Cardiovascular Disease.

Low-income Neighbourhood = +Cardiovascular Disease.

Model Summary

Step	-2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
1	119,729 [a]	0.088	0.136
2	115,588 [a]	0.117	0.182

a. Estimation terminated at iteration number 5 because parameter estimates changed by less than 0.001.

(**a**)

Classification Table[a]

Observed			Predicted q3.2cardiovascular_disease_si No	Predicted q3.2cardiovascular_disease_si Yes	Percentage Correct
Step 1	q3.2cardiovascular_disease_si	No	100	0	100.0
		Yes	27	0	0.0
	Overall Percentage				78.7
Step 2	q3.2cardiovascular_disease_si	No	97	3	97.0
		Yes	21	6	22.2
	Overall Percentage				81.1

a. The cut value is 0.500

(**b**)

Variables in the Equation

		B	S.E.	Wald	df	Sig.	OR
Step 1[a]	Q6.5_Age(years)	1.023	0.342	8.964	1	0.003	2.781
	Constant	−5.160	1.361	14.381	1	0.000	0.006
Step 2[b]	Q6.5_Age(years)	0.858	0.341	6.310	1	0.012	2.357
	Neighbourhood_li_si	0.968	0.474	4.170	1	0.041	2.634
	Constant	−4.917	1.328	13.700	1	0.000	0.007

a. Dependent variable: cardiovascular diseases. b. Dependent variable: cardiovascular diseases included two probabilities
OR: odds ratio; SE: standard error; df: degree of freedom

(**c**)

Figure 12. (**a**) Summary of the regression model for people's perception of whether they have cardiovascular disease. (**b**) Classification table to explain people's perception of whether they have cardiovascular disease. (**c**) Coefficients in the regression model to explain people's perception of whether they have cardiovascular disease.

6. Conclusions

The assessment of the perception of health co-benefits in energy retrofitting yields several conclusions that shed light on the insufficiency of the existing knowledge. The awareness of the health co-benefits of housing conditions does not significantly influence residents' decision-making to undertake retrofitting. Only 6.3% of the participants listed health improvements as an influencing factor when asked about their willingness to do an energy retrofitting. It seems that economic factors influence the decision-making process much more than health co-benefits, with 25.2% of the participants listing the economic aspect as an influencing factor, as presented in Section 5.1.6. However, when viewed as a whole, including other factors, health co-benefits associated with efficient homes would have a positive impact on willingness to undertake energy retrofits. Secondly, it is noted that people feel more uncomfortable in summer (65.4% of surveyed households) (Figure 4b) than in winter, which corroborates with what is currently happening primarily because of climate change, which has driven longer and hotter summers [29]. Thirdly, the level of education attainment of the participants played a statistically significant role in their awareness of the relationship between housing conditions and the residents' health. Higher levels of education were associated with greater awareness (OR = 2.11, 95% CI, Sig. 99%).

Based on the findings of this study, it is clear that neighbourhoods with lower income levels are those with greater comfort deficits, which could have a greater impact on cardio-respiratory diseases. Public health awareness campaigns are extremely important to raise awareness of health co-benefits related to housing conditions and should be targeted primarily at these lower-income neighbourhoods.

Discussion, Limitations of the Study, and Future Research

The findings of this research have brought to light valuable information on the impact that the resident's awareness of the relationship between health and housing conditions has on the resident's willingness to undertake energy retrofits. Firstly, the perception of satisfaction with indoor environmental quality (IEQ) can be further developed by covering other environmental aspects, such as visual comfort, with factors such as the amount of daylight reaching the dwelling and the impact that this has on the perception of health. Secondly, with regard to future studies in housing retrofits, it would be important to explore the difficulties of reaching an integrated management or consensus for a retrofit among the owners of the same residential building. This kind of detailed knowledge would allow better public policies to be directed to enable more efficient energy retrofits. Additionally, it is important to mention that the focus of this study was on the possible renovation of the insulation of windows and external walls, covering only part of the housing attributes. There are still various aspects that affect occupant comfort, such as solar radiation and adequate shading in the apartment. Future research can contribute to developing various strategies to assess the perception of indoor comfort.

The present article has some limitations that should be acknowledged. First, the 127 surveys conducted in this study are not enough to draw clear conclusions on each district separately but rather to offer an understanding of the residents' willingness to undertake retrofits based on their perception of their health in the general scope of the whole municipality of Barcelona. Further, limitations of the present study are the absence of lighting issues and the absence of objective measurements because of the assessment of thermal comfort satisfaction using subjective judgment scales based on their perceptions. Another limitation of the research on indoor comfort regarding the perception of noise is that the noise coming from neighbouring apartments, the interior courtyards, or the apartment itself was excluded, while only external noise coming from the street was included in the survey. This is because in this study, the focus was set on researching the retrofit of the external walls and windows. Additionally, in indoor air quality with regard to the perception of odours, many elements are undetectable to the sense of smell, and micro-organisms are present in indoor air (e.g., PM 10 and PM 2.5, formaldehyde); therefore, it is likely that in many cases the air quality is worse but was not perceived as such. Also, the health perceptions of the residents researched in this study might be disproportionally affected by the season during which the surveys were conducted. The season was the summer of 2023 when many people living in Barcelona were going through one of the worst heat waves in Europe [23,29]. For further studies, a year-round balance in the surveys should be further developed. Finally, the results of the research may have been affected due to possible unwillingness to answer honestly to the self-perception of health-related questions in the format used, face-to-face interviews, despite ASHRAE standard 55 and ISO 10551, due to the stigma on health issues and social desirability biases [30]. Nonetheless, to counteract these potential biases, the survey was partially conducted using anonymous online surveys, and a greater willingness to answer sensitive questions online was observed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14010236/s1. The questionnaire S1: Survey to assess the Households' Perceptions of Health Co-Benefits.

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buildings

Article

A Method to Compute Shadow Geometry in Open Building Information Modeling Authoring Tools: Automation of Solar Regulation Checking

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Abstract: Building solar protection regulations is essential to save energy in hot climates. The protection performance is assessed using a shading factor computation that models the sky irradiance and the geometry of shadow obstructing the surface of interest. While Building Information Modeling is nowadays a standard approach for practitioners, computing shadow geometry in BIM authoring tools is natively impossible. Methods to compute shadow geometry exist but are out of reach for the usual BIM authoring tool user because of algorithm complexity and non-friendly BIM implementation platform. This study presents a novel approach, dubbed solid clipping, to calculate shadow geometry accurately in a BIM authoring tool. The aim is to enhance project delivery by enabling solar control verification. This method is based on typical Computer Aided Design (CAD) in BIM authoring tools. The method is generic enough to be implemented using any BIM authoring tool's visual and textual API. This work demonstrates that a thermal regulation, here the French overseas one, can be checked concerning solar protection, thanks to a BIM model. Beyond automation, this paper shows that, by directly leveraging the BIM model, designs presently not feasible by the usual process can be studied and checked.

Keywords: shading factor; building information modeling; solar protection; shadow geometry; regulation checking; automation

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1. Introduction

The incorporation of renewable energy sources is essential for attaining enduring sustainability [1]. Limitless solar energy is necessary to mitigate the construction sector's greenhouse gas (GHG) emissions [2]. There are two methods for converting radiative energy. The first is thermal transfer, where the energy is used for heating purposes or to generate hot water by passing it through the building envelope. The other method involves the absorption of solar radiation by solar panels, which then convert it into electric energy using photovoltaic (PV) systems [3]. Optimizing both conversion systems is crucial to achieving optimal performance throughout the seasons, particularly in tropical climates [4–6]. It is essential to consider the unique characteristics of each building, like shadows. Considering shadows is crucial to guarantee the dependable functioning of systems. While building designers may prioritize assessing the overall performance of a structure, such as energy consumption per square meter, they can also utilize more minor scale performance indicators, such as the shading factor, to evaluate specific components. This factor quantifies the proportion of energy that reaches the glass surface of a window, taking into account any potential barrier caused by the surrounding environment, compared to the energy that comes to the surface without any obstruction. Subsequently, it can be employed, specifically in regions with tropical climates, to assess the efficacy of shade devices. Similarly to the regulations followed in Indonesia and India [7], the French regulation for tropical climate (RTAADOM) presents a parametric model and tables of acceptable values for determining the shading factor of some building components such as walls or windows. These values are contingent upon the location of the building and the orientation of the windows [8–11].

Figure 1 shows the framework of this paper. The left part of the figure illustrates this point of view and highlights each stage's important input and output. The right part shows different implementation alternatives regarding the computation stages. The left part of Figure 1 shows that regulation based on the shading factor relies on three stages: (1) evaluation of shadow geometric features such as area, (2) integration in a shading factor model to compute the value of shading factor, and, finally, (3) comparison to a reference value to check a regulation. This paper focuses on this framework of regulation checking thanks to a shading factor. While the second stage is nowadays straightforward, thanks to accessible numerical tools such as a spreadsheet or a scripting language, the computation of 3D shadow geometry features (first stage) remains a challenging task.

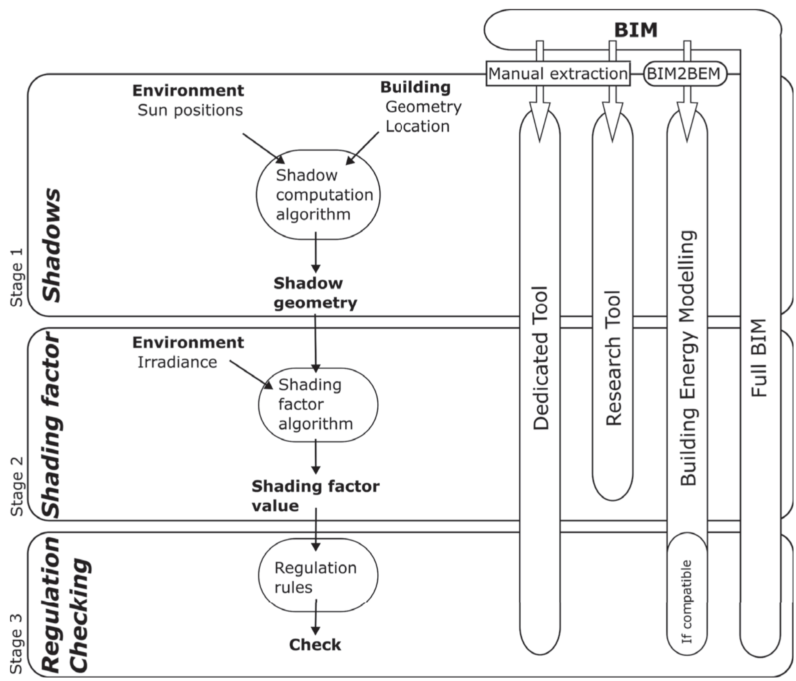
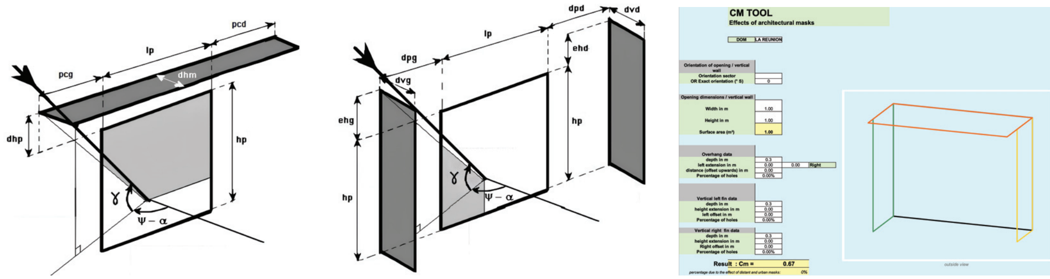


Figure 1. Checking of a regulation based on shading factor computation is split into three stages: (1) shadow geometry computation, (2) shading factor computation, and (3) checking regulation.

The RTAADOM offers a specialized tool in a secure spreadsheet that combines all steps necessary to calculate shading factor values. The system utilizes a basic parametric geometric model of solar protection, requiring the user to manually map their building design onto the parameter space of the geometric model. Figure 2 shows both the geometric configurations modeled in the RTAADOM and a snapshot of the user interface. Figure 2a shows all the parameters used to parametrize the overhang protection. If vertical fins are added, Figure 2b shows all the supplementary parameters to parametrize them. The official and protected spreadsheet that implements this model can be found on the French government website [12] and a snapshot of the interface is shown in Figure 2c. While the user directly inputs most parameters to describe the solar protection geometry, the parameters ψ and ϕ correspond to the sun's position in the computation and are not exposed to the user. Real designs are generally more complex than the geometric model and the projection represents a critical step in the process. To overcome this point, in other words, to compute the shading factor with complex geometry, two alternative approaches are identified. The first one is to use research tools that implement various approaches over the first two stages of the process. While very flexible and capable thanks to cutting-edge algorithms, by design, its purpose is not oriented through checking and relies on tailored inputs.



(**a**) (**b**) (**c**)

Figure 2. RTAADOM geometric model: (**a**) configuration and parameters to describe overhang, (**b**) configuration and parameters to describe fins, and (**c**) snapshot of the translated protected spreadsheet implementing the model with overhang in orange, vertical left fin in green and vertical right fin in yellow.

Designers can use Building Energy Modeling (BEM) approaches and established and reliable tools like EnergyPlus. EnergyPlus incorporates a shading factor as an intermediate outcome in the overall performance assessment. Proficiency in software development is necessary to make any adjustments to this implementation based on many modeling assumptions. Therefore, it is essential to ensure that the shading factor used in BEM matches the one used in the software. Nevertheless, this alignment needs to be more consistently apparent, as exemplified by the instance of RTAADOM. Integrating Building Information Modeling (BIM) into building performance modeling is a significant step in sustainable design. This collaboration enhances the ability to use parametric design, allowing architects and engineers to quickly evaluate multiple potential solutions, leading to more knowledgeable and effective decision-making processes [13]. In addition, the seamless integration of BIM with building rating systems can transform the green certification process by automating several components and enhancing a building's sustainability credentials. The BIM approach, known for extracting material quantities from models automatically, makes green building assessments easier and faster by expediting sustainability evaluations [14,15]. Furthermore, integrating BIM into evaluations of environmentally friendly construction dramatically improves project completion efficiency and data organization while supporting sustainability goals. BIM also has a crucial function in optimizing the efficiency of regulatory compliance and certification procedures. An example is the emphasized advantages of integrating Building Information Modeling (BIM) with energy simulation as part of the LEED certification procedure [16]. Nevertheless, exporting the BIM model amplifies the likelihood of flaws inside the file, which could compromise the outcomes' precision. Another method involves directly processing BIM model data within the modeling software to avoid any data loss, although this necessitates using proprietary software. To tackle more extensive issues related to accessibility, some authors have proposed using tools that rely on the IFC format. The utilization of IFC files simplifies the implementation of external tools, especially in cloud environments. An instance of a BIM platform that operates in the cloud and includes a calculation tool to verify the Envelope Thermal Transfer Value (ETTV) calculation showcases the potential of this technique to improve accessibility and scalability while guaranteeing the precision of essential calculations [17].

Nowadays, Building Information Modeling (BIM) workflow and associated authoring tools have become standard practice in designing buildings. Beyond software, BIM is a way to structure and efficiently share the building data's complexity. Over the last two decades, the Industry Foundation Classes (IFC) data scheme has become the standard for open BIM. The Industry Foundation Classes (IFC) file format is a crucial Building Information Modeling (BIM) standard. IFC, developed by BuildingSMART, aims to enhance interoperability within the architectural, engineering, and construction (AEC) sector. The open data model, compliant with the Standard [18] , facilitates the transfer and dissemination of information often utilized in BIM workflows, surpassing the constraints imposed by proprietary software. An IFC file is a complete data container containing detailed metadata and geometric information about building elements. The file format encompasses specific information such as the geometric depiction, material characteristics, and spatial connections of building elements. It facilitates interoperability in AEC but true interoperability between BIM software using IFC has not been achieved. Nonetheless, based on open or closed data schema, BIM authoring tools should be the original source of information to compute the shading factor. In other words, the inputs of the three previously presented approaches (Dedicated Tool, Research Tool, and BEM) should be extracted and/or converted from BIM to a suitable data format. Due to their specificity, manual extraction prevails for the first two. Concerning BEM, automating the generation of the BEM model from BIM data is an active topic of research [19] but remains challenging due to the complexity of both data models. Even if automation works, the benefits of BIM workflow could be limited by any data flow without automatic feedback from BEM to BIM. To overcome that challenge, a solution is to embrace a total BIM approach where the needed shading factor is computed using a BIM authoring tool with native data. This is the primary goal of this paper.

The primary obstacle lies in calculating the shadow geometry, specifically within a BIM authoring tool. Although they may be seen, they lack practicality and must be recalculated as simple geometric entities. This research introduces a novel technique dubbed "solid clipping" that utilizes common elements of the Computer Aided Design (CAD) kernel found in BIM authoring tools. The method is easily comprehensible and uncomplicated to execute with either a visual or textual API. This paper demonstrates implementing a technique in openBIM using IFCOpenshell and Python. The method is then employed to calculate the RTAADOM shading factor in a BIM model. The results of the geometric reference model are discussed.

This paper is structured as follows. Section 2.1 provides information regarding the calculation of the shading factor, encompassing both Stage 1 and Stage 2. Section 2.2 entails an exposition of the solid clipping technique. Section 3 covers applying solid clipping to calculate the RTAADOM shading factor in BIM.

2. Methodology

This section provides a brief state of the art about the computation of shading factor. It also introduces the shading factor used in the RTAADOM that has to be checked on the BIM model. A new method to compute the BIM authoring tool's shadow geometry easily is introduced.

2.1. An Overview of Shading Factor Computation

2.1.1. Shadow Geometry Computation

Computation of shadow is a mature field in video games, virtual reality, and 3D modeling. Over the last few decades, numerous techniques have been created to, most of the time, render better and faster [20], in other words, to optimize software and hardware to achieve realistic views for human eyes through pixels. The goal here is different. It is to compute the geometry of the direct shadow of a single light source for quantitative analysis needed in design and engineering. Unfortunately, standard BIM authoring tools or viewers compute and display such shadows but do not expose them as actionable objects for quantitative analysis. Intuitively, lighting simulation software would be a perfect candidate to compute shadow. Still, most of the effort is oriented to rendering a realistic view and predicting lighting conditions inside buildings [21–24]. Moreover, direct shadow geometries are intermediate and unreachable computation results as a step of a building energy analysis workflow. In the same way, direct shadows are an intermediate result of Building Environmental Modeling (BEM) based on zone model [25]. Beyond the expertise needed to extract such results, these modeling approaches need to convert and augment BIM data to a suitable dedicated model [26–28]. Even if progress has been made in this task, the cost and expertise needed to build such a model to extract shadow are disproportionate.

In the context of solar radiation modeling, shadow computation methods can be classified into four categories: trigonometric (TgM), polygon clipping (PgC), pixel counting (PxC), and ray tracing (RT). Trigonometric models use parametric geometry of obstructions to analytically project them on the surface of interest [29]. While computationally efficient, they are limited in terms of geometry [30]. The French regulation RTAADOM proposes such a model, implemented in a spreadsheet, to compute the shading factor for a parametric model of solar protection [31]. Polygon clipping (PgC) computes shadow as the intersection of polygons on the surface of interest [32]. The polygons are the projection of the faces of obstructing objects. This method is much more versatile but shows limitations with non-convex or holed shapes in standard implementations [33]. Despite these limitations, PgC is primarily implemented in the BEM tools. Pixel counting computes the number of lighted (oppositely shaded) pixels representing the surface of interest from the sun's viewpoint. While this method provides an estimation due to sampling through pixels, it is versatile and precise [33,34] thanks to modern graphic hardware that can efficiently deal with high-resolution images. In order to achieve optimal results, it is necessary to apply this technique using a visual programming language like OpenGL, which consequently demands specialized expertise. Ray tracing involves the casting and propagating of numerous basic rays that eventually undergo reflection [35–37]. In the forward version, the rays are cast from the sun and those that hit the surface of interest can be used to evaluate the shadow area. In the backward version, the rays are cast from the surface of interest and the counts of the number of rays intercepted by the obstruction can be used to estimate shadows. As a sampling method based on randomness, precision should assessed [38]. One significant advantage is that the multireflection of rays can be modeled.

2.1.2. Shading Factor

For a given surface, the shading factor describes the ratio between incoming irradiance with obstruction I^s and irradiance without I. The shading factor comprises two models: a sky model to describe the different irradiance components caught by a surface of interest and a shadow model to compute the shaded area. The sky model generally decomposes the total irradiance into direct, diffuse, and reflected components, and projects it on a tilted surface. The shadow model describes how each irradiance component is impacted by obstructions in front of the surface of interest.

Sky model decomposes the total irradiance I on a tilted surface in the direct I_b and the diffuse I_d ones for a given location and time on earth. Numerous models have been developed [39], varying in terms of physical and mathematical complexity to offer better precision in predictions [40]. Models mainly differ in how they decompose the diffuse component I_d into different contributions: isotropic from the sky dome, circumsolar, horizon brightening, and reflected from the ground.

This work will only use a basic model with isotropic diffuse radiation for both sky and ground [41,42]. Such a model allows us to consider essential physical traits of the problem without much mathematical complexity. Moreover, the thermal regulation that has to be checked automatically is based on this model. The total irradiance I is then written as $I = I_b + I_d + I_r$ with:

$$I_b = I_{h,b} R_b \tag{1}$$

$$I_d = I_{h,d} \left(\frac{1 + \cos\beta}{2} \right) \tag{2}$$

$$I_r = I_h \rho \left(\frac{1 - \cos\beta}{2} \right) \tag{3}$$

where $I_{h,b}$ is the direct-normal component of solar irradiance on the horizontal surface, R_b is a geometric factor, $I_{h,d}$ is the global diffuse horizontal solar irradiance, β is the tilt angle of the surface from the horizon, I_h is the global horizontal solar irradiance, and ρ is the soil albedo.

To compute a shading factor, including diffused irradiance, one needs to consider the effect of shadow on diffuse component I_d. One common approach is to consider the non-direct source of radiance as a sum of direct sources from different directions with associated direct shadows. In other words, the shaded diffuse component is computed via the integration of discretized shaded sources [30,32,40,43]. Following [29], the instantaneous shading factor S_f is defined for one solar position by the ratio between the irradiance with shadow and without:

$$S = \frac{I^s}{I} = \frac{F_b I_b + F_d I_d + F_r I_r}{I_b + I_d + I_r} \quad (4)$$

where F_b, F_d, and F_r are the geometric shading factors for direct, diffuse, and reflected irradiance components, respectively. For direct irradiance, F_b is given by the ratio of the sunlit area and its total area: $F_b = A_s/A$. For diffuse component and a given hemisphere discretization, F_d is given by:

$$F_d = \frac{\sum_i \sum_j F_{b,ij}.R_{ij}.\cos\theta_{ij}.\delta\Omega_{ij}}{\sum_i \sum_j R_{ij}.\cos\theta_{ij}.\delta\Omega_{ij}} \quad (5)$$

where i and j denote the discretized height and latitude coordinates of the considered portion of sky hemisphere, R_{ij} is the radiance passing through the portion of hemisphere calculated according a sky model, θ_{ij} is the angle between the sky element and the normal of the surface, and $\delta\Omega_{ij}$ is the solid angle of the sky portion seen from the surface. A similar approach can compute a geometric shading ratio for the reflected component depending on the use case and the modeling hypothesis about ray reflection. While the instantaneous shading factor can be interesting to assess predictions minutely, the average overtime period is often used in application, $\langle S_f \rangle_t$. Alternatively, the RTAADOM uses an integral form to define the shading factor:

$$S_R = \frac{\sum_t I_t^s}{\sum_t I_t} \quad (6)$$

2.2. A New Method to Compute Shadow Geometry: Solid Clipping

BIM authoring tools generally implement a Computer Aided Design (CAD) kernel suitable to model the shapes of building components using surface and solid modeling. The proposed method is based on essential solid modeling operations such as extrusion and intersection to compute shadow, inspired by the polygon clipping approach. It is an oversimplified version of the shadow volume technique [44], a well-known method capable of rendering complex scenes in terms of geometry and daylighting. Indeed, our goal is to compute shadow on one face F of the model for a unique direct light source.

As it can be seen in Figure 3, where the method is applied to cast shadows on a window, the shadow computation method consists of four steps:

1. Identification of the building walls or elements that can cast a shadow regarding sun exposition, as in Figure 3a;
2. Extrusion of a three-dimensional (3D) sun path in the direction of the wall where shadows have to be evaluated, as in Figure 3b;
3. Calculation of 3D intersections of the sun path with the building to identify the parts that can generate shadows on the considered walls, as in Figure 3c;
4. Extrusion of previous 3D intersections, reduced to intersection surfaces, up to the considered walls to trace and calculate the shadows, as in Figure 3d.

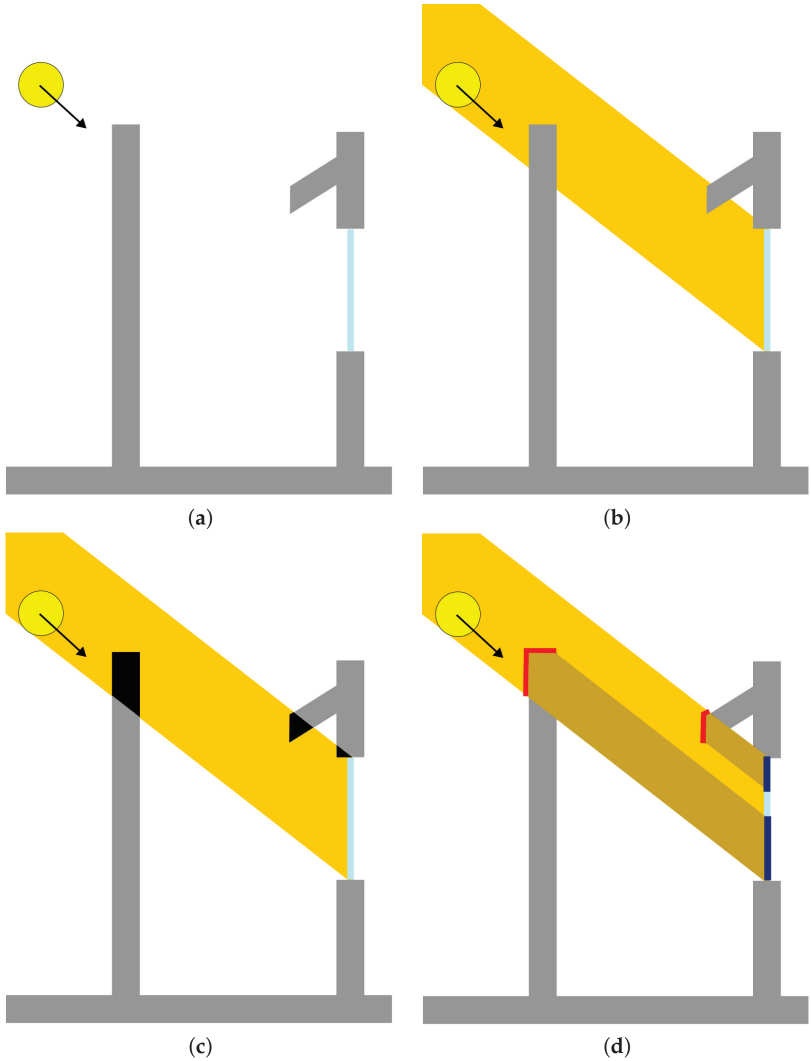


Figure 3. Successive stages of computation for a simple 2D model: (**a**) The model of interest with a window and a few wall elements that can cast a shadow. The vector $\overrightarrow{sun}$ is plotted. (**b**) Extrusion. (**c**) Intersection with $volumeIntersection$ in black. (**d**) Face selection (red), extrusion of faces along $\overrightarrow{sun}$ (dark yellow), intersection with F gives F_{shadow} as a patch of surface (dark blue).

This method has inspired the algorithm described in Algorithm 1.

Algorithm 1: Algorithm to compute shadow

```
   Input  : A flat face F
   Output : A flat face F_shadow
1  Light = Extrude(F, -sun→, ∞)
2  CatchedLight = Intersect(Light, Building)
3  List = [ ]
4  foreach face in CatchedLight.faces() do
5      if n_face→ · sun→ ≤ 0 then
6          PartialShadowVolume = Extrude(face, sun→, ∞)
7          PartialShadowSurface = Intersect(PartialShadowVolume, face)
8          List.append(PartialShadowSurface)
9      end if
10 end foreach
11 ShadowSurface = Union(List)
12 return ShadowSurface
```

Let us detail line by line Algorithm 1 along with a 2D illustration in Figure 3. The extension to 3D is straightforward.

Line 1 The $\overrightarrow{sun}$ points downward, i.e., from the sun through the face of interest F. F is extruded to the infinite along $-\overrightarrow{sun}$ to create the "solid of light" $Light$. It represents the light flux without obstruction, as shown in Figure 3a.

Line 2 The Boolean intersection between the solid $Light$ and all the other solid of the BIM model ($Building$) is computed and stored in $CatchedLight$. Shown in black in Figure 3c.

Line 5 to 8 Each face of $CatchedLight$ with normal oriented through the sun (red in Figure 3d) is extruded back to F (dark yellow in Figure 3d) to build $PartialShadowVolume$. The face resulting from the intersection between $PartialShadowVolume$ and F is computed and stored in $PartialShadowSurface$.

Line 10 The Boolean union of all the $PartialShadowSurface$ (dark blue in Figure 3d) defines the face shadow F_{shadow}.

The order of solid operation has been optimized to propose a robust algorithm. Indeed, one can think of uniting the extrusion to perform one unique intersection, thus saving time. It has been found that the intersection of a unique volume resulting from the union of multiple possibly overlapping extrusions is more error-prone than the union of multiple intersections on the face F. In other words, for the sake of robustness, it is better to deal with the most straightforward atomic geometry. The advantages and limitations of this method regarding application results will be discussed at the end of the paper.

3. Application: Checking the RTAADOM on BIM Models

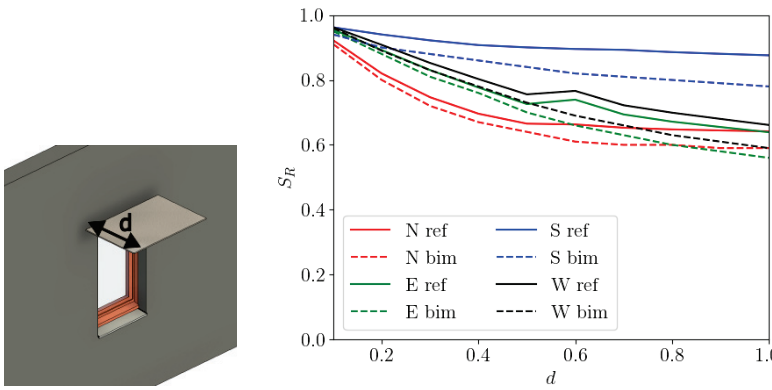
The solid clipping method has been applied to compute the RTAADOM shading factor. Thanks to the IFCOpenShell library, a Python tool has been developed to implement the solid clipping method to compute the RTAADOM shading factor S_R^{bim}.

Validation of RTAADOM Shading Factor Computed Using BIM

In this section, a comparison of shading factor values given by the RTAADOM official Excel sheet S_R^{ref} with those computed using our automatic analysis of an IFC file S_R^{bim} has been made. Varying window configuration regarding protection geometry and orientation, S_R values were quantitatively compared. The first model comprises four walls and 10 identical windows with solar protection hosted on the same linear wall. An overhang of different depths is associated with each window, as shown in Figure 4a. For each window, the overhang depth d increases from 0.1 m to 1.0 m by 0.1m steps. This BIM model, and thus these 10 protection configurations, are strictly geometrically equivalent to those managed by the parametric model of the RTAADOM (see Figure 2).

The window's orientation can be controlled by setting the angle between the project north and the true north. The comparison of the S_R values for a window oriented to the four cardinal orientations can be achieved.

Figure 4b shows S_R values as a function of d_o for four orientations. Table 1 shows the corresponding raw data. The solid line represents values computed from the IFC file with solid clipping S_R^{bim} and the dashed lines correspond to the values given by the regulation Excel tool S_R^{ref}. As expected, S_R decreases as d_o increases. Except for the south orientation, there is an excellent agreement between S_R^{bim} and S_R^{ref} values.



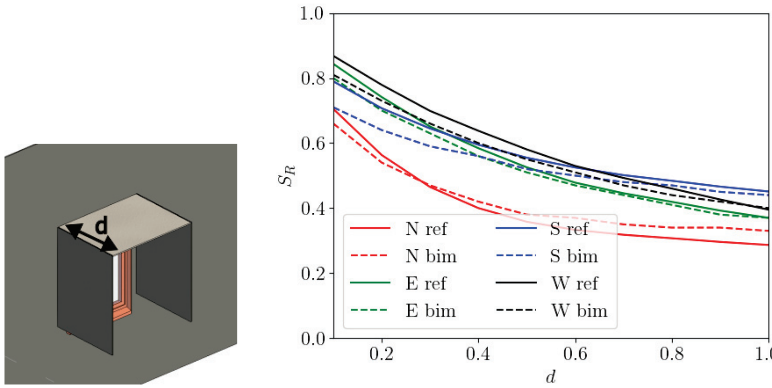
(**a**) (**b**)

Figure 4. (**a**) Snapshot of a window with an overhang of depth d. (**b**) Shading factor S_R as a function of the overhang depth d for the four cardinal orientations (color) and the two computation methods (line style).

Table 1. Shading factor values computed with the spreadsheet (left) and with our approach (right) for solar protection with overhang.

Reference					BIM				
d	**North**	**South**	**East**	**West**	**d**	**North**	**South**	**East**	**West**
0.1	0.91	0.94	0.95	0.96	0.1	0.92	0.96	0.96	0.96
0.2	0.80	0.90	0.88	0.89	0.2	0.82	0.89	0.94	0.91
0.3	0.72	0.88	0.81	0.83	0.3	0.75	0.83	0.92	0.85
0.4	0.67	0.86	0.76	0.78	0.4	0.70	0.78	0.91	0.80
0.5	0.64	0.84	0.70	0.73	0.5	0.67	0.73	0.90	0.76
0.6	0.61	0.82	0.66	0.69	0.6	0.66	0.74	0.90	0.77
0.7	0.60	0.81	0.63	0.66	0.7	0.65	0.69	0.89	0.72
0.8	0.60	0.80	0.60	0.63	0.8	0.65	0.67	0.89	0.70
0.9	0.59	0.79	0.58	0.61	0.9	0.64	0.66	0.88	0.68
1.0	0.59	0.78	0.56	0.59	1.0	0.64	0.64	0.88	0.66

A second model was created by adding vertical fins to each overhang, as shown in Figure 5a. Table 2 shows the corresponding raw data. Figure 5b shows an even better agreement between S_R^{bim} and S_R^{ref} when vertical fins are added.



(**a**) (**b**)

Figure 5. (**a**) Snapshot of a window with an overhang and rectangular vertical fins of depth d. (**b**) Shading factor S_R as a function of the overhang and vertical fins depth d for the four cardinal orientations (color) and two computation methods (line style).

Table 2. Shading factor values computed with the spreadsheet (left) and with our approach (right) for solar protection with overhang and vertical fins.

Reference					**BIM**				
d	**North**	**South**	**East**	**West**	**d**	**North**	**South**	**East**	**West**
0.1	0.66	0.71	0.80	0.81	0.1	0.70	0.84	0.79	0.87
0.2	0.54	0.64	0.70	0.73	0.2	0.56	0.74	0.71	0.78
0.3	0.47	0.59	0.63	0.66	0.3	0.46	0.65	0.64	0.70
0.4	0.42	0.56	0.56	0.60	0.4	0.40	0.58	0.59	0.64
0.5	0.38	0.52	0.51	0.55	0.5	0.36	0.53	0.56	0.58
0.6	0.37	0.50	0.47	0.51	0.6	0.33	0.48	0.53	0.53
0.7	0.35	0.48	0.44	0.47	0.7	0.32	0.45	0.50	0.49
0.8	0.34	0.47	0.41	0.44	0.8	0.31	0.42	0.48	0.46
0.9	0.34	0.45	0.38	0.42	0.9	0.30	0.39	0.47	0.43
1.0	0.33	0.44	0.37	0.40	1.0	0.29	0.37	0.45	0.40

Table 3 shows the Mean Absolute Error (MAE) for each orientation and protection configuration. The MAE is below five percent except for the overhang facing south. Merging all the data, MAE is equal to 0.038. The raw data can be found in Tables 1 and 2. The discrepancy can be attributed to the modeling of the diffuse part. While the RTAADOM gives an explicit formula, our implementation requires an integration process sensitive to many parameters. Nonetheless, the results are very close and such small errors should be balanced by the automation gain, both in time and quality.

Table 3. Mean absolute error between computed value of S_R^{ref} and S_R^{bim}.

Wall Orientation	**Overhang**	**Overhang and Fins**
North	0.037	0.030
East	0.045	0.018
South	0.064	0.036
West	0.044	0.028

4. Conclusions and Perspectives

This paper introduces a new method to compute the exact shadow geometry necessary to evaluate shading factors. This method, called solid clipping, uses simple computational geometry tools implemented in BIM authoring tools and actionable through textual or visual API. Implementing the shading factor with a reference tool associated with French regulation has been validated. It has also been qualitatively shown that the design is unverifiable with the regulation and can be easily checked with our implementation. From an engineering perspective, two main benefits can be identified. Firstly, proper automation makes the cost of regulation checking plummet. Thus, checking a regulation becomes a quality assessment tool throughout the whole life of the project not just at the end. Secondly, implementing solid clipping using the BIM API allows us to deal with the geometry of shadows as complex as those of the building elements that generate them. In other words, if a solar protection design is created with a BIM authoring tool, the generated shadow can be leveraged to compute a shading factor. Combining these benefits will lead to a better cost–quality–delay balance in delivering sustainable buildings designed in BIM.

4.1. Extending Regulation Using BIM

Having assessed the precision and thus validated the implementation of shading factors, it is possible to extrapolate the computation to a configuration not handled by the regulation. So, S_R^{bim} was computed for protection with triangle-shaped fins instead of rectangular ones. Intuitively, this is an intermediate solution in terms of performance between the previously studied configurations: overhang with and without rectangular fins. Figure 6b confirms this by showing S_R^{bim} for the three studied protection configurations. As expected, the triangle-shaped fins generate intermediate values of S_R^{bim}. Beyond such a design as is currently implemented in the tropical French territory, the original and creative design can be assessed usingour method. For example, Figure 7 shows three examples of the solar protection of different architectural complexity for illustration. While inefficient, they highlight the capability of the solid clipping method to deal with complex geometries.

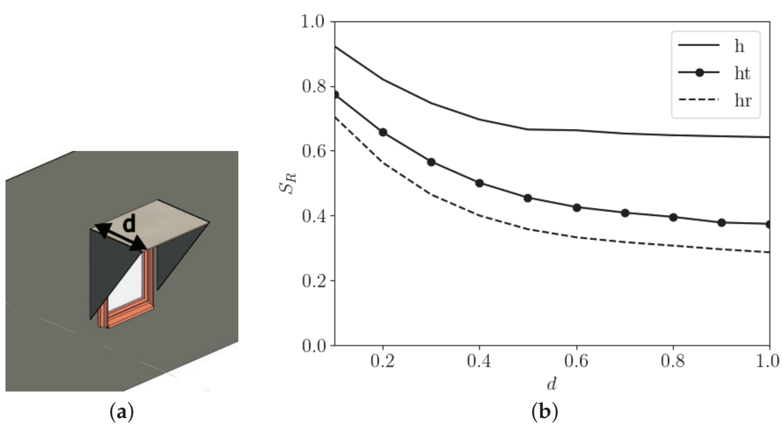


Figure 6. (**a**) Snapshot of a window with an overhang and triangular vertical fins of depth *d*. (**b**) Shading factor S_R as a function of the overhang and triangular vertical fins depth *d* for the north orientation is represented by the dotted curve (labeled *ht*). The overhang with (labeled *hr*) and without (labeled *h*) vertical rectangular fins is added for comparison.

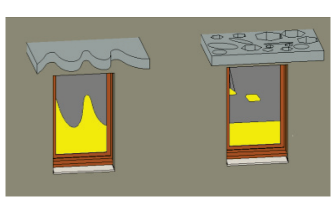


Figure 7. Snapshot of shadow computed by solid clipping for original solar protection design: (left) curved boundary parametrized by a spline, (right) rectangular shape with holes

4.2. Research Directions

From a research perspective, this work paves the way in multiple directions. For example, advanced components such as phase-changing material or thermochromic glasses are exposed to non-uniform irradiance on their surface. Having easy access to realistic shadow geometries thanks to solid clipping and BIM modeling will improve models and thus their deployment for energy saving. More broadly, such exact and potentially complex shadows can be used as an input table in BEM tools to assess the impact of advanced solar protection. Smart solar protection could also use precise knowledge of shadow geometry. Indeed, having an internal reference in addition to sensors could help smart systems make better decisions and detect faults.

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Article

Indoor Environmental Quality Assessment of Train Cabins and Passenger Waiting Areas: A Case Study of Nigeria

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Abstract: The adequacy of the indoor environmental quality (IEQ) in mass transit microenvironments is crucial to the well-being of exposed commuters. By 2050, many developing tropical countries will host even more megacities, which will feature an increase in people mobility and higher occupancy density. The paucity of IEQ studies, the technology gap, and inadequate policy measures to assure safer and sustainable mobility in many developing tropics have reinforced the current study objective. Also, the recent COVID-19 pandemic has highlighted the IEQ links and risks to health in transport, which, given the climate peculiarities, transport reforms, and huge commuter traffic in Nigeria, inform the study motivation. The indoor air quality (CO_2, PM, VOCs, NO_2), thermal, acoustic, and visual environments were objectively assessed in train passenger cabins and waiting areas, during 15 trips in the dry and rainy seasons in Nigeria. The results were analyzed by following the IEQ requirements defined in the ISO, CEN, ASHRAE, and SAE standards. The results indicate gaps in the IAQ (inadequate ventilation in 9 trains), defective thermal comfort (9 trains), exceedance in the PM limit (PM_{10}: 47.9–115 μg/m^3, $PM_{2.5}$: 22.5–51.3 μg/m^3), noise (L_{eq} range: 64–85 dBA), and low illuminance levels (10 trains), hence the need for IEQ, interventions, stakeholder awareness, and broader IEQ studies on transport cabins in these regions.

Keywords: indoor environmental quality; thermal comfort; indoor air quality; particulate matter; noise; visual comfort; trains; Nigeria; developing tropical countries

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1. Introduction

In many cities, a significant part of mobility needs are met via mass transit on trains and buses, hence the need to minimize the imminent and potential risk associated with the poor indoor environment quality (IEQ) in transport vehicles is necessary to ensure comfort, well-being, health, productivity, and safety.

IEQ refers to the condition of an indoor environment concerning the air quality and comfort parameters such as the indoor air quality (IAQ), thermal comfort, visual comfort, acoustic comfort [1], and ergonomics, including vibration and harshness (in the case of transportation means). These parameters that jointly influence the IEQ should be assured by following regulations and standard requirements depending on the relevance and applicability to the indoor environments.

By 2050, most megacities will be hosted by developing tropical countries, suggesting that these regions will be characterized by significant population density and high mobility traffic. Moreover, the existential high level of outdoor pollutants in several African cities [2] informs the need to ensure an adequate IEQ in these regions since outdoor environmental conditions influence the IEQ of indoor space. Therefore, the need to ensure safer, adequate, energy-efficient, and sustainable transportation in developing tropical countries is essential.

Although modern people spend a greater part of their time in buildings (including offices, shopping centers, schools, homes, religious buildings, hospitals, etc.), a significant amount of time is also spent in transport microenvironments such as cars, buses, trains, aircraft, and other vehicles. Furthermore, mass transit vehicles, such as buses and trains, are prone to a high risk of epidemic outbreaks and health safety [3], coupled with the risk of thermal discomfort from high solar radiation penetration of vehicle cabins [4], thus necessitating adequate IEQ measures and interventions in developing tropics.

Only a few studies have evaluated the IEQ parameters of buildings and mobile indoor spaces in the developing tropics [5], which contributes to justifying the reason for the current study. In the following section, a few studies of the IEQ parameters in train transport microenvironments are now referenced according to the specific parameters investigated, unique findings, and recommendations where applicable. Moreover, in the current study, attention to IEQ assessments of intercity trains during real-time travels in Nigeria has been presented, analyzed, and discussed according to the relevant global IEQ requirements.

Literature review:

Several factors have been identified that impact passenger well-being and comfort in trains including indoor climate parameters like the air and radiant temperatures, air velocity, humidity, and air exchange rate while other aspects such as noise, vibration, barometric variation, light and shadow, colors, and odors are important for achieving passenger comfort during travels [2]. Remarkably, a recent study has evaluated cultural differences in conceptual models of ride comfort in high-speed trains, comparing four viewpoints on the effect of intercultural variables, and classifying critical effects as common (objective effects) and uncommon (subjective effects) [3]. This approach to evaluating ride comfort highlights the peculiarities of occupant behavior that can influence the perception of overall comfort in transport microenvironments considering that culture influences behavior. In developing African countries such as Nigeria with diverse cultural spectra, IEQ studies might need to investigate these influences. There is a global concern about climate change, sustainability, and energy efficiency. Improving transport infrastructure and technology, reducing carbon emissions through energy-efficient alternatives, and the indoor environments of vehicles are concerted efforts for human well-being and safety. Also, the impact of the recent COVID-19 pandemic has informed several reforms and awareness for the minimization of the risk of infectious disease transmission in transport cabins. In developing sub-Saharan countries, several factors contribute to poor IEQ, including environmental policy gaps [4,6], paucity of scientific studies [7,8], poor transport infrastructure [9], alarming environmental pollution [4], poor IEQ awareness, and socioeconomic challenges. As these regions have a high occupancy density in transport vehicles [8], assessing the IEQ conditions is essential to ensure minimal health and comfort risks. Furthermore, only a few studies have investigated IEQ parameters in the developing tropics [7]. Also, there was no published study found on IEQ assessment in trains in Nigeria but two studies on thermal comfort and ventilation in buses by Kamiyo [10] and Odekanle et al. [11] assessed the particulate matter (PM) exposure of commuters in different transport modes. However, studies have investigated the IEQ parameters of trains in other regions.

Thermal comfort: Although thermal comfort is a subjective mental state of occupants' expression of the thermal environment [12], it can be quantitatively determined by evaluating the combined effects of six critical parameters in indoor environments including four physical parameters such as the air temperature (T_a), mean radiant temperature (T_r), relative humidity (RH), air velocity, and two occupant-related parameters such as clothing and human activity level or metabolic rate [13]. The operative temperature (T_O) is representative of the occupant's physiological response to the indoor thermal environment and can be used to evaluate thermal comfort, which can be correlated on a thermal sensation scale to assess the degree of occupants' dissatisfaction or satisfaction with the indoor thermal conditions [14]. Predicted mean vote (PMV) and percentage of persons dissatisfied (PPD) indices are used to evaluate the thermal sensation from the thermal parameters measured on each train trip in the cabin. The PMV–PPD model was proposed by P.O Fanger in 1970 [15] and adopted by ISO 7730 [16]. Furthermore, it applies to conditions in which the metabolic rate has not exceeded 4 Met [17] such as in offices, hospitals, vehicles, and trains because occupants are in sedentary positions and have minimal activities.

In Tehran, Abbaspour et al. objectively assessed the thermal environments of metro stations and carriages to optimize passenger thermal comfort, and their conclusions suggested that thermal comfort was acceptable, even for the warmest period of the year [18]. In Taiwan, the findings of Lin et al.'s assessment of the thermal perceptions and adaptations of 2129 passengers exposed to short (less than 30 min) and long-haul (more than 60 min) journeys in air-conditioned buses and trains have attributed thermal discomfort to high temperatures, strong solar radiation, and low air movements, while passenger thermal adaptive behaviors were comparatively distinguished in the journey types [19]. The impact of solar radiation on thermal comfort and sensation in high-speed trains was recently studied by Yang et al. Their findings from the evaluation of PMV, PPD, and persons dissatisfied (PD) affirm that solar irradiation infiltration into the cabins increases the thermal load and discomfort whereas the use of roller curtains was recommended to improve the thermal environments and enhance uniformity in the thermal environment [20]. Chen et al. investigated the IAQ of three types of train compartments with varying conditions of speed, outdoor parameters, and window setting, with the conclusion being that more fresh air improves the IAQ [21]. Ye et al. subjectively evaluated the thermal comfort and air quality of 91 train travelers in long-distance passenger rail cars in China, revealing that the IAQ was not as satisfactory as thermal comfort since a cumulative of 76% of passengers wanted improvements in the IAQ regarding fresh air and air velocity [22].

Indoor air quality: Several air pollutants can originate internally or infiltrate vehicle microenvironments, including CO_2, carbon-monoxide (CO), volatile organic compounds (VOCs), PM, black carbon (BC), and other volatile inorganic compounds (VIC_S) like no, which have been studied regarding vehicle IAQ. In Malaysia, the findings by Masyita et al., assessing the IAQ in trains using measurements and subjective evaluations of 129 persons, were that the CO_2 and PM_{10} levels exceeded the acceptable limits, leading to recommendations for IAQ interventions and stakeholder awareness including the need for further IAQ studies [23]. Ongwandee et al. investigated commuter exposure to VOCs (benzene, toluene, ethylbenzene, and m,p-xylene) in four public transport modes in Bangkok, and their comparative finding was that the VOC levels in the in-sky train were statistically lower than for AC/non-AC buses and boats, suggesting that the elevated levels of the sky trains might be reasons for the lesser infiltration of the pollutants [24]. In Singapore, Xiao reported poor IAQ ventilation in the train cabin during passenger peak times on the North–South Line and East–West Line, and passenger thermal discomfort on the North–East Line during less cabin occupation [25]. Similarly, Li et al. seasonally assessed the IAQ parameters in passenger cars of the Beijing Ground Railway Transit System, using mixed methods, leading to the conclusions that the IAQ was acceptable but highlighted the variations in the IAQ due to peak times and passenger density [26]. Chan et al. investigated commuter exposure to PM in various transport modes in Hong Kong, including three railway types, and the findings suggest that the transport mode and ventilation system have a significant influence on the PM level.

Furthermore, railway transport and air-conditioned cabin vehicles are recommended as a substitute for non-air-conditioned vehicles, whereas the highest PM (175 mg/m^3) levels were recorded in trams, being 3–4 times more than in trains [27]. Nasir et al. investigated PM pollution in transport microenvironments in the UK, leading to results that showed higher mean PM levels in non-air-conditioned train coaches whereas, during passenger peak times, the PM levels were higher in air-conditioned coaches, highlighting the influence of the peak time (high occupancy density) and PM resuspension, resulting in higher levels in the assessed coaches [28]. Meanwhile, Bai et al.'s assessment of the IAQ in three types of air-conditioned train compartments reported a poor IAQ for all but found comparatively better conditions in the lower-speed train (80 km/h) than in the higher-speed train

(120 km/h) with the conclusion that a fresh air supply is crucial to the IAQ [29]. Russi assessed the IAQ parameters in different transport vehicles including trains in Lisbon. Their findings suggest the PM levels did not exceed the standard limits of Portugal, WHO, and ASHRAE but in comparison to the levels recorded in buses and cars, the PM and aerosol exposure concentrations were lowest in trains while the CO_2 levels in all transport modes were linked to the occupancy density in the cabins [30].

Other IEQ comfort parameters: Other IEQ parameters that impact overall passenger comfort have been investigated, such as acceleration effects, vibration, seat static comfort [31–33], and aural pressure effects, highlighting the experience of motion sickness and discomfort in passengers. Significantly, Peng recently reviewed and discussed the main comfort parameters in passenger trains, classifying them into six parameters: lighting, noise, static comfort, vibration, thermal, and aural pressure [34,35]. Xu et al. [36], using a multidimensional approach to assess and evaluate the visual comfort of five subway line cabins, compared an objective measurement with subjective perceptions, exploring five aspects of the visual environment including the effect of the seating layout on visual performance, vertical and horizontal illuminance, spatial brightness, correlated color temperature preference, and the glare uniformity rating in the investigated cabins. Their conclusion implied that there was a measure of compliance with the Chinese and EU requirements regarding illuminance levels. Whereas some studies have investigated links between whole-body vibration (WBV) to metabolic rate, suggesting that an increase in WBV can increase the metabolic rate [37,38]. Meanwhile, changes in the metabolic rate can affect the passenger thermal sensation of the thermal environment [39]; therefore, minimizing vibration and acoustic discomfort in transport cabins can enhance the IEQ conditions.

The main findings from the literature reviewed highlight that most studies have evaluated the indoor climate of train passenger compartments using mixed methods of objective measurements and subjective assessments. Passenger discomfort has resulted more from thermal, visual, and vibration comfort issues but more studies have found unacceptable levels of PM in the cabins. Finally, besides PM infiltration and inadequate fresh air supply, the factors commonly discussed in the reviewed literature were particle resuspension, peak time (high passenger density), strong solar radiation, and low air movements.

2. Materials and Methods

Study area: Rail transit infrastructure is still developing in Nigeria, although the Nigerian Railway Corporation (NRC) is 112 years old. It operates a network of less than 4000 Km including single- and double-tracked lines of 150 km from Lagos to Ibadan. However, the rail infrastructure development is progressive with plans to ensure a functional connection within cities such as the light rail project for the Lagos rail mass transit system [40], and between cities such as Lagos, Ibadan, Ota, Calabar, Abuja, Kaduna, Warri, Itakpe, Kano, Jigawa, and Katsina, and even across the nation into Niger [41,42].

Figure 1 shows the railway travel path of the investigated trips as well as field survey photos in the train station and passenger car. The study area spans 156 km of railway or trains traveling from Lagos metropolitan city to Abeokuta and Ibadan metropolis. The main system of transport for these travel routes includes trains, mini-buses, medium coach buses, saloons, and wagon vehicles. The train travel was on the Lagos–Abeokuta–Ibadan rail service operated by the Nigeria Railway Corporation (NRC), which commenced in June 2021. The trips occur from morning and late afternoon, with the departing and returning operations from Lagos and Ibadan railway stations. There are four mains departing and stopping stations in both directions including Mobolaji Johnson Station (Lagos), Babatunde Raji Fashola Station (Lagos), Wole Soyinka Station (Abeokuta), Samuel Ladoke Akintola (Ibadan) Station, and Obafemi Awolowo Station (badan). The longest travel time spans an average of two hours, executing an average of four trips per day according to the Lagos–Ibadan Train Service (LITS). Records show that the passenger traffic has exceeded 30,000 persons monthly since its commencement in the year 2021. The trains consist of executive and regular passenger interior coaches; however, the current study has conducted measurements of the IEQ only in the regular passenger interior areas/cabins during the reported trips, given that passenger occupancy is typically higher in the regular cabins of no less than 80 persons per coach in capacity. The mobility traffic potential of these trains is high given the high population and socioeconomic activity of Lagos, including its surrounding cities such as Ibadan and Abeokuta. Again, these revamped railway systems are part of an effort by the government, in a private–public partnership agenda, to ensure better transportation and its availability; similarly, other intra-city train transport such as the Lagos blue and red line railway lines are being commissioned. Furthermore, the intercity railway network spans the routes of the entire country, primarily to serve commuters as well as freighting. Therefore, ensuring an adequate IEQ in these trains in developing tropics will contribute to achieving healthier, more comfortable, safer, and sustainable cities, in direct or indirect alignment to the sustainable development goals 7, 9, 11, and 13.

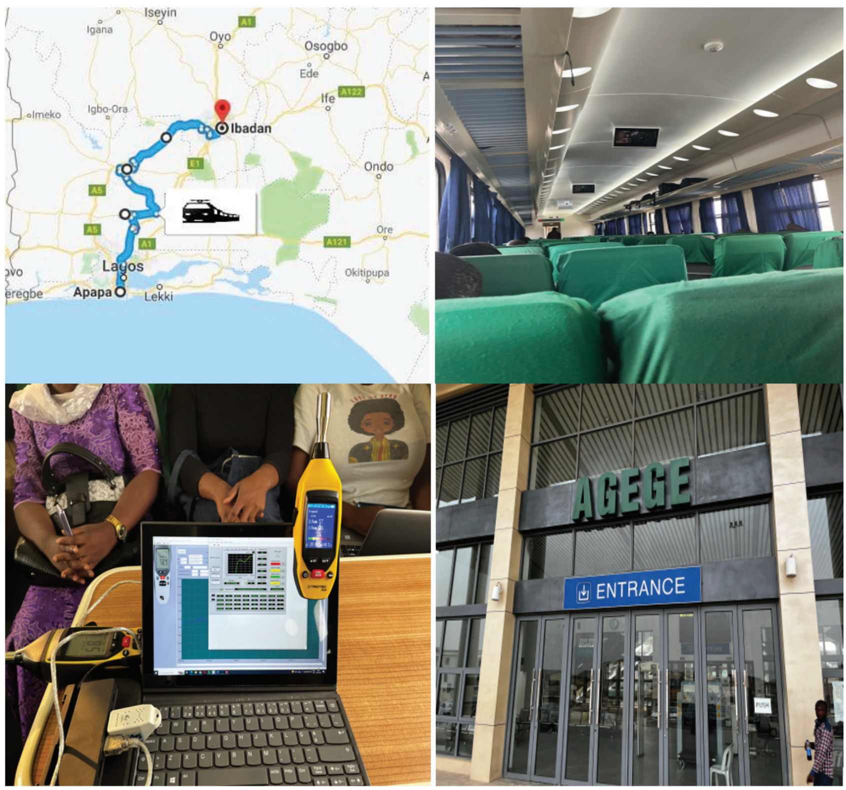


Figure 1. Map excerpt showing study area and railway route [43] and photos of the field survey.

Field survey: The field measurements were conducted during real-time travels between February and May 2023 in newly deployed air-conditioned trains for the investigated route. The measurements performed during the trips in February were for the dry season while those in May were considered rainy season assessments. A total of 15 trips were investigated using a calibrated IEQ multiprobe device, connected to a laptop computer via the USB port, which enables easy connection with the computer, ensuring data acquisition and visualization process accordingly [44,45], as shown in Figure 2. Also, a class 2 Trotec SL400 sound meter was used to measure and record the A-weighted sound pressure level. A particle counter, TROTEC BQ20 device, was used to measure the PM2.5 and PM_{10} concentrations during the IEQ assessments in the train cabins. The IEQ multiprobe sensors were calibrated via the following procedures for these reference types of equipment: a Bruel & Kjaer 1212 Thermal Comfort Meter (operative temperature reference); a Trotec DL200X Data Logger (relative humidity reference); a Trotec DL200L Data Logger (CO_2 concentration reference). These values were obtained for the expanded uncertainties (coverage factor = 2, 95% probability) of the measured variables: operative temperature, $T_O = \pm 0.2$ °C; relative humidity, RH = ±1%; CO_2 concentration = ±35 ppm. For more details regarding the calibration, range, and settings of the measuring equipment used in the objective campaign, see Table S1 in the Supplementary Material. It is noteworthy to indicate that the IEQ multiprobe device used in the current study measures the operative temperature, T_O (°C), by default, considering the air temperature (T_a) and radiant temperature (T_r) parameters. It was also included to ensure consistent metrological data from the IEQ multiprobe device and complementary calibration software. Table 1 presents information regarding the travel routes, sitting information, and the season during which the measurements were taken.

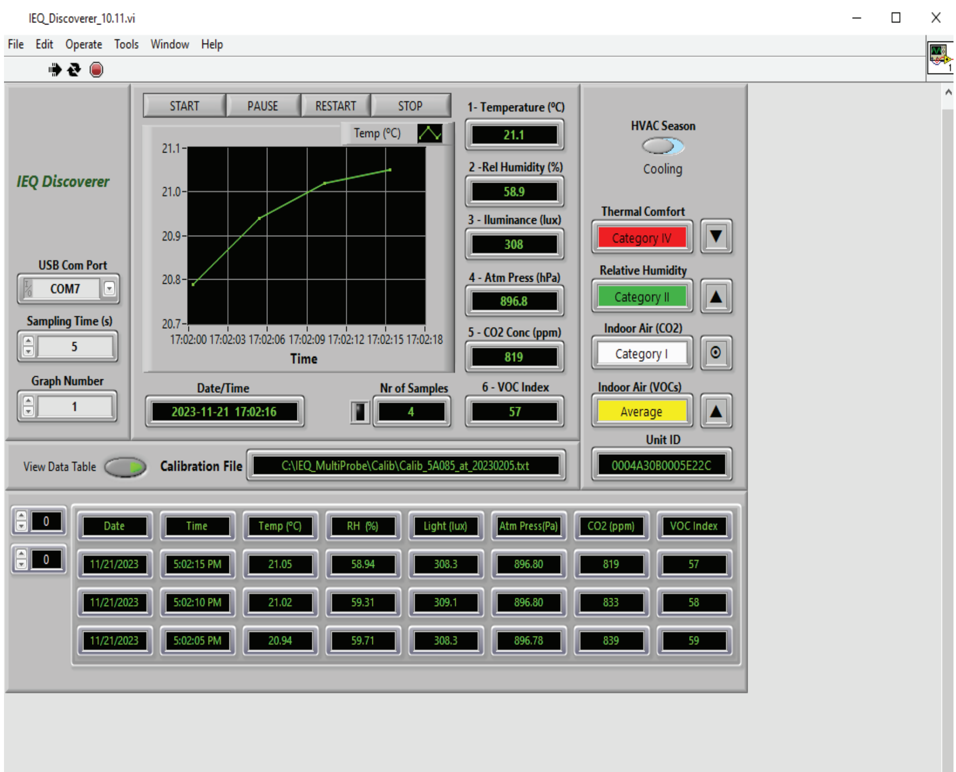


Figure 2. Screenshot imagery of the typical data logging and visualization interface of IEQ multiprobe device.

Table 1. All train trips, routes, seat and cabin details, travel dates, and seasons.

Train Trip	Route	Operator	Day-Month	Coach-Seat	Season
1	Ibadan–Lagos	NRC	16-Feb	C8_40	Cooling
2	Lagos–Ibadan	NRC	21-Feb	C4_10	Cooling
3	Ibadan–Lagos	NRC	21-Feb	C5_85	Cooling
4	Lagos–Ibadan	NRC	23-Feb	C6_41	Cooling
5	Ibadan–Lagos	NRC	23-Feb	C5_34	Cooling
6	Lagos–Ibadan	NRC	05-May	C4_20	Cooling

Table 1. *Cont.*

Train Trip	Route	Operator	Day-Month	Coach-Seat	Season
7	Ibadan–Lagos	NRC	05-May	C6_2	Cooling
8	Ibadan–Lagos	NRC	06-May	C7_18	Cooling
9	Lagos–Ibadan	NRC	06-May	C8_88	Cooling
10	Ibadan–Lagos	NRC	08-May	C5_12	Cooling
11	Ibadan–Lagos	NRC	09-May	C4_5	Cooling
12	Ibadan–Lagos	NRC	12-May	C6_34	Cooling
13	Lagos–Ibadan	NRC	12-May	C6_52	Cooling
14	Lagos–Ibadan	NRC	13-May	C6_41	Cooling
15	Ibadan–Lagos	NRC	13-May	C4_03	Cooling

The IEQ multiprobe was used to obtain data for the CO_2 levels in ppm, operative temperature (T_O in °C), relative humidity (RH in %), atmospheric pressure (Pa), and lighting levels (lux) including an embedded IAQ index for measuring VOCs. The measurements were taken in a passenger seat at a height of about 110 cm above the cabin floor whereas the IEQ multiprobe sensors functioned omnidirectionally. This allowed for the calculation of the mean values of all the physical parameters according to EN 13129 [46]. In addition, a handheld FLOW air quality measuring device, from Plume Labs, was used to measure and register $PM_{2.5}$, PM_{10}, VOCs, and NO_2. The air quality index (AQI) data acquired via the Flow device were automatically logged wirelessly via Bluetooth connection to a mobile phone during the trips, with the possibility of access via the mobile app interface and otherwise exported via email in Excel format. The timestamps in the CSV files exported allowed for the easy identification and collection of the relevant data. In the current study, the PM was investigated during five trips carried out during the dry season on account of permits and logistics. Furthermore, HVAC applications in both seasons were identified as applicable to cooling in this region as outdoor temperatures generally exceeded 25 °C. The consideration for the metabolic rate was 1 met [47] and 0.1 m/s for air velocity as passengers were typically in sedentary positions. For clothing, an average clothing insulation (Icl) of 0.6 clo was used for both seasons surveyed. The measured environmental data and the assumed parameters were used to calculate the predicted mean vote (PMV) thermal comfort index. The air quality conditions have been discussed based on the measured parameters of the CO_2, VOCs, and PM concentration levels. Noise levels were measured using a TROTEC SL400 (Class 2) sound level meter. The noise equivalent level was calculated for each trip surveyed, whereas these noise levels have been evaluated considering the requirements of relevant indoor noise standards and regulations from Nigeria, the EU, the USA, and Japan, including the Occupational Safety and Health Administration (OSHA). Furthermore, calculations and computations have been made via Microsoft Excel, and the thermal comfort indices using the PMV–PPD spreadsheet calculator of Gameiro da Silva [17], while indoor climate parameters have been categorized and evaluated by following the requirements of the EN 16798-1 standard [48]. National railway standards such as TB/T 1951:1987 [49], GB/T 12817:2004 [50], UIC 553:2004 [51], and BS EN 14750–1:2006 [52], addressing the thermal environments in trains, have mainly prescribed temperature ranges, humidity, and wind speed without including human thermal sensation and thermal comfort, hence the recommendation of thermal comfort requirements by ASHRAE 55 [12] and ISO 7730 [16], according to [34]. All the IEQ parameters (including the noise and PM) were measured concurrently in a passenger car for each trip during the journey. The measurements were taken during the first morning trip, starting at 08.00 h, originating from Lagos to Ibadan, and during the return trips, with the departure time to Lagos at 16.00 h. The average journey time spanned two hours. Meanwhile, a few measurements performed in the waiting areas before departure at various stations have been presented because many passengers usually wait before the scheduled departure time.

Evaluation method for the ventilation parameters: The recommended indoor fresh air flow rate, Q m^3/h per person corresponding to achieving the recommended CO_2 concentrations (1000 ppm to 1200 ppm) correlations, is as follows: for 1200 ppm (2160 mg/m^3)

of CO_2 concentration, Q should be 24 m^3/h, while for 1000 ppm (1800 mg/m^3), Q should be 30 m^3/h per person. An illustration using the first train trip scenario has first been presented whereas all the ventilation parameters for all the trips were also calculated as shown in the Results and Discussion Section. Using Equations (1) and (2) and the average CO_2 level of 450 ppm (810 mg/m^3) for $C_{external}$, and the average CO_2 values to compute the $C_{equilibrum}$ in mg/m^3, the calculations were made. Also, it was observed during the investigations that all cabins were always fully occupied, a passenger count (PC) of 80 persons were seated for more than 90% of the assessed travel time.

$$Q = (G)/\left(C_{equilibrum} - C_{external}\right) \quad (1)$$

$$\lambda_v = \frac{Q}{V} = \frac{1}{t} \quad (2)$$

Evaluation method for the noise parameters: These noise sources are typically both airborne and structural. In the current study, only the noise levels have been assessed during six of the fifteen trips investigated. The noise source was not investigated nor categorized. The current study has evaluated the noise levels using the noise equivalent level (L_{eq}), a descriptor used to characterize the sound effect on humans in the evaluation of noise in vehicles. The L_{eq} represents the sound pressure level (SPL) of a continuous constant sound that would have produced the same sound energy at the same time as the actual noise history [53]. Meanwhile, the raw data of the noise measurements correspond to the time series of the A curve weighted SPL values, with the sound meter configured in Fast Mode (125 ms, sampling time), as typically used to evaluate automotive noise. The L_{eq} values were calculated for a time interval of the travel duration in each of the investigated train trips [12], and it can be quantitatively determined by using Equation (3).

$$L_{eq} = 10 \log_{10} \sum_{i=1}^{n} \left\{ \left(10^{\frac{SPL_i}{10}} \times t_i \right) \right\} \quad (3)$$

L_{eq} (dBA) is the noise equivalent level for each trip, SPL_i is the sound pressure level measured in dBA, n is the total number of samples taken on each trip, and t_i is the fraction of the total sample time. The study results are now presented graphically, analyzed, and discussed in the following sections accordingly.

3. Result and Discussion

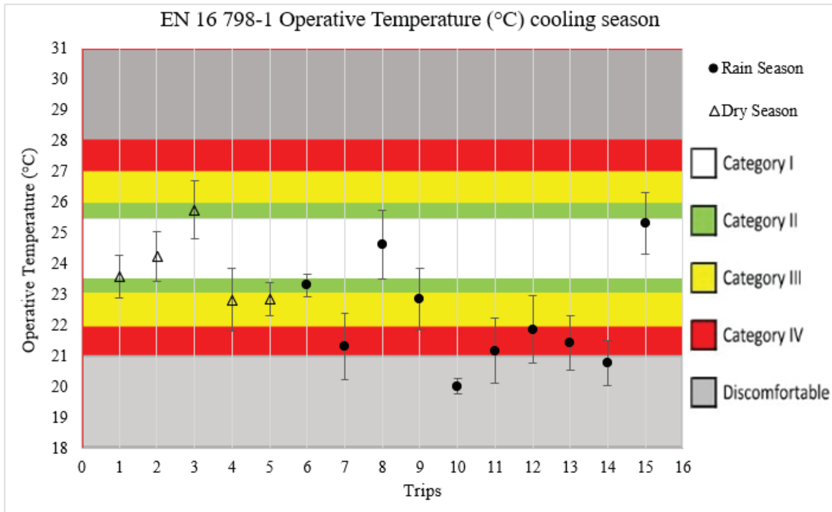
This study objectively assesses the indoor environmental quality (IEQ) conditions that train passengers are exposed to in Nigeria, as the region prospects a revamp and expansion of railway transportation. This study offers scientific data on the IEQ of a transport microenvironment (trains), an exemplary developing tropic, with a paucity of scientific studies, and the need for reforms in IEQ development, infrastructure, and policy. Ultimately, it highlights gaps and recommendations for future investigations and possible stakeholder interventions. The results are presented in the following subsections for thermal comfort, indoor air quality, and other comfort parameters such as lighting and noise. The indoor climate, considering thermal comfort and the indoor air quality, was assessed for two seasons, while the particulate matter and noise parameters were reported for the six trips in the dry season. Table 2 presents the mean and standard deviation of all the investigated IEQ parameters.

Table 2. Mean and standard deviation of all IEQ parameters measured during all train trips.

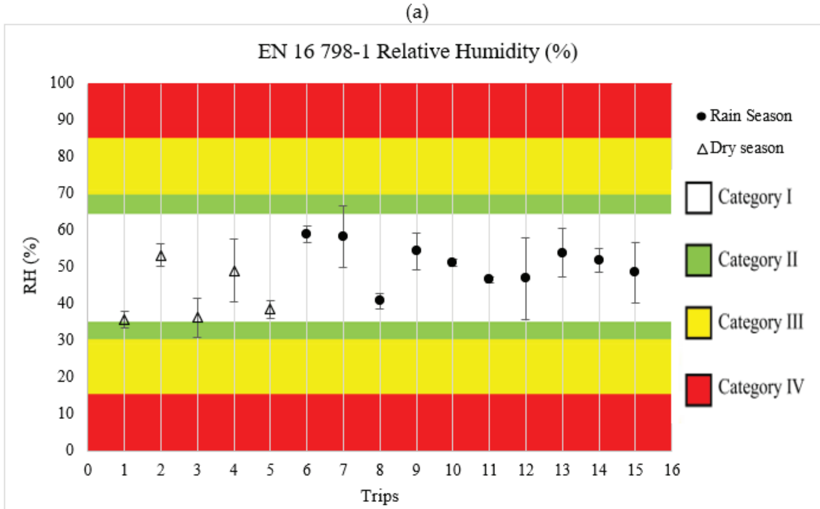
Trips	T_O (°C)	SD	RH (%)	SD	Light (lux)	SD	CO_2 (ppm)	SD	VOC index	SD
1	23.6	0.7	36	2.3	48	27	820	133	12	4.7
2	24.2	0.8	53	3.1	53	15	924	120	47	6.0
3	25.8	0.9	36	5.3	77	53	789	60	13	10.2
4	22.9	1.0	49	8.7	1556	1308	696	115	38	17.1
5	22.9	0.5	39	2.4	863	460	894	111	18	4.8
6	23.3	0.4	59	2.3	628	1423	1298	90	58	4.6
7	21.3	1.1	58	8.4	30	10	1368	84	56	16.5
8	24.6	1.1	41	2.2	47	31	1242	174	22	4.3
9	22.9	1.0	54	4.9	42	15	1684	151	48	9.6
10	20.0	0.2	51	1.0	74	33	1288	30	42	1.9
11	21.2	1.1	47	0.9	128	245	1024	41	33	1.8
12	21.9	1.1	47	11.2	168	160	1787	289	34	22.0
13	21.4	0.9	54	6.6	76	27	1493	203	48	13.1
14	20.8	0.7	52	3.2	245	101	1451	127	43	6.3
15	25.3	1.0	49	8.1	29	20	1170	100	37	15.9

Thermal comfort parameters: Ensuring adequate thermal comfort can enhance the perceptions of IAQ [54] besides its significant impact on the overall passenger comfort in the indoor transport environment. The investigated train cabins were equipped with curtains that minimized the infiltration of solar radiation in the cabins. However, the passengers sitting by these windows determined how these curtains were used, open or partially closed. Meanwhile, the current study scope did not include the assessment of thermal radiation. The studied trains were air-conditioned and during all trips, the coaches assessed all 80 seats, which were always all occupied in the selected cabins for the trips investigated. The omnidirectional IEQ multiprobe device measured five parameters including the operative temperature and relative humidity, and the graphical representations of these parameters are presented and analyzed accordingly to categorize the thermal environments in the train cabins investigated.

Figure 3 shows the average and standard deviation values of the operative temperature and relative humidity for all the trips, using as a background a color scheme with the thermal comfort quality categories, for the cooling season, of the EN16981-1 standard [48]. As shown in Figure 3a, the mean T_O (°C) values of trips 7, 10, and 14 were in the discomfort zone according to the C requirements. The thermal environment was of lower temperatures (less than 21.5 °C), perhaps due to overcompensations from the HVAC settings, which also impacted the PPD for these trips. Given that outdoor temperatures in the south-western region of Nigeria, such as in the investigated case study area, are sometimes akin to those levels recorded during the summer for some countries including Spain and Portugal with Mediterranean and temperate climates, we may compare the summer indoor thermal expectations of these regions to those in the current study. Also, there are limited studies including the significant absence of well-defined local IEQ standards in the study region (Nigeria), hence the reference to other known standards like the EN16981-1 [48]. Nine of the fifteen trips exceeded the suggested temperature upper limit of 21.8 °C by Nicol et al. [55], which he prescribed in agreement with the corrected effective temperature (CET) limit for comfort proposed by Bell et al. [56], applicable to sedentary people during summer conditions whereas none of the computed T_O averages exceeded the recommended physiological and safety temperature limit of 30.6° [56]. As shown in Figure 3b, the RH (%) was adequate between 35% and 65%, within the prescribed safe and comfort limit of 40% to 60% [57]. The RH (%) values computed for this study followed the EN 13129-1 [46] requirements: RH < 65% when $T \leq 23$ °C, and RH < 45% when $T \leq 29$ °C [58]. Also, Božič et al. recommended an approximate range of 50% for the minimal risk and spread of infectious aerosols in indoor spaces [59]. The mean values of the current study rolling stock did not exceed the prescribed values for a guaranteed pleasant interior, considering the recommended values (in the EN 13129-1 [46], mainline rolling stock) of 27 °C and 51.6% maximum mean interior temperature and RH, respectively, in summer conditions for southern European countries (zone 1), which have outdoor temperatures nearing 40 °C [47].



(a)



(b)

Figure 3. Mean and SD values of thermal comfort parameters: (**a**) the T_O (°C), and (**b**) the RH (%) in all trips investigated.

PMV (predicted mean vote) and PPD (pre-visible percentage of dissatisfied) index: The thermal comfort sensation of the exposed occupants in the studied train is quantitatively predicted using the PMV–PPD index now presented and analyzed accordingly. Table 3 presents the PMV–PPD indices computed from the averages of the thermal comfort parameters considering a metabolic rate of 1 met and 0.6 clo has been adopted, considering that for both seasons, the clothing worn is typically summer-like and the HVAC is mostly for cooling in this tropic region.

Table 3. PMV–PPD parameters for all trips.

Trips	PMV	PPD	Season	HVAC Use
1	−0.53	10.80	Rain	Cooling
2	−0.31	7.00	Rain	Cooling
3	0.26	6.40	Rain	Cooling
4	−0.77	15.50	Rain	Cooling
5	−0.77	17.60	Rain	Cooling
6	−0.63	13.40	Dry	Cooling
7	−1.34	42.20	Dry	Cooling
8	−0.17	5.60	Dry	Cooling
9	−0.77	17.60	Dry	Cooling
10	−1.79	66.00	Dry	Cooling
11	−1.37	44.00	Dry	Cooling
12	−1.13	31.80	Dry	Cooling
13	−1.3	40.30	Dry	Cooling
14	−1.51	51.50	Dry	Cooling
15	0.08	5.10	Dry	Cooling

Figure 4 shows the PMV values computed for all the trips. Six trips are observed in the discomfort zone and category IV. On most trips, the thermal environments were not adequate according to the ASHRAE and EN 16798-1 requirements. It was observed during most trips that the air conditioning made the cabins rather cold, as shown by the PMV index. The HVAC systems may have been set to overcompensate for the typical high outdoor temperature in tropical regions. Also, most people in the tropics are dressed in summer-like clothing and coupled with the low metabolic rate of sedentary persons, the thermal sensation accounts for higher PPD values. Also, following the PMV index graph, higher PPD values were computed for the rainy season trips. In the dry season, outdoor temperatures are usually higher than in the rainy season; therefore, the AC settings should be regulated accordingly. Otherwise, the same settings may account for colder cabins since during both seasons in the tropics, AC works for cooling. Most of the rainy season trips recorded a higher PPD, suggesting that adequate regulation of cabin AC is needed to avoid overcompensation in cabin cooling. Summarily, thermal comfort still requires some intervention in some of the assessed train cabins, perhaps better HVAC settings to achieve prescribed limits while the adequate use of curtains for shading can reduce overall thermal loads vis-a-vis energy used for climatization.

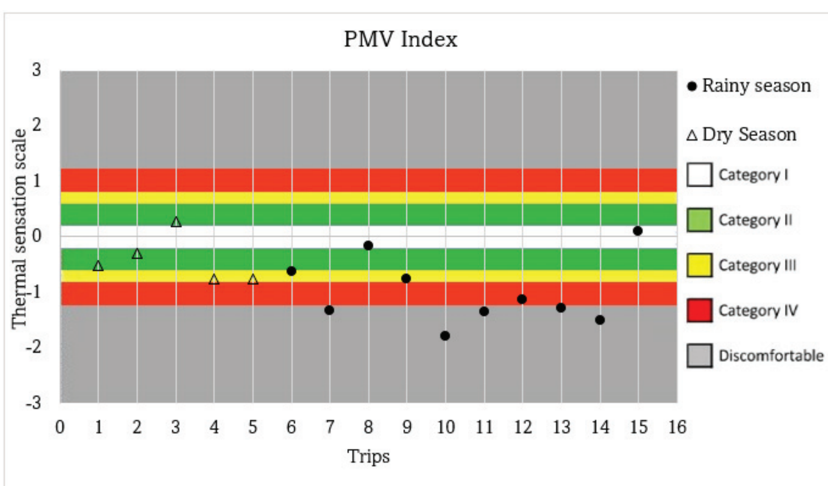


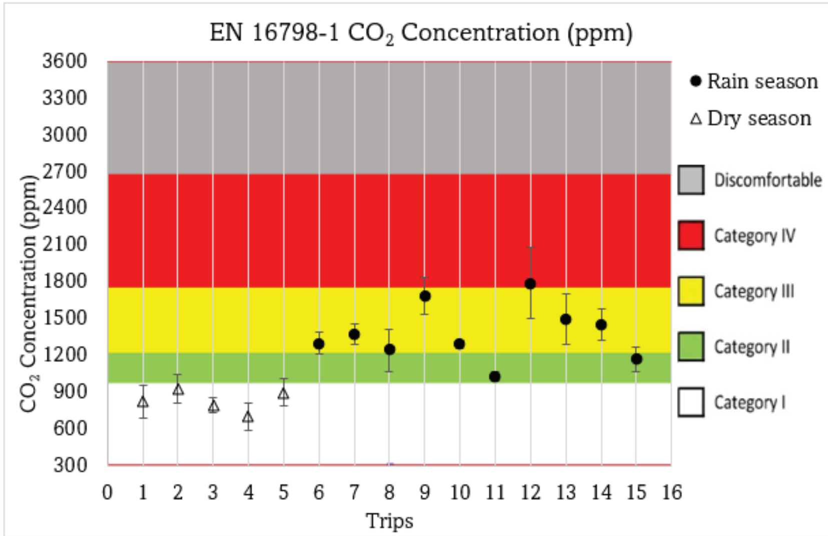
Figure 4. Graphical representation of the PMV index for all train trips investigated.

Indoor air quality parameters: The indoor concentrations of PM, inorganic compounds (CO_2, CO, O_3, SO_2, NO_X), and organic compounds (benzene, polyaromatic hydrocarbons, VOCs), including biological organisms (fungi, viruses, bacteria), are common determinants of the IAQ of transport indoor microenvironments. There are risks to health, comfort, and general safety to exposed occupants if acceptable IAQ levels are violated. PM concentrations exceeding the threshold are of significant concern because studies have reported negative health outcomes associated with PM penetrating respiratory and pulmonary systems depending on their size [60]. Also, short, or chronic exposure to CO_2 exceedance levels have been associated with a myriad of health risks, decreased cognition and performance, and increased discomfort in exposed occupants [61]. The present study's results, regarding the investigated IAQ parameters (CO_2, VOCs, NO_2, $PM_{2.5}$, and PM_{10}) during the train trips, are presented below. The averages and standard deviation values have been categorized according to the EN 16 798-1 requirements.

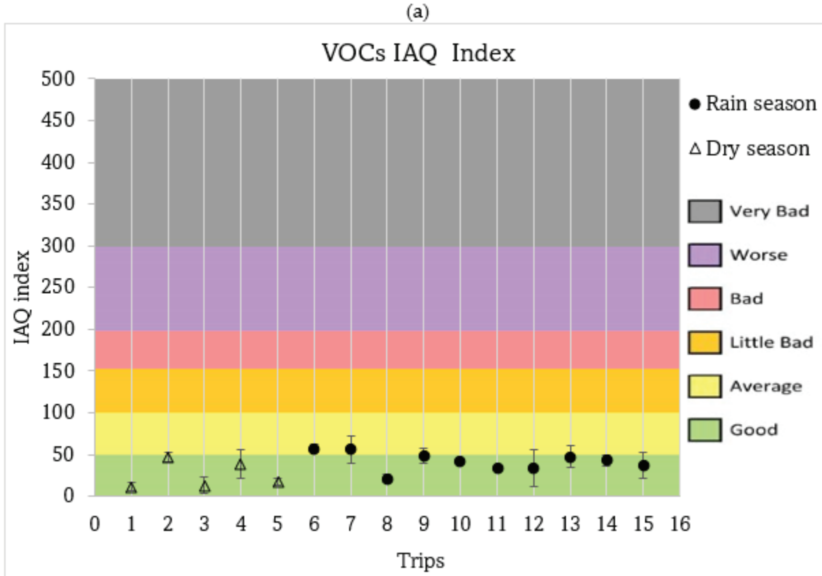
Figure 5 shows the mean and standard deviation distribution of the CO_2 and VOC parameters as measured using the IEQ multiprobe device, whereas these measured values have been categorized according to EN16798-1 and evaluated [45]. In Figure 5a, the CO_2 levels (ppm) fall into categories I, II, III, and IV. There was no trip in the discomfort zone. Comparatively, trip 12 presents the poorest indoor climate parameters considering the mean CO_2 level (1786.80 ppm in category IV) and the PPD (31.8%) reported. Meanwhile, the average VOC levels computed suggest that the VOCs were within acceptable limits for all trips investigated (Figure 5b). Although no subjective evaluations concerning the IAQ and perceived air quality (PAQ) were performed for the current study, it is possible to deduce from the results of the experimental value averages obtained for the CO_2 and VOCs that the IAQ was acceptable in the cabins investigated considering the categorization and requirement of the EN16798-1 standard. Regarding the PM, the TROTEC BQ400 particle counter and FLOW air quality devices were used to investigate six trips. The PM average and standard deviation values are presented in Table 4 as computed from the measurements obtained from the two particle counter devices and analyzed by the known standard limits. Martins et al., in a review study, reported that no PM regulatory standards were found for most African countries and Asian countries [60]; therefore, the current study's results were evaluated according to the acceptable requirements of standard regulations from other regions.

Table 4. Fresh air flow rate and air exchange rate parameters in all trips.

Trip	PC	C_{ext} (mg/m^3)	G (mg/m^3)	C_{equi} (mg/m^3)	Q (mg/h^3)	Q (all PC)	PCV (m^3)	λ (h^{-1})
1	80	810	37,000	1476	55.6	4444.4	145.6	30.5
2	80	810	37,000	1667	43.2	3452.7	145.6	23.7
3	80	810	37,000	1424	60.3	4823.2	145.6	33.1
4	80	810	37,000	1256	83.0	6638.3	145.6	45.6
5	80	810	37,000	1613	46.1	3685.7	145.6	25.3
6	80	810	37,000	2342	24.1	1931.9	145.6	13.3
7	80	810	37,000	2468	22.3	1784.9	145.6	12.3
8	80	810	37,000	2241	25.9	2068.3	145.6	14.2
9	80	810	37,000	2941	17.4	1388.9	145.6	9.5
10	80	810	37,000	2318	24.5	1962.3	145.6	13.5
11	80	810	37,000	1843	35.8	2864.9	145.6	19.7
12	80	810	37,000	3217	15.4	1230.0	145.6	8.4
13	80	810	37,000	2687	19.7	1576.6	145.6	10.8
14	80	810	37,000	2612	20.5	1642.8	145.6	11.3
15	80	810	37,000	2106	28.5	2284.0	145.6	15.7



(**a**)



(**b**)

Figure 5. Mean and SD values of IAQ parameters in all train trips: (**a**) the CO_2 levels and (**b**) shows the VOC levels.

Ventilation parameters: The fresh air flow rate, Q (m^3/h), and air exchange rate, λ (h^{-1}), are essential ventilation parameters that impact the IAQ of indoor spaces. The results of the calculated parameters using the equations are presented in Table 4.

The calculation illustration using the first train trip is as follows: PC of 80 persons (fully occupied cabins in all seating without standing). With an internal width of 2.8 m, interior height of 2.0 m, and a coach length of 25.9 m per coach, we can obtain the passenger car volume (PCV).

$$PCV = L \times W \times h = 145.6 \text{ m}^3$$

Taking $C_{external}$ to be 810 mg/m^3 (equivalent to an outdoor CO_2 of 450 ppm), $C_{equilibrum}$ is 1476 mg/m^3 (820 ppm), and the generated CO_2 per occupant, G as 37,000 mg/m^3, the Q = 55.6 m^3/h per passenger. A fresh air flow rate of 55.6 m^3/h implies that the occupants of the illustrated trip's coach were exposed to an overventilated cabin. The results presented in Table 4 show that, in 9 of the 15 trips, the fresh air flow rates Q (mg/h^3) were inadequate, while the remaining trips were within the recommended range (24 m^3/h to 30 m^3/h). Meanwhile, the fresh flow rate of the fully occupied coach was 4444.4 m^3/h (the Q per person multiplied by the PC). Using Equation (2), the air exchange rate was calculated as follows.

$$\lambda_v = \frac{Q}{V} = \frac{444.4}{145.6} = 30.5\ h^{-1}$$

Regarding the air exchange rate, λ_v (h^{-1}), to achieve the CO_2 concentration of a range of 1000 ppm to 1200 ppm for an ideal IAQ in the coaches (taking PCV as 145.6 m^3), a range of 13 h^{-1} to 16.5 h^{-1} is required. Comparing the air exchange rates obtained (Table 4) to this requirement, only four trips were within the ideal range of 13 h^{-1} and 16.5 h^{-1}, although two trips, 7 and 9, were near suitable in the air exchange rate and their fresh air flow rate parameter values, 22.3 mg/h^3 and 25.9 mg/h^3. In total, 60% of the studied train coaches have shown inadequate levels of fresh air flow rate and air exchange rate parameters, suggesting that ventilation gaps exist and the need for IAQ interventions.

Particulate matter: Assessing the in-cabin PM level in addition to CO_2 is also crucial to defining the IAQ condition because it is an air pollutant that can result in a myriad of health problems in exposed occupants to unrecommended thresholds. $PM_{2.5}$ (all the airborne particles not exceeding 2.5 μm in diameter) is an inhalable fine particulate that can pose a serious risk to human health depending on its chemical composition whereas PM_{10} (all the airborne particles not exceeding 10 μm) is also inhalable and can be harmful to human health. Table 5 presents the mean and SD of the measured parameters ($PM_{2.5}$, PM_{10}, NO_2, and VOCs) for 6 of the 15 studied trips.

Table 5. Computed PM, NO_2, and VOC measurements from the two devices.

Trips	TROTEC BQ400 Device				FLOW Air Quality Device							
	$PM_{2.5}$ (μg/m^3)		PM_{10} (μg/m^3)		$PM_{2.5}$ (μg/m^3)		PM_{10} (μg/m^3)		NO_2 (ppb)		VOC (ppb)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	51.3	14.7	99.4	14.3	45	7	115	15	40	19	87	31
2	49.5	19.1	99.3	17.2	43	11	108	22	16	4	113	44
3	24.4	7.9	54.9	17.5	29	10	108	13	0	0	159	18
4	25.9	6.6	72.1	15.8	32	9	109	20	6	3	190	16
5	51.3	30.4	79.3	40.3	34	7	87	21	58	4	117	32
6	22.5	7.9	47.9	21.2	28	5	109	10	20	18	146	27

PM was assessed in the dry harmattan season, and the mean values computed from the FLOW air quality device were comparable to the values computed for the TROTEC BQ 400 device. The mean PM levels computed show exceedances, referencing the EU outdoor limits, comparable to the evaluations performed by Maggos et al. for the in-train measurements of PM and NO_2 levels exceeding the outdoor daily limits for PM_{10} (50 μg/m^3), $PM_{2.5}$ (25 μg/m^3), and hourly limit for NO_2 (200 μg/m^3). The indicative comparison of poor IAQ, as described by Maggos et al. [62], was due to the infiltration of smokestack emissions into the investigated cabins. Rivas et al. [63], assessing commuter exposure to air pollution in different transport modes and routes including other varied influences, reported higher PM concentrations in underground trains with openable windows as $PM_{2.5}$ = 37.4 μg/m^3, while non-openable window trains, as those of the current study were, as $PM_{2.5}$ = 16.4 μg/m^3 (non-open windows), which is less than the mean $PM_{2.5}$ values reported for all the trips of the current study trains traveling at the ground surface level.

Figure 6 presents a graphical distribution of the mean and standard deviation values computed for all the trips using the two devices. The similarity in the graphical distribution of the computed mean and deviation PM values considering both counting devices indicates that the in-train PM levels were in exceedance of the recommended limits by the WHO, ASHRAE, and the Portuguese legislation ($PM_{2.5}$ limit of 25 μg/m^3 and PM_{10} limit of 50 μg/m^3) in all the investigated train trips. The PM_{10} levels measured (TROTEC device: 47.9 μg/m^3–99.4 μg/m^3, and Flow device: 87 μg/m^3–115 μg/m^3) were comparatively higher for all the trips than $PM_{2.5}$. (TROTEC device: 22.5 μg/m^3–51.3 μg/m^3, FLOW device: 28 μg/m^3–45 μg/m^3). Contrastingly, the VOCs were not in exceedance in the current study unlike the findings by Russi [30] that the VOCs (2516 μg/m^3) were significantly high in trains. Similarly, the VOC levels in the current study were found to be lacking, as reported by Ongwandee et al. [24]. Considering ASHRAE's recommendation that in-cabin CO_2 should not exceed 1000 ppm [64], only five computed mean CO_2 values, mostly the trips surveyed in the dry season, complied. However, no mean CO_2 value computed was of toxic concentration levels. Also, all the mean PM values computed were less than the permissible limit of 150 μg/m^3 in contrast to the findings of Masyita et al. [23]. The preliminary assessments of the IAQ indicate that its inadequacy was not toxic, although the elevated PM levels and typical risk of high occupancy density in these regions are good reasons to ensure adequate HVAC settings to enhance fresh air and indoor climate conditions.

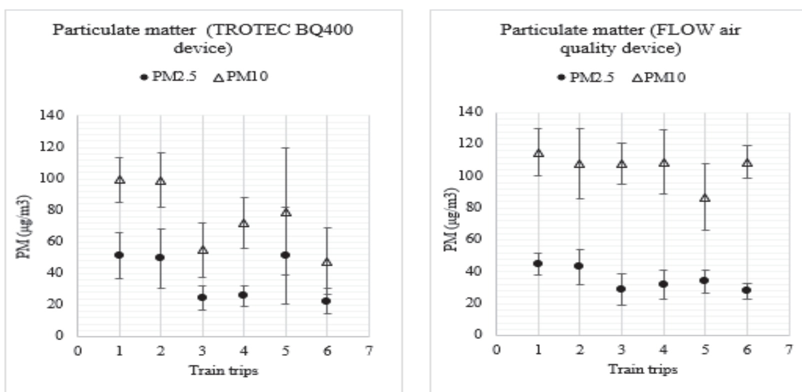


Figure 6. The mean and SD values of PM by the two measuring devices.

The indoor climate in passenger waiting areas: The indoor climate of some passenger waiting areas has also been investigated and reported, categorizing and analyzing the exposure according to the EN 16798-1 requirements. Typically, passengers, including railway workers, are exposed to the indoor climate of the waiting areas, which sometimes accommodates the ticket service areas. Due to the train schedules and apprehension to avoid missing the trains, passengers sometimes usually wait for varying lengths of time until departure. The indoor climate, including the thermal comfort and IAQ parameters, was within permissible limits considering the temperature, CO_2, RH, and VOCs. The investigated waiting areas have been recently built and equipped with functional HVAC, while the frequently open entrance and exit doors allow for the easy infiltration of fresh outdoor air. Table 6 presents the mean and SD values of the IEQ parameters measured by the IEQ multiprobe device. The values computed indicate a measure of compliance with the prescribed indoor climate standard requirements.

Table 6. Mean and standard deviation value IEQ parameters of passenger waiting areas.

Station	T_O °C	SD	RH (%)	SD	CO_2 (ppm)	SD	VOC Index	SD
AG	21.9	0.1	57	1.6	631	41	53	3.1
MJ	27.4	0.4	69	1.8	541	35	77	3.4
OA	24.2	0.9	46	2.8	627	22	32	5.5
OA	23.0	0.4	60	0.8	801	21	59	1.6

Figure 7 shows the main indoor climate parameters. In Figure 7b,d, the mean CO_2 (ppm) and VOCs computed suggest that the IAQ was adequate. Also, the mean values of TO (°C) and RH (%) (in Figure 7a,c) are indicative of good thermal environments in the assessed passenger waiting areas. The waiting areas were also huge enough to accommodate the high passenger density as observed during the time of the current study survey. However, the measurement of PM was not conducted for the passenger waiting areas due to train management permission and other logistics for the field study. It is recommended that future studies assess the infiltration of PM and VOCs, including VICs (volatile inorganic compounds), to adequately characterize the IAQ of exposed passengers as many stations are situated around unpaved surroundings, vehicle traffic-prone areas, markets, and industries.

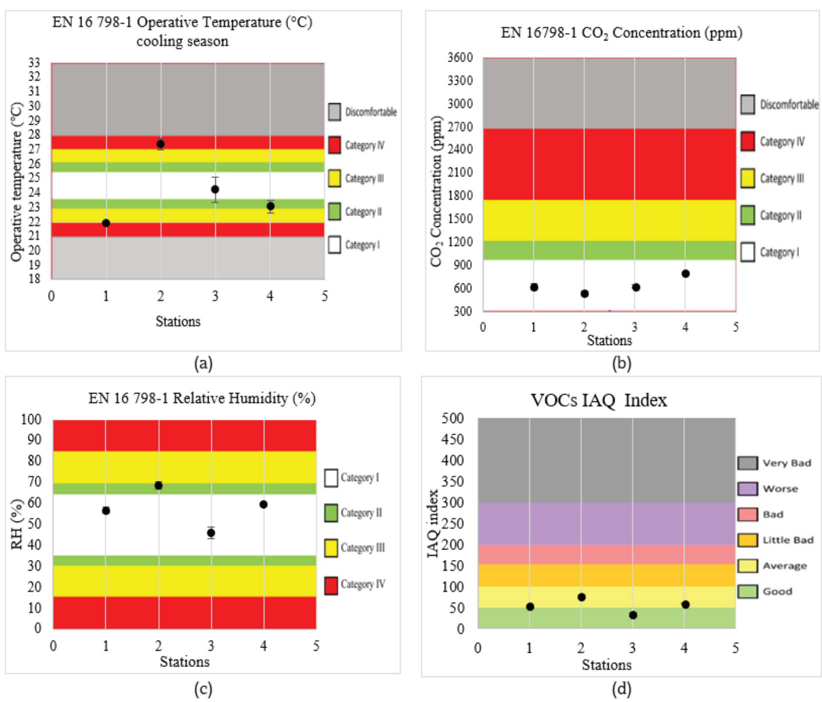
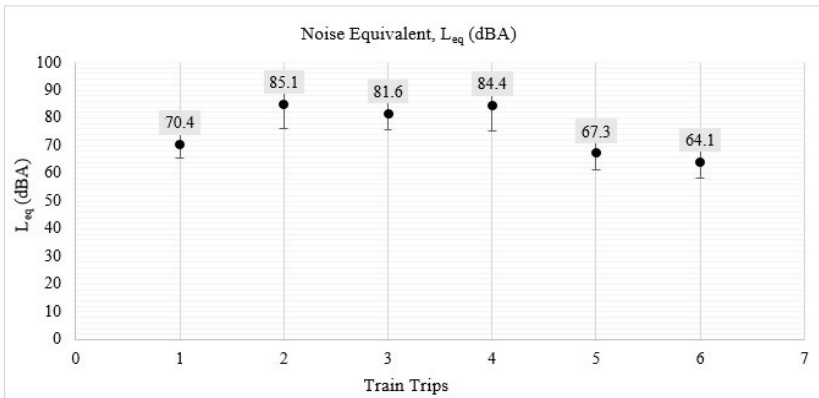


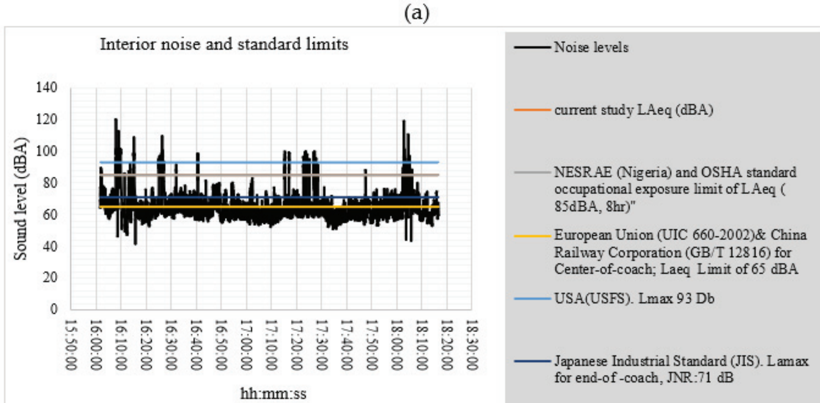
Figure 7. Graphical representation of the mean and SD indoor climate parameters of passenger areas: (**a**) operative temperature values, (**b**) CO_2 concentration level, (**c**) relative humidity, and (**d**) VOC index.

Noise: Noise is referred to as unwanted sound. In vehicle and train cabins, passengers are prone to noise exposure from internal and external sources. The noise equivalent levels for each of the assessed train trips was calculated according to Equation (3) and presented graphically. The noise levels have been analyzed according to the standard limits found in the accessible published science literature; however, there was no record of any national indoor noise limit or regulation for mass transit vehicles nor train passenger cars for Nigeria or similar sub-Saharan African countries as at the time of the current study report.

In Figure 8, the calculated L_{eq} (dBA) is presented, and the various limits are reported. The noise equivalent was computed for each trip, as shown in Figure 8a, while Figure 8b presents the comparison of the interior noise evolution and the L_{eq} (dBA) in one of the studied trains (trip 4) with the accessible referenced standards now discussed. The total journey time did not exceed three hours in any of the investigated train trips; therefore, no L_{eq} computed violated the Occupational Safety and Health Administration (OSHA) 85dBA 8 hr exposure limit. The highest value obtained for L_{eq} was 85 dBA. According to Bryan et al.'s [65] noise criterion for passengers in vehicles, noise levels were designated as quiet if at 67 dBA, noticeable at 73 dBA, intrusive at 79 dBA, annoying at 85 dBA, and very annoying at 91 dBA. The L_{eq} calculated for each trip surveyed suggests that the noise levels during trips 2, 3, and 4 were annoying while on the trip, the noise level could be simply noticeable but trips 5 and 6 are better described as quiet. However, the target is to have an A-weighted equivalent interior sound pressure level of between 65 dBA and 70 dBA, which is commonly chosen to achieve passenger comfort [66]. Recently, Peng et al. [34] presented relevant train interior noise standard limits for the China Railway Corporation (GB/T 12816 [50]), the European Union (UIC 660-2002 [67]), the Japanese Industrial Standard (JIS), and the USA (USFS). According to the UIC 660-2002 [67] noise L_{Aeq} requirements for open air with train speeds of 250 km/h, for the center-of-coach it is 65 dBA, for the passing platform it is 75 dBA, and for the windshield it is 80 dBA. The L_{Aeq} in the current study pertains to center-of-coach, implying that only trip 6 (L_{Aeq} of 64.1 dBA) complied. Furthermore, the USFS recommends that for speeds greater than 75 km/h, in any train track and electric multiple units (EMUs), the L_{max} should not exceed 93 dB. This implies that all trips in the current study followed the USFS train interior noise requirement. The GB/T 12816 [50] requirement (tunnel or open air, not specified) for a speed of 200 km/h is 78 dBA for the train cab, 65 dBA for the center-of-coach, and 67 dBA for the end-of-coach. Only trip 6 in the current study complied with the GB/T 12816 [50] requirement, considering the 65 dBA limits for the center-of-coach. The findings by Winter et al. [2] on passenger comfort sensation regarding noise-simulated different scenarios of tunnel and line conditions, involving 60 participants, indicate that occupants were more comfortable with noise levels of 62 dBA in the tunnel and line conditions than at 72 dBA. Comparatively, the lowest L_{eq} computed in the current study (64.1 dBA) exceeds the comfort level of 62 dBA reported by Winter et al. Meanwhile, the Brazilian N-17 Standard requirements indicate that noise exposure exceeding 65 dBA during 8 h of a workday is considered uncomfortable [68]. Although most L_{eq} computed in the current study exceeds this limit, the maximum time was less than 3 h during each trip, considering that besides the passengers, train agents (workers) and cabin hands were also occupants during all trips. Invariably, there is a need to ensure a better acoustic environment in most of the trains investigated by the current study, although the noise levels may not pose an occupational hazard considering the OSHA and Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA) occupational noise exposure limit of 85 dBA for an 8 h working period [69]. There is no known national regulatory standard for interior noise in transport vehicles in Nigeria; most regulations concern environmental noise. Given that the trains in Nigeria are still of low- and mid-range speeds, including other peculiarities relating to transport infrastructure, climate, and policy, it is therefore suggested that an adapted national railway standard be developed for the region. It is important to mention that other sound descriptors exist that are useful in the evaluation of the acoustic environment of indoor spaces including vehicle and train microenvironments. Apart from the computed L_{eq} per trip, which represents the sound pressure level (SPL) of a continuous constant sound that would have produced the same sound energy in the same time (T) span as the actual noise history, the current study has not evaluated other sound descriptors and indices such as the articulation index (AI), predicted speech interference level (PSIL), composite rate of preference (CRP), including other sound parameters such as the sound power level (PWL), and the sound intensity level (SIL) [53]. Particularly, the evaluation of the AI, a frequency analysis of sound, and a useful index to characterize the influence of parasite noise on the intelligibility of speech [70], in indoor spaces as in transport passenger compartments could be a useful noise descriptor in developing tropics such as Nigeria where several studies [71–74] have reported significant existential noise in the outdoor and indoor spaces. The indoor noise in transport cabins includes noise intrusion from ambient outdoor and internal noise sources including the vehicle (structural and engine sources and occupant sources like talking, use of portable gadgets, and other behavioral activities). Furthermore, considering some cultural and communication peculiarities of commuters in mass transit vehicles in Nigeria, it is recommended for consideration in future studies to evaluate the AI.



(a)



(b)

Figure 8. Graph showing noise equivalent L_{eq} (dBA) for each train cabin assessed and interior noise for a selected train trip. (**a**) presents the L_{eq} levels in each trip and (**b**) the interior noise of a selected train passenger car compared to the referenced standards.

Visual Comfort: Indoor lighting impacts occupants' comfort, well-being, and safety. Nowadays, the use of energy-efficient lighting, adequate illuminance, suitable illuminance distribution, color temperature, and seat arrangements including the interior decorative materials for better passenger comfort and ride experience in trains is crucial to assure sustainability and profitability for train operators. If trains are more comfortable for passengers, in experience and safety, there is a likelihood that patronage of trains for travel will increase. Hence, the current study has objectively assessed the cabin illuminance during all the trips investigated.

Figure 9 presents the graphical representation of the average lighting levels computed during each of the trips investigated. In Nigeria and many developing tropics, there are no guidelines for rail transit passenger compartment lighting design. EN 13272-2012 [75] recommends that the average illuminance should be 150 lux with an illuminance uniformity of 0.8 lux–1.2 lux in the passenger seat area. In standing areas, an average illuminance of 50 lux with an illuminance uniformity of 0.5 lux–2.5 lux is required. Meanwhile, other standards like JIS E 4016-2009 [76] and GB/T 7928-2003 [77] require that normal lighting areas should be 200 lux or more [78]. Following the average illuminance values (already presented in Table 2), only five passenger compartments exceeded 150 lux considering the average illuminance recorded during each trip, meeting the EN 13272-2012 [75] recommendations. In the current study, the illuminance levels were measured only for the sitting areas. Other lighting parameters such as glare and luminance were not assessed in the current study. It is important to highlight that most of the trains were equipped with window curtains that may have contributed to shading in the passenger compartment. Shading the passenger compartments could be advantageous for ensuring an adequate thermal environment (LESS heat penetration into the cabin from irradiation) in the tropics such as Nigeria; therefore, adequate lighting can be achieved in the train by equipping OLED (organic light-emitting diodes) luminaires. By visual observation, we remark that the trains investigated in the current study were not equipped with OLED luminaires; meanwhile, OLED luminaires are preferred for performance, as suggested by the studies [2,79,80].

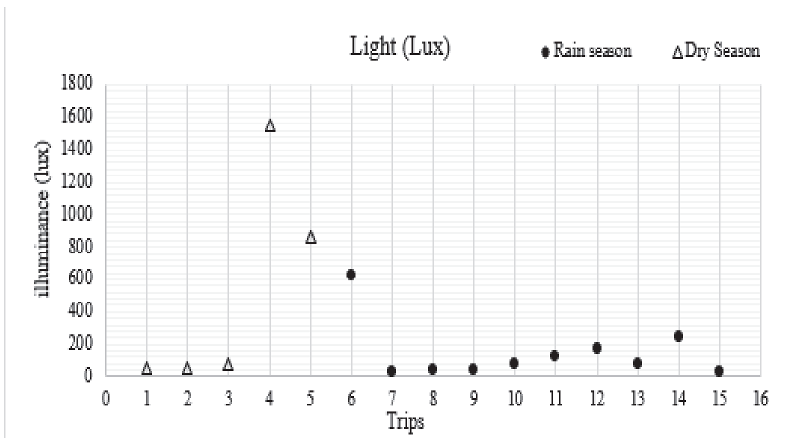


Figure 9. Mean illuminance and atmospheric pressure in all trips investigated.

4. Limitations of the Study

The current study has used only objective methods to assess and evaluate the IEQ parameters. It is recommended that for a more holistic evaluation, subjective assessments also be performed in future works. Also, other comfort parameters impacting the overall IEQ conditions such as vibration and passenger seat comfort have not been assessed in the current study. The PM measurements in the current study have been performed considering only the dry season; it could be useful to conduct a comparison of PM for the dry and rainy seasons. Furthermore, more attention and evaluation should be given to thermal comfort measurements, visual comfort technologies, and distribution in the cabin vis-a-vis the evaluation of passenger comfort. Finally, due to permit constraints, limited transport stakeholder cooperation, and the inherent challenges with real-time travel assessments, a simple methodology was adopted and adapted to focus more on the indoor climate parameters. Future works should ensure wider stakeholder collaboration and support for ensuring the use of more robust study methods and measuring tools according to the EN 13272-2012 [75] recommendations. Although this study reported that the trains were equipped with curtains for shading, future works must assess the risk of increased thermal loads linked to high solar radiation in the tropics, which can contribute to awareness regarding thermal management and energy-efficiency targets for in-cabin climatization.

5. Conclusions

The current study has assessed the IEQ of passenger compartments in air-conditioned trains during real-time travel between the Lagos and Ibadan metropolitan cities in Nigeria including a preliminary assessment of the indoor climate parameters of passenger waiting areas in train stations. This study objectively assessed and analyzed the IAQ (specifically, CO_2, VOCs, NO_2, $PM_{2.5}$, and PM_{10}), thermal, visual, and noise comfort parameters according to the recommended limits. The indoor climate parameters were mainly categorized and analyzed according to EN 16798-1. Other IEQ parameters have also been analyzed according to some relevant requirements from the ASHRAE, EN 13272-2012, OSHA, WHO, and other known national regulations.

The main findings indicate that IEQ gaps exist concerning the passenger cabins of the studied trains. The PMV index suggests cooling over-compensation from settings in the air conditioners. Concerning the IAQ, the mean levels of the measured CO_2, NO_2, and VOC pollutants did not present toxic or severe discomfort levels, but $PM_{2.5}$ and PM_{10} were in exceedance of the referenced WHO limits in six of the train cabins investigated, indicative of a poor IAQ. The current study did not characterize the source of elevated levels of PM nor its effects on exposed occupants; however, owing to previous study reports, in-cabin PM infiltration has been linked to intrusion during the opening of doors, windows, fresh air supply, ineffective filters, compromised ventilation systems, and particle resuspension phenomenon. These apply to the study case since there is elevated pollution in ambient outdoor air due to high vehicle traffic, industries, socioeconomic activities, and environmental policy gaps in the region. Also, the ventilation parameters, fresh air flow rate and air exchange rate, were inadequate in 60% of the studied train passenger cars. The findings suggest that the indoor climate of passenger waiting areas was thermally comfortable and of a non-toxic IAQ. The noise equivalent calculated in six trips assessed suggests that passengers and train workers are not exposed to annoying noise, but it is noticeable and intrusive. Although the least noise equivalent level (L_{eq} of 64.1 dBA) exceeds the comfort level of 62 dBA reported by Winter et al., there was no exceedance of the exposure noise limits of the OSHA and NESREA. The mean illuminance computed suggests that only five of the fifteen trips evaluated complied with the EN 13272-2012 recommendation of 150 lx in the train passenger compartment.

The current study leverages the urgent need to improve mass transit in developing sub-Saharan countries, considering their geometric population growth, urbanization, and sustainability trends. It behooves transport stakeholders to improve passenger comfort and safety and minimize the risk to health while providing energy-efficient and sustainable mobility solutions. This study serves as the first scientific evaluation of IEQ in trains in Nigeria and the developing West African region where several efforts have recently been ongoing to revive and improve the train transportation systems. Its findings present a preliminary assessment that will help sensitize transport stakeholders to IEQ gaps. Enhancing local IEQ regulations for transport indoor microenvironments is necessary given the climate peculiarity, transport technology, culture, and high commuter traffic tendencies in developing tropics, hence the recommendation for more IEQ and outdoor environmental scientific studies and an increase in IEQ awareness among commuters and transport stakeholders in Nigeria and similar sub-Saharan countries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152316533/s1, Table S1. The field measurement equipment parameters.

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editing, J.O.O., J.-P.K.B.N., M.G.d.S. and A.S.N.R.; supervision, M.G.d.S. and A.S.N.R.; project administration, M.G.d.S. and A.S.N.R.; funding acquisition, M.G.d.S. and A.S.N.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data generated and analyzed during this study can be found within the published article and its Supplementary Files. They are also available from the corresponding author upon reasonable request.

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Article

Multi-Objective Decision-Making Tool for Envelope Energy Retrofitting Measures of Gated Community Housing in Egypt

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Abstract: Due to climate change, Egypt has recently suffered from recurring electricity crises. Despite efforts made to increase electricity production in Egypt, recently, in the summer months, the energy demand has increased at unprecedented rates, especially in the housing sector. Therefore, the government and homeowners should work together to improve the energy performance of residential buildings. This paper aimed to develop a decision-making tool that helps homeowners choose optimal energy retrofit measures that suit their priorities. The study began with the data-collection and case study selection. Then, the thermal evaluation of the base case for dwellings in the case study was conducted through simulation runs using the DesignBuilder v7.1 software. Then, the optimal envelope energy retrofitting measures were determined, followed by a retrofitting-measure scenario simulation process. Then, the payback periods were calculated for all scenarios, and the tool database was developed using an Excel spreadsheet. Finally, the user interface for envelope energy retrofitting measures for gated communities (EERMGCs) tool was designed by Visual Basic for Applications. EERMGCs, the tool developed in this paper, is a simple, multi-objective and interactive tool that provides the optimal envelope retrofit measures according to user priorities, either a specific budget, the shortest payback period, the lowest possible costs, or the highest energy saving rate. The outcome of this research is developing a framework that can be considered a basis for developing decision-making tools for gated community housing in Egypt.

Keywords: energy retrofitting; decision-making tool; cost-effectiveness; gated communities; luxury housing; energy efficiency; homeowners; payback period; sustainable housing

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1. Introduction

Energy consumption rates are increasing rapidly in all countries around the world. For example, the average global electricity consumption grew by nearly 1% annually between 2011 and 2016 [1]. Energy production is mainly responsible for global greenhouse gas emissions (GHG), leading to global warming and climate change. The buildings sector, especially residential buildings, is considered the most energy-consuming and greenhouse-gas-emitting cause of global warming. The building and residential sectors accounted for nearly 40% and 27% of the world's energy usage between 2011 and 2016, respectively. Therefore, the most effective strategy to reduce this phenomenon is to improve the energy efficiency of the housing sector [1,2].

Despite increased electricity production rates, Egypt has recently faced recurring electricity crises due to climate change and the global energy crisis. Recently, in Egypt, especially in the summer months, the demand for electricity has increased unprecedentedly, coinciding with temperatures rising due to people resorting to operating air conditioners to achieve thermal comfort [3]. The housing sector is the main energy consumer, compared with the other sectors, accounting for about 42.4% of total electricity consumption. This is due to several reasons, the most important of which is the excessive use of air conditioning in the summer season. The increase in energy demand is expected to continue in the coming years, with rapid urban development and population growth, which exceeded 100 million in the year 2021 [4].

Egypt is moving, along with the global interest in improving the energy efficiency of buildings. Egypt's 2030 vision aligns with some of the United Nations' sustainable development goals to enhance energy efficiency in the building sector [5]. Accurate and cost-effective retrofit activities for existing buildings significantly affect energy savings [6]. It was reported that existing building retrofitting contributes to global warming reduction, as it reduces more than 40% of energy consumption [7].

Although energy conservation these days is receiving attention from the public, designers, and decision-makers in Egypt, due to the increasing burden of energy consumption in the building sector, specifically residential buildings, Egypt has a lack of decision-making tools for energy retrofitting of residential buildings, especially in the luxury category of housing. Also, the financial obstacle remains the biggest problem facing homeowners in implementing energy retrofit measures. This is the problem that the study tries to solve. The main objective of the research is to develop the first decision-making tool for energy efficiency retrofit measures in gated residential communities in Egypt. This is to achieve the most prominent goal: to contribute to solving the energy crisis and raising building energy efficiency in Egypt.

The research methodology consists of six phases; each phase consists of some organized steps. The first phase was surveying, collecting data and selecting the case study. The second phase was to evaluate the thermal performance of the case study dwellings through simulation processes using the DesignBuilder v7.1 software. The third phase was to investigate the optimal envelope retrofitting measures. Then, all envelope retrofit scenarios were simulated for each representative dwelling model, while the fifth phase was economic analysis to calculate the scenarios' payback periods. Then, the tool database was created consisting of all previous results. Finally, the user interface for the EERMGCs tool was designed.

This research provides a framework for developing the first tool of this kind in Egypt, as no tool has been created before to help homeowners in gated communities retrofit their homes. The EERMGCs tool is also distinguished from the rest of the tools studied in the literature review by providing optimal energy efficiency solutions within any budget determined by the homeowner. It also provides the user other options according to their priorities in presenting the optimal retrofit scenarios, whether their priorities are the shortest payback period, the lowest cost, or the highest energy savings, which encourages homeowners to invest in retrofitting their homes, whatever the goals and priorities of their retrofitting. This tool is also easy to use, fast, simple, and does not require time or effort to learn; it can also be further developed and updated at any time.

2. Literature Review

The research began with the literature review phase, which included a comprehensive study of all topics related to the research goal. The most critical issues addressed in the literature review are as follows:

- The Egyptian energy profile and electricity crises;
- Gated community housing;
- Sustainable energy retrofitting for existing buildings;
- Existing global energy retrofit decision-making tools for homeowners.

2.1. The Egyptian Energy Profile and Electricity Crises

In all energy-related activities, Egypt relies mainly on three primary sources: oil, natural gas, and hydroelectric power generated from the Grand Dam [8]. The Egyptian Electricity Holding Company (EEHC), affiliated with the Ministry of Electricity and Renewable Energy (MOERE), is mainly responsible for producing, transmitting, and distributing electricity, as it encapsulates 16 companies, including six for electricity transmission, one for transmission, and the rest for distribution. The average growth rate of installed capacity is 5.7% annually from 2017 to 2019. In 2021, the total installed capacity reached 58.818 GWe. More than 99% of the Egyptian population has access to electricity, and the number of subscribers at all effort levels increased to 37.9 million customers in 2021, compared to 37.1 million subscribers in 2020, with an increase of 2.2% [9].

The distribution of installed capacities by source is 90.1% from thermal sources, 4.8% from hydropower sources, and 5.1% from renewable energy sources. Despite the continuous increase in electricity production, consumption rates also increased. For example, the total electricity consumption increased from about 331 PJ in 2005 to 556 PJ in 2019, a compound annual increase rate of 4.73% [9]. The increase in consumption is due to several reasons, the most important of which are the increase in population, climate change with unprecedented high temperatures, and urban expansion [4].

2.2. Gated Community Housing

Gated community housing is a new type of urbanization that began to appear in the late twentieth century. These residential projects quickly expanded and spread around and within the cities. They are isolated by walls and gates with distinct capabilities, miscellaneous services, and robust security measures [10]. Gated communities are spreading rapidly worldwide: in Egypt, the number of gated communities in Cairo increased from 466 in 2010 to 500 in 2013 [11]. They are distributed on the outskirts of Cairo in the new cities surrounding it, such as New Cairo, 6th of October, El-Obour, and El-Shorouk City [12]. Gated community dwellings vary from one-family separate villas and semi-detached units to apartment complexes. Most of the gated communities in Egypt are luxury housing, targeting a segment of the population with a high economic level. Therefore, they are distinguished by having a luxurious lifestyle, especially using air conditioners and other electricity-consuming devices. Consequently, this is considered one of Egypt's most electricity-consuming sectors [13].

2.3. Sustainable Energy Retrofitting for Existing Buildings

Residential buildings constitute a large proportion of the Egyptian building stock, about 83.2% of the existing buildings with low thermal efficiency [4]. The solution is to rapidly implement energy retrofit projects for the existing buildings. Sustainable retrofitting of existing buildings is one of the most effective ways to save energy and improve the environment. Therefore, over the past decade, many countries have made great efforts to improve the energy efficiency of existing buildings. Figure 1 shows the major phases of the overall process of a building retrofit project [14].

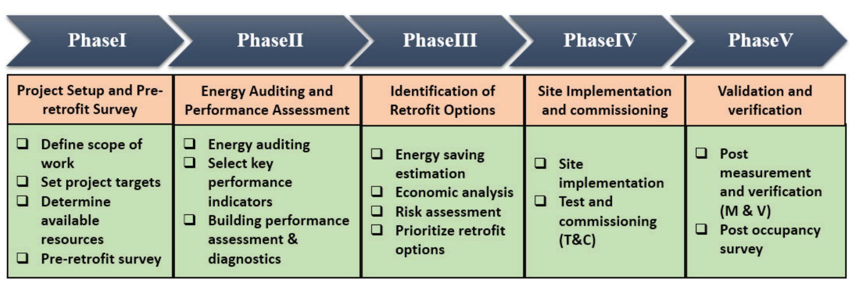


Figure 1. The major phases of the overall process of a building retrofit project.

Heat loss or gain for any building occurs through the envelope, as each element of the envelope contributes to the building's heat loss or gain. This varies from one building to another depending on the conditions and design of the building. In general, heat in a multi-storey building is lost by a percentage of 40% from the exterior walls, 30% from the windows, 17% from air leaks, 7% from the roof, and 6% from the basement slab. In many retrofit projects, envelope retrofitting is the optimal solution that is more logical than other retrofitting types, as it is more effective in saving energy and costs less when compared to other retrofitting types [15]. Many studies have reported the significant impacts of envelope retrofitting measures on increasing energy efficiency. For example, Frieza and Rakhshan found that thermal insulation for housing buildings in the UAE can reduce energy consumption by 20% [16]. The performance of a double-skin roof was 28–34% higher than the typical single-layer insulated roof in terms of reducing heat gain in Singapore [17]. In the hot and dry climate of Djibouti, it was found by Abdou Omar et al. that roof efficiency improved by 85% after installing the double roof [18]. A study of the energy retrofit of an existing affordable building envelope in Spain reported that applying expanded polystyrene 6 cm for wall insulation, extruded polystyrene 8 cm for roof insulation, and a light-coloured façade led to a 25–88% reduction in energy consumption [19]. The application of cool and green roofs in Italian residential buildings reduces overheating hours by 98%, according to Pisello et al. research [20].

The research addressed a review of many building retrofit studies in Egypt, focusing on residential buildings, to investigate the most effective retrofit measures for energy efficiency in Egypt. These studies have shown that retrofitting measures have significantly reduced building energy consumption. For example, Ingy El-Darwish and Mohamed Gomaa reported that retrofitting measures in Egypt could achieve 23% energy savings by using 0.5 cm metal louvres as window shading [21]. In a study of one of the luxury residential buildings in Egypt, Bassent Adly and Tamir El-khouly found that energy consumption can be reduced by 20.68% when retrofitting shading devices. They also used wall insulation material with thermal resistances R-value = 1.54, like expanded polystyrene 4 cm and rock wool 4 cm, which achieved a 9.21% energy saving [1]. Mohammad Abdollah and Rossano Scoccia studied applying building envelope measures for affordable housing in Egypt, such as wall insulation and glazing retrofitting from available options in the Egyptian market. They reported that energy consumption decreased by 40% after applying these measures with a maximum payback period of 6.3 years [22].

2.4. Existing Global Energy Retrofit Decision-Making Tools for Homeowners

Community participation and cooperation between the government sector and homeowners is necessary for improving energy efficiency. So it is important to have tools that encourage homeowners to invest in energy efficiency in their homes. These tools also help them choose the optimal energy efficiency measures in terms of energy savings and cost savings. In many countries around the world, many decision-making tools for energy retrofitting have been produced by the public or private sectors to inform occupants and homeowners about energy retrofitting measures and encourage them to invest in energy retrofitting procedures [23]. Some types specialize in only one aspect of energy retrofitting measures, such as insulation calculation tools [24], solar panel calculation tools [25], building envelope efficiency tools, and renewables selector tools. Some tools deal with overall building retrofit measures, whether these are the building envelope, building systems, or renewable energy. Some decision-making tool types include economic analysis for energy efficiency measures, such as the life cycle and payback period calculation [26].

The French Scientific and Technical Center for Buildings developed ALICE (Amélioration des Logements en Intégrant les Contraintes du Confort d'Été). ALICE is an Excel tool that analyses the possibility of the impact on summer comfort of different thermal renovation measures and the effects of different behavioural scenarios of building occupants. Two thousand four hundred thermal simulations were conducted to calculate the interior temperature of a set of dwellings representing France's most common building typologies. Occupants can assess and compare the impact of different retrofitting configurations on summer energy use [27]. Home Energy Saver is an internet-based tool developed by the US Department of Energy; the tool calculates detailed energy consumption in housing buildings in the US and offers detailed evaluations of retrofitting measures such as yearly savings, annual electricity savings, yearly gas savings, annual carbon-emission reduction, investment cost, and payback period. One of the advantages of this tool is that it gives users the choice between two input and output modes, the first is the quick mode, which gives approximate results based on multiple assumptions, and the second is the detailed mode, whose output is more accurate, but requires a lot of input and consumes a long time [28].

Researchers from British Colombia University, Canada, developed SWAHO (sustainability weighting assessment for homeowners). This tool provides easier decision-making for occupants and homeowners for their sustainable retrofitting projects. The SWAHO tool was developed by using Microsoft Excel with Visual Basic for Applications (VBA). It assesses 48 retrofitting measures in terms of 12 sustainability criteria using a knapsack problem method to optimize measures. The Excel database contains the assessments of the retrofitting measures. The SWAHO tool takes into account social criteria, so it presents particularity to users. Also, SWAHO enables homeowners to determine their priorities from among environmental and social criteria [29]. 4ECasa is a home energy check tool developed by the National Agency for New Technologies in Italy. The tool helps users choose retrofitting measures for the building envelope and the heating system. The retrofitting measures are evaluated in terms of energy savings, economic savings, the complexity of implementation works, and CO_2 reduction. The evaluation of energy savings is conducted by a normative simplified calculation method considering standard conditions of use of the building. Compared to the other existing tools, the main advantage of this tool is to consider technological criteria such as the complexity of implementation works [26].

3. Methodology

This study aimed to develop a multi-objective decision-making tool that helps homeowners choose the optimal envelope energy retrofitting measures for their homes according to the priorities of each homeowner. This tool is applied to luxury housing in gated communities in Cairo. The methodology shown in Figure 2 was followed to develop the EERMGCs tool. The methodology consists of six phases, which are briefly explained in as follows:

- Phase 1—Data gathering and case study selection
  This phase included collecting and analyzing data for:
  (a) Luxury dwellings in Cairo's gated communities and their structural, architectural, and thermal attributes: These gated communities are spread around Cairo, located within new urban areas on the capital's outskirts. Each gated community is wholly designed and built by a real estate development company. Therefore, the dwellings within these communities have the same architectural and structural attributes. Each gated community often has various luxury models of villas, duplexes, or apartments. "Madinaty City" was chosen as a case study for applying the EERMGCs tool. All the data required for the selected case study were collected through three methods (visiting and surveying the site, the official website of the company that owns this gated community, conducting interviews and questionnaires with residents). The questionnaire, as shown in Appendix A Figure A1, was prepared and delivered in print or online to the occupants during the site visits.
  (b) The local construction market: This step aimed to collect data about the locally available energy retrofitting measures and their costs. This phase was preceded by the literature review through which the most effective measures of envelope energy retrofitting for residential buildings in Egypt were studied. These retrofit measures are only for the elements of the building envelope (walls, roofs, glazing, and shading). The measures were filtered according to what suits the attributes and characteristics of the housing in the gated community. All the information required in this section was collected by three methods (communicating with the companies concerned, asking specialists, visiting the construction market) to find out the available measures on the local market, and then making a list of the most important ones along with their costs, including the materials and installation prices.
- Phase 2—Representative dwelling thermal performance assessment

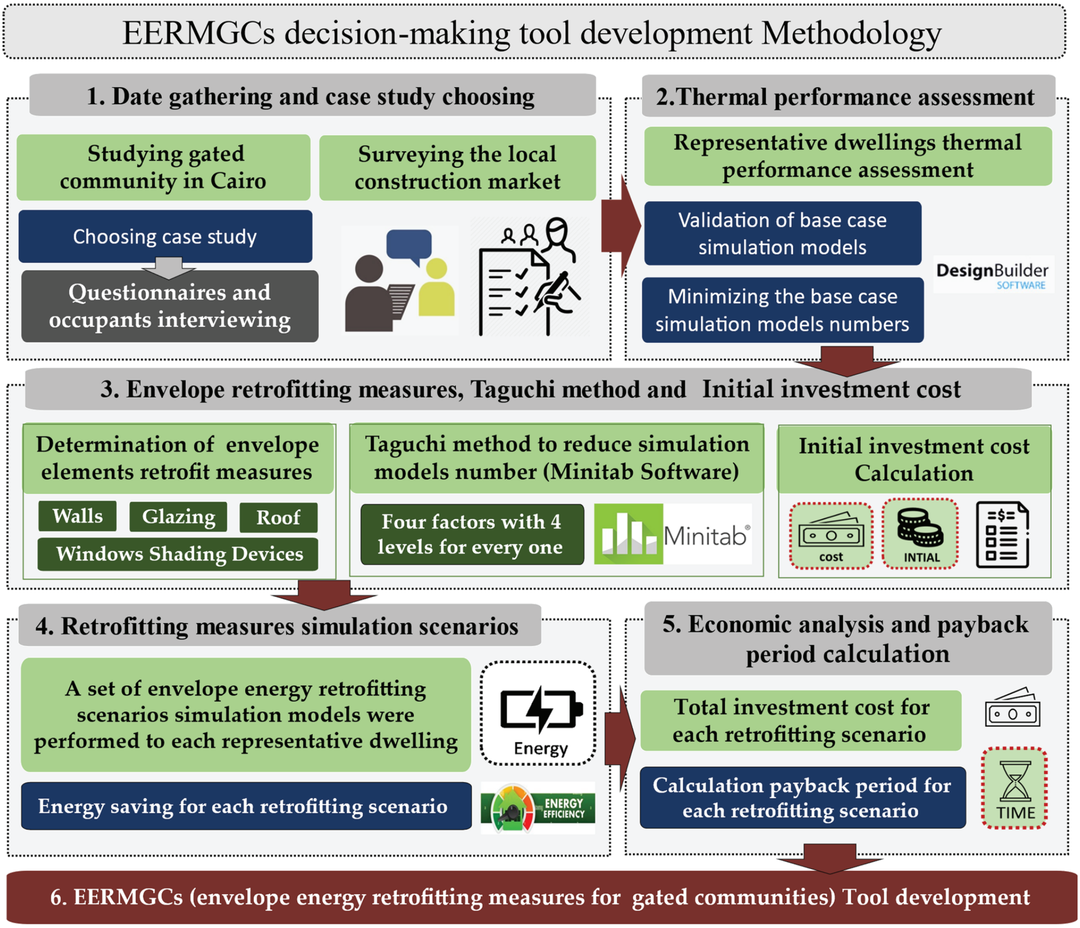


Figure 2. Methodology phases of the EERMGCs tool development.

A set of dwelling models was selected from the chosen case study area to be representative models to cover all dwelling types and to evaluate the base case thermal performance of case study dwellings. Then, a thermal simulation process was conducted for each representative dwelling model using the DesignBuilder v7.1 software. The data required for the simulation process were collected in the first phase. Phase 2 also included the step of verifying the simulation models by comparing actual consumption with consumption resulting from the simulation process for eight dwelling models. Changes in the cooling set-point and the occupancy schedule were conducted in order for energy simulation models to come as close as possible to actual consumption. Minimizing the number of simulation models for representative dwellings was conducted to simplify the simulation processes in the following phases. The details of all phase steps are explained in detail in Section 4.

- Phase 3—Envelope energy retrofitting measures and Taguchi method application

This phase aimed to investigate the most effective envelope retrofit measures. A set of energy retrofit measures was identified for each building envelope element, based on the data collected from the Egyptian market and the literature review in the first phase, in addition to the selection criteria explained in Section 5.1.

This phase also included applying one of the principles of experiment design (the Taguchi method), which is a quality control method and an engineering approach developed by the Japanese engineer Genichi Taguchi [30]. In the beginning, the Taguchi method was created to produce a high-quality product at a low cost by conducting some statistical operations that indicate the factors that most influence the quality of the product or vice versa without consuming a lot of time and cost. Then, this method came to be widely used in experiments and scientific research to investigate the effect of factors and their variables on a dependent response without the need to repeat the experiment multiple times [31]. This method can be applied with some statistical tools; the most common is the Minitab v21 software.

In this paper, application of the Taguchi method aimed to reduce the number of required simulation models and determine the most effective energy-saving measures to simplify the simulation process. Initial retrofit scenarios were determined by the Taguchi method to investigate the effectiveness of retrofit measures. In Section 5.2, all steps of this process are explained in detail. In this phase, the initial investment cost was calculated for each energy retrofit alternative chosen for all representative dwelling models based on price data collected from the construction market.

- Phase 4—Envelope energy retrofitting measures scenario simulation

The objective of this phase was to conduct simulation of all retrofitting scenarios. These scenarios were created based on the results of the Taguchi method and initial economic analysis in the previous phase, where the most energy-saving and least costly retrofitting measures were identified. The number of simulation models for each dwelling model was 81 envelope energy retrofitting scenarios. In this phase, 810 simulation runs of envelope energy retrofitting scenarios were performed for all dwelling models using the DesignBuilder v7.1 software. The results of the simulations included the annual energy-saving percentages for the scenarios in order to create the EERMGC tool database. All phase details are mentioned in Section 5.4.

- Phase 5—Economic analysis and payback period calculation

In this phase, the total investment cost was calculated for each retrofitting scenario based on the results of the previous phases. Then, the payback periods were calculated for all scenarios to develop the EERMGCs tool database.

- Phase 6—EERMGCs tool development

The EERMGCs tool database was developed by using an Excel spreadsheet. This database was an aggregation point for all previous results. Finally, the user interface for the EERMGCs tool was designed by Visual Basic for Applications (VBA). It is a simple and easy-to-use tool; it adapts to the different priorities of homeowners, offering them the optimal retrofitting measures according to their objectives. It provides the user with the optimal retrofit measures for their home within any budget they determine. Also, the user can control the criteria for the generated retrofit scenarios according to their priorities: the fastest payback period, the lowest investment costs, or the highest energy saving rate.

4. Representative Dwelling Simulation Models

4.1. The Case Study Dwelling Simulation Models

"Madinaty City" is the gated community chosen as a case study in this research. It is a luxurious housing complex located in the east of Cairo, as shown in Figure 3. It was built in 2005, containing sets of several dwelling models that vary between single-family houses and multi-family housing complexes. The "Golf area", as shown in Figure 4, is a single-family villa district in "Madinaty City"; this area was chosen to apply the EERMGCs tool. All villa models in this gated community have the same structural, architectural, and thermal attributes, as shown in Table 1. They differ in the total area and the orientation of each villa. As shown in Figures 5 and 6, the "Golf area" has two models of villas with different total areas, model A and B, of 600 m^2 and 350 m^2, respectively. Each villa consists of a ground, first, and roof floor. In this phase, the thermal performance of the base case of the case study dwellings was evaluated through simulation processes for a set of representative dwelling models using DesignBuilder v7.1 software. Figure 7 shows the simulation models for villa model A and villa model B. Sixteen simulation models were conducted for models A and B in eight orientations (north N, northeast NE, east E, southeast SE, south S, southwest SW, west W, northwest NW) to ensure that the simulation results would be accurate and robustly representative of all dwellings in the chosen gated community district.

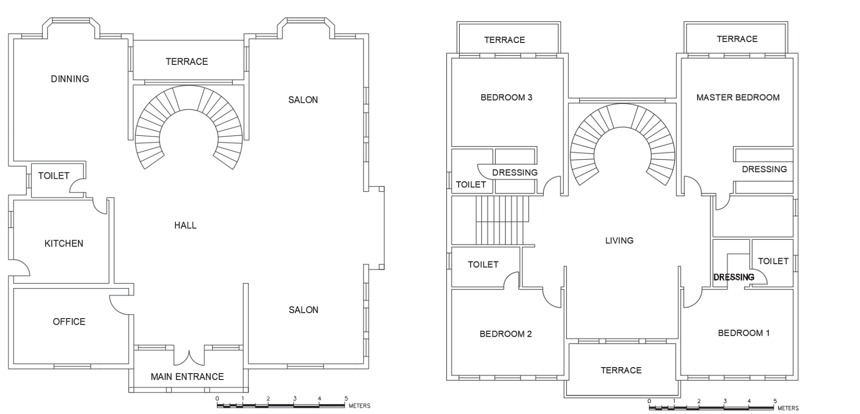
Figure 3. The location of the case study, "Madinaty city" is on the outskirts east of Cairo.

Figure 4. The research case study, the "Golf area" layout; single-family villa district.

In most cases, each separate villa is owned by a nuclear family consisting of a husband, wife, and a number of children, ranging on average from two to four. Therefore, the number of occupants was assumed to be five and six for the Villa A and Villa B models, respectively. Occupancy schedules for weekdays were assumed as follows: occupants wake up at 6:30 a.m. and leave the house at 8 a.m., except for one person. The occupants return at 6:30 p.m. and stay up until 11:30 p.m. The schedule is slightly changed for the weekends. Lighting units in each room vary from incandescent lamps to halogen ceiling spotlights, with a diversity of lighting-power intensity levels for each space. The lighting schedule was assumed to correspond to the occupants' schedule. Each room has a split air-conditioner (AC) unit serving mainly bedrooms and living rooms. Air-conditioner units operated during the summer season from 1 June to 30 September following the occupancy schedules. The occupancy schedule was assumed based on the interviews of and questionnaires submitted by occupants. Also, the data about other appliances (ceiling fans, refrigerators, water heaters, stoves, etc.) and operating schedules were determined according to the information collected from the interviews and questionnaires. The questionnaire sample, shown in Appendix A Figure A1, was created using Google Forms. A number of questionnaires were printed and distributed to the occupants, and others were sent online to be filled out, this was carried out during the site visits to the case study gated community. Data were collected from 36 questionnaires, about 19 of them from the villa model A, and the rest were from the villa Model B. The results of the questionnaires in this experiment were merely indicators to assume schedules of occupancy, activities, and operation of devices, as these data were assumed based on the outputs of the most common data from questionnaire results.

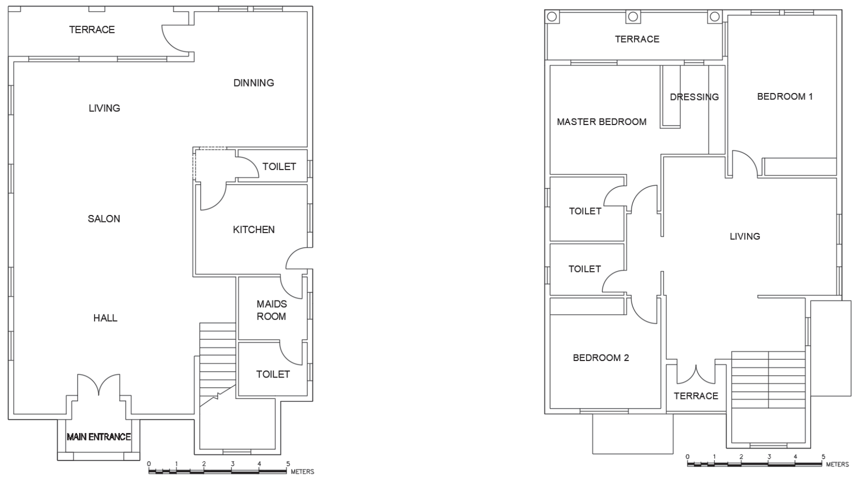
Table 1. The common attributes for all case study dwelling models.

Building Attributes	Type A and B
Building shape	Rectangular
External Wall	U-value = 1.5 W/m^2/K
	Brick 25 cm
	Mortar on each side 2.5 cm
	Plaster on each side 1.5 cm
Roof	U-value = 0.52 W/m^2/K
	Cement tiles 2 cm
	Mortar 2 cm
	Sand 6 cm
	Plain concrete 7 cm
	Expanded polystyrene 5 cm
	Vapour barrier 4 cm
	Reinforced concrete 10 cm
	Plaster 1 cm
Glazing	U value including frame = 5.013 W/m^2/K
	Solar heat gain coefficient (SHGC) = 0.78
	Window-to-wall ratio (WWR) = 30%
	Single-glazed panel 3 mm thickness, with aluminium frames, no shading devices



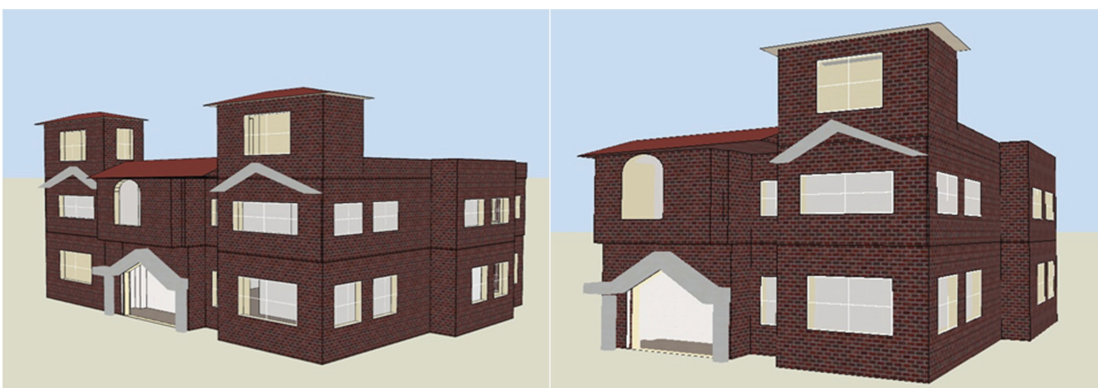
(**a**) (**b**)

Figure 5. Representative dwelling models for villa model A: (**a**) ground floor (**b**) first floor.



(**a**) (**b**)

Figure 6. Representative dwelling model for villa model B: (**a**) ground floor (**b**) first floor.



(**a**) (**b**)

Figure 7. Simulation model perspectives for (**a**) villa model A and (**b**) villa model B.

4.2. Validation of Simulation Models

The accuracy of the simulation models has been verified by comparing the eight simulation models' energy consumption results with the actual consumption from the electricity bills of these eight villas. Electricity bills collected for the eight villas were for monthly consumption from January 2022 to December 2022. After conducting a number of calibration models with some changes in the cooling set-point and the occupancy schedule, the closest simulation models for the actual consumption were performed, and then these adjustments were applied to all simulated models. The difference between the actual electricity consumption and simulation model consumption does not exceed the acceptable range. For example, Figures 8 and 9 show the difference in monthly electricity consumption between the actual dwelling models and the simulated models for villa model A with southwest orientation (SW) and villa model B with eastward orientation (E), which does not exceed 4.5%.

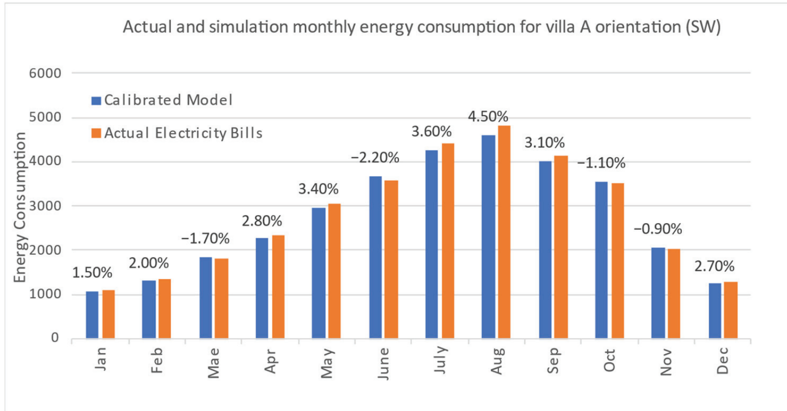


Figure 8. Actual and simulation monthly energy consumption for villa A orientation (SW).

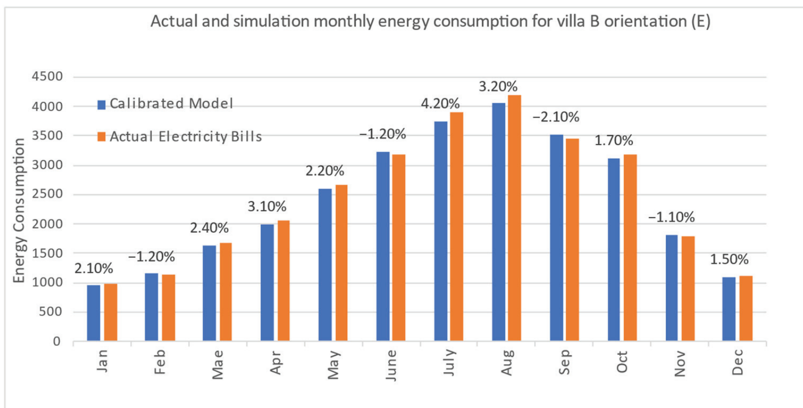
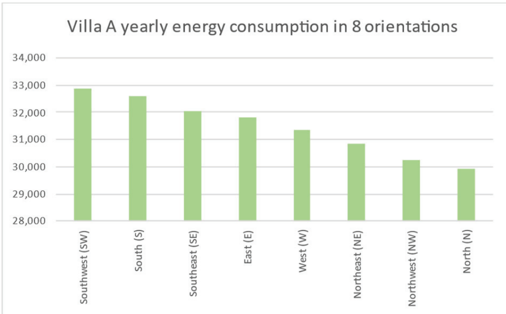


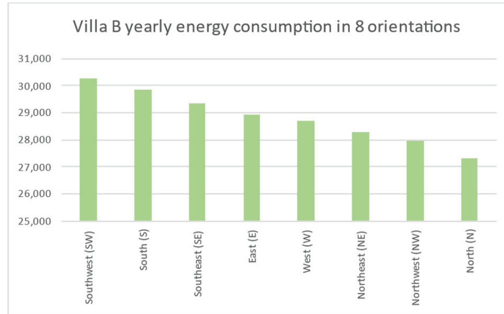
Figure 9. Actual and simulation monthly energy consumption for villa B orientation (E).

4.3. Minimizing the Number of Simulation Models for Case Study-Representative Dwellings

This step aimed to simplify the simulation runs and reduce their numbers. As mentioned above, each A and B villa model's thermal performance was evaluated in eight orientations with a total of 16 simulation models. The simulation results showed that the annual energy consumption in some orientations is very close for the same villa model, and the difference between them does not exceed 2%, as shown in Figure 10. Therefore, the number of villa models representing all case study dwellings was five for each villa model, A and B, meaning that the number of the simulation models for the representative dwelling models in the base case was reduced from 16 to 10. Where the southwest orientation represents the south, the southeast orientation represents the east, and the northwest orientation represents the north, as shown in Figure 11. The selection criteria were for the orientation with the highest consumption rate, meaning that for every two close orientations in consumption rate, the selection priority was for the orientation with the highest consumption.



(**a**)



(**b**)

Figure 10. Yearly energy consumption in eight orientations for (**a**) villa model A and (**b**) Villa model B.

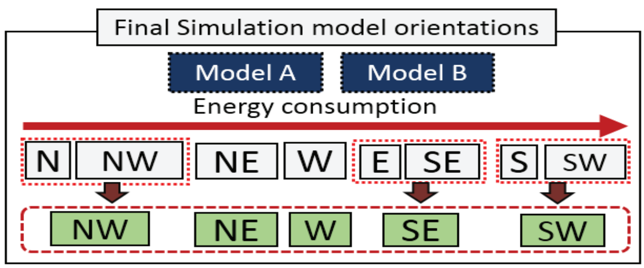


Figure 11. The final simulation model orientations.

5. Envelope Energy Retrofitting Measures and the Taguchi Method

5.1. Envelope Energy Retrofitting Measures

A set of envelope energy retrofitting measures was selected for each building envelope element (wall, roof, glazing, and shading). Selection criteria were determined based on what was studied in the literature review in the first phase and the recommendations of the Energy Code for Residential Buildings in Egypt. Also, among the selection criteria are the availability of retrofitting measures on the Egyptian market, their common use on the local construction market, and their ease of application. Choosing the lowest priced retrofitting measures, which have high energy efficiency, was always the selection priority. For example, there are some materials used for thermal insulation on the local market that have similar energy-saving rates; the material with the lowest price was chosen, such as expanded polystyrene EPS. This was the strategy for selecting all retrofit alternatives in this study.

Table 2 shows the four retrofitting alternatives chosen for each building envelope element (walls, roofs, glazing, and shading devices) to apply in the thermal performance simulation for representative dwellings models. For simplicity, a shortcut code was given for each energy retrofitting alternative to be used in the following research phases, as shown in Table 2. Thermal performance for all case study models must be evaluated after applying these measures individually or as a package by the thermal simulation process in order to test the energy-saving efficiency of the energy retrofitting alternatives and scenarios. This process would require a huge number of thermal performance simulation runs. To reduce the total number of simulation runs, principles from the Design of Experiment (Taguchi method) were used.

Table 2. The energy retrofit measures for envelope elements (walls, roofs, glazing, and shading devices).

Code	Wall Insulation	Code	Roof Insulation	Code	Glazing	Code	Shading Devices
W_1	Expanded polystyrene (EPS) 3.00 cm	R_1	Tile foam of extruded polystyrene (XPS) 3 cm	G_1	Single glazing 6 cm with silver p20 sun control film coating	SH_1	Metal inside shading louvres
W_2	Expanded polystyrene (EPS) 5.00 cm	R_2	Polyurethane foam 3 cm	G_2	Coloured double glazing with 6 mm/ 13 mm air	SH_2	Metal exterior roller blinds
W_3	Expanded polystyrene (EPS) 10.00 cm	R_3	Expanded polystyrene (EPS) sheet coated on both sides with cement mortar and fibreglass mesh 3 cm	G_3	Clear double glazing with 3 mm/ 13 mm air	SH_3	Metal exterior shading louvres
W_4	Polyurethane 5 cm	R_4	Tile foam of extruded polystyrene (XPS) 5 cm	G_4	Clear double glazing with 6 mm/13 mm air	SH_4	Inside shade roll—light translucent
W_0	Without wall insulation	R_0	Without roof insulation	G_0	Without glazing retrofitting	SH_0	Without shading devices

5.2. Design of Experiment (DOE—Taguchi Method) Application

Design of Experiment (DOE) is a branch of applied statistics that evaluates the factors that control the value of a parameter or a group of parameters. DOE provides predictive knowledge of multi-variable and complex processes with few trials that reduce project time and costs. There are different types of DOE designs, and the choice of type depends on the study objectives. DOE can be applied by several methods, such as mixture designs for different purposes, Taguchi design and response surface designs [30]. The Taguchi method is a statistical method that reduces the variation in a design or production process by the robust design of experiments. It is one of the best optimization techniques to achieve high quality without consuming much time and cost [32]. The Taguchi method has recently been used in energy efficiency optimization in buildings studies [33].

The Taguchi mix-mode design method was used in this study phase to reduce the required model simulation runs. This method uses a fractional factorial order layout, termed Orthogonal Arrays (OA) to investigate the most effective energy retrofitting measures in order to reduce the number of simulations required [31]. The Taguchi method uses the signal-to-noise ratio (SNR), which is a measure of robustness that aims to reduce the effect of noise and optimize the performance of the process [33].

A signal-to-noise ratio (SNR) is the measure used in the Taguchi method; it is a robustness measure that can be used to determine the control factor settings that minimize the effect of noise on the response. It is an indicator of the influence of factors and their levels on the final response. The higher the SNR of a particular factor, the greater its influence on improving the final dependent response. This is because the higher the SNR, the smaller the noise factor influence (noise factors reduce final response improvement). Minitab software shows a separate SNR for each factor level combination in the process. The user has four options for outputting the SNR: larger is better, smaller is better, and two nominal is best ratios; it can determine it according to the goal of the study [34–36].

For further clarification, in this study, the final response was considered to be energy consumption, and the influencing factors are the envelope elements. Each of the envelope elements has four levels that were the retrofitting measures. Therefore, the factor levels with a higher SNR are higher energy consumption. This study aimed to investigate the measures that have lower energy consumption, so these measures have lower SNR. Therefore, in this research, the smaller the SNR is, the better.

The Taguchi method was applied in this study by using the Minitab tool, which is a statistical software tool. The first step was inputting the four elements of the envelope (walls, roofs, glazing, and shading devices) as the main factors. The energy retrofitting alternatives for each envelope element were inputted as sub-variables which are named levels in the Minitab software. Then, the number of simulation runs was determined as 16 for every representative dwelling model. The Taguchi method determined an adequate fraction of the retrofitting measure combinations from all possible simulated scenarios. The retrofitting simulation scenarios determined by the Taguchi method were performed by Designebuilder software. Then, the energy consumption results for each scenario were inputted again into Minitab software to investigate each alternative's effectiveness on energy efficiency and its impact on energy consumption. This process was repeated ten times, as there were ten different representative dwelling models, and these steps were performed for each one. For example, Table 3 shows the Taguchi method orders layout and the required energy consumption data of simulation runs for villa model B in (S and SW) orientation.

Table 3. Taguchi orders layout and required energy consumption data of simulation runs for villa model B (S and SW).

Villa Model B (S and SW)					
Simulation Run Order	**Wall Insulation**	**Roof Insulation**	**Glazing**	**Shading Devices**	**Annual Energy Consumption (kWh)**
1	W_1	R_1	G_1	SH_1	22,078
2	W_1	R_2	G_2	SH_2	18,961
3	W_1	R_3	G_3	SH_3	21,361
4	W_1	R_4	G_4	SH_4	21,226
5	W_2	R_1	G_2	SH_3	19,445
6	W_2	R_2	G_1	SH_4	21,768
7	W_2	R_3	G_4	SH_1	19,619
8	W_2	R_4	G_3	SH_2	20,084
9	W_3	R_1	G_3	SH_4	21,303
10	W_3	R_2	G_4	SH_3	20,103
11	W_3	R_3	G_1	SH_2	20,877
12	W_3	R_4	G_2	SH_1	19,561
13	W_4	R_1	G_4	SH_2	19,910
14	W_4	R_2	G_3	SH_1	21,052
15	W_4	R_3	G_2	SH_4	20,335
16	W_4	R_4	G_1	SH_3	22,716

The Taguchi method results determined the most and the least effective energy-saving measures. In this study, the measures with smaller signal-to-noise were the most energy-effective. From the SN ratios shown in Figure 12, it seems that the most effective retrofitting measures for wall, roof, glazing, and shading devices were (EPS) 5.00 cm, Polyurethane foam 3 cm, coloured double glazing with 6 mm/13 mm air and metal exterior roller blinds, respectively.

5.3. Calculation of Initial Investment Cost

This step aimed to calculate the initial investment cost of each retrofit measure individually. Through the data collected from the Egyptian market in the first phase, a list of the prices for materials and installation of each alternative was prepared. The initial investment cost was calculated for each energy retrofit measure to all representative dwelling models.

Response Table for Signal to Noise Ratios

Smaller is better

Level	Wall	Roof	Glazing	Shading
1	−29.73	−29.94	−28.83	−30.04
2	−30.36	−30.14	−30.94	−30.61
3	−30.18	−30.10	−29.97	−29.71
4	−29.64	−29.73	−30.40	−29.54
Delta	0.72	0.41	2.11	1.07
Rank	3	4	1	2

Figure 12. The Taguchi method SNR results for each level of the main factors (retrofitting alternatives).

5.4. Envelope Energy Retrofitting Simulation Scenarios

Both the results of the Taguchi method and the initial economic analysis investigated energy efficiency and cost efficiency for all energy measures implemented in the study. A matrix of retrofitting scenarios was formed for each representative dwelling model based on both the most effective energy-saving and the lowest cost alternatives. Every matrix consisted of 81 optimal scenarios that achieve energy and cost efficiency. Table 4 shows the 81 scenarios that represent the possible scenarios for all the mixes for the chosen retrofitting measures. As mentioned in previous phases, the number of representative dwelling models was 10 (Villa A and B models in five different orientations). Therefore, 81 simulation runs were conducted for each representative model, with a total of 810 simulation runs to apply various energy retrofitting measures and scenarios by using DesignBuilder v7.1 software. At the end of this step, the energy-saving rates for all simulated retrofitting scenarios were determined. For example, energy can be saved by 22.8% annually for villa model A with orientation of (S and SW), if the following measures are applied: expanded polystyrene (EPS) 3.00 cm for walls, polyurethane foam 3 cm for the roof and coloured double glazing with 6 mm/13 mm air for glazing. For example, the yearly energy consumption for all 81 retrofitting scenarios of villa type A with the orientation of (S & SW) is shown in Figure 13.

Table 4. All possible scenarios for all the mixes of the chosen retrofitting measures.

Scenario Number	Wall Insulation	Roof Insulation	Glazing	Shading Devices	Scenario Number	Wall Insulation	Roof Insulation	Glazing	Shading Devices
1	W_0	R_0	G_0	SH_0	42	W_1	R_1	G_1	SH_2
2	W_0	R_0	G_0	SH_1	43	W_1	R_1	G_2	SH_0
3	W_0	R_0	G_0	SH_2	44	W_1	R_1	G_2	SH_1
4	W_0	R_0	G_1	SH_0	45	W_1	R_1	G_2	SH_2
5	W_0	R_0	G_1	SH_1	46	W_1	R_2	G_0	SH_0
6	W_0	R_0	G_1	SH_2	47	W_1	R_2	G_0	SH_1
7	W_0	R_0	G_2	SH_0	48	W_1	R_2	G_0	SH_2
8	W_0	R_0	G_2	SH_1	49	W_1	R_2	G_1	SH_0
9	W_0	R_0	G_2	SH_2	50	W_1	R_2	G_1	SH_1
10	W_0	R_1	G_0	SH_0	51	W_1	R_2	G_1	SH_2
11	W_0	R_1	G_0	SH_1	52	W_1	R_2	G_2	SH_0
12	W_0	R_1	G_0	SH_2	53	W_1	R_2	G_2	SH_1
13	W_0	R_1	G_1	SH_0	54	W_1	R_2	G_2	SH_2
14	W_0	R_1	G_1	SH_1	55	W_2	R_0	G_0	SH_0
15	W_0	R_1	G_1	SH_2	56	W_2	R_0	G_0	SH_1
16	W_0	R_1	G_2	SH_0	57	W_2	R_0	G_0	SH_2

Table 4. *Cont.*

Scenario Number	Wall Insulation	Roof Insulation	Glazing	Shading Devices	Scenario Number	Wall Insulation	Roof Insulation	Glazing	Shading Devices
17	W_0	R_1	G_2	SH_1	58	W_2	R_0	G_1	SH_0
18	W_0	R_1	G_2	SH_2	59	W_2	R_0	G_1	SH_1
19	W_0	R_2	G_0	SH_0	60	W_2	R_0	G_1	SH_2
20	W_0	R_2	G_0	SH_1	61	W_2	R_0	G_2	SH_0
21	W_0	R_2	G_0	SH_2	62	W_2	R_0	G_2	SH_1
22	W_0	R_2	G_1	SH_0	63	W_2	R_0	G_2	SH_2
23	W_0	R_2	G_1	SH_1	64	W_2	R_1	G_0	SH_0
24	W_0	R_2	G_1	SH_2	65	W_2	R_1	G_0	SH_1
25	W_0	R_2	G_2	SH_0	66	W_2	R_1	G_0	SH_2
26	W_0	R_2	G_2	SH_1	67	W_2	R_1	G_1	SH_0
27	W_0	R_2	G_2	SH_2	68	W_2	R_1	G_1	SH_1
28	W_1	R_0	G_0	SH_0	69	W_2	R_1	G_1	SH_2
29	W_1	R_0	G_0	SH_1	70	W_2	R_1	G_2	SH_0
30	W_1	R_0	G_0	SH_2	71	W_2	R_1	G_2	SH_1
31	W_1	R_0	G_1	SH_0	72	W_2	R_1	G_2	SH_2
32	W_1	R_0	G_1	SH_1	73	W_2	R_2	G_0	SH_0
33	W_1	R_0	G_1	SH_2	74	W_2	R_2	G_0	SH_1
34	W_1	R_0	G_2	SH_0	75	W_2	R_2	G_0	SH_2
35	W_1	R_0	G_2	SH_1	76	W_2	R_2	G_1	SH_0
36	W_1	R_0	G_2	SH_2	77	W_2	R_2	G_1	SH_1
37	W_1	R_1	G_0	SH_0	78	W_2	R_2	G_1	SH_2
38	W_1	R_1	G_0	SH_1	79	W_2	R_2	G_2	SH_0
39	W_1	R_1	G_0	SH_2	80	W_2	R_2	G_2	SH_1
40	W_1	R_1	G_1	SH_0	81	W_2	R_2	G_2	SH_2
41	W_1	R_1	G_1	SH_1					

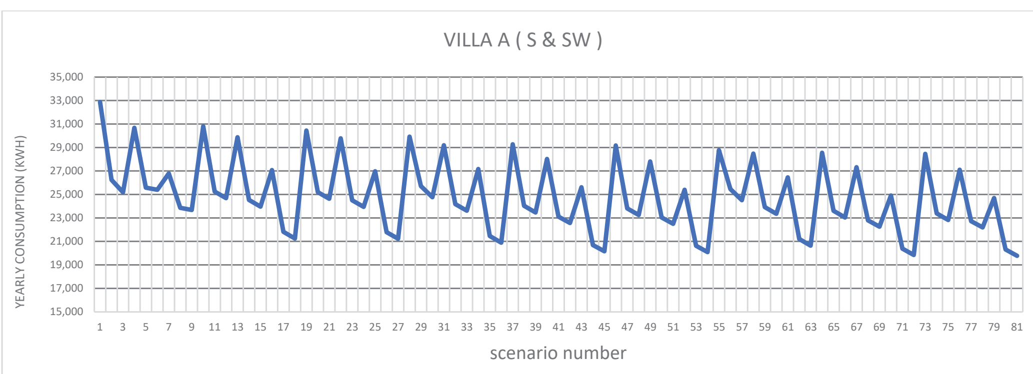


Figure 13. Villa A (S and SW) yearly energy consumption for various retrofitting scenarios.

5.5. Economic Analysis and Payback Period Calculation

This step aimed to calculate the payback period for each energy retrofit scenario. A payback period is a method used to determine the number of periods (usually years) required to cover the initial investment costs, taking into account interest rates and inflation. After the end of that period, the return on investment begins [26].

Based on what was calculated in the initial investment cost analysis for each energy retrofit measure, all the investment costs for each retrofit scenario were calculated. Then, the payback period was calculated for each retrofit scenario based on the previous results of investment cost and energy consumption predicted from the simulation process.

Before calculating the payback period for the retrofit scenarios, inflation and market interest rates were set with the annual increase in electricity prices as determined by the Egyptian Ministry of Electricity. Prices were compiled in local currency (Egyptian pound), then converted into US dollars (USD) at the current exchange rate for the year 2023, where the age of the building is assumed to be 40 years. For example, Figure 14 shows the payback period calculation for retrofitting scenario No. 2 for Villa type A (S and SW).

Year	Cash Flow	Present Value of Cash Flow	Cumulative Cash Flow
0	−$1463	−$1463	−$1463
1	$241	$274	−$1189
2	$253	$326	−$863
3	$265	$389	−$473
4	$279	$465	−$9
5	$293	$554	$546
6	$307	$661	$1,207
7	$323	$789	$1,997
8	$339	$942	$2,938

Discount Rate	−12%
POSTIVE Cash Flow (Years)	48
Last Negative Cash Flow	−$9
Cash Flow in the Next Year	$554
Fraction Period (Years)	0.02
Payback Period (Years)	4.02
Electricity Pirce yearly Increase	5.00%

Figure 14. The payback period calculation for retrofitting scenario No. 2 for Villa type A (S and SW).

6. EERMGCs Tool Development

6.1. Database Creation

The database of the EERMGCs tool is considered the collection point for the findings of all previous phases, and it combined all the collected information and results by using an Excel spreadsheet in order to set up a basis for the EERMGCs tool. The database involved all envelope energy retrofitting scenarios for all dwelling models in the case study. The data of each retrofitting scenario included its investment cost, energy consumption, energy saving rate, and the payback period. Table 5 presents the database sample for villa type A with the orientation of (S and SW). After creating and developing the database, the ERMGC tool was developed using Microsoft Excel with Visual Basic for Applications (VBA).

Table 5. Database sample of ERMGC tool for villa type A with the orientation of (S and SW).

VILLA A (S & SW)											
Scenario Number	**Wall Insulation**	**Roof Insulation**	**Glazing**	**Shading Devices**	**Yearly Consumption Saving**	**Yearly Consumption (kwh)**	**Yearly Consumption Cost ($)**	**Yearly Consumption Saving (kwh)**	**Yearly Consumption Saving ($)**	**Retrofitting Investment Cost ($)**	**Payback Period (years)**
1	W_0	R_0	G_0	SH_0	0.00	32,876	1151	0	0	0	0.00
2	W_0	R_0	G_0	SH_1	20.20	26,236	919	6640	242	1464	4.02
3	W_0	R_0	G_0	SH_2	23.40	25,184	882	7692	279	1913	4.36
4	W_0	R_0	G_1	SH_0	6.70	30,674	1075	2202	80	563	4.44
5	W_0	R_0	G_1	SH_1	22.20	25,578	896	7298	266	2026	4.70
6	W_0	R_0	G_1	SH_2	22.74	25,400	890	7476	272	2476	5.29
7	W_0	R_0	G_2	SH_0	18.50	26,794	939	6082	221	3938	7.89
8	W_0	R_0	G_2	SH_1	27.43	23,859	836	9017	328	5401	7.55
9	W_0	R_0	G_2	SH_2	27.97	23,681	830	9195	335	5851	7.81
10	W_0	R_1	G_0	SH_0	6.30	30,805	1079	2071	76	1276	7.67

Table 5. *Cont.*

VILLA A (S & SW)											
Scenario Number	**Wall Insulation**	**Roof Insulation**	**Glazing**	**Shading Devices**	**Yearly Consumption Saving**	**Yearly Consumption (kwh)**	**Yearly Consumption Cost ($)**	**Yearly Consumption Saving (kwh)**	**Yearly Consumption Saving ($)**	**Retrofitting Investment Cost ($)**	**Payback Period (years)**
11	W_0	R_1	G_0	SH_1	23.22	25,243	885	7633	278	2739	5.56
12	W_0	R_1	G_0	SH_2	24.93	24,681	865	8195	298	3188	5.87
13	W_0	R_1	G_1	SH_0	9.14	29,872	1047	3004	110	1838	7.64
14	W_0	R_1	G_1	SH_1	25.39	24,529	859	8347	304	3301	5.93
15	W_0	R_1	G_1	SH_2	27.10	23,967	840	8909	324	3751	6.16
16	W_0	R_1	G_2	SH_0	17.66	27,072	948	5804	211	5213	9.33
17	W_0	R_1	G_2	SH_1	33.65	21,814	765	11,062	402	6676	7.58
18	W_0	R_1	G_2	SH_2	35.36	21,252	744	11,624	422	7126	7.65
19	W_0	R_2	G_0	SH_0	7.40	30,444	1066	2432	89	2551	10.06
20	W_0	R_2	G_0	SH_1	23.36	25,197	882	7679	279	4013	7.01
21	W_0	R_2	G_0	SH_2	25.07	24,634	863	8242	300	4464	7.14
22	W_0	R_2	G_1	SH_0	9.43	29,776	1043	3100	113	3114	9.85
23	W_0	R_2	G_1	SH_1	25.46	24,506	858	8370	304	4576	7.18
24	W_0	R_2	G_1	SH_2	27.17	23,944	839	8932	324	5026	7.29
25	W_0	R_2	G_2	SH_0	17.95	26,977	945	5899	214	6488	10.27
26	W_0	R_2	G_2	SH_1	33.72	21,791	764	11,085	403	7951	8.32
27	W_0	R_2	G_2	SH_2	35.43	21,229	744	11,647	423	8401	8.35
28	W_1	R_0	G_0	SH_0	9.00	29,918	1048	2958	108	1201	6.03
29	W_1	R_0	G_0	SH_1	21.78	25,716	901	7160	260	2663	5.70
30	W_1	R_0	G_0	SH_2	24.66	24,769	868	8107	295	3114	5.82
31	W_1	R_0	G_1	SH_0	11.22	29,188	1023	3688	135	1764	6.64
32	W_1	R_0	G_1	SH_1	26.47	24,174	847	8702	317	3226	5.68
33	W_1	R_0	G_1	SH_2	28.18	23,612	827	9264	337	3676	5.95
34	W_1	R_0	G_2	SH_0	17.38	27,164	951	5712	208	5139	9.33
35	W_1	R_0	G_2	SH_1	34.73	21,459	752	11,417	415	6601	7.40
36	W_1	R_0	G_2	SH_2	36.44	20,896	732	11,980	435	7051	7.48
37	W_1	R_1	G_0	SH_0	10.98	29,267	1025	3609	131	2476	8.14
38	W_1	R_1	G_0	SH_1	26.91	24,030	842	8846	321	3938	6.36
39	W_1	R_1	G_0	SH_2	28.62	23,467	822	9409	342	4389	6.54
40	W_1	R_1	G_1	SH_0	14.77	28,021	982	4855	177	3038	7.74
41	W_1	R_1	G_1	SH_1	29.72	23,105	810	9771	355	4501	6.49
42	W_1	R_1	G_1	SH_2	31.35	22,569	791	10,307	375	4951	6.66
43	W_1	R_1	G_2	SH_0	22.11	25,609	897	7267	264	6414	9.25
44	W_1	R_1	G_2	SH_1	37.06	20,693	725	12,183	442	7876	7.88
45	W_1	R_1	G_2	SH_2	38.69	20,158	707	12,718	462	8326	7.94
46	W_1	R_2	G_0	SH_0	11.27	29,171	1022	3705	135	3751	9.89
47	W_1	R_2	G_0	SH_1	27.57	23,813	834	9063	329	5213	7.38
48	W_1	R_2	G_0	SH_2	29.28	23,250	814	9626	350	5663	7.47
49	W_1	R_2	G_1	SH_0	15.43	27,804	974	5072	185	4313	9.09
50	W_1	R_2	G_1	SH_1	29.93	23,037	807	9839	358	5776	7.47
51	W_1	R_2	G_1	SH_2	31.56	22,501	789	10,375	377	6226	7.56
52	W_1	R_2	G_2	SH_0	22.77	25,392	889	7484	273	7688	9.97
53	W_1	R_2	G_2	SH_1	37.27	20,625	723	12,251	445	9151	8.50
54	W_1	R_2	G_2	SH_2	38.90	20,089	704	12,787	465	9601	8.52
55	W_2	R_0	G_0	SH_0	12.50	28,767	1008	4109	150	1501	5.63
56	W_2	R_0	G_0	SH_1	22.56	25,461	892	7415	269	2963	5.97
57	W_2	R_0	G_0	SH_2	25.44	24,514	859	8362	304	3414	6.05
58	W_2	R_0	G_1	SH_0	13.40	28,473	997	4403	160	2064	6.56
59	W_2	R_0	G_1	SH_1	27.25	23,919	838	8957	325	3526	5.91
60	W_2	R_0	G_1	SH_2	28.96	23,357	818	9519	346	3976	6.13

Table 5. *Cont.*

VILLA A (S & SW)											
Scenario Number	Wall Insulation	Roof Insulation	Glazing	Shading Devices	Yearly Consumption Saving	Yearly Consumption (kwh)	Yearly Consumption Cost ($)	Yearly Consumption Saving (kwh)	Yearly Consumption Saving ($)	Retrofitting Investment Cost ($)	Payback Period (years)
61	W_2	R_0	G_2	SH_0	19.55	26,449	927	6427	234	5439	9.07
62	W_2	R_0	G_2	SH_1	35.51	21,204	743	11,672	424	6901	7.50
63	W_2	R_0	G_2	SH_2	37.22	20,642	724	12,234	445	7351	7.56
64	W_2	R_1	G_0	SH_0	13.16	28,552	1000	4324	158	2776	7.85
65	W_2	R_1	G_0	SH_1	28.21	23,602	827	9274	337	4238	6.46
66	W_2	R_1	G_0	SH_2	29.92	23,040	807	9836	358	4688	6.63
67	W_2	R_1	G_1	SH_0	16.91	27,318	957	5558	202	3338	7.56
68	W_2	R_1	G_1	SH_1	30.67	22,793	799	10,083	366	4801	6.62
69	W_2	R_1	G_1	SH_2	32.30	22,257	780	10,619	386	5251	6.78
70	W_2	R_1	G_2	SH_0	24.24	24,907	872	7969	290	6714	9.05
71	W_2	R_1	G_2	SH_1	38.01	20,381	714	12,495	454	8176	7.94
72	W_2	R_1	G_2	SH_2	39.64	19,845	696	13,031	473	8626	7.99
73	W_2	R_2	G_0	SH_0	13.45	28,456	997	4420	161	4051	9.42
74	W_2	R_2	G_0	SH_1	28.87	23,385	820	9491	345	5513	7.42
75	W_2	R_2	G_0	SH_2	30.58	22,823	800	10,053	366	5963	7.51
76	W_2	R_2	G_1	SH_0	17.57	27,101	949	5775	211	4613	8.80
77	W_2	R_2	G_1	SH_1	30.88	22,724	796	10,152	369	6076	7.55
78	W_2	R_2	G_1	SH_2	32.51	22,189	778	10,687	388	6526	7.63
79	W_2	R_2	G_2	SH_0	24.90	24,690	865	8186	297	7988	9.71
80	W_2	R_2	G_2	SH_1	38.22	20,313	712	12,563	456	9451	8.53
81	W_2	R_2	G_2	SH_2	39.85	19,777	693	13,099	476	9901	8.55

6.2. EERMGCs Tool Interface Description and Method of Use

EERMGCs is a simple support tool that enables homeowners to choose the optimal energy retrofitting solution for their houses. It is a multi-objective tool that offers the optimal energy solutions according to the user's objective and priorities, whether these are the highest energy-saving rate, the fastest payback period, or the lowest investment cost. It also provides the optimal possible energy retrofitting measures within a budget specified by the user. It is easy to use, fast, and scalable at any time. The following shows a description of the interface of the tool and how to use it:

6.2.1. The Components of the Input Window and the Use Method

The input tab, as shown in Figure 15, has three main sections.

- The first section, as shown in Figure 16, is where the user determines the type and orientation of his villa model. The user has two choices for his villa type, either model A or model B. As for the orientation, the user has eight options: (N, NE, E, SE, S, SW, W, NW).
- The second section, as shown in Figure 17, allows the user to choose the retrofit measures they prefer. This section shows the retrofitting measures for each element of the building (wall, roof, windows glazing, and shading devices). The user can select the retrofit measures they prefer and exclude the ones that do not suit them; therefore, the results shown do not contain these excluded measures.
- The third section, as shown in Figure 18, is where the user determines their objective and priorities in choosing the energy measures shown later. In this section, the user has four options: (1) the highest energy savings, (2) the fastest payback period, (3) the lowest investment cost for retrofit measures, (4) the last option enables the user to determine a range for a specific budget within which they want to invest in the

energy retrofitting of their house. The user must choose one of these four options according to their energy improvement objectives, priorities, and budget. These four options are considered evaluation criteria that control the outputs of the retrofitting measures that will appear for the user in the following window. At the bottom of the input tab is a start button, which the user clicks on when they finish entering all the required inputs, so the retrofit scenarios appear in the output table.

Figure 15. Input window of EERMGCs tool user interface.

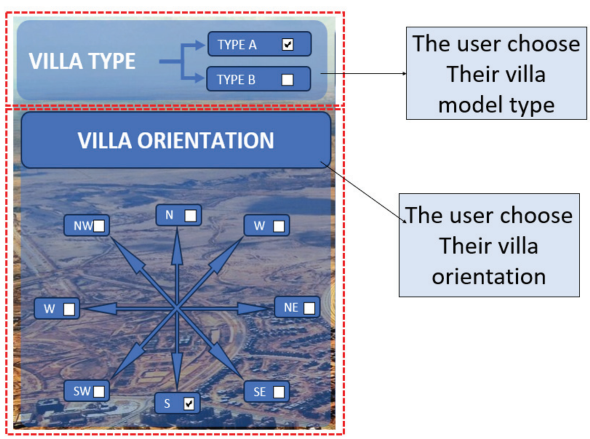


Figure 16. The first section of EERMGCs tool input tab, where the user determines his villa type and orientation.

6.2.2. The Components of the Output Tab and the Use Method

After the user determines all the inputs in the previous step and then presses the start button, the five optimal envelope energy retrofitting scenarios that suit their priorities will be shown in the outputs tab, based on the tool's database. The output tab, as shown in Figure 19, also has three main sections.

- The first section, as shown in Figure 20, is a table of the five optimal envelope energy retrofitting scenarios that suit the user's priorities, which are shown in the outputs tab based on the tool's database. The displayed scenarios are arranged from the most appropriate to the least according to the user's priorities. The first scenario in the table is the most suitable scenario that most closely matches the user's priorities, and so on. This gives the user more choices and flexibility to help and encourage them to invest in energy retrofits for their home. Also shown in the scenarios table is each scenario's energy consumption rate, energy saving rate, investment cost, and payback period.

- The second section, as shown in Figure 21, contains four illustrative charts to compare the shown scenarios in terms of payback period, annual energy saving percentage, yearly cost saving in USD, and retrofitting investment cost in USD.
- The third section, as shown in Figure 22, contains a detailed key table that explains the description of the energy retrofitting measures in the main scenarios table.

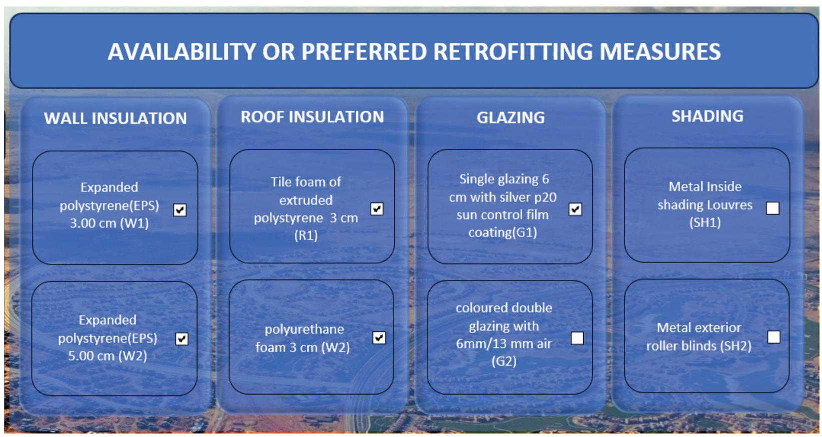


Figure 17. The second section of EERMGCs tool input tab, where the user determines the retrofit measures that suit them.

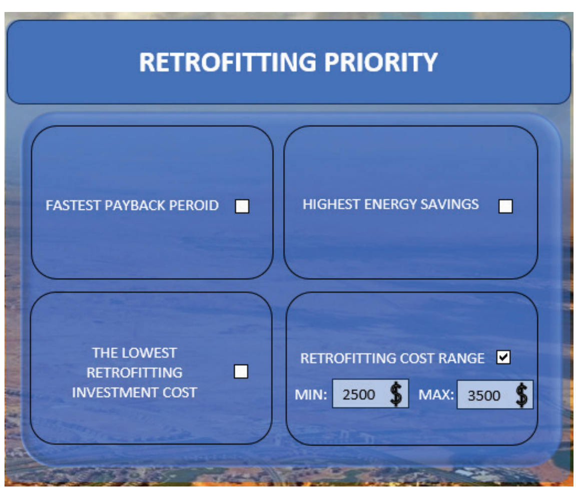


Figure 18. The third section of the EERMGCs tool input tab, where the user determines their objective and priorities in choosing the energy retrofitting measures.

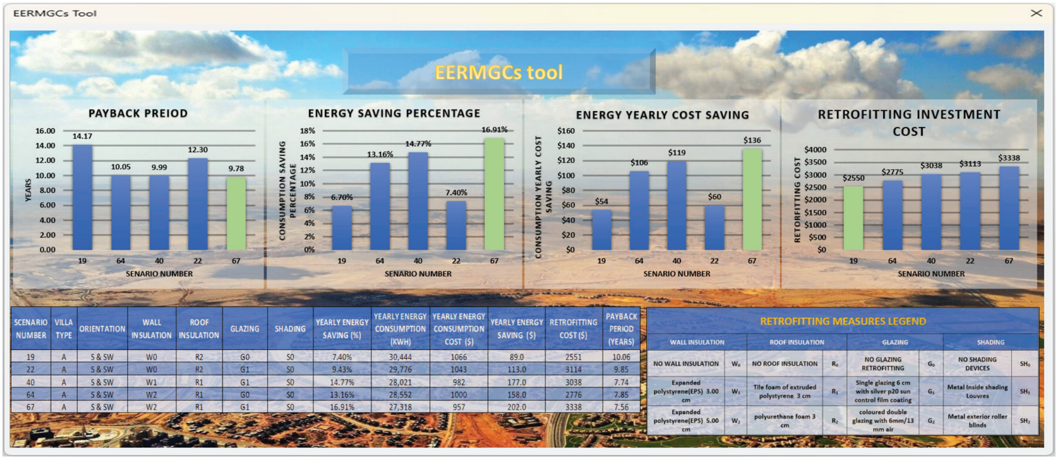


Figure 19. Outputs tab of the EERMGCs tool's user interface.

SCENARIO NUMBER	VILLA TYPE	ORIENTATION	WALL INSULATION	ROOF INSULATION	GLAZING	SHADING	YEARLY ENERGY SAVING (%)	YEARLY ENERGY CONSUMPTION (KWH)	YEARLY ENERGY CONSUMPTION COST ($)	YEARLY ENERGY SAVING ($)	RETROFITTING COST ($)	PAYBACK PERIOD (YEARS)
19	A	S & SW	W0	R2	G0	S0	7.40%	30,444	1066	89.0	2551	10.06
22	A	S & SW	W0	R2	G1	S0	9.43%	29,776	1043	113.0	3114	9.85
40	A	S & SW	W1	R1	G1	S0	14.77%	28,021	982	177.0	3038	7.74
64	A	S & SW	W2	R1	G0	S0	13.16%	28,552	1000	158.0	2776	7.85
67	A	S & SW	W2	R1	G1	S0	16.91%	27,318	957	202.0	3338	7.56

Figure 20. The table of the most suitable envelope energy retrofitting scenarios of the ERMGCs tool application example.

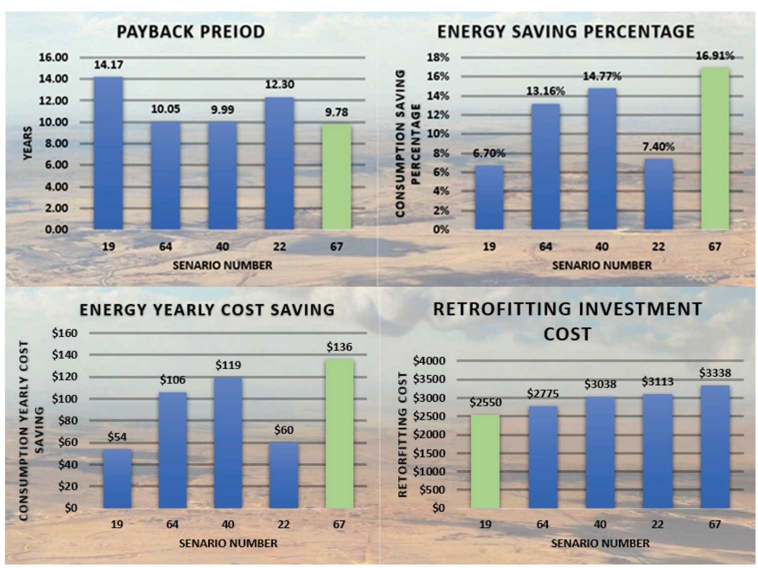


Figure 21. The four comparative charts for the most suitable envelope energy scenarios of the application example of the EERMGCs tool.

RETROFITTING MEASURES LEGEND							
WALL INSULATION		ROOF INSULATION		GLAZING		SHADING	
NO WALL INSULATION	W_0	NO ROOF INSULATION	R_0	NO GLAZING RETROFITTING	G_0	NO SHADING DEVICES	SH_0
Expanded polystyrene(EPS) 3.00 cm	W_1	Tile foam of extruded polystyrene 3 cm	R_1	Single glazing 6 cm with silver p20 sun control film coating	G_1	Metal Inside shading Louvres	SH_1
Expanded polystyrene(EPS) 5.00 cm	W_2	polyurethane foam 3 cm	R_2	coloured double glazing with 6mm/13 mm air	G_2	Metal exterior roller blinds	SH_2

Figure 22. The third section on the output tab, the legend of retrofitting measures.

6.3. Application Example of the EERMGCs Tool

This part addresses an example of how to use the EERMGCs tool; Figure 15 shows the inputs tab for this example. In this example, it was assumed that the user chose villa model type A and the south orientation, as shown in Figure 16. Then, the user moved to the second section, where they filtered the energy retrofitting measures and excluded the energy measures that did not suit them, as shown in Figure 17. Then, the last section in the input screen for user priority determination is shown in Figure 18. The user's priority in this example was to set a specific budget ranging from USD 2500 to USD 3500, and then the user pressed the Start button. The output tab appeared, as shown in Figure 19, containing a table of the five optimal envelope energy retrofitting scenarios based on the user's objectives. As shown in Figure 20, the scenarios table shows the retrofitting measures for each scenario, energy consumption rate, energy saving rate, investment cost, and payback period.

Figure 21 shows the four comparative charts for the most suitable envelope energy retrofitting scenarios. The first chart shows the payback period of each scenario; the second chart shows the annual energy saving percentage; the third chart shows yearly cost saving in USD for each scenario; and the fourth one shows retrofitting investment cost in USD for each scenario. Also, the retrofitting measures legend contains a detailed key table that explains the description of the energy retrofitting measures is shown in Figure 22.

7. Conclusions

This paper developed a multi-objective decision-making tool for envelope energy retrofitting in gated community housing in Cairo. This tool enables users and homeowners to determine the optimal retrofitting solutions that suit their objectives and priorities. This tool was developed by following a methodology consisting of successive steps. The research started by conducting a comprehensive review of previous studies, surveying the Egyptian construction market, communicating with building companies and conducting interviews with housing occupants. Then, the research moved to the data analysis phase, thermal performance simulation, and economic analysis. Finally, the database was created, and the EERMGCs tool was developed. This research will lead to essential impacts in encouraging the homeowners of luxury housing to implement energy retrofitting measures for their homes by showing them the energy and cost savings and the payback period of the energy retrofitting process. Egypt is in dire need of such a tool, especially with the multiple energy problems that it has experienced recently. Each phase of the study had significant results, and all of these results combined to create a huge database consisting of 810 energy retrofit scenarios with the investment cost for each scenario and its payback period. For example, according to scenario 52 for villa A (S and SW), energy can be saved by 22.8% annually if the following measures are applied: expanded polystyrene (EPS) 3.00 cm for the walls, polyurethane foam 3 cm for the roof, and coloured double glazing with 6 mm/13 mm air for glazing, with a payback period of 9.9 years. The final outcome of this study is developing the EERMGCs tool that helps and encourages homeowners to invest in retrofitting their home; it is simple and easy to use. It adapts to the different priorities of homeowners, offering them the optimal retrofitting measures according to their preferences. Also, the research provides a framework that can be considered a basis for developing decision-making tools for GCs housing in Egypt.

The limitations of the research are that it was allocated only to luxury residential buildings in gated communities in Cairo, and it only applied retrofitting measures for the building envelope. Also, it is only concerned with the total cost for each scenario and the payback period. Future research can expand the scope of research to make this tool valid for use on other housing types in Egypt, in addition to searching for new energy measures that will suit these conditions and include them in the tool. We recommend that the official authorities encourage the development of this tool to make it suitable for all luxury housing, and make it available free of charge to homeowners.

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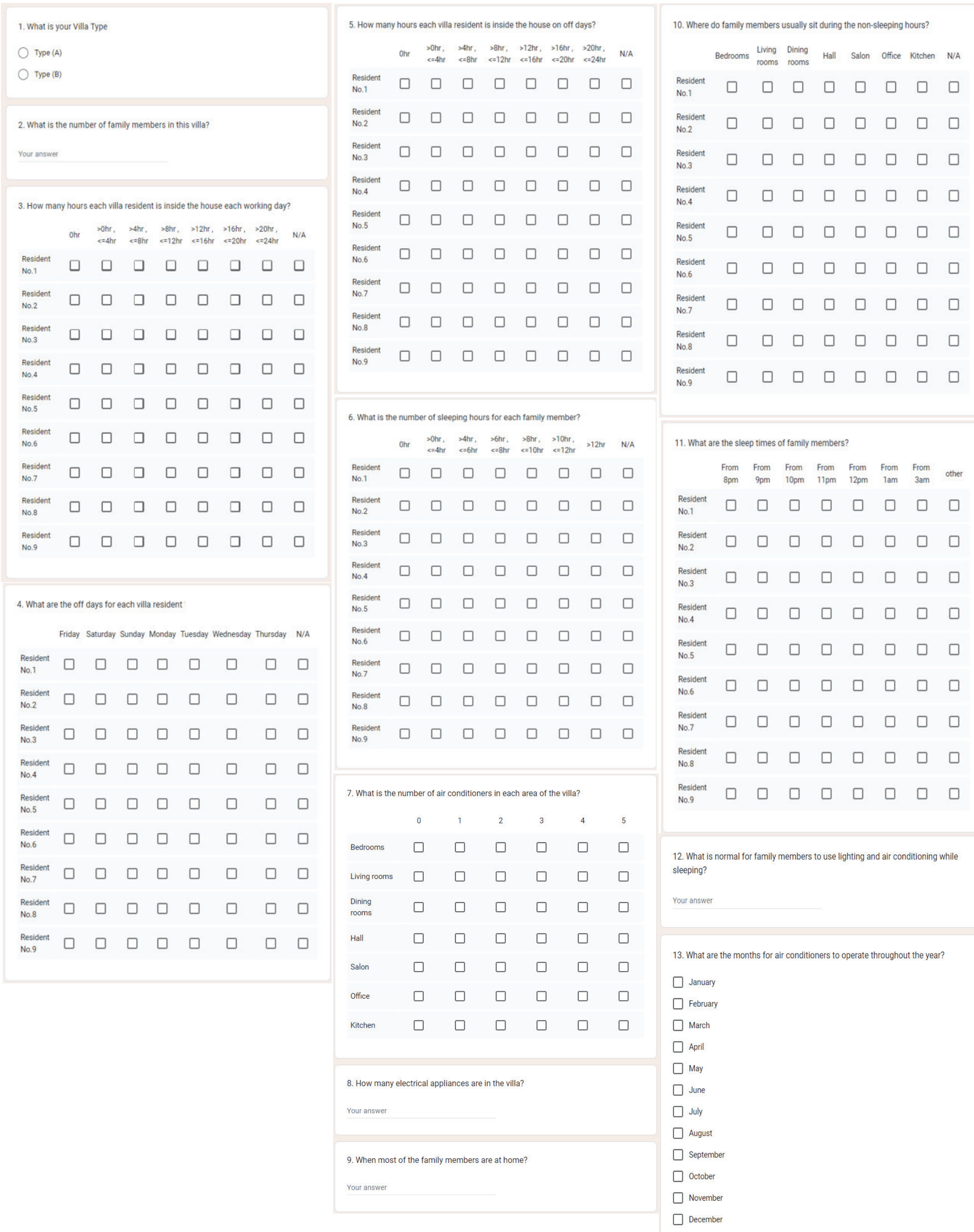
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



1. What is your Villa Type

◯ Type (A)

◯ Type (B)

2. What is the number of family members in this villa?

Your answer

3. How many hours each villa resident is inside the house each working day?

	0hr	>0hr, <=4hr	>4hr, <=8hr	>8hr, <=12hr	>12hr, <=16hr	>16hr, <=20hr	>20hr, <=24hr	N/A
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

4. What are the off days for each villa resident

	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	N/A
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

5. How many hours each villa resident is inside the house on off days?

	0hr	>0hr, <=4hr	>4hr, <=8hr	>8hr, <=12hr	>12hr, <=16hr	>16hr, <=20hr	>20hr, <=24hr	N/A
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

6. What is the number of sleeping hours for each family member?

	0hr	>0hr, <=4hr	>4hr, <=6hr	>6hr, <=8hr	>8hr, <=10hr	>10hr, <=12hr	>12hr	N/A
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

7. What is the number of air conditioners in each area of the villa?

	0	1	2	3	4	5
Bedrooms	☐	☐	☐	☐	☐	☐
Living rooms	☐	☐	☐	☐	☐	☐
Dining rooms	☐	☐	☐	☐	☐	☐
Hall	☐	☐	☐	☐	☐	☐
Salon	☐	☐	☐	☐	☐	☐
Office	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐

8. How many electrical appliances are in the villa?

Your answer

9. When most of the family members are at home?

Your answer

10. Where do family members usually sit during the non-sleeping hours?

	Bedrooms	Living rooms	Dining rooms	Hall	Salon	Office	Kitchen	N/A
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

11. What are the sleep times of family members?

	From 8pm	From 9pm	From 10pm	From 11pm	From 12pm	From 1am	From 3am	other
Resident No.1	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.2	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.3	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.4	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.5	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.6	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.7	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.8	☐	☐	☐	☐	☐	☐	☐	☐
Resident No.9	☐	☐	☐	☐	☐	☐	☐	☐

12. What is normal for family members to use lighting and air conditioning while sleeping?

Your answer

13. What are the months for air conditioners to operate throughout the year?

☐ January
☐ February
☐ March
☐ April
☐ May
☐ June
☐ July
☐ August
☐ September
☐ October
☐ November
☐ December

Figure A1. A sample of the questionnaire that was delivered in print or online to the occupants during the site visits to the case study in the data collection phase.

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Article

Building Information Modeling and Building Performance Simulation-Based Decision Support Systems for Improved Built Heritage Operation

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Abstract: Adapting outdated building stocks' operations to meet current environmental and economic demands poses significant challenges that, to be faced, require a shift toward digitalization in the architecture, engineering, construction, and operation sectors. Digital tools capable of acquiring, structuring, sharing, processing, and visualizing built assets' data in the form of knowledge need to be conceptualized and developed to inform asset managers in decision-making and strategic planning. This paper explores how building information modeling and building performance simulation technologies can be integrated into digital decision support systems (DSS) to make building data accessible and usable by non-digital expert operators through user-friendly services. The method followed to develop the digital DSS is illustrated and then demonstrated with a simulation-based application conducted on the heritage case study of the Faculty of Engineering in Bologna, Italy. The analysis allows insights into the building's energy performance at the space and hour scale and explores its relationship with the planned occupancy through a data visualization approach. In addition, the conceptualization of the DSS within a digital twin vision lays the foundations for future extensions to other technologies and data, including, for example, live sensor measurements, occupant feedback, and forecasting algorithms.

Keywords: built heritage; performance-based management; building information modeling; building performance simulation; digital twins

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1. Introduction

The architecture, engineering, construction, and operation (AECO) sector accounts for a large amount of global energy use and environmental impact [1–3]. Buildings are responsible for approximately 75% of primary energy consumption in cities [4] and contribute to 40% of annual environmental impact in terms of greenhouse gas emissions [5]. The World Green Building Council has set an ambitious goal for global buildings and infrastructure to reduce carbon emissions by 40% before 2030 and to achieve complete carbon neutrality in buildings by 2050 [6].

The built environment sits, therefore, at the crossroads of many policies and international initiatives like the European Green Deal [7], sustaining the ambitious objectives of the Renovation Wave [8] and aligning with the bold aims of the New European Bauhaus [9]. Within this context, the Built4People Agenda 2021–2027 identified the main challenges as the absence of comprehensive innovation that adopts a systemic approach and that considers the entire lifecycle of buildings, the need to minimize the significant carbon and environmental impact of the construction and built environment, and the limited adoption of innovative solutions with limited potential for long-term transformative change [10].

Moving towards a sustainable and energy-sensible built environment involves two key aspects. Firstly, it requires the development of long-term strategic plans to renovate existing building stocks. Secondly, it necessitates optimizing building operations in the short term, focusing on reducing energy consumption, minimizing environmental impacts, and lowering operational costs, all while ensuring comfortable conditions for occupants. Addressing the latter aspect is crucial, as energy consumption and costs during the operational phase can account for up to 75% of those incurred during the construction phase [11].

The challenges related to the built environment are particularly pronounced when considering the built cultural heritage (BCH) [12], which includes buildings with an important historical, artistic, cultural, and aesthetic significance, usually listed by local regulations, to allow their protection and sustainable conservation. In the case of BCH, traditional energy renovation and upgrade approaches often prove incompatible with heritage buildings' characteristics. These constructions were originally designed to accommodate past lifestyles and uses, and preserving their adaptability to the current needs is vital for their resilience. Since the conservation regulations in place to safeguard BCH restrict extensive and intrusive interventions, finding reversible and minimally disruptive solutions becomes essential for successfully adapting them, while also considering the associated costs of such measures.

The ongoing digitalization of the AECO sector demonstrates innovative strategies for the improvement of monitoring, management, and operation of BCH, linking energy savings with lower maintenance costs and better preservation [13]. Advanced digital methods and tools, capable of generating valuable knowledge in the form of information, are emerging for providing decision support to building administrators [14]. However, synthesizing existing buildings' knowledge seems very challenging today due to the articulation of the exposed demanding framework. Among the various topics, the knowledge issue is critically important concerning energy management [15,16]. A better understanding of the energy behavior of heritage buildings is typically necessary in comparison with non-listed ones since typical energy retrofit interventions, such as wall insulation, are often limited for them [17].

The complexity of such a framework demands a holistic approach to integrate both economic–financial asset management and technical–functional management within the context of performance-based strategies, aiming to achieve two key goals. First, improving the buildings and their physical performance characteristics; second, optimizing the balance between functional requirements and energy demands and environmental impacts. It means that, on the one hand, built heritage needs to be maintained and improved in terms of performance to ensure its effective use [18,19]. On the other hand, administrations must meet additional functional needs for optimizing logistics and planning occupancy and maintenance while minimizing operational costs and considering the relationship with the urban context and its services. According to this key, a paradigmatic divergence emerges between the increasingly complex instances of dynamism that characterize the current demanding framework and the static nature of the physical apparatus where it is hosted. In order to grasp such complexity and readily adapt outdated building stocks to the mutability of the current demanding framework, it is necessary to combine the "static knowledge" of the containers—the buildings—with the "dynamic knowledge" of the contents—users, and activities inside them.

Nevertheless, various gaps hinder building management practices from fully grasping such knowledge, often resulting in inefficient construction use and waste of technical and financial resources [20]. These gaps are usually related to scarce building managers' expertise in the information science field (knowledge gap) [21], poor coordination of the multiple players traditionally involved in building management (coordination gap) [22], serious financial limitations (finance gap) [23], information unavailability or untraceability (information gap) [24,25], and insufficient data visualization tools (visualization gap) [26].

In order to address such challenges, the digital twin (DT) paradigm is emerging to enable new ways of sharing existing buildings' knowledge towards cost–benefit optimization during their use [27–30]. Based both on real-time measurement and building performance simulations (BPS), DTs can improve the understating of building performance by evaluating important key performance indicators (KPIs) regarding day-to-day use (space management and facilities), consumption (energy and resources), and impact (cost, environment, and users' well-being), which support asset managers in their decision-making and strategic planning.

Paper Scope and Structure

This paper presents and demonstrates the method followed for delivering a BPS-based decision support system (DSS) designed to provide the asset managers of a significant educational heritage building at the Faculty of Engineering of Bologna [31,32] with valuable information about its energy performance.

The primary application of the digital decision support system focuses on energy-aware occupancy scheduling for buildings that exhibit intermittent space usage, such as university buildings, schools, recreational spaces, co-working areas, museums, as well as large office environments that have recently undergone the working-from-home implementation wave [33,34].

The DSS services provided can be utilized even by non-digital experts through user-friendly dashboards, allowing administrations to capture the benefits of digitization in the short term without disrupting the organizational structure of their technical offices. Geometrical, construction, functional, and operational information regarding the building is collected, processed, and encapsulated in the services to facilitate the consultation of digital models and, thus, improve data understanding. More specifically, in the presented experimentation, information related to the planned occupancy of the building (number of occupants, functions, and space use) provided by the asset management system (AMS) is combined with data about the building performance (heating energy and electricity need), calculated by an energy simulation performed through the Energy Plus calculation engine [35].

Using the developed tools, a study is conducted to analyze the energy consumption of significant rooms operating under different occupancy conditions in a case study building and compare their behavior during a significant winter operational day. This application identifies energy, environmental, and cost KPIs, creating an information system supporting energy-oriented occupancy-planning processes.

The paper is organized as follows: Section 2 provides a background on the research. Section 3 presents the materials and methods used to implement the DSS conceptually and practically. Section 4 showcases the results of applying the DSS to the selected case study building, as mentioned earlier. Section 5 expands on the results within the broader context of building performance-based management and demand-driven controls. Lastly, Section 6 concludes the paper by highlighting its limitations and suggesting areas for future research and development.

2. Background

2.1. Large Public Building Stock Management

Over the past century, a vast building stock was built in Europe to respond to the dramatic urban population increase resulting from internal migratory movements toward industrialized cities. Today, this heritage could appear unsuitable and, in some ways excessive, compared to the contemporary needs, in terms of quantity, quality, and location. The major problem of controlling the quantity of the national building stock while increasing its quality now emerges. While it is possible to think of replacement actions in cases where a noticeable physical and functional deterioration of buildings is so strong as to affect urban settlement quality, most of the built heritage needs to be preserved and upgraded: indeed, almost 75% of the building stock is inefficient according to the current regulatory framework, and about 85–95% of today's existing buildings will still be standing in 2050 [36]. In these cases, it is necessary, in fact, to recover or improve the quality gradually lost over time to respond also to contemporary needs, whose complexity is progressively increasing.

For instance, this issue represents one of the main critical issues that public administrations record when managing large assets since they are responsible for managing significant portions of the national building stock. In Italy, local governments own approximately 80% of the 1 million public real estate cadastral units, of which 60% were built before 1980 (Figure 1), covering an area of 325 million square meters—about 10% of the entire Italian building stock [37].

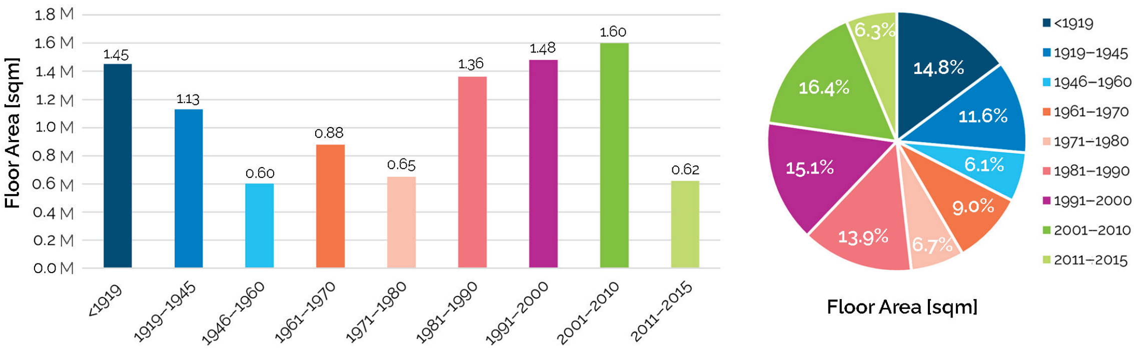


Figure 1. Public building stock managed by Italian local public authorities according to a report provided by the Ministero dell'Economia e delle Finanze in 2016. Authors' graphical elaboration [37].

The amount of money spent annually to manage these buildings is very large due to their obsolescence, functional complexity, and dimensions, and can reach up to 75% of the overall lifecycle cost [11]. These buildings face daily performance requirements and regulatory upgrades concerning safety, operation, and maintenance [38]. Furthermore, conservation and renovation are even more challenging for listed buildings due to their subjection to the protection constraints dictated by the Cultural Heritage and Landscape Code [39]. The extraordinary cost and the time necessary to reach a whole deep renovation of this building stock requires strategies and tools capable of correctly planning the allocation of public administration's technical and economic resources to reduce operation and maintenance (O&M) costs [38]. This goal can be achieved if an adequate understanding of the heritage performance is reached beforehand.

For administrations, a twofold issue arises. On the one hand, it is necessary to conserve and improve the containers, i.e., the buildings, their physical characteristics, and their state of conservation. On the other hand, they need to ensure functional, environmental, and economic compatibility of their contents, respecting the current requirement framework in terms of logistics and technological modernization.

2.2. Gaps and Challenges in Building Management

Current building management practices demonstrate several areas for improvement that hinder the goal of sustainable building operation. According to a recent literature review by Abuimara et al. [20], building management gaps can be grouped into knowledge, coordination, finance, information, and visualization issues.

Concerning the knowledge gap, building management professionals often need more information science expertise. Without comprehensively understanding these issues, technical difficulties emerge in predicting the economic, environmental, and financial impacts of management actions. Among the various causes, the lack of standardized training bodies and educational programs has a principal role [21].

Second, many coordination problems exist in current management practices. Building management teams are often temporary and outsourced, needing more spatial and temporal connectivity. Shared information language is rare among actors, limiting trust and causing misunderstandings [22,40]. Conflicting relationships and biases among actors can arise, resulting in delays, inefficiency, and economic waste, making it difficult to predict the immediate benefits of digitization for public building owners [23].

Regarding finance, public building managers often have limited budgets and decision-making power in strategic investment planning, and opportunities for savings need to be systematically framed within strategic visions or highlighted by sufficient tools.

From the information point of view, low traceability and inadequate sensing infrastructure are frequent in outdated buildings. When collected, data are fragmented into different data silos belonging to various actors and not cross-integrated [41]. In addition, although occupancy data critically influence a building's operation, it is often disregarded due to the technical difficulties in modeling it, as well as privacy issues [25]. The BCH field presents additional problems, as it can be difficult to find and share information about unique historical architectures, which is usually fragmented across numerous paper archives [42].

Finally, there are several challenges in visualizing information related to large asset management, including the need for more user-friendly, scalable, and customizable tools to visualize data in the context of the entire portfolio or city [26,43].

All these challenges can limit the ability to effectively understand and improve management activities, making it difficult for stakeholders with low technical digital skills to use human-building interfaces.

2.3. Digital Transition for the Built Environment

The digital transition allows various sectors, including construction and building management, to move towards sustainable development.

Despite the several barriers that exist to digitizing the AECO industry, the international scientific and professional community has introduced new digital paradigms in the construction industry in recent decades, such as BIM [44], heritage BIM (HBIM) [45], smart and cognitive buildings [46,47], DTs [48], Internet of Things (IoT) [49], and artificial intelligence (AI) [50]. In response to the frenetic pace imposed by digitization, various national and international institutions have proposed standards, protocols, specifications, and regulations. In Italy, the modification of the procurement code d.lg. 50/2016, UNI 11337-4: 2017 [51], and UNI EN ISO 19650: 2019 [52] were released. In addition, the software industry has also contributed to the development of new digital practices. BIM authoring tools have been introduced and updated, and their interoperability with BPS software has been implemented to develop advanced shared digital environments [53]. The idea of open tools, data, and models is now widely accepted [54,55]. In addition, smart contracts and blockchains are being introduced to make all information exchanges between the parties involved transparent and reliable [56].

Nevertheless, all these advances are likely to produce "bewilderment" among actors within the dense forest of the digital transition. As a result, the goals, outcomes, and benefits of adopting new processes could become unclear. For instance, DTs' potential benefits are clear for building operators; nevertheless, there is still a lack of clarity surrounding their definition and uses [28]. The literature underlines that developing higher-level conceptual constructs is necessary to promote the sector's digital innovation. This means that two different knowledge levels must be investigated. The former must define new ontological models to enable the organic development of new digital practices, activate standardized and shared information protocols, and encourage the involvement of all operators in the computerized technical management of built assets [57]. The latter must provide valuable tools and methods for enhancing existing buildings' use by demonstrating practical application within significant case studies [58,59].

2.4. Energy-Related Operational Issues in University Campuses

In this broad context, the research focuses on energy-related issues that emerge in higher education buildings during their operation. The topic is becoming relevant since, over the past few years, higher education institutions globally have set target goals for energy savings and emission reductions, leading to the implementation of numerous measures to reduce energy usage [60–62]. These measures include adopting advanced techniques such as renewable energy sources, renovating older buildings, and promoting awareness of energy conservation practices.

In these buildings, energy needs are strictly related to occupancy conditions [33]. The energy usage and intensity of buildings on a higher education campus are influenced by several factors, including the climate, building systems, construction type, and occupancy conditions [63]. Occupancy variables, such as the presence of students and staff members and their activities, can play a significant role in determining energy consumption levels, although their consideration is often overlooked [34]. In this context, adopting a DT environment could enable an understanding of complex relationships between the asset and its contents, from the scale of individual buildings to the urban scale of the portfolio [64].

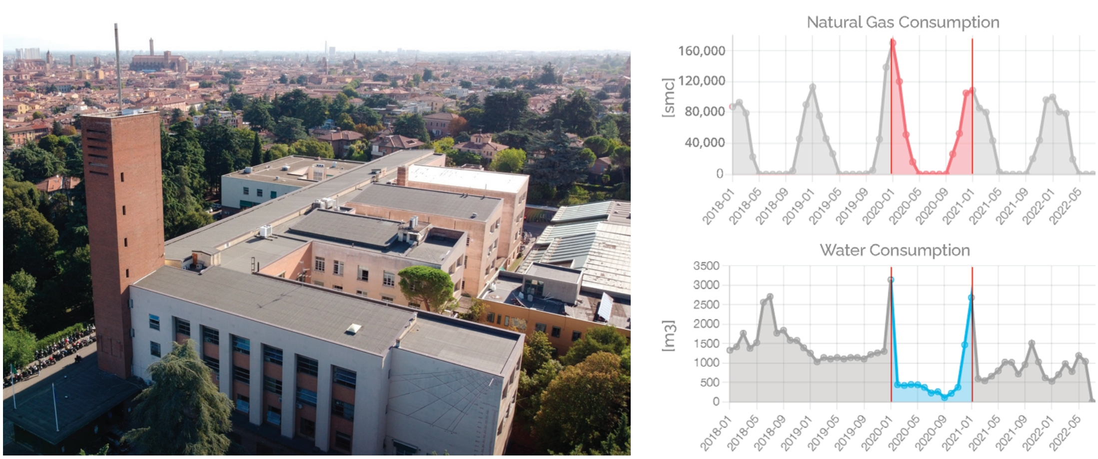
3. Materials and Methods

This section presents the methodology used for the development of the DSS. It begins by providing an overview of the selected case study. Then, the conceptualization of the DT system is reported, followed by a detailed explanation of its methodological implementation. In the next section, instead, the results of a study that utilized the developed tools in the case study building are presented.

3.1. Case Study

The university campus owned by the University of Bologna is taken as a test bed. It holds around one million square meters of public real estate assets in the Emilia–Romagna region, with a population of approximately 70,000 people and various functions.

In particular, an emblematic case study is identified in the building of the Faculty of Engineering at the University of Bologna (Figure 2a). Built between 1932 and 1935, it is one of the first 20th-century buildings to be listed in the city and is considered a local rationalist heritage gem due to its use of industrial systems and materials, innovative finishes, and lack of decorations [31,32]. With its 19,200 sqm of net floor area and four levels, its maximum capacity amount to 5000 users (including researchers, employees, and students), with approximately 2500 students using the building during academic timetable hours 5 days a week, 11 months a year.



(**a**) (**b**)

Figure 2. The Faculty of Engineering of Bologna: (**a**) aerial photography (2022); (**b**) natural gas and domestic hot water consumption for the operation of the building from 2018 to 2022.

Like many modern buildings constructed between the 1920s and 1960s, this building is affected by inherent characteristics that limit its potential for improvement. Specifically, due to its old HVAC systems and construction type, it lacks energy flexibility, as demonstrated by higher-than-normal heating consumption during the COVID-19 pandemic, despite the building being unoccupied for several months. During that period, a noticeable decrease in building occupancy was observed, resulting in many spaces remaining unoccupied for several months, as demonstrated by the evident reduction of domestic hot water consumption in Figure 2b. However, there was no corresponding decrease in natural gas consumption for heating, which remained similar to pre-COVID years, indicating a critical mismatch between energy demand and usage.

3.2. Decision Support System Conceptualization

3.2.1. Digital Twin Model

According to the literature, a DT can be defined as an information environment capable of abstracting, structuring, processing, and visualizing relevant information about an object, process, environment, or system that exists in the real physical world [65].

In the AECO sector, building DTs hold great potential to describe, inspect, monitor, maintain, and manage built assets throughout their lifecycle [48]. In the future, building DTs are expected to reason, learn, optimize, predict, make decisions, and, eventually, autonomously transform their real twins by employing data and intelligent computational models.

The developed DSS adopted refers to the DT model conceptualization proposed by Tao et al. [66], who define a five-dimensional and service-oriented DT model (Figure 3). This model, developed in the Smart Manufacturing (SM) domain [67], expands on the three-entity model proposed by Grieves [68]. The five DT entities are:

1. Physical asset, the asset entity in the physical space;
2. Virtual asset, the asset entity in the virtual space;
3. Connections, the data and information connections (or flows) that bind the physical and virtual entities;
4. DT data, which consists of the fusion and integration of all data related to the physical and virtual entities and their elaboration into more accurate and complete information;
5. Services, facilitate the visualization and use of the information collected or processed by the DT, which is standardized and "encapsulated" according to the needs of different actors and functions [69].

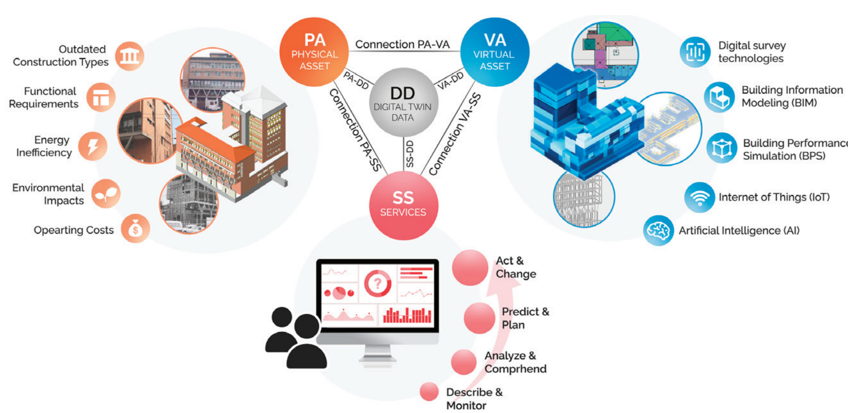


Figure 3. Five-dimension digital twin model and its purposes. (VA: virtual asset, PA: physical asset, DD: digital twin data, SS: services).

3.2.2. Information Management Framework

A conceptual framework is proposed to support the delivery of the DSS and allow efficient information tracking and management during the development process (Figure 4). It outlines the information covering the description, documentation, and analysis of the physical asset in the digital asset as it increases its technology readiness level (TRL). Formulated as an extension of the Lifecycle Information Transformation and Exchange (LITE) framework proposed by Succar and Poirier [57], the framework consists of many concepts:

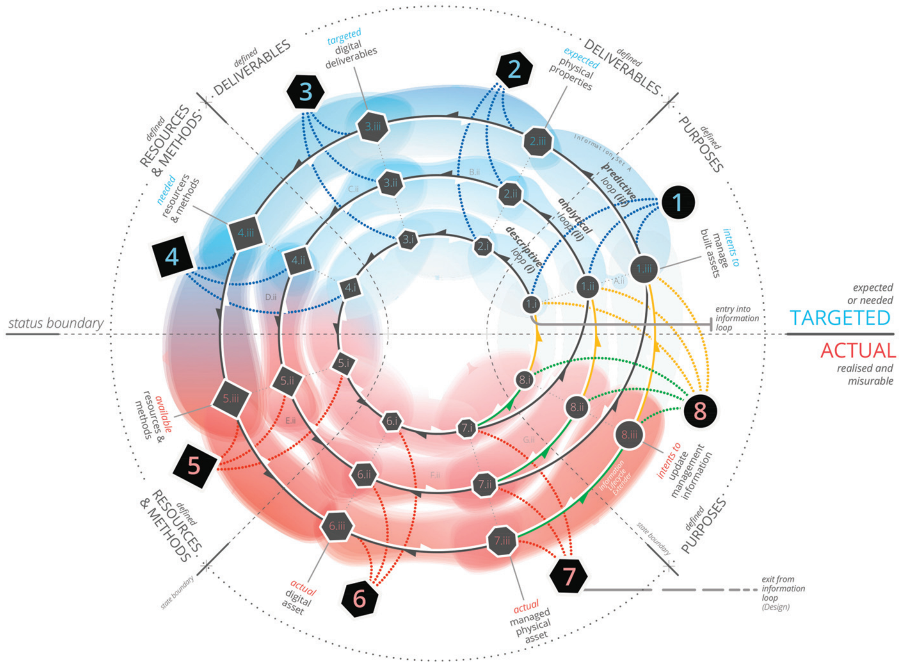


Figure 4. Information lifecycle management framework.

- Information statuses describe information while continuously exchanging, processing, and transforming during its lifecycle from a programmatic state (targeted state) to an applicative state (actual state).
- Information states capture the information transformation and describe it from being a simple purpose to a digital deliverable and a resource.
- Information loops identify the maturity of information through four consequential levels describing the capability of the DT system. These include a Descriptive Loop (i), a BIM-based level to document and describe information related to the current state of the physical asset; an Analytical loop (ii), a BPS-based level to analyze and process information related to the current or future state of the physical asset by using deterministic models; a Predictive loop (iii): an IoT-based level to analyze and process information related to the current or future state of the physical asset through data monitoring or predictive models (ML) based on sensor data coming from the physical asset; a Proactive loop, to integrate all the information acquired or processed in the previous levels within a centralized data environment and allow filtered visualization and interaction of information through DT Services to benchmark the building operational issues or predict new ones.
- Information milestones represent, for each loop, the steps that information traverses throughout its lifecycle.
- Information flows refer to the movement of information between information milestones (forward flows for actions and reverse flow for checks) or within information milestones (inward flows for data acquisition and outward flows for data sharing).

- Information links refer to the migration of information throughout information loops, allowing interoperability between different models, documents, data, resources, methods, and actors involved in other information loops.

The development of the DSS involves eight steps, defined as Information Milestones, which pass from the conceptualization of the DT to its actual use. These are:

1. Determining the intent to manage the physical asset (PA);
2. Identifying the physical properties to collect from the PA as well as the properties to investigate through the DSS;
3. Targeting the digital deliverables to produce for storing the collected data and create the DSS;
4. Comprehending what the resources and methods needed to set up the DSS are;
5. Setting up an actual method and using the available resources to implement the DSS;
6. Realizing the actual digital deliverables and integrating them into the digital asset (DA);
7. Letting asset managers adopt and use the DA;
8. Thinking about possible improvements or new uses of the DA.

As shown in the next section, the information milestones define the steps followed in the practical implementation of the research.

3.3. Implementation

This section presents the steps followed to deliver the DSS, guided by the above-discussed framework. DSS services are created to allow asset managers to interact with data stored in complex models through user-friendly dashboards. These services allow for searching, querying, filtering, and visualizing information related to building performance by linking and processing data provided by building information models (BIM) and building energy models (BEM). At this research stage, the analytical information loop has been reached, which means a BPS-based application capable of analyzing and processing information related to the current or future state of the physical asset using calibrated deterministic simulation models.

3.3.1. Purposes

The first implementation step consists of defining the intent to digitally manage the physical asset and the motivation behind developing the DSS. It means compiling the explicit reasons behind the required functions and the value sought from procuring the new DA for operating the PA.

In this case, as mentioned, the primary intent of the DSS is to enable performance-based operation of existing buildings by creating an information environment capable of sharing knowledge about their energy performance and relating it to information about planned occupancy conditions. The aim is to help to ensure managers are more aware of the energy behavior of the buildings they manage when planning occupancy. For instance, with reference to the selected case study, whose analysis is shown in the next section, this can be achieved by understanding the energy needs associated with specific occupancy patterns and activities in order to prioritize the use of the most energy-efficient areas inside the building during appropriate hours and seasons.

Since sensors or IoT devices are not yet installed in the discussed case study, which is a frequent condition in most heritage buildings, the platform uses time-series data simulated by BPS models and data commonly shared by the energy services providers, such as monthly natural gas and electricity bills. The developed DSS, therefore, can be seen as a transitional tool towards realizing the concept of a smart heritage [70], bridging the gap between the current state and the smarter future one.

3.3.2. Deliverables

Information Requirements

In the second implementation phase, information requirements are defined. These include the specifications of information needed to set up the DSS and clarify functions expected to be delivered by it to achieve the defined purposes. This stage involves two key steps. Firstly, it requires defining an ontological data model that effectively organizes the data. Secondly, it entails listing the expected properties of the PA that need to be collected or analyzed.

The knowledge data model establishes semantic and hierarchical rules between building elements for organizing data and encapsulating it in services. Employing a proper data structure makes it possible to seamlessly associate the expected properties to be collected with specific building elements, treating them as attributes. Moreover, this coherent attachment ensures a well-organized representation of the data.

Figure 5 depicts an overview of the data model used in the research. It is based on five types of entities connected by specific relationships:

- Elements (el), which represent the spatial (buildings, storeys, zones, and spaces) and construction components of buildings (walls, floors, roofs, and openings);
- Property sets (ps), which assign properties to the elements grouped by theme and type;
- Naming conventions (nc), which standardize the language of different models;
- Points (pt) are discrete units of information about an observation at a given time, as in the Brick's ontology [71];
- Key performance indicator sets (ks) are collections of metrics and measures that are used to evaluate the performance of building spatial elements.

A modular approach is used to create a flexible network structure for packaging and exchanging information.

After defining the knowledge data model, information templates are formalized. They consist of pre-organized tabular models describing element properties in the form of property sets, naming conventions, or points. These properties may be related to specific uses, disciplines, purposes, and operators. Moreover, they can include details about the data provider, the sources from which the data was acquired, its unique identification, its type and description, and the data itself. For example, when the DSS is used for energy management purposes, a physical element such as a thermal zone can be described with basic descriptive properties (e.g., identifier, name, size, and function) or more elaborated properties (e.g., heating demand, cooling demand, and lighting demand) that can be exchanged between the building manager and the energy modeler. Appendix A provides a detailed listing of information templates associated with the elements involved in the analysis proposed in Section 4.

Digital Models

The "deliverables" stage also involves targeting the digital deliverables to realize storing and structuring the PA's data and transforming it into valuable information shareable via the DSS.

For this application, three main digital deliverables are established: a building information model (BIM), a building energy model (BEM), and a schedule database (SD).

The building information model (BIM) consists of building elements, their basic geometry, and their static properties at a LoD200 level of development. In this level, spaces are modeled with enclosing elements like walls, elevations, floors, and roofs whose geometry is represented using generic objects. Moreover, the BIM is used to assign the semantic relationships between the elements necessary to map them according to the proposed ontology, which is based on the Industry Foundation Classes (IFC) and Green Building XML (gbXML) schema, as reported in Figures 5 and 6. BIM is also used as the basis for energy analysis; it encloses spaces, zones, and envelope elements whose function and characteristics are relevant to perform energy simulations.

The BEM consists of a physics-based model, realized in energy analysis software, to simulate the building energy behavior. By taking as input local weather data and a description of a building (including geometry, materials, occupancy, and HVAC systems), the BEM allows for calculating thermal loads, system response to those loads, resulting energy use, and related metrics like occupant comfort and energy costs through physics equations. It can allow for conducting dynamic analyses for a full year of calculations on an hourly basis, allowing evaluation system interactions between occupancy and energy hour by hour and zone by zone.

The SD contains information about occupancy, lighting, heating, cooling, and ventilation schedules, such as the number of people expected to occupy each space at a given time of the year and the HVAC operation times. Regarding educational buildings, occupancy information strictly related to the academic timetable can be provided by the university's Asset Management Services (AMS).

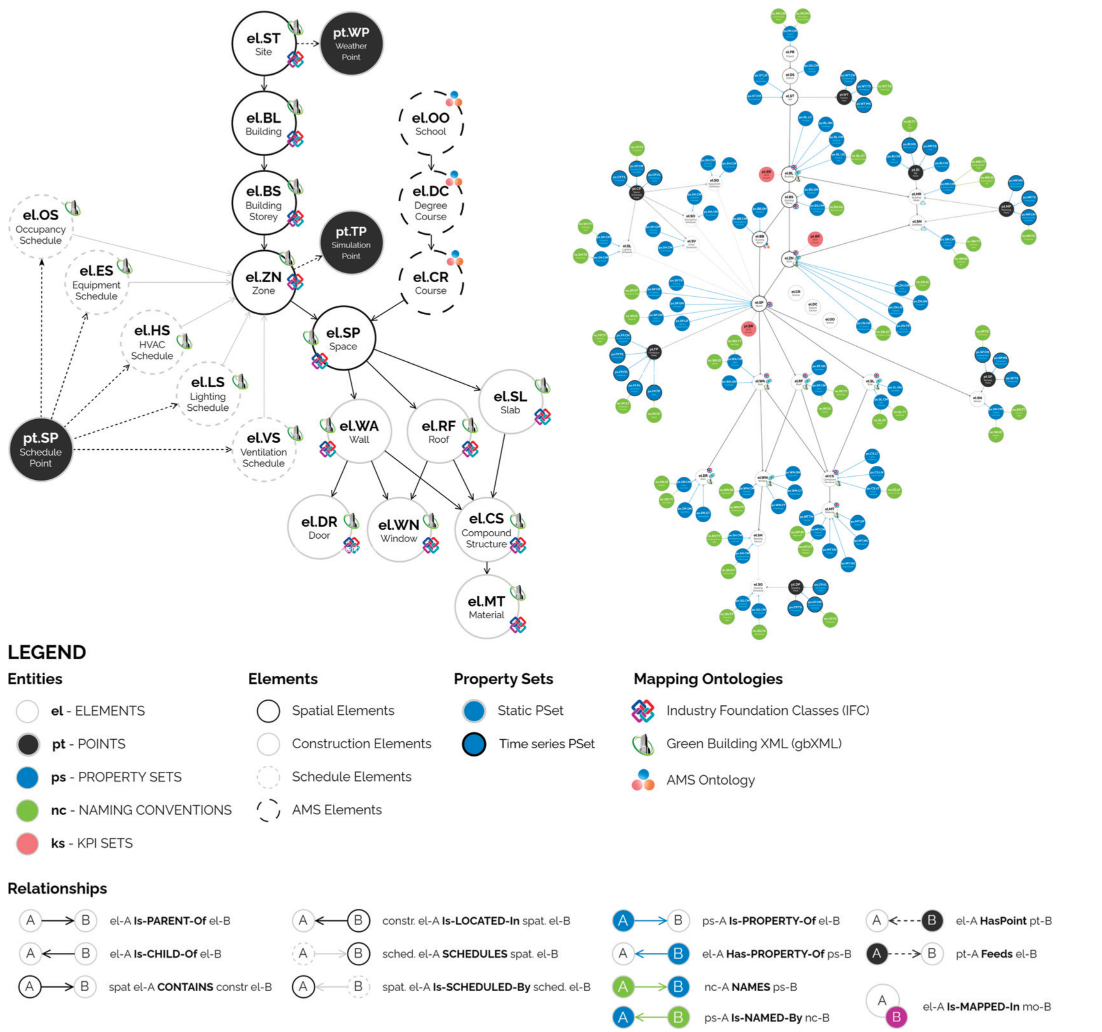


Figure 5. Ontology data model designed to implement the digital twin prototype in a network graph visualization.

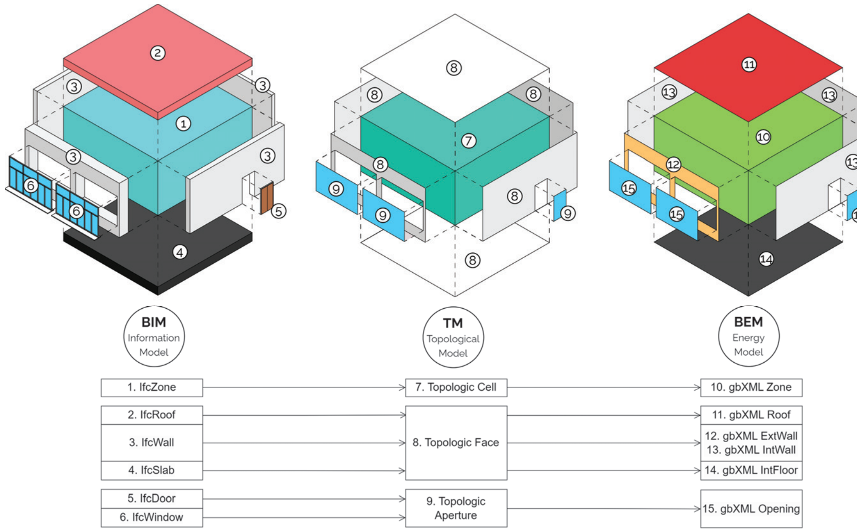


Figure 6. IFC, Topologic, and gbXML ontology alignment in the BIM to BEM workflow.

3.3.3. Resources and Methods

Once the digital deliverables are defined, the resources and methods are identified for delivering them. Resources refer to the human and machine actors and the physical, technical, financial, and other resources to be invested in transforming the targeted deliverables into actual ones. Methods refer to all the methodologies and tools for achieving DT purposes.

In particular, data collection, processing, and integration methods are defined at this stage. The first involves techniques for acquiring extensive knowledge about the asset's current condition. The seconds include workflows to deliver reliable digital models, such as BIM generation workflows, BPS analysis workflows, and strategies for achieving interoperability between BIM and BEM. The last provides techniques for linking the data available across multiple decentralized models, such as the BIM, the BEM, and the AMS' database. This integration is usually not straightforward because these models and systems rely on different modeling approaches, languages, and protocols, which are usually incompatible by definition.

Data Collection

In this application, the data collection strategy involves several preliminary in situ investigations; the consultation of historical and archival sources in public and private archives to know the construction features of buildings; the analysis of bibliographical work on the building; terrestrial laser scanner (TLS) surveys, the acquisition of drawings by the asset managers for getting the geometrical properties of building elements; discussions with administrators for understanding the actual uses of the different zones of the building, as well as to acquire energy bills and information related energy costs; the consultation of the AMS to know the occupation times.

Data Modeling

Data modeling and processing procedures and tools are also set.

Autodesk Revit is chosen as the BIM authoring software, while Topologic, a software library proposed by Jabi et al. [72], is used for performing BIM to BEM interoperability. The proposed approach consists of creating a topological model (TM) as means for data exchange between the BIM and the BEM (Figure 7). Visual programming (VP) algorithms in Grasshopper are used for achieving this task by using application programming interfaces

(APIs) to interoperate both with Autodesk Revit—via the Rhino.Inside add-on [73]—and with Energy Plus BPS engine—through the Ladybug Tools library [74].

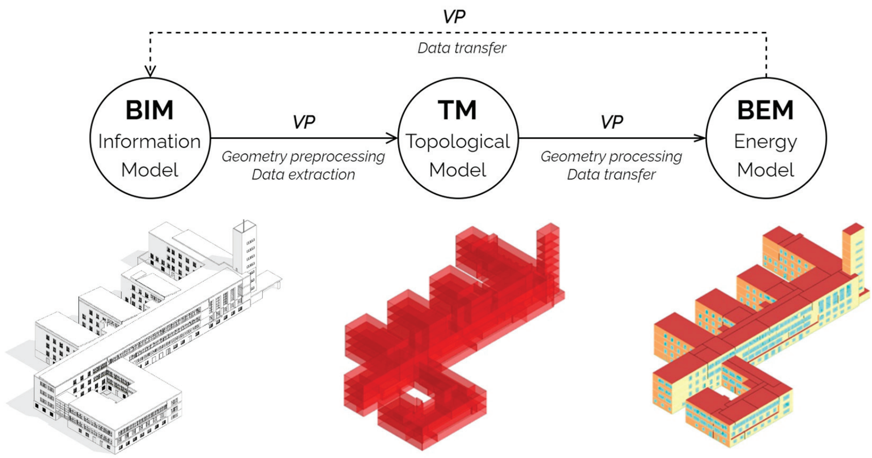


Figure 7. BIM to BEM conceptual workflow.

On the one hand, such tools allow complex geometrical operations to help BIM volume-based geometries match with BEM surface-based geometries; on the other hand, every change or modification on the BIM model is automatically registered in the topological and BEM model without loss of information or need to update the other models manually. Moreover, by working through VP algorithms, information can easily be imported and exported to tabular formats, as preferred. For instance, starting from the data provided by the University's AMS application [75], the classroom occupancy schedules, in .CSV format, are linked to the TM and the BEM through Grasshopper (GH), allowing us to estimate people's internal gains. Climatic data are also input in the BEM following a similar approach but using the EnergyPlus Weather File (EPW) format. At the same time, the results of the energy analyses are exported in .CSV file according to the predefined information templates so that they can be easily transferred to a centralized data repository. In the case of geometrical or information changes to the BIM model, such as variations in occupancy type, all the models can be automatically updated while maintaining the same data structure. This is achieved by rerunning the Grasshopper (GH) script after editing the BIM.

The initial phase of the BIM to BEM workflow involves creating the BIM, which serves as the foundation for the TM and BEM. The BIM combines geometric data of building components with information about space uses, thermal envelope characteristics, and zone energy loads. It incorporates spatial elements such as ifcBuilding, ifcBuildingStorey, ifcSpace, and ifcZone, along with construction elements like ifcWall, ifcRoof, ifcSlab, ifcWindow, and ifcDoor.

In the workflow, BIM space elements are selected from Autodesk Revit using the Rhino.Inside.Revit plug-in. The spaces with similar characteristics (in terms of functions, occupancy patterns, exposure conditions, and HVAC systems) are grouped into thermal zones. Then, a geometry voxelization algorithm is applied to simplify the high-resolution and volume-based geometries of the BIM in order to make them lighter and compatible with the TM and BEM. The zones are abstracted as Topologic Cells, and the properties of the BIM zone elements are transferred to these using the "Topology.SetDictionary" function. Next, the opaque envelope elements, represented as layered objects in the BIM, are linked to Topologic Faces, planar surfaces that bind the TM cells. As the cells act as the fundamental spatial units of the TM, the properties of the faces can be interpreted as attributes of the cells. By associating the TM faces with the corresponding BIM objects, the thermal properties of the construction, such as walls, roofs, and slabs, can be transferred from the BIM elements to the TM faces and subsequently to the TM cells. In the subsequent step, the glazed envelope elements are represented in the TM as Topologic Apertures, which are the openings within the faces that define the cells. Window, curtain wall, and door elements are selected in Grasshopper from the BIM using a similar approach as for spaces and opaque envelope elements. Their 2D profile is extracted and projected onto the corresponding TM faces. Finally, in the last stage, the TM cells, enriched with valuable information from the BIM, are aggregated into a single entity called the Topologic CellComplex. This CellComplex represents the entire building as the aggregation of the zones.

After this stage, the BEM is constructed based on the TM using the Honeybee plug-in from Ladybug Tools. The TM cells are transformed into gbXML Zone elements, while the cell faces and apertures are transformed into gbXML construction elements according to the ontology alignment in Figure 6. Once the ontologies are federated, the BEM model creation is brought off to assign all the BIM's information to the BEM reported in Appendices A and B.

The EnergyPlus Weather File (EPW) format is used to input climatic data. It consists of a header with location information and 8760 data lines representing each hour of the year, including weather parameters like temperature, humidity, radiation, illuminance, wind speed, and sky cover. Thanks to unique IDs, the HVAC and occupancy schedules are created in a CSV file and linked to the BIM, TM, and BEM models. The occupancy schedules are obtained from the academic timetable. In particular, the number of students attending each course is determined by leveraging the AMS information, including details about each lesson, such as time, classroom, and course. This allows for estimating the expected number of classroom occupants throughout the academic year, directly affecting the building's energy behavior.

To prepare for the energy simulation in EnergyPlus, simulation options are configured using components from Ladybug Tools. After the simulation is executed, the resulting energy data is saved in a CSV output file. Energy model calibration is then conducted by comparing the average actual annual energy consumption over the past three years, as indicated in the energy bills, with the calculated values from the energy simulation for the entire building. These results are subsequently parsed and linked to BIM zones using a unique identifier, enabling further analysis and integration with the building model.

Data Linking, Processing, and Visualization

From the data integration perspective, to deliver a DSS accessible from the web, a web application has been developed.

This app uses JavaScript for both the back- and front-end development. Python is also used in the back-end for interacting with the Energy Plus engine. One of its key functionalities is linking data from different models, displaying the 3D geometry of IFC spatial elements in a web browser, and visualizing related performance data by coloring them in gradient colors. Additionally, the application allows for visualizing time-series data related to spaces by selecting them intuitively, which is a poorly developed function in commercial energy modeling software and university digital services [26]. The data is then presented on dashboards with a user-friendly interface that enables building managers to view and interact with the building data even if they lack digital expertise.

For the purposes of this study, the DSS is developed for combining BIM, BPS, and SD data according to the data conversion and storage infrastructure shown in Figure 8.

First, the BIM model, created in Autodesk Revit (RVT), is exported in IFC and read into JavaScript Object Notation (JSON) thanks to the IFC.js toolkit [76]. Then, the RVT is used to generate the BEM through VP algorithms in Grasshopper, as exposed. An Energy Plus Input Data File (IDF) is created, a dynamic energy simulation is run, and time series results are stored in CSV. Also, occupancy data from the AMS are collected in CSV. BEM and SD produce 8760 data points for each zone of the building since the simulation is run for every hour between 1 January 2022 to 31 December 2022 to calculate zone energy use (cooling load, heating load, electric light and equipment loads), gains and losses (people gains, solar gains). These CSVs are converted to JSON files and stored in the linked data repository (Figure 9). Specific data pipelines carry out data transformations by linking data gathered through the various models and then processing, refining, and providing access to it based on the specific information needs of data consumers and applications. Finally, valuable data is visualized on interactive dashboards thanks to the use of a web application.

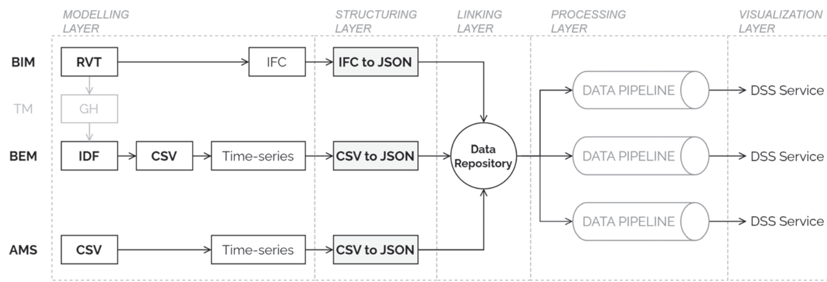


Figure 8. Data flow for delivering DT services.

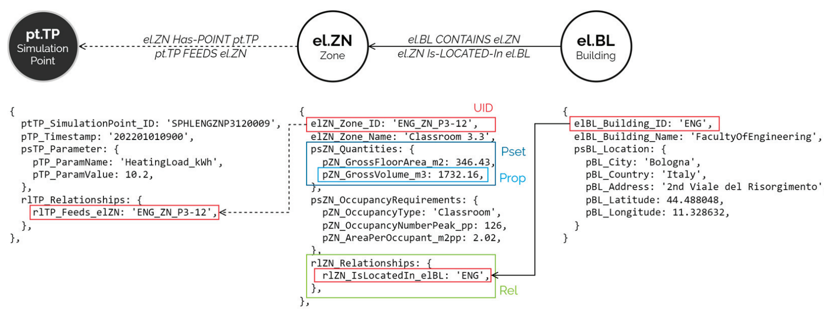


Figure 9. Example of JSON object definition for simulation points (pt.TP), zone elements (el.ZN), and building (el.BL).

The adoption of open BIM technology enables establishing an informational standardization layer, allowing the implementation of various applications without necessitating alterations to the data structure. By utilizing a linked data (LD) approach, a data lake architecture, and extract–transform–load (ETL) processes, the developed models can be easily augmented with static and dynamic data from other databases, IoT devices, software, or occupants, ensuring interoperability, scalability, and customization of the solution to meet specific user information requirements.

An example of BIM, BEM, and SD data is provided in Table 1.

Table 1. Example of BIM, BEM, and SD data extraction.

Zone UID (BIM)	Zone Name (BIM)	Net Area (BIM) (m^2)	Timestamp (Y–M–D H:M)	Occupancy Rate (SD) (%)	Heating Demand (BEM) (kWh)
ENG_ZN_P3-12	Classroom 3.3	346.43	21 January 2022 09:00 21 January 2022 10:00	0.85 0.90	10.20 4.59
ENG_ZN_P3-15	Classroom 3.6	252.97	21 January 2022 09:00 21 January 2022 10:00	0.00 0.75	4.13 2.04

3.3.4. Service Interaction

Once the DSS is completed, it is utilized as a decision support system (DSS) to simulate various scenarios. These simulations allow for exploring how energy loads may vary across different building zones at an hourly scale. The variations can be observed in response to different occupancy conditions and times, as well as the implementation of smart technologies aimed at enhancing controls (such as thermostats and occupancy detectors for lighting).

All elements included in the dashboards are interactive and allow sorting, filtering, and aggregating data by building, zone, hour, and function. Upon selecting a specific area in the 3D model and setting a date and time, the application recognizes the element's unique identifier (UID) and the chosen date and time. It then employs a query function to access data from the repository and display it related to that space in gradient colors. The information window presents space-related metrics, including net area, volume, occupancy type, and energy-related KPIs. Furthermore, the dashboard features line charts that exhibit time-series data. Users can examine KPIs for individual spaces or entire buildings and aggregate them over different timeframes. In this way, the DSS offers a snapshot of crucial building areas during various periods, which can differ significantly due to seasonal fluctuations in occupancy and energy requirements (e.g., academic schedules, heating and cooling demands).

The visualization of such data in an interactive and filterable environment could be of great help to building administrators, for example, to analyze and monitor the energy performance parameters of the entire building portfolio and to understand what the major critical issues are to be solved to optimize energy management, limiting impacts, consumption, and costs. This functionality can also enable managers to prioritize maintenance and renovation efforts, particularly in extensive and outdated building stocks that necessitate regular updates and enhancements.

An example of the service's graphical user interface (GUI) is illustrated in Figure 10. The indicators demonstrate that on 13 February 2022, the heating demand for the chosen classroom was nearly nonexistent between 1:00 p.m. and 7:00 p.m. when the room was fully occupied, and internal gains from occupants were substantial. This data contrasts with the HVAC system's operation, which is consistently scheduled to be active during these hours. The misalignment between energy demand and HVAC usage indicates potential energy waste and subsequent financial loss. Utilizing this information, building managers can adjust the HVAC system's schedule to optimize energy management within the building.

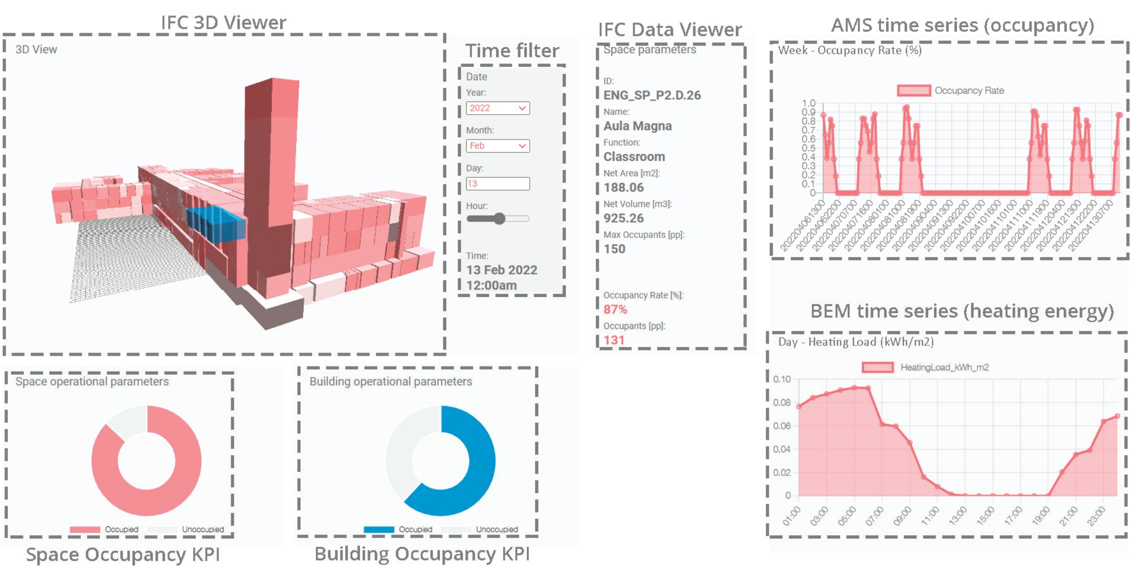


Figure 10. Dashboard prototype for visualizing energy- and occupancy-related data on IFC files.

4. Results

4.1. Energy Modeling Hypotheses

The building energy model, calibrated with actual energy bills, was subsequently employed for a comprehensive evaluation using the developed tools. This model considers the building zones' dimensions, construction, and occupancy characteristics, as well as the respective electricity and natural gas demands categorized by end uses. This section presents the main findings to compare the energy performance among the classrooms in the case study building on a significant winter operational day.

Table 2 displays the fundamental input parameters used for the analysis, while Table 3 shows the most important weather data for the selected day. The study utilized the EPW file of Bologna-Borgo Panigale, Italy, which contains hourly weather data for the specified location (Longitude: 11.30, Latitude: 44.53), situated in the Köppen–Geiger climate zone Cfa (humid subtropical climate with no dry season) at 49 m above sea level. Table 4 presents a summary of the EPW data.

Table 2. Input parameters for the energy analysis.

Analysis Day	Natural Gas Cost	Electricity Cost	Emissions for Electricity Mixes	Emissions for Heat Production from Natural Gas
23 February 2022 [1]	0.054 EUR/kWh [2]	0.159 EUR/kWh [2]	0.49 $kgCO_2eq/kWh$ [3]	0.25 $kgCO_2eq/kWh$ [3]

[1] The day is representative of a winter condition in Bologna (Italy) with mild cold and a typical day of classes, as the academic calendar schedules exams until mid-February. [2] Energy costs are derived from the average energy bills of 2020, 2021, and 2022. The conversion from standard cubic meters (smc), as in the bills, to kilowatt-hours (kWh) for natural gas is achieved by applying a conversion factor of 10.69, considering the calorific value of the gas. [3] Emission factors are based on the greenhouse gas emissions from the energy database of the International Energy Agency (IEA) that include global annual GHG emissions of each state from energy and related indicators, including CO_2, CH_4, N_2O emissions from fuel combustion, and fugitive emissions.

Table 3. Main weather data for 23 February from EPW.

Min Temperature	Mean Temperature	Max Temperature	Min Humidity	Max Humidity
5.9 °C	7.6 °C	10.2 °C	44%	94%

Table 4. Summary of weather data from EPW.

Average Yearly Temperature	Hottest Yearly Temperature	Coldest Yearly Temperature	Annual Cumulative Horizontal Solar Radiation	Percentage of Diffuse Horizontal Solar Radiation
13.0 °C	31.7 °C	−3.1 °C	1142.24 Wh/m^2	53.7%

The academic calendar of the selected case study is divided into two main periods: exams and class periods. In 2022, the exam period spanned from 10 January to 20 February and then from 13 June to 18 September. On the other hand, the class period encompassed the periods from 21 February to 12 June and from 19 September to 23 December. To illustrate a representative scenario, 23 February 2022 was chosen as it represented the coldest day during the class period in the selected context. On this day, the building was occupied to a significant extent, in contrast to the exam period when there were fewer individuals present.

In the analysis, it is assumed that each zone is equipped with thermostats. The heating setpoints are considered to be 20 °C from 7:00 a.m. to 8:00 p.m. and 16 °C during the night. The lighting is assumed to be always on from 8:00 a.m. to 8:00 p.m., while the occupancy conditions reflect the planned number of occupants based on the AMS apps. Mechanical ventilation has not been taken into account, as the building is naturally ventilated. Cooling has also not been considered since the analysis refers to winter conditions. The natural ventilation rate is assumed to be 0.3 h^{-1}, based on the findings of the study of Semprini et al., who conducted an energy audit for the same case study building [77].

Due to the challenges of obtaining comprehensive information about the HVAC system, it is not extensively incorporated into the BEM. As a result, the main key performance indicator (KPI) related to the energy behavior of each zone is an approximation based on considering the energy demanded by each zone instead of the energy supplied to it by the HVAC system. This approximation is justified by the uniformity of the HVAC system throughout the entire building. Therefore, to evaluate the expected costs and emissions associated with zone operation, the energy demand (in kWh) is multiplied by the factors mentioned in Table 2.

Table 5 presents the summarized data of the energy model.

Table 5. Energy model overview.

Gross Conditioned Area	Gross Unconditioned Area	Gross Conditioned Volume	Mean U-Value Opaque Envelope	Glazed/Opaque Envelope Surface Ratio
18,738 m^2	523 m^2	81,382 m^3	1.10 W/m^2K	29%

Furthermore, the KPIs in Table 6 are used to compare the energy demand and associated costs among various building zones. These KPIs are categorized into dimensional KPIs, energy KPIs, cost KPIs, and environmental KPIs. Additionally, solar and people's internal gains are taken into account to provide further insight into grasping the energy behavior of each classroom.

Table 6. Comparative key performance indicators (KPIs) used in the analysis to assess thermal zone behavior.

Dimensional KPIs	Energy KPIs	Cost KPIs	Emissions KPIs
Net area (sqm) Occupancy number at peak (people count)	Energy demanded for heating (kWh) Energy demanded for lighting (kWh) Energy demanded for equipment (kWh) Natural Gas demanded for heating (kWh) Electricity demanded for lighting and equipment (kWh)	Costs for heating (EUR) Costs for lighting (EUR) Costs for equipment (EUR) Total costs (EUR)	Equivalent emissions for heating ($kgCO_2eq$) Equivalent emissions for lighting ($kgCO_2eq$) Equivalent emissions for equipment ($kgCO_2eq$)

4.2. Zone Clustering

To facilitate a meaningful comparison of the energy performance among the zones, they were clustered in groups. Specifically, the zones were grouped into five clusters based on their area and peak occupancy number. Only rooms designated for classroom functions were considered for this analysis. The K-means algorithm was utilized for this purpose. In brief, it consists of a machine-learning technique that partitions data points into clusters based on their similarity.

As shown in Figure 11, Cluster A comprises classrooms with an area of less than 80 sqm and accommodating up to 50 people, representing the smaller-sized classrooms in the building. Cluster E consists of classrooms with an area larger than 190 sqm and accommodating up to 175 occupants, representing larger classrooms. Cluster B includes classrooms with an occupancy range of 80 to 120 people and an area between 100 and 150 sqm. Cluster C contains classrooms with an occupancy range between 125 and 150 people and an area between 100 and 120 sqm. Lastly, Cluster D represents classrooms with an occupancy range of 140 to 150 people and an area between 160 and 180 square meters. Each cluster is assigned a distinct color, as depicted in the figure, and will be consistently identified with that color throughout the analysis.

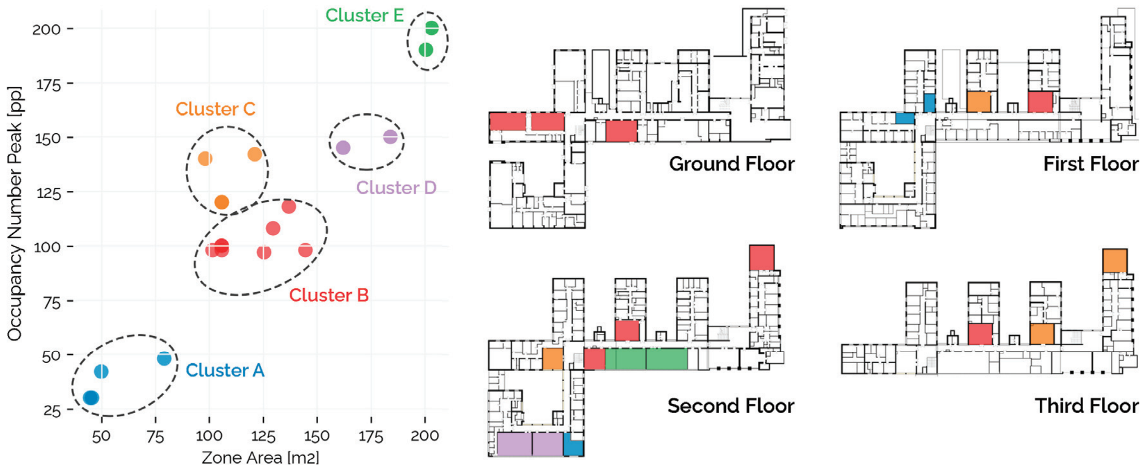


Figure 11. K-means clustering of the classrooms by area and peak occupancy number.

4.3. Energy Simulation Results

4.3.1. Energy Demand

For the specific day considered, the classrooms alone are projected to have the following energy and environmental impacts:

- The total heating demand is estimated to be 3405.77 kWh;
- The electricity demand for lighting and equipment is estimated to be 321.36 kWh;
- The overall management costs are calculated to be EUR 183.9 for heating and EUR 51.11 for lighting and equipment;
- The total equivalent emissions for the day are estimated at 1668.83 kgCO_2eq for heating and 76.56 kgCO_2eq for lighting and equipment.

The classrooms considered have a total area of 2355 sqm, accounting for 13% of the entire building area, and a maximum capacity of 2174 students, as defined in the building's fire plan, constituting approximately 43% of the total hypothetical occupants.

Figure 12 presents several results for the selected day, organized by zones. It is evident that there is a notable correlation between occupancy and heating demand, as the demand becomes almost negligible when the classrooms are fully occupied.

4.3.2. Space Ranking

In order to calculate the costs and emissions, the energy demand is multiplied by the appropriate factors, taking into account natural gas for heating and electricity for all other end uses (lighting and equipment). The same approach is applied for both costs and emissions calculations. This allows us to rank classrooms based on cost and emission metrics, as shown in Figure 13. Cluster by cluster, this ranking provides insights into the relative performance of classrooms in terms of their associated costs and environmental emissions.

4.3.3. Space Comparison

Figure 14 enhances the synthesis of results by providing a comprehensive overview through a parallel coordinate graph. The parallel graph utilizes a series of parallel axes, each representing a different variable or attribute. For each classroom, a data line connects the points on each attribute axis, representing the values of the variables for individual observations. It attempts to offer a synthetic visual representation that enables the exploration, comparison, and interpretation of the complex datasets deriving from the Energy Plus simulation.

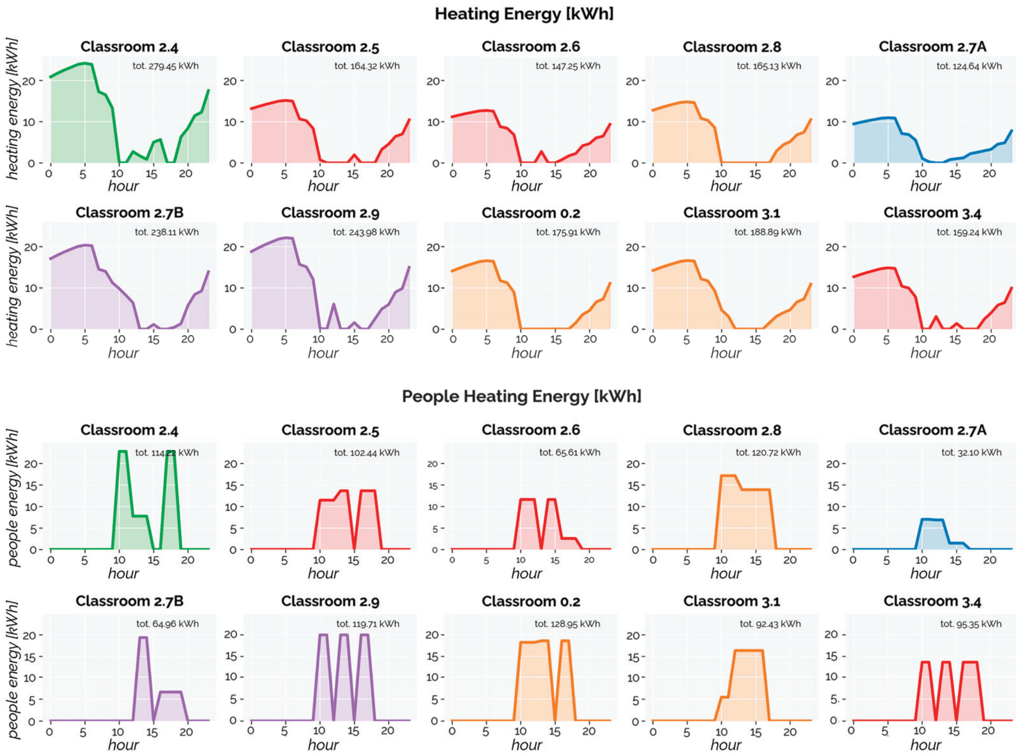


Figure 12. Visualization of hourly heating demand for some classrooms on the specified date and time. Data are colored according to the clusters identified in Figure 11.

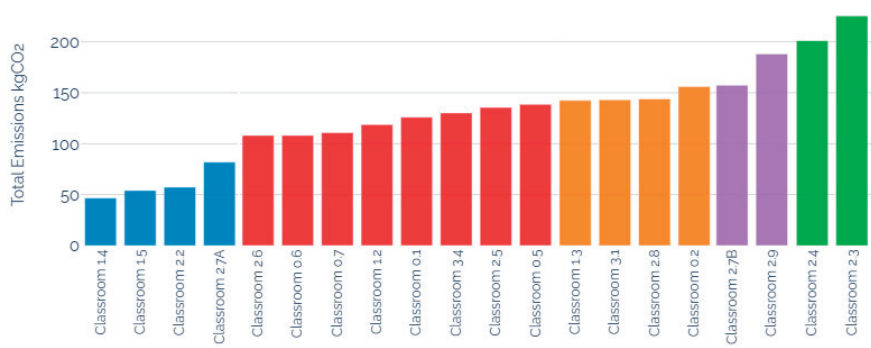


Figure 13. Total emissions for each classroom during the analysis day. Data are colored according to the clusters identified in Figure 11.

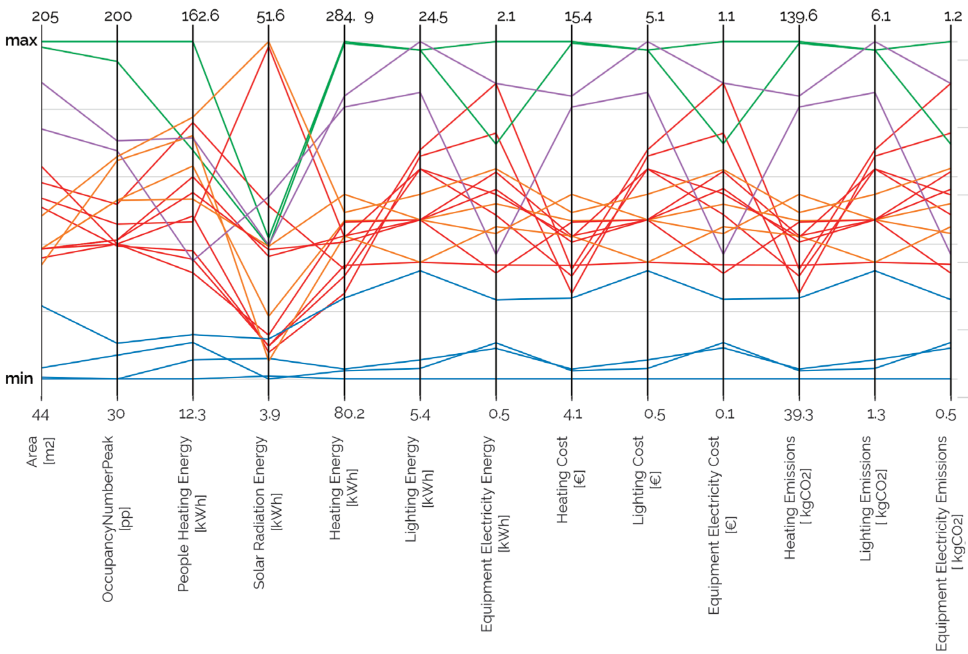


Figure 14. Parallel coordinate graph showcasing a comparison of the classrooms through the KPIs identified in Table 5. Lineplots are colored according to the clusters identified in Figure 11.

5. Discussion

5.1. BIM to BEM Interoperability

Numerous research studies have reported on the issue of interoperability between BIM and BEM. These studies consistently indicate several unresolved challenges associated with developing BIM-based building energy modeling [78]. For example, the complexity of geometry in digital environmental simulations can lead to computational bottlenecks [79]. BIM-based simulation models often result in high polygon counts, making simulations more time-consuming and less controlled. BPS tools usually require models with regular squared mesh for tasks like daylight analysis, computational fluid dynamics, or safety pathfinding simulations. Furthermore, BIM and BEM systems might employ different geometry kernels and data dictionaries, impacting their performance and compatibility with various software tools [80]. This discrepancy in underlying data structures can hinder smooth data exchange and integration between the two systems, further complicating the interoperability challenge.

The data exchange between BIM and BEM systems typically occurs through two file formats: IFC and gbXML. Each format offers distinct advantages in this context. IFC is widely recognized as the standard format for information exchange in BIM. It comprehensively represents building elements and their properties, allowing for detailed modeling and collaboration across different software platforms. On the other hand, gbXML is specifically designed for energy simulation purposes. Rather than object-based modeling, it is based on rectangular-shaped surfaces and attributes. gbXML can store a wide range of building information required for energy simulations, making it suitable for BEM applications. However, integrating IFC with gbXML is not straightforward due to the differences in modeling approaches, languages, and protocols employed by these systems. Compatibility issues can arise, and additional effort may be required to bridge the gap and enable seamless data exchange between the two formats.

Improving interoperability between BIM and BEM remains challenging, despite advancements made through file formats such as IFC and gbXML. The current approach involves creating a separate, unlinked digital model (the BEM) based on the BIM, rather than achieving bidirectional data exchange and storing energy data within a unified model. This data integration process is not optimal in terms of data flow.

To address this issue, this research proposes an alternative method, relying on both IFC and gbXML, for BIM-BEM bidirectional integration based on the creation of a Topological Model (TM) as a means of data exchange between the two models thanks to VP algorithms. The TM simplifies the representation of buildings by breaking them down into cells (spaces) that are bounded by faces (walls, floors, and roofs) and connected by openings (windows and doors), helping the BIM be compatible with the BEM modeling environment. The use of VP offers several advantages. Firstly, it enables the integration of complex geometric operations to align BIM's volume-based geometries with BEM's surface-based geometries. Secondly, any changes made to the BIM model are automatically reflected in both the TM and BEM models and vice versa, eliminating the need for manual updates. This eliminates the need for file exporting, reducing the risk of losing information and avoiding time-consuming coordination issues. Furthermore, VP allows access to energy-related data from external sources (such as occupant schedules, energy bills, and monitoring data), which can be used in simulations for comprehensive and accurate analyses. As cons, this method requires advanced digital skills and proper data flow management to ensure standardized procedures.

5.2. Energy Consumption Prediction Methods

In recent decades, scientists and engineers have dedicated significant efforts to developing approaches for predicting energy consumption. These approaches can be broadly categorized into three types: building physical energy models (referred to as "white box" models), data-driven models (referred to as "black box" models), and hybrid models (referred to as "grey box" models) [81].

The first category of building energy models, known as the "white box" model, relies on detailed building parameters and heat balance equations. This approach involves modeling the physical characteristics of a building, such as its construction materials, insulation, ventilation systems, and thermal properties, and the contextual factors, such as solar radiation, weather conditions, and occupancy patterns. The modeling and calibration process of "white box" software poses significant challenges for building energy stakeholders due to the extensive input parameters required, leading to time-consuming development on a physical software platform and high simulation economic costs. However, when well calibrated, the physical models' prediction accuracy can be higher than the statistical models [82], as well as their interpretability.

Given the limitations of white box models and the rapid advancements in big data technologies like sub-metering and smart buildings, data-driven models have emerged as a viable alternative in the last decade. Black box models offer a simpler approach by capturing the linear and nonlinear relationships between input and output variables. The main research efforts in the last period focused on investigating deep learning techniques and optimizing two key aspects: the significance of features to train models and the choice of algorithms. However, training these models and achieving accurate predictions under different conditions typically require vast amounts of historical data and a lengthy training period [81]. Moreover, while black box models have the advantage of needing less building information for their development, their prediction accuracy fluctuates, particularly when applied to different building scenarios. To address these challenges, a solution known as the "grey box" approach has been suggested by the literature. This method incorporates a simplified physical model and readily available data to simulate building energy demand, effectively combining the benefits of white and black box approaches.

White box models were employed in the presented application because of the absence of measurement data and their higher level of standardization in already developed software ontologies (compared to the black box and grey box models currently available in the literature). By adopting this approach, the connection between input and output for analysis becomes more comprehensible, particularly in terms of educating building managers about building behavior. However, some approximations were made due to the complexity of inputting the many input parameters required by Energy Plus for calculation, as discussed in the previous section.

5.3. Limitations and Future Developments

Numerous limitations and potential future developments of the developed DSS can be highlighted.

First, conducting a detailed analysis and refining the evaluation of various scenarios concerning different occupancy conditions is crucial. This analysis will provide insights into how operations can be improved effectively through occupancy. Moreover, assessing the potential impact of implementing diverse demand-control technologies within the building, such as thermostats, occupancy sensors, and lighting sensors, is essential. As demonstrated by Mosteiro-Romeiro et al. [33], integrating these technologies harmoniously with occupancy planning strategies can make it possible to ensure that the building's supply aligns with the demand, thereby encouraging flexible attendance modes and reducing energy use and related costs and emissions.

In the proposed analysis, only the classrooms have been evaluated. However, the analysis could be further extended to include other areas, such as offices, in order to assess the long-term effects of the increased prevalence of remote working and studying due to the COVID-19 pandemic or variations in the academic calendar [34]. This will enable better planning and optimization of resources to accommodate the evolving needs and trends in workspace utilization.

The extension of the exposed information system to more categories of building management (e.g., water consumption, indoor air quality, and waste management) and the scale of the entire building portfolio may aid administrators in assessing the scale interactions subsisting between buildings within the portfolio, the city, and the environment. In addition, if similar systems are framed in administration performance goals, they may enable the development of comprehensive decision-support tools for improving knowledge about actual conditions of use of buildings, making related information immediately and easily accessible, and the planning of management and renovation roadmap capable of considering the priorities of intervention within the administered estate quantitatively.

Lastly, only BPS data are currently used in the DSS. The lack of real sensor data from buildings, as opposed to just simulated data from building performance simulations, can bring the "performance gap" in evaluations, introducing significant discrepancies between simulated and real energy use [83]. To overcome this limitation, using smart energy meters and sensors for real-time monitoring of energy parameters could provide more reliable estimations. Following a similar approach, data from sensors and IoT devices will be inserted into the DSS to predict building performance more reliably.

6. Conclusions

Managing outdated public heritage buildings in Europe has become increasingly significant in recent years. These buildings, which include those operated by public administrations, require ongoing upgrades and improvements related to safety, operation, and maintenance to meet current needs. However, building management practices are not always equipped to address the complexity of these issues effectively. Several gaps in public building management of building stocks make it difficult to conserve the physical characteristics of buildings while ensuring functional, environmental, and economic compatibility with the current demanding framework, producing high costs for owners and environmental impact.

Digital technologies like Digital Twin (DT) are emerging to solve this issue and allow informed building management practices. However, there is still a lack of clarity surrounding their definition and uses. On the one hand, higher-level conceptual constructs are necessary to promote an organic DT development activating standardized and shared information modeling protocols; on the other hand, applicative examples are required to demonstrate the advantages of adopting such technologies, which require high digital skills and, so, high initial investments of resources for public administrations to face their digital transition.

The paper introduced a top-level framework for delivering built assets' information lifecycle management and its application for creating a DT prototype. From the initial intent to digitally manage an existing asset until the end of its lifecycle, the framework defines information transformations during its continuous updates. It is articulated according to eight information milestones: intents to improve the physical asset, expected properties, targeted deliverables, needed resources and methods, available resources and methods, actual digital asset development, digital asset adoption, and intents to improve the digital asset. In the study, this framework guided the development of a DT web application for sharing information related to energy and occupancy issues of a selected case study from the alma mater's building stock. The application prototype allowed the visualization of expected building performance data through KPI-based dashboards by linking different data models, such as building information models (BIM) and building energy models (BEM), forming a decision support system usable by building managers.

The research aimed to go beyond individual case studies and provide a comprehensive framework to modularly integrate and utilize various types of information, regardless of their nature. Despite some limitations discussed in the text, the presented analysis showcased an evaluative and testing nature of a developed DSS, highlighting how BIM and BPS can contribute to addressing some digitization challenges in the AECO sector if framed within a systemic perspective. By systematizing BIM and BEM data into an information environment, easily accessible to building operations staff, the information stored in the models can be inspected to understand building performance better and support decision-making processes.

The paper, therefore, offered an interpretation of the challenge of integrating BPS and BIM within a DT framework. It acknowledged that this effort represents a small step towards defining such systems and attributes its potential usefulness in scenarios where data quality and quantity are lacking, such as in outdated existing buildings. Within this perspective, even if not using live data, the research has leveraged the concept of DT to support the vision of data integration, considered one of the fundamental layers in defining and implementing DT systems. In future developments, sensor data measured from the real physical asset will be integrated to perform an effective coupling between the physical asset and the digital asset, improving data reliability and fidelity, as well as the DT sensitivity to catch the behavior of the building with higher accuracy.

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

Appendix A

Table A1. Cell properties transferred from the building information model (BIM) to the topolgical model (TM).

Property Set	Properties
Cell.Common	Zone ID (str), Zone Name (str)
Cell.Relationships	ChildOf: Building (rel), ChildOf: Building Storey (rel), ParentOf: Faces (rel), ParentOf: Apertures (rel)
Cell.Quantities	Gross Volume (m^3), Net Volume (m^3), Gross Area (m^2), Net Area (m^2), Gross Height (m), Net Height (m)
Cell.LightingAndEquipment	ArtificialLighting (bool), IlluminanceSetpoint (lux), LightingPowerDensity (W/m^2), EquipmentPowerDensity (W/m^2), LightingSchedule (rel), EquipmentSchedule (rel)
Cell.OccupancyRequirements	IsOccupied (bool), AreaPerOccupant (mq/pp), OccupancyNumber (pp), OccupancType (str), OccupancySchedule (rel)
Cell.ThermalRequirements	IsHeated (bool), IsCooled (bool), IsVentilated (bool), TemperatureSummerMax (°C), TemperatureSummerMin (°C), TemperatureWinterMax (°C), TemperatureWinterMin (°C), HumidityMax (%), HumidityMin (%), NaturalVentilationRate ($m^3/(s\cdot m^2)$), MechVentilationRate ($m^3/(s\cdot m^2)$), CoolingSchedule (rel), HeatingSchedule (rel), VentilationSchedule (rel)

Table A2. Face properties transferred from the BIM to the TM.

Property Set	Properties
Face.Common	Face ID (str), Face Name (str), Face Type (str)
Face.Relationships	ChildOf: Building (rel), ChildOf: Building Storey (rel), ChildOf: Cell(rel), ParentOf: Apertures (rel)
Face.Quantities	Length (m), Width (m), Height (m), GrossSideArea (m^2), NetSideArea (m^2), GrossVolume (m^3), NetVolume (m^2), GrossWeight (kg), NetWeight (kg)
Face.Materials	MaterialLayer1: (Name (rel), Thickness (m), Conductivity (W/mK), Density (kg/m^3), SpecificHeat (K/kgK); MaterialLayer2: (Name (rel), Thickness (m), Conductivity (W/mK), Density (kg/m^3), SpecificHeat (K/kgK); MaterialLayerN: (Name (rel), Thickness (m), Conductivity (W/mK), Density (kg/m^3), SpecificHeat (K/kgK)
Face.ThermalProperties	U-Value (W/m^2K), R-Value (m^2K/W), VolumetricHeatCapacity (J/km^3)
Face.Common	Face ID (str), Face Name (str), Face Type (str)

Table A3. Aperture properties transferred from the BIM to the TM.

Property Set	Properties
Aperture.Common	Face ID (str), Face Name (str), Face Type (str)
Aperture.Relationships	ChildOf: Building (rel), ChildOf: Building Storey (rel), ChildOf: Cell (rel)
Aperture.Quantities	Width (m), Height (m), Area (m^2), Perimeter (m)
Aperture.ThermalProperties	U-Value (W/m^2K), SolarHeatGainCoefficient (float), VisibileTrasmittance (float)

Appendix B

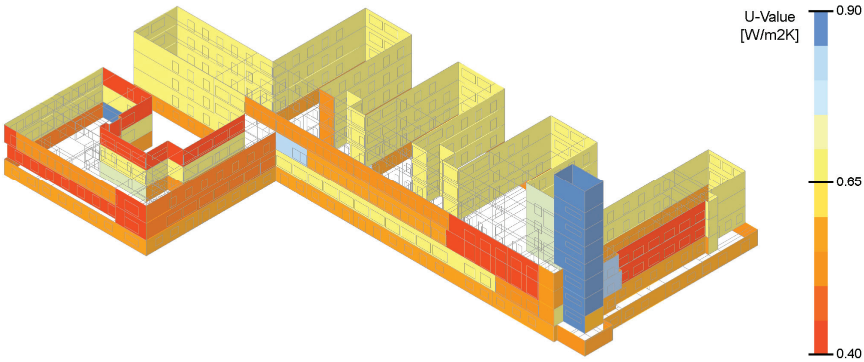

Figure A1. U-values of opaque construction elements input in the BEM model.

Table A4. U-values of opaque construction elements input in the BEM model.

Construction Type	Element	Materials (External to Internal Layers)	U-Value (W/m^2K)
AreatedBrickWall_36cm	Wall	Plaster_2cm, Areated brick_32cm, GypsiumPlaster_2cm	0.72
BrickWall_50cm_2	Wall	Plaster_2cm, SolidBrick_14cm, Air_16cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.68
MixedBrickConcreteWall_120cm	Wall	Plaster_2cm, SolidBrick_14cm, SolidBrick_14cm, ReinforcedConcrete_45cm, Air_36cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.55
MixedBrickConcreteWall_160cm	Wall	Plaster_2cm, SolidBrick_14cm, SolidBrick_14cm, SolidBrick_14cm, Air_16cm, ReinforcedConcrete_95cm, GypsiumPlaster_2cm	0.41
SolidBrickWall_45cm	Wall	SolidBrick_14cm, SolidBrick_14cm, SolidBrick_14cm	0.45
SolidBrickWall_47cm	Wall	SolidBrick_14cm, SolidBrick_14cm, SolidBrick_28cm, GypsiumPlaster_2cm	0.54
SolidBrickWall_50cm	Wall	Plaster_3cm, SolidBrick_14cm, SolidBrick_14cm, SolidBrick_28cm, GypsiumPlaster_2cm	0.51
SolidBrickWall_30cm	Wall	SolidBrick_14cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.85
SolidBrickWall_34cm	Wall	Plaster_2cm, SolidBrick_14cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.76
SolidBrickWall_37cm	Wall	Plaster_3cm, SolidBrick_14cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.72
SolidBrickWall_49cm	Wall	Plaster_2cm, SolidBrick_14cm, Air_, SolidBrick_14cm, GypsiumPlaster_2cm	0.68
SolidBrickWall_62cm	Wall	Plaster_2cm, SolidBrick_28cm_30cm, Air_14cm, SolidBrick_14cm, GypsiumPlaster_1cm	0.49
SolidBrickWall_64cm	Wall	Plaster_2cm, Air_17cm, SolidBrick_14cm, Air_16cm, SolidBrick_14cm, GypsiumPlaster_1cm	0.64
SolidBrickWall_64cm	Wall	Plaster_2cm, SolidBrick_14cm, SolidBrick_14cm, SolidBrick_14cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.40
SolidBrickWall_72cm	Wall	SolidBrick_28cm, Air_28cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.50

Table A4. *Cont.*

Construction Type	Element	Materials (External to Internal Layers)	U-Value (W/m^2K)
SolidBrickWall_77cm	Wall	SolidBrick_14cm, SolidBrick_28cm, Air_30cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.46
SolidBrickWall_79cm	Wall	Plaster_2cm, SolidBrick_14cm, SolidBrick_14cm, Air_31cm, SolidBrick_14cm, GypsiumPlaster_1cm	0.46
SolidBrickWall_82cm	Wall	SolidBrick_28cm, Air_38cm, SolidBrick_14cm, GypsiumPlaster_2cm	0.47
HollowConcreteFloor_60cm	Floor	CeramicTiles_2cm, LightConcrete_8cm, HollowSlab_48cm, GypsiumPlaster_2cm	1.16
HollowConcreteFloor_52cm	Floor	CeramicTiles_2cm, LightConcrete_8cm, HollowSlab_40cm, GypsiumPlaster_2cm	1.35
HollowConcreteRoof_52cm	Roof	Gravel_10cm, WaterProofMembane_1cm, HollowSlab_40cm, GypsiumPlaster_2cm	1.41
GroundFloor_50cm	Floor	CeramicTiles_2cm, LightConcrete_8cm, ConcreteSlab_20cm, Gravel_20cm	3.03

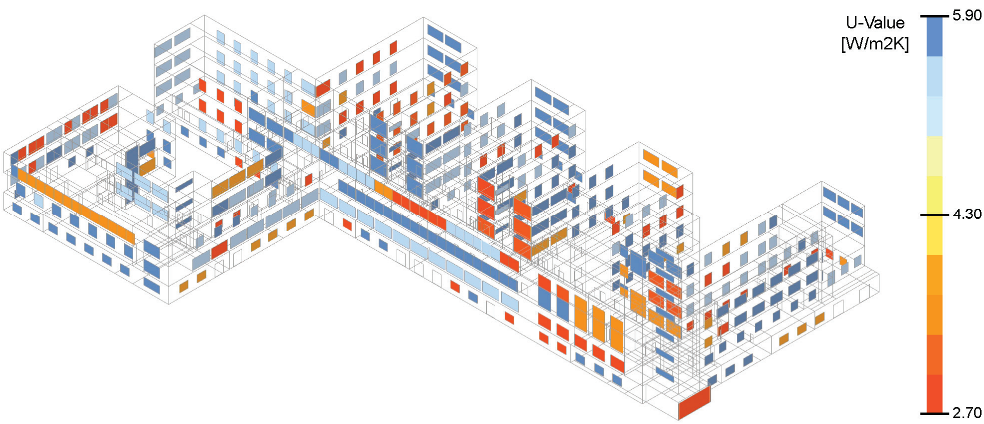

Figure A2. U-values of glazed construction elements input in the BEM model.

Table A5. U-values of glazed construction elements input in the BEM model.

Opening Type	Frame Material	Glass Type	U-Value (W/m^2K)
SteelFrame_SingleGlass_Old	Steel	Single Layer	5.5–5.8
AluminiumFrame_DoubleGlass_Old	Alluminium	Double Layer	3.0–3.4
WoodFrame_SingleGlass_Old	Wood	Single Layer	4.5–4.9
WoodFrame_DoublGlass_Recent	Wood	Double Layer	2.7–2.9

Appendix C

Table A6. Descriptive properties of the spaces selected for the analysis.

Space Name	Building Storey	Cluster ID	Area (m^2)	Occupancy Number Peak (pp)	Area/Occupant (mq/pp)
Classroom 0.1	Second Floor	B	129.6	108	1.20
Classroom 0.2	Third Floor	C	121.1	142	0.85
Classroom 0.5	Ground Floor	B	136.9	118	1.16
Classroom 0.6	Ground Floor	B	125.4	97	1.29
Classroom 0.7	Ground Floor	B	144.6	98	1.48
Classroom 1.2	First Floor	B	105.8	98	1.08
Classroom 1.3	First Floor	C	105.8	120	0.88
Classroom 1.4	First Floor	A	44.7	30	1.49
Classroom 1.5	First Floor	A	45.6	30	1.52
Classroom 2.2	Second Floor	A	49.9	42	1.19
Classroom 2.3	Second Floor	E	203.1	200	1.02
Classroom 2.4	Second Floor	E	200.5	190	1.06
Classroom 2.5	Second Floor	B	105.8	100	1.06
Classroom 2.6	Second Floor	B	101.5	98	1.04
Classroom 2.7A	Second Floor	A	79.1	48	1.65
Classroom 2.7B	Second Floor	D	162.1	145	1.12
Classroom 2.8	Second Floor	C	98.1	140	0.70
Classroom 2.9	Second Floor	D	184	150	1.23
Classroom 3.1	Third Floor	C	105.8	120	0.88
Classroom 3.4	Third Floor	B	105.7	100	1.06

Table A7. Energy results of the spaces selected for the analysis for the mentioned operational winter day. Energy demand.

Space Name	Equipment Energy (kWh)	Lighting Energy (kWh)	Heating Energy (kWh)	People Heating Energy (kWh)	Solar Radiation Energy (kWh)
Classroom 0.1	0.82	17.28	166.11	82.33	50.93
Classroom 0.2	0.91	15.84	181.2	128.94	51.62
Classroom 0.5	1.22	18.36	146.77	126.60	28.43
Classroom 0.6	0.74	17.28	142.64	69.41	8.61
Classroom 0.7	1.04	18.00	132.17	84.94	7.73
Classroom 1.2	0.53	14.40	175.37	59.60	10.17
Classroom 1.3	0.78	14.40	176.14	107.21	12.82
Classroom 1.4	0.15	5.40	80.19	12.31	4.41
Classroom 1.5	0.26	6.48	86.24	20.85	6.88
Classroom 2.2	0.28	6.00	85.23	28.56	3.98
Classroom 2.3	1.37	24.00	284.92	162.64	23.85
Classroom 2.4	1.00	24.00	283.86	114.21	22.71
Classroom 2.5	0.90	14.40	166.99	102.43	21.28
Classroom 2.6	0.56	12.00	149.11	65.61	8.62
Classroom 2.7A	0.44	11.52	129.30	32.09	9.63
Classroom 2.7B	0.60	21.60	245.20	64.95	29.73
Classroom 2.8	0.70	12.00	166.95	120.72	6.50
Classroom 2.9	1.22	24.48	251.85	119.70	22.86
Classroom 3.1	0.68	14.40	192.22	92.42	22.70
Classroom 3.4	0.84	14.40	163.21	95.35	22.25

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The Hotel Architectural Design Factors Influencing Consumer Destinations: A Case Study of Three-Star Hotels in Hua Hin, Thailand

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Abstract: This study employs a mixed-methods research design to explore the architectural design and service factors influencing consumer choices in three-star hotels in Hua Hin District, Prachuap Khiri Khan Province. Initial data were gathered through in-depth interviews with 60 architects, designers, and marketing experts to identify key factors. These factors were then used to conduct in-depth interviews with 70 Thai consumers and tourists. The qualitative data from both groups were analyzed using thematic content analysis to identify significant themes, while the quantitative data were assessed using chi-square goodness of fit tests to evaluate the significance of the identified factors. Findings indicate that aesthetic appeal, physical comfort, emotional comfort, and security and sensibility are critical in influencing hotel choice. These results provide valuable insights for hotel owners, designers, and marketers, emphasizing the importance of aligning hotel design and service offerings with consumer preferences. These factors will help create positive impressions, enhance satisfaction, and influence consumers' decisions to choose and utilize hotel services.

Keywords: hotel design; architecture; consumer destination; three-star hotel

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1. Introduction

The design of a hotel is a critical factor enabling businesses to compete effectively [1,2]. The role of architecture in shaping consumer motivation is evident as it influences tourists' behaviors and perceptions [1–3]. Effective hotel design not only enhances economic and social value but also reinforces a robust brand identity [1–3]. The consideration of materials, surface textures, and technologies enhances visitor comfort while fostering a relaxing atmosphere [3–6]. As consumer behavior profoundly impacts various business sectors, architects and designers must adapt to convey art and architectural beauty effectively to users. Recent studies highlight the growing importance of environmental design in enhancing customer satisfaction and loyalty [7,8].

Neil Morgan [9] highlighted the significance of integrating ideas from both marketing and architecture, necessitating adjustments for comprehensive design services. Diverse evaluations of architectural beauty are influenced by knowledge, background, and experience [10–13]. This underscores the challenge for architects relying on personal attitudes, making it difficult to accurately assess the needs of the general public [13–16]. Understanding consumer needs is crucial for marketers to strategically plan products and services, as aesthetics emphasizing value and positive perception significantly contribute to public satisfaction [17,18].

The outbreak of COVID-19 has significantly impacted the hospitality and tourism industry [19–21]. Even though the epidemic has subsided, COVID-19 continues to have long-term negative impacts on the hotel business [22,23]. Hotels must adapt their marketing strategies as consumer accommodation preferences have changed due to this circumstance [23,24]. Thus, researching effective hotel strategies to influence consumers' accommodation choices is essential. Recent research indicates a shift in consumer preferences towards hygiene and safety, highlighting the need for hotels to adapt [25].

While hotel design may seem like a long-term marketing strategy that influences consumer accommodation choices, academic understanding of this aspect remains surprisingly sparse. This is an interesting gap worth exploring in research. Previous studies often compare only the perspectives of architects and the general public or focus on consumer satisfaction in large hotels. However, there is limited research comparing stakeholders in the hotel industry with consumers, especially in the context of three-star hotels. Additionally, integrating the perspectives of hotel design experts, architects, and marketers working together is rarely seen in existing studies [25–28].

This is particularly pertinent given the changing consumer demands for three-star hotels, which have evolved significantly, especially post-COVID-19. A comprehensive examination of how these factors collectively influence consumer choices in this specific segment is needed. Therefore, our study aims to bridge this gap by examining the architectural design factors that transform hotels into consumer destinations. By employing primary consumer data as the foundation for analysis, we aim to obtain conclusive answers regarding their effectiveness in addressing the post-COVID-19 situation.

To achieve the objective of exploring the architectural design and service factors that influence consumer choices in three-star hotels: Expected Benefits: 1. Provide valuable insights for hotel owners, designers, and marketers, emphasizing the importance of aligning hotel design and service offerings with consumer preferences. 2. Help create positive impressions, enhance satisfaction, and influence consumers' decisions to choose and utilize hotel services. 3. Contribute to the academic literature and practical applications in the hospitality industry by bridging the gap in understanding the impact of hotel design on consumer behavior.

Thus, we pose the question: What are the characteristics of the hotel architectural design factors that influence consumer destinations from the consumer's perspective?

This document consists of five sections: Section 1 provides an introduction, offering an overview of this research study, including the background, problem statement, research objectives, importance of this study, and research questions. Section 2 discusses the literature review, covering important topics such as aesthetics, physical comfort, emotional comfort, safety, and feelings. Section 3 outlines the methodology, describing the research methods used, research planning, and the development of interview guidelines and questionnaires. It also details the sample group combination and the integration of qualitative and quantitative methods, including statistical tests. Section 4 presents the research results, highlighting the importance of various factors that influence consumer decision-making. Section 5 provides a summary and discussion of the key research findings, their implications for hotel owners, designers, and marketers, addresses this study's limitations, and offers suggestions for future research, considering geographic and demographic boundaries and other related factors.

2. Literature Review

2.1. The Characteristics of Hotels in Aesthetic Perception and Evaluation Approach

The aesthetic assessment of architectural design extends beyond the realm of the architect–designer and should encompass various professional groups, including the general public. The aesthetic appeal of the built environment holds intrinsic value and plays a significant role in overall satisfaction [26,28]. Comparative studies have examined how architects and other professionals perceive and evaluate the aesthetic aspects of a building façade, revealing differences in views on uniqueness, novelty, complexity, and the importance of design in meeting public needs [22–28]. These factors have been shown to positively influence consumers.

Previous research indicates that both architects and other experts possess a moderate understanding of the complexity of beauty [29,30]. However, only architects and designers understand higher complexity better than consumers, which does not always reflect the true needs of consumers. This discrepancy can create challenges. Architects face difficulties when evaluating perceived beauty, especially when assessments are carried out by experts from non-architectural fields and by consumers, who are the actual users of the building [27,30]. Additionally, simplicity positively affects the beauty of building façades, while excessive complexity can hinder understanding [18,28,29]. Elements of uniqueness, novelty, and originality strongly influence physical perception and overall aesthetics, particularly among individuals outside the architectural profession.

Various factors influence consumer judgment and perception, including design concept themes, beauty, style, environment, and creativity. An attractive perspective and appearance, harmony, and balance are crucial in architectural design. The materials used should correspond to existing physical properties, and complexity should be carefully managed to maximize satisfaction, as excessive simplification can lead to decreased satisfaction [26,30,31]. A deeper understanding of aesthetic perception and building evaluation highlights the multifaceted nature of architectural aesthetics and underscores the importance of considering diverse perspectives, including those of non-architects and experts from other fields, to create designs that resonate with a wide audience.

2.2. The Characteristics of Hotels in Physical Comfort Approach

Understanding Perspectives of Architects, Experts, and Consumers on Urban Design. Research by Llinares and colleagues [31,32] highlights the differences in perspectives between architects, other experts, and consumers, extending beyond building styles into urban design awareness. This research provides valuable insights into physical features, space, size, shape, and emotional impressions that significantly influence spatial decision-making.

Both architects and other experts, including consumers, share similar perceptions of colors. Emotional factors influencing space selection result in similar opinions when choosing living spaces. However, differences arise in investment decisions, where appearance, elegance, and value hold varying degrees of importance. Variability in perception of space, beauty, width, and landscape significantly affects both groups, highlighting the importance of physical aspects in the decision-making process. Studies by Devlin and Nasar and Gibson et al. suggest that there are no significant differences in urban district selection between architects, other professionals, and consumers [33–35]. Despite minor differences, their basic personality traits and emotional factors remain similar. However, the analysis of the physical environment and space within city management aims to improve overall appearance, with nature significantly affecting consumer stimulus [36,37].

Beyond buildings, the perception of the overall physical environment serves as an important motivator, representing satisfaction and aesthetic evaluation. This factor differs greatly between architects and other professions [11,38]. Aesthetics and physical comfort profoundly influence perception, interpreting physical and emotional interference, and playing a crucial role in understanding and evaluating creative design insights [39]. Interpreting physical structures is essential for the systematic analysis, development, and understanding of design perspectives [40]. Architects and other professionals differ in their understanding and knowledge of the design process, contributing to varied perspectives that are communicated as stimuli to the consumer [41]. Architects use a systematic scanning method of gaze, while other professionals exhibit fragmented, emphatic, and irregular gazes [40,41]. These different approaches have important implications for stimulus judgment.

Architects and experts in other fields, including consumers, have different approaches to perception and analysis. Architects often require less time and fewer revisions, indicating differences in views and priorities [42,43]. Architects' opinions often differ from those of other experts and consumers due to the challenges of anticipating architectural assessments or understanding the needs and perceptions of individuals from other fields. The tendency among architects to support their ideas and consider them superior is evident, with differences in aesthetics and physicality between architects and other professions highlighted in various studies [11,14].

Some architects may struggle to anticipate the needs and perceptions of other professions, but a subset shows the ability to predict those needs. This ability often comes from sharing experiences with other professions or a deep understanding of consumer behavior, allowing architects to align their views with those of the general public [44,45]. The inherent differences in perception and prediction are rooted in architects' limited exposure to other professions, lack of thorough study of diverse behaviors, and insufficient mutual awareness and sharing among professional fields [45]. To effectively bridge this gap, architects must increase their understanding of other professions, study their behavior closely, promote mutual awareness, and remain open to new perspectives. Differences in physical perception, aesthetics, and perspectives between architects and marketers contribute to different attitudes and perceptions [45–48]. This recognition emphasizes the importance of promoting cooperation and cross-understanding across professional boundaries to achieve a more cohesive and inclusive approach to design and marketing.

2.3. The Characteristics of Hotels in Emotional Comfort, Safety, and Security: Influencing Consumer Perceptions

In contemporary society, emotional comfort emerges as a significant determinant in decision-making processes [49]. This influence stems from meticulously crafted designs that establish profound emotional bonds between individuals and their physical environments. Thoughtfully designed spaces seamlessly integrate into one's identity, offering both sanctuary and support for mental well-being [50]. The significance of security and exclusivity within these spaces cannot be overstated, as individuals actively seek reassurance and solitude [51]. Factors such as color, lighting, and aesthetic style assume pivotal roles in shaping perceptions and fostering comfort, particularly within settings like hotel lobbies [52]. Emotional comfort encompasses various elements, including a sense of place, security, lighting, and visual aesthetics, all contributing to an individual's overall impressions and experiences. Features like warmth and tranquility further elevate feelings of comfort and trust, ultimately enhancing the allure of hotels.

The correlation between captured images and stimuli in virtual reality significantly influences the creation of virtual spaces. Achieving a necessary level of presence is crucial for enhancing the persuasive efficacy of virtual reality [52–54]. Tussyadiah has underscored the role of mixed augmented reality and virtual reality in enhancing the appeal of hotels on social media. The utilization, necessities, and engagement in the realism of virtual reality profoundly shape consumer perceptions. A positive inclination towards virtual tourism enhances the immersive experience, consequently increasing intentions to visit [55,56].

Despite their importance, some emotional factors are often overlooked, such as good service, calmness, warmth, impressiveness, and friendliness. According to David Uzzell [57], usability, hedonic benefits, emotional benefits, social benefits, and attitudes influence behavioral intention. Attachment to virtual reality and cognitive and affective responses play pivotal roles in influencing visit intention. Perceived immersion, interest, perceived enjoyment, and perceived usefulness significantly affect the intention to use virtual reality for travel planning [56]. In essence, the emotional comfort approach not only shapes decision-making but also highlights the intricate relationship between design, emotional well-being, and the immersive potential of virtual experiences.

The safety and security approach plays a crucial role in shaping consumer perceptions, particularly concerning emotional comfort and mental well-being. This approach involves spatial utilization to promote a sense of security, utilizing shapes, colors, and materials strategically to evoke feelings of safety, especially in matters of cleanliness [58,59].

Colkaba's theory defines comfort as a positive outcome across physical, spiritual, social, emotional, and environmental dimensions. It is an immediate state of being strengthened, categorized into relief, comfort, and transcendence. The transcendence, linked to performance, encourages health-seeking behaviors, emphasizing the importance of a conducive physical environment [60].

Maslow's hierarchy of needs positions safety needs, including the need to feel secure, as paramount after physiological needs. In today's context, personal space and privacy are vital for overall well-being and communal quality of life [61]. The intertwining of privacy and security involves controlling the physical environment, allowing organization and customization of space [62]. Personalization often occurs in the presence of physical or psychological barriers, fostering isolation or protection against intrusion in homes, workspaces, or rest areas.

A stable location with ample space and proper placement significantly contributes to safety [63], and the emotional bond between an individual and a suitable object or environment can be integrated into one's identity [49]. Effective allocation of space is not only imperative for safety but also plays a significant social role, as it fosters a sense of security through controlled access [50]. Ultimately, the safety of the physical environment profoundly influences emotional comfort, mental well-being, and the fundamental need for security, thereby establishing a reassuring space for individuals.

In light of the ongoing repercussions of the COVID-19 pandemic, hotels, despite their certifications, must prioritize instilling a sense of security in the minds of their customers. It is imperative to utilize spaces that evoke feelings of safety, employing secure shapes, colors, and materials, particularly in matters concerning hygiene [64,65]. Consistent with Maslow's hierarchy of needs, addressing safety needs encompasses providing personal space and privacy, which are essential for individual and community well-being, improving quality of life, and addressing the intertwined concepts of privacy and security [66,67].

Control over one's physical environment allows individuals to organize and personalize spaces, reflecting the essence of privacy and security [25,68]. This personalization may persist despite barriers, aiming to safeguard against intrusion, notably in domestic and professional settings [69,70]. A stable environment with adequate space inherently fosters security [71,72], becoming ingrained in an individual's identity and establishing an absolute sense of security through control over space by individuals or groups [72,73].

2.4. Sensitivity of Mind Approach: Influencing Consumer Emotions and Decision-Making

Creating stimuli aligned with preferences significantly influences consumers' emotions and decision-making processes. Beck and Egger emphasized that integrating technology into virtual reality enhances interactivity, providing users with a compelling sense of presence and extending their imaginative experiences, consequently leading to increased intentions to visit [74]. Additionally, Tussyadiah et al. explored the concept of experiential value, which pertains to the subjective feelings a customer experiences during the consumption process. Such experiences contribute substantially to heightened levels of satisfaction and provide enterprises with a competitive advantage [54].

Consumer behaviors before purchasing are influenced by emotional and psychological perceptions, with a hotel's image playing a crucial role [75–77]. Zeithaml asserted that consumers assess products and services with emotions and satisfaction before making purchase decisions [78]. Aaker shed light on the interconnectedness of perception and consumer experiences, which ultimately lead to consumer satisfaction [79–81].

While price certainly influences purchasing decisions, consumers often prioritize elements that provide greater satisfaction, such as exemplary service [82]. Confidence and trust are pivotal in shaping consumers' psychological perceptions [83], highlighting the importance for hotels to demonstrate sincerity in establishing trustworthiness and fostering strong relationships while delivering services [84].

Leveraging trust to cultivate awareness and solidify relationships significantly influences and creates substantial value for hotels [78,84]. underscored the significance of perceived value by consumers, which involves a trade-off among benefits. Psychological value is shaped by experiential factors and evaluated based on functional benefits such as service quality, perceived value for money, time efficiency, satisfaction, impression, and attractiveness [85]. Despite individual variations, the inherent value of a hotel remains consistently perceived by consumers.

3. Methodology

This study employed a mixed-methods research design, combining qualitative and quantitative approaches to investigate the architectural design and service factors influencing consumer choices in three-star hotels in Hua Hin District, Prachuap Khiri Khan Province. This comprehensive approach enabled the collection of rich, detailed data and the validation of findings through multiple data sources and methods. Mixed-methods research is widely recognized for its robustness in providing comprehensive insights and validating findings through triangulation [86,87].

3.1. Data Sources

3.1.1. Professional Group

The professional group comprised 60 participants, including architects and designers. These professionals provided comprehensive insights from theoretical, practical, and experiential perspectives. The data obtained from this group served as a foundation for classifying words to identify design rule conditions and contributed to the identification of the most current design and marketing management factors. The use of expert interviews in qualitative research is a well-established method for gathering in-depth knowledge from specialists in the field [88].

3.1.2. Consumer Group

The consumer group consisted of 70 Thai consumers and tourists who had stayed in three-star hotels in Thailand within the past six months. Participants were aged between 21 and 59 years, representing a demographic with the potential and means to travel, make independent decisions regarding hotel stays, and have the willingness to spend. This study focused on gathering insights from this group to compile research findings due to the importance of consumer opinions in hotel design. Consumer interviews are crucial in understanding preferences and behaviors, often used in hospitality research [89].

3.2. Data Collection

3.2.1. In-Depth Interviews with Professionals

Open-ended questions were used to allow the professional group to fully express their opinions without interference during the conversation. This qualitative approach ensured a comprehensive understanding of the factors from an expert perspective. The steps included the following:

- Interview preparation: Develop a semi-structured interview guide with open-ended questions to explore key topics. The use of semi-structured interviews helps in capturing detailed and nuanced responses while allowing flexibility to explore new insights that emerge during the conversation [90].
- Conducting interviews: engage participants in face-to-face or virtual interviews, allowing them to elaborate on their experiences and insights.
- Recording and transcription: record the interviews (with consent) and transcribe them for detailed analysis.

3.2.2. Open-Ended Questions with the Consumer Group

Open-ended questions were also used for the consumer group to gather genuine consumer opinions. The main question posed to participants was, "What factors influence your decision when choosing a hotel?" Participants were encouraged to freely explain details without interruption. Key answers and keywords were saved and categorized for later analysis. The use of open-ended questions allows for broad exploration of consumer experiences and preferences, which is crucial for understanding complex decision-making processes [91].

3.2.3. Developing a Questionnaire for Consumer Groups

Factors repeatedly mentioned and summarized from the professional group were used to create a structured questionnaire for the consumer group, utilizing semi-structured open-ended questions to maintain consistency and depth.

- Draft development: a draft questionnaire was developed to collect relevant information.
- Reliability testing: The reliability of the questionnaire was tested through preliminary interviews with 15 experts, including architects, owners, and marketers. This iterative process was repeated three times until consistent responses were obtained, ensuring the reliability and validity of the questions.
- Revisions: based on feedback, the questionnaire was revised to enhance clarity, reliability, and alignment with the research objectives.

The iterative process of developing and refining questionnaires ensures data quality and is a standard practice in survey research [92,93]. Utilizing semi-structured open-ended questions in developing the questionnaire aligns with methods used in previous studies to ensure comprehensive data collection and respondent engagement [94,95].

Pilot test: the questionnaire was tested with a real sample group to ensure its effectiveness and reliability.

Collection of Main Data

- Open-ended questions: Gathered genuine consumer opinions using open-ended questions. The main question posed to participants was, "What factors influence your decision when choosing a hotel?"
- Encouragement to explain: participants were encouraged to freely explain details without interruption.
- Categorization: key answers and keywords were saved and categorized for later analysis.

Data collection was conducted in January 2024. All interviews were recorded, and notes were taken during the sessions. This study did not require ethics approval as it did not involve personal data. All collected data were anonymized and securely stored, accessible only to the researchers.

3.3. Data Analysis

The collected data were analyzed using both content analysis and quantitative methods:

- Content analysis: Thematic analysis was conducted to identify and categorize key factors mentioned by participants. Keywords and phrases from the open-ended responses were grouped according to relevant themes. This method is widely used in qualitative research to derive patterns and themes from textual data [96].
- Quantitative analysis (chi-square goodness of fit test):
- Objective: to determine if there were significant differences in the distribution of mentions for various factors.
- Procedure:
    - Coding: convert qualitative data into quantitative data by coding responses into categories based on themes identified during content analysis.
    - Expected frequencies: calculate the expected frequency for each category under the assumption of equal distribution.
    - Chi-square calculation: use the formula

$$x_c^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

    where O_i is the observed frequency for category $_i$ and E_i is the expected frequency for category ($_i$).

- Degrees of freedom: calculate the degrees of freedom (df) as the number of categories minus one.
- Comparison with critical value: Compare the calculated chi-square value with the critical value from the chi-square distribution table at a specified significance level (e.g., 0.05). If the calculated value is greater than the critical value, reject the null hypothesis of equal distribution.

The use of chi-square goodness of fit tests is a common statistical method for examining the distribution of categorical data and has been effectively applied in various research contexts. Combining qualitative data collection methods with quantitative analysis provides a robust framework for understanding complex phenomena, as evidenced by numerous studies in the hospitality and social sciences [86,87,93,97–99].

4. Results

4.1. Aesthetics Perspectives

Chi-square goodness of fit test results for Group 1: aesthetic
Hypotheses:

Null Hypothesis: *The proportions of mentions of each factor in the aesthetic group are equal.*

Alternative Hypothesis: *The proportions of mentions of each factor in the aesthetic group are not equal.*

The degrees of freedom (df) for this test is 8, and the critical value at the 0.05 significance level is 15.507. Since the calculated chi-square value is 10.16, which is less than the critical value, the null hypothesis of equal proportions cannot be rejected. This indicates that there is no significant difference in the proportions of mentions of each factor in the aesthetic group, suggesting that the mentions are uniformly distributed.

The chi-square goodness of fit test results suggest that the distribution of mentions for factors in the aesthetic group is uniform, meaning no single factor is disproportionately mentioned more than the others. This indicates that respondents equally value all factors in this group. Among the factors, "Beautiful" was the only factor that showed a significant difference from the expected frequency, indicating that it might be valued differently compared to others as shown in Table 1.

Table 1. Shows the chi-square goodness of fit test results for aesthetic factors.

Grroup 1: Aesthetic Group				
Factor	**Observed Frequency (O)**	**Expected Frequency (E)**	**$(O-E)^2/E$**	**Test Result**
Design Concept Theme	55	47.56	1.17	Not Significant
Harmony	41	47.56	0.91	Not Significant
Balance	40	47.56	1.2	Not Significant
Space	39	47.56	1.54	Not Significant
Style	53	47.56	0.63	Not Significant
Beautiful	61	47.56	3.92	Significant
Creativity	47	47.56	0.01	Not Significant
Environment	50	47.56	0.13	Not Significant
Perspective & Visual	42	47.56	0.65	Not Significant

4.2. Physical Comfort Perspectives

Hypotheses:

Null Hypothesis: *The proportions of mentions of each factor in the physical comfort group are equal.*

Alternative Hypothesis: *The proportions of mentions of each factor in the physical comfort group are not equal.*

The degrees of freedom (df) for this test is 10, and the critical value at the 0.05 significance level is 18.307. Since the calculated chi-square value is 15.56, which is less than the critical value, the null hypothesis of equal proportions cannot be rejected. This indicates that there is no significant difference in the proportions of mentions of each factor in the physical comfort group, suggesting that the mentions are uniformly distributed.

The chi-square goodness of fit test results suggest that the distribution of mentions for factors in the physical comfort group is uniform, meaning no single factor is disproportionately mentioned more than the others. This indicates that respondents equally value all factors in this group. Among the factors, "Function", "Shape", and "Comfortable" were the only factors that showed significant differences from the expected frequency, indicating that they might be valued differently compared to others as shown in Table 2.

Table 2. Shows the chi-square goodness of fit test results for physical comfort as factors.

Group 2: Physical Comfort Group				
Factor	**Observed Frequency (O)**	**Expected Frequency (E)**	$(\mathbf{O}-\mathbf{E})^2/\mathbf{E}$	**Test Result**
Function	60	47.56	3.19	Significant
Shape	35	47.56	3.38	Significant
Proportion & Mass	48	47.56	0	Not Significant
Texture & Material	49	47.56	0.05	Not Significant
Human Scale	38	47.56	1.92	Not Significant
Durability	43	47.56	0.44	Not Significant
Color	50	47.56	0.13	Not Significant
Furniture	45	47.56	0.14	Not Significant
Comfortable	60	47.56	3.19	Significant
Facilities	38	47.56	1.92	Not Significant
Circulation	40	47.56	1.2	Not Significant
Total	466	523.16	15.56	Not Significant

4.3. Emotional Comfort Perspectives

Hypotheses:

Null Hypothesis: *The proportions of mentions of each factor in the emotional comfort group are equal.*

Alternative Hypothesis: *The proportions of mentions of each factor in the emotional comfort group are not equal.*

The degrees of freedom (df) for this test is 10, and the critical value at the 0.05 significance level is 18.307. Since the calculated chi-square value is 16.55, which is less than the critical value, the null hypothesis of equal proportions cannot be rejected. This indicates that there is no significant difference in the proportions of mentions of each factor in the emotional comfort group, suggesting that the mentions are uniformly distributed.

The chi-square goodness of fit test results suggest that the distribution of mentions for factors in the emotional comfort group is uniform, meaning no single factor is disproportionately mentioned more than the others. This indicates that respondents equally value all factors in this group. Among the factors, "Sense of Place", "Service", and "Social" were the only factors that showed significant differences from the expected frequency, indicating that they might be valued differently compared to others as shown in Table 3.

Table 3. Shows the chi-square goodness of fit test results for emotional comfort as factors.

Group 3: Emotional Comfort Group				
Factor	**Observed Frequency (O)**	**Expected Frequency (E)**	**$(O-E)^2/E$**	**Test Result**
Sense of Place	52	40.45	3.26	Significant
Location	35	40.45	0.73	Not Significant
Feeling	38	40.45	0.15	Not Significant
Relationships & Ties	33	40.45	1.38	Not Significant
Natural Touch	47	40.45	1.07	Not Significant
Relax	42	40.45	0.06	Not Significant
Warmth	37	40.45	0.29	Not Significant
Peaceful	40	40.45	0.01	Not Significant
Service	55	40.45	5.3	Significant
Social	28	40.45	3.79	Significant
Friendly	45	40.45	0.51	Not Significant
Total	452	445	16.55	Not Significant

4.4. Security and Sensibility of Mind Perspectives

Hypotheses:

Null Hypothesis: *The proportions of mentions of each factor in the security and Sensibility group are equal.*

Alternative Hypothesis: *The proportions of mentions of each factor in the security and sensibility group are not equal.*

The degrees of freedom (df) for this test is 17, and the critical value at the 0.05 significance level is 27.587. Since the calculated chi-square value is 21.70, which is less than the critical value, the null hypothesis of equal proportions cannot be rejected. This indicates that there is no significant difference in the proportions of mentions of each factor in the security and sensibility group, suggesting that the mentions are uniformly distributed.

The chi-square goodness of fit test results suggest that the distribution of mentions for factors in the security and sensibility group is uniform, meaning no single factor is disproportionately mentioned more than the others. This indicates that respondents equally value all factors in this group. Among the factors, "Safety", "Quality", and "Cleanliness" were the only factors that showed significant differences from the expected frequency, indicating that they might be valued differently compared to others as shown in Table 4.

Table 4. Shows the chi-square goodness of fit test results for security and sensibility as factors.

Group 4: The Security and Sensibility Group				
Factor	**Observed Frequency (O)**	**Expected Frequency (E)**	**$(O - E)^2/E$**	**Test Result**
Safety	50	39.56	2.75	Significant
Security	35	39.56	0.53	Not Significant
Risk	30	39.56	2.31	Significant
Satisfaction	48	39.56	1.79	Significant
Loyalty	45	39.56	0.75	Not Significant
Communication	33	39.56	1.09	Not Significant
Legal Requirements	36	39.56	0.32	Not Significant
Modernity	38	39.56	0.06	Not Significant
Innovation	47	39.56	1.4	Significant
Sustainability	32	39.56	1.44	Not Significant
Value/Equality	39	39.56	0.01	Not Significant
Quality	55	39.56	6.05	Significant
Efficiency	40	39.56	0	Not Significant
Expectations	42	39.56	0.15	Not Significant
Convenient	38	39.56	0.06	Not Significant
Cleanliness	47	39.56	1.4	Significant
Room Comfort	45	39.56	0.75	Not Significant
Remember	32	39.56	1.44	Not Significant
Total	724	711.08	21.7	Not Significant

5. Conclusions and Discussion

The characteristics of hotel architectural design factors that influence consumer destinations from the consumer's perspective include aesthetic appeal (beauty), physical comfort (functionality and comfort), emotional comfort (sense of place and social environment), and security and sensibility (safety, quality, and cleanliness). These factors collectively shape the overall guest experience and significantly impact consumer choices.

The discussion of the findings of this research aligns with the existing literature, emphasizing the importance of aesthetic appeal, physical comfort, emotional comfort, and security in influencing hotel guest satisfaction. For instance, Jiang and Kim (2020) highlighted the significant impact of aesthetic factors on guest satisfaction, which supports our finding that "beautiful" is particularly valued [96–100]. Similarly, Zhang and Leung (2019) underscored the importance of functional and comfortable room designs, aligning with our results indicating the significance of "Function", "Shape", and "Comfortable" [101]. Wu and Yang (2021) also emphasized the role of service quality and emotional comfort, which corresponds with the significance of "Sense of Place", "Service", and "Social" in our study [102]. Additionally, Lee and Kim (2020) and Shin and Park (2022) stressed the importance of safety, quality, and cleanliness, consistent with our findings that these factors are crucial in the security and sensibility group [101–104].

This conclusion shows the architectural and service design factors that influence consumer choice in three-star hotels in Hua Hin District, Prachuap Khiri Khan Province. Using a mixed-methods approach, it gathered qualitative data from open-ended surveys and quantitative analysis through the chi-square goodness of fit test, collected from 70 respondents. This study identified four key groups of factors: aesthetics, physical comfort, emotional comfort, and safety and feelings. Aesthetics emerged as a highly valued factor, indicating the importance of visual appeal in guest satisfaction. Physical comfort included key elements such as function, form, and comfort, highlighting the necessity for designing rooms that are both practical and comfortable to meet guest expectations. Emotional comfort was driven by factors like sense of place, service, and social environment, emphasizing the need for a welcoming atmosphere and high-quality service to enhance guest satisfaction. Safety and feelings encompassed safety, quality, and cleanliness, reflecting the critical role these aspects play in influencing consumer decision-making.

These results suggest that stakeholders in the hotel industry, including owners, designers, and marketers, should prioritize these identified factors to develop and improve three-star hotels in line with consumer preferences. Enhancing these areas can lead to higher guest satisfaction and competitiveness, providing valuable insights for practical applications in hotel management and design.

This research identified several limitations and future directions. Despite focusing on four main groups—aesthetic, physical comfort, emotional comfort, and security and sensibility—this study may have overlooked other potentially important factors. Literature reviews suggest that factors such as technological integration, environmental sustainability, and personalized services could also play significant roles in influencing consumer choices. Future research should consider including these factors to provide a more comprehensive understanding.

In terms of geographical and demographic scope, this research was limited to consumers with experience staying in three-star hotels in Hua Hin, Prachuap Khiri Khan, Thailand. The specific cultural and regional context might have influenced the findings. To achieve more generalizable results, future studies should expand to different geographic locations and include a broader demographic of consumers to understand varying preferences and behaviors across different regions and hotel categories.

The results of this study, while indicative, have certain limitations. The uniform distribution of mentions within each group suggests a balanced importance of the factors, but further studies are needed to test these findings in different contexts. Researchers should replicate this study in various settings, such as luxury hotels or budget accommodations, and consider integrating additional factors such as technological advancements and sustainability to validate and extend the findings. The primary aim of this research was to fill the gap identified in previous studies by exploring the architectural design and service factors that influence consumer choices in three-star hotels. This study found that aesthetic appeal, physical comfort, emotional comfort, and security and sensibility are crucial factors for guests. This aligns with the existing literature, which emphasizes the importance of these elements in enhancing guest satisfaction [99–101,103,104].

The characteristics of the hotel architectural design factors that influence consumer destinations from the consumer's perspective were addressed by identifying key factors in each of the four groups. The findings suggest that stakeholders in the hotel industry, including owners, designers, and marketers, should be aware of these identified factors to develop and improve three-star hotels in line with consumer preferences. By prioritizing aesthetic appeal, functionality, emotional comfort, and security, hotels can better meet the needs and preferences of their guests, ultimately leading to higher levels of satisfaction and loyalty.

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sustainability

Systematic Review

Transboundary Fisheries Management in Kavango–Zambezi Transfrontier Conservation Area (KAZA-TFCA): Prospects and Dilemmas

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Abstract: Inland fisheries in the Kavango–Zambezi Transfrontier Conservation Area (KAZA-TFCA) offer food security to the riverine communities across the region. They also contribute towards the attainment of the United Nations' Sustainable Development Goals 1 and 15, which aim to alleviate poverty and maintain biodiversity conservation. Despite this significant role, the fisheries have suffered severe declines in the previous decades due to multiple factors, such as overfishing and poor legislation. Furthermore, climate change is exerting pressure by altering the ecology and productivity of the river systems. The unprecedented challenges of the COVID-19 pandemic have further constrained management efforts. Attempts to address these challenges have pointed towards transboundary fisheries management as a silver bullet in moving towards sustainable fisheries management. However, the implementation of this strategy in the region has encountered numerous roadblocks, thereby subjecting the river ecosystem to a wider environmental threat, with dire consequences on livelihoods. This paper reviews existing management and governance structures together with key informant interviews to elicit primary and secondary data essential for management at the regional level. The study identifies conflicting regulations, and inadequate policies and institutions across the region as major bottlenecks affecting the successful implementation of transboundary fisheries management. Finally, the paper offers some suggestions for the improvement of fisheries management in the region.

Keywords: governance; inland fisheries; transboundary; Kavango–Zambezi; CCRF

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1. Introduction

Inland fisheries in the KAZA-TFCA play a multifaceted role in providing food security, employment opportunities, and a cheap source of protein [1–3]. However, over the last half-century, there have been considerable reports of fish decline and shifts in fish species composition from inland water sources [4,5]. Studies suggest that the biodiversity crisis is more severe today in inland ecosystems than terrestrial ones, partly due to overfishing, weak institutions, and habitat degradation [5]. These combined and synergistic effects have negatively affected the abundance and range of inland fisheries [6–8]. Furthermore, given the acknowledged acceleration of climate change, weather patterns are expected to be more variable and unpredictable, thereby creating stochastic changes that will alter the ecology and ecosystem processes of river systems [9–11]. KAZA-TFCA exemplifies this sustainable challenge [12]. The area is drained by the palaeo-evolutionary linked Kavango and Zambezi River systems, which cover five countries, namely Angola, Botswana, Namibia, Zambia, and Zimbabwe (Figure 1). Hackenberg et al. [12] notes that the changes in flood patterns over the Zambezi River basin imply that the natural characteristics of these aquatic resources are constantly changing with regards to functional responses of fishes, such as distribution and migration patterns. In addition to these problems, the COVID-19 pandemic has constrained management efforts of various countries to engage in timely fisheries management programs [13]. Aquaculture has been widely identified as a possible intervention to resuscitate inland fisheries in the region [14]. However, the prospects of the aquaculture sector are threatened by several factors, such as deterioration of pure brood stock due to the introduction of invasive fish species, such as *Oreochromis niloticus*, which has the capability to distort native *Oreochromis* fish species through hybridization and predation. Other invasive fish species, such as crayfish (*Cherax quadricarinatus*), may be risk factors (vectors) for the transfer of fish diseases and parasites [15]. Several studies have revealed that most of the fisheries in the KAZA-TFCA have experienced severe declines in fish catch rates [16–18]. The KAZA-TFCA is a regional and international collaborative initiative to effectively manage natural resources, such as wildlife, fisheries and forestry, that straddle across boundaries in line with the Southern Africa Development Community (SADC) protocol of 2001 [19]. Fish decline in this region is a serious concern among different actors along the agri-fisheries value chain [20,21]. For nearly over a decade now, transboundary fisheries management efforts have attempted to scale up conservation to a larger scale [22–24]. However, these efforts have encountered numerous roadblocks, and fish decline and illegal fishing practices are still widely reported [8,17,25,26]. As the population increases and exerts pressure on the entire Kavango–Zambezi River system, the need to have a viable transboundary fisheries management regime is crucial [27,28].

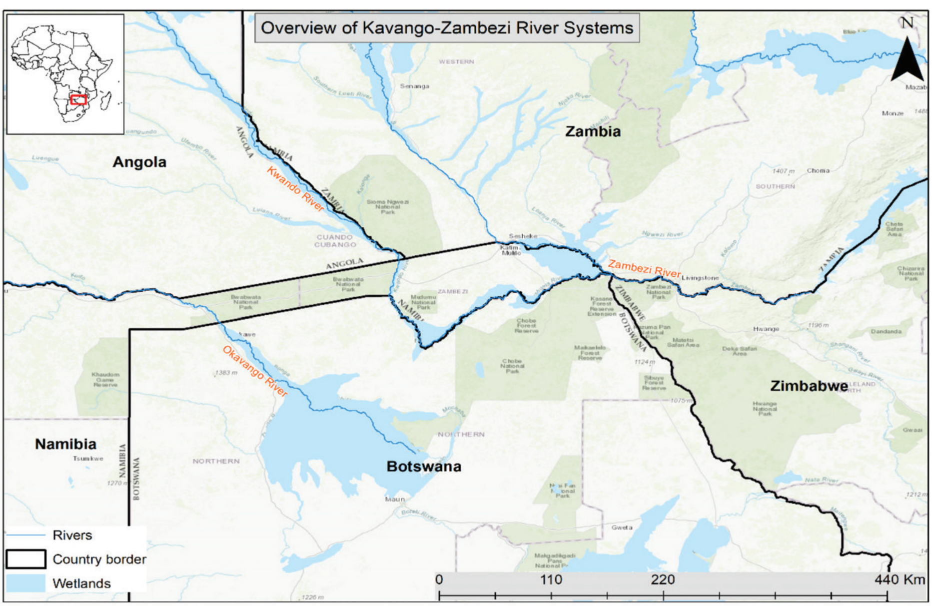

Figure 1. Map showing Kavango–Zambezi River system and member countries in the KAZA-TFCA. Source: adopted and modified from Linell [28].

In 2006, several stakeholders, such as Peace Parks, Southern Africa Development Community (SADC), and political actors, such as Nelson Mandela, initiated the idea of a transboundary natural resources management in the world's largest transfrontier conservation area, the KAZA-TFCA [23,28]. It created an enabling environment in which communities of resource users, especially fisheries, could be empowered to participate in the "planning, management, and development of resources through their relevant institutions" [28,29]. This was expected to foster socio-economic development and sustainable resource use [28]. Although the literature cites successful cases of transboundary natural resources management through collective action responsibilities, the concept may be constrained by incompatible regulations and policies between member countries [29–31]. This assertion calls for a standard methodological strategy in prescribing a conservation plan across the region [32]. This is not an easy task in a social-ecological system characterized by diverse layers of governance [30–32]. It is worthy to note that while management requires implementation at a local level, initiatives made at the national and regional level are critical to link both local and international requirements [33].

The review is based mainly on the cited literature, through examining diverse resource management practices, and our active participation in regional fisheries technical consultation meetings in the region. The focus is on reviewing the governance and management of inland fisheries in the KAZA-TFCA and how it affects the utilization of fisheries resources for food security and biodiversity conservation. The study will provide a window of opportunity to set out management options that can inform conservation practices and policy reforms across the African landscape. It is against this background that this paper seeks to: (i) review the governance and management of fisheries in the KAZA-TFCA in the context of the mentioned socio-political and economic contexts; (ii) examine challenges affecting the implementation of transboundary fisheries management in the region; and (iii) outline possible interventions to optimize the utilization of the fisheries for food security and biodiversity sustainability.

2. Methodology

Study Area

KAZA-TFCA has one of the largest thriving transboundary fisheries in Africa and holds 85 forest reserves, 11 sanctuaries, 20 national parks, and 103 wildlife management areas [19]. The primary objective was to foster transboundary collaboration in implementing ecosystems and natural resource management in the region that straddles across boundaries [19,23]. Fisheries in KAZA-TFCA are among the most important economic activity for the five partner countries.

The starting point was an electronic search on the FAO country profiles website (http://www.fao.org/countryprofiles/en/) (accessed on 14 June 2021). Two methods of accessing data relevant to the topic of study in the KAZA region included: (i) FAO country profiles; (ii) internet searches using the country name; and (iii) specific keywords related to the management and governance of inland fisheries in the KAZA-TFCA. Each country's profile was downloaded, and the heading on fisheries' constraints and institutional frameworks was used to extract the titles of relevant information. An Internet web search was used to search for information that could not be accessed in the FAO country profile through the references listed within the identified literature. Titles were copied and pasted into a Google Scholar search, the outcome of which provided an array of related literature on the topic of study [34]. The study further used proceedings from the regional stakeholder workshop conducted in 2018 in Namibia to better understand fisheries' management practices at national and regional levels. Key informant interviews were held along the sidelines of the regional stakeholder's workshop. The selection of key informants followed a purposive random sampling technique. The technique is useful for generalizations, since it was not feasible to interview all the participants [34].

A total number of 10 key informants were identified, based on the list of participants obtained from the KAZA secretariat (n = 10). Five (5) of these participants were representative (fisheries officials) from each participating country, three (3) participants were drawn from each participating stakeholder, namely the Namibian Nature Foundation, the World Wide Fund (WWF), and the KAZA secretariat. Two (2) participants were members of participating fisher community conservancies from Namibia and Zambia (Situnga and Simalaha conservancies, respectively). The idea was to verify the accuracy of secondary data sources [35]. The interview questions were based on success, opportunities, and challenges of transboundary fisheries management in the region. This information was used for analytical work. Finally, our experience and knowledge on the fisheries of the area as researchers and work experience for many years from 2000 up to date as fisheries officers in the area was utilized. The experience helped to broaden the understanding of challenges and success stories of managing transboundary fisheries' resources over time, especially issues related to power relations.

The United Nations's Food and Agriculture Organization Code of Conduct for Responsible Fisheries was employed (FAO, CCRF) as a conceptual framework together with related technical guidelines, such as the precautionary approach. The CCRF recommendation is based on science and experience, it promotes collaboration arrangements among member countries and sharing resources that straddle across boundaries. It's tenets support community participation in the management of resources; it is generally acknowledged as an ideal way of fostering effective governance [36,37]. Furthermore, CCRF provides guidance on policy formulation, which is often a missing link in the operationalization of fisheries activities in most of the developing countries [36].

3. The Rationale behind Transboundary Fisheries Management in the KAZA-TFCA

Transboundary fisheries management in the KAZA-TFCA was coined within the context of Southern Africa Development Community (SADC) regional integration and collaboration management of shared resources as a key to the sustainable utilization of natural resources [21]. The term 'transboundary' is defined in the context of international collaboration [31,37] and refers to the development of co-operation across boundaries to enhance the efficiency of achieving objectives of natural resource use and conservation [38,39]. Griffin [37] defined it in a similar way, but he added that transboundary management should benefit the parties involved in the initiative. Social-ecological systems are interconnected in temporal and spatial terms, where the extent of organization and decisions made in a particular place affects the environment and people elsewhere [38]. Consequently, the concept of 'bioregionalism' recognizes that ecosystems do not overlap with political boundaries [37]. As well as the global recognition to promote collaborative arrangements in the management of shared inland fisheries, most threatened inland fishes require distinct habitats for growth, feeding, refuge, and reproduction as such migration institutes an inherent characteristic in their life cycle [39,40]. Therefore, political boundaries must not limit conservation at a larger scale. The idea is to sustain biological and socio-economic gains from aquatic resources that straddle several countries to reduce habitat fragmentation [27,28]. Evidence of increased fishing pressure on inland fisheries shared by various countries has been widely reported [5,17], suggesting that fisheries' conservation efforts can no longer be implemented in isolation. Therefore, the transboundary management approach to aquatic resource is necessary for responsible fisheries.

4. Conceptualizing Transboundary Fisheries Management in KAZA-TFCA

The Kavango–Zambezi River system and its network of tributaries is among Southern Africa's most important natural resources [28]. Governance and management approaches for inland fisheries in the KAZA-TFCA is examined to contextualize constraints regarding the implementation of transboundary fisheries management. This information is then used to prescribe potential interventions for transboundary fisheries management in the KAZA-TFCA. According to the FAO Code of Conduct for responsible fisheries, the overall goal of fisheries management is based on sustainable resource utilization [41]. This implies: (i) maintaining the fish stock at the level required to ensure their continuous productivity; (ii) profit maximization of the resource user (fisher); and (iii) optimum employment opportunities for fisher-dependent communities [41]. The simultaneous optimizing of these objectives is rarely achieved [42]. For instance, the maximum exploitation of fisheries for employment opportunities means intensifying fish exploitation, which may abrogate the FAO Code of Conduct on conservation objectives [43]. As a result, identifying a suitable management approach in a shared social and ecological system can be complex due to diverse regulations and conflicting policies among member countries [28]. These regulations are fundamental for the successful management and development of fisheries [26]. While transboundary fisheries management has been widely accepted, it is moderately practiced, based on a classical fisheries management approach, such as fishing ban seasons, gear and mesh size restrictions, among other tools [44,45]. Classical fisheries management in Africa is partly based on ideas drawn from Hardin's Tragedy of the Commons model; the basic assumption towards natural resource management has been to privatize the common resources [46]. Subsequently, Pauly [45] introduced the idea of a quota system as an option to privatization of the commons, essentially to incorporate some form of ethics in management regimes [45].

Apparently, classical management approaches in tropical fisheries are subject to debate on whether anthropogenic activities (artisanal fisheries) have a huge impact on the fish productivity [25,46]. Several researchers [14,25,46] argue that in tropical fisheries, the correlation between human activities and the level of the future fish stock has no considerable impact; it is characterized by uncertainties, where placing a maximum level of fishing effort may not lead to a fixed state of fishing mortality [43]. Thus, fish stock abundance and distribution are largely influenced by environmental parameters, such as river flows that are seasonally driven by the amount of precipitation received in the catchment [43]. Several studies [5,25,45] have shown that classical management perspective is incongruent with the nature and dynamics of inland fisheries in tropical regions, because they do not account for external factors, such as flooding nutrients (humus, cow and wildlife dung, or the build-up of organic matter, which contribute to biological productivity in tropical inland fisheries) [47]. It is further argued that the classic management approach is derived from temperate regions used in marine single-stock management; these classic approaches have based their foundation on a single-species harvest [47]. They are replete with a "hypothetical" equilibrium model for the management of marine fisheries [45]. These models use the idea of maximum sustainable yield (MSY) as the basis of management. The assumption behind MSY is a standard parameter system in fisheries exploitation [48]. Attributes of this concept led to the introduction of mesh size and fishing effort regulations [45]. The classical fisheries management approach restricts the weave size of fishing nets with the goal of restricting smaller fish catches [12]. Over time, evidence has shown that certain fish species in flood plain environs are naturally small, even as adults, for instance, the *cyprinids.* Thus, excluding their catch affects the utilization of the fishery for food security [12,14]. Although the use of classical management approaches has been questioned in tropical inland fisheries, their application in their management is so great that the tenets of the Code of Conduct for responsible fisheries demand that decisions can be made based on experience and existing science to support available management options [41].

5. Results

5.1. Governance and Management of Fisheries in Zambia

Fisheries and aquaculture development in Zambia is placed under the Department of Fisheries in the Ministry of Fisheries and Livestock. The Fisheries Act No. 22 of 2011 is a principal piece of legislation governing fisheries, together with regulation No. 24 of 2012 [49]. The Act stipulates the establishment of fisheries management areas and the decentralization of fisheries management that includes community involvement in the enforcement of fisheries regulations [50]. These regulations include fish gear, type, mesh size restrictions, and the issuance of fish licenses to regulate fishing effort and access to the fishery areas [49]. However, the regulations do not specify the number of fishing nets a fisher can use [22,33]. The fish closed season is annually imposed from 1st December to the end of February as a way of protecting the fish stock during the production phase to ensure successful recruitment [49]. This regulation has been largely criticized in tropical fisheries due to insufficient data in support of it [51,52], which may also be relevant for inland fresh water fisheries. Several researchers [24,25,51] have argued that floodplain fish species have different life cycles and natural fluctuations in recruitment are triggered by flood regimes [25].

The fisheries sector in Zambia presently does not have a stand-alone policy on the management aspect of fisheries and aquaculture [42]. The policy statement is covered by the National Agricultural Policy (NAP) (2004–2015) that governs the development of the agriculture sector in Zambia [42]. A close analysis of interventions in the NAP shows more emphasis on crop production than on fisheries development. Furthermore, the policy focuses more on maximizing fish production and employment opportunity than on sustainable utilization of the fisheries resource [43]. This approach poses a management dilemma due to a lack of adequate fisheries data on which to base effort restriction. While fisheries co-management is enshrined in the Zambian Fisheries Act No. 22 of 2011 [49], the Act does not explicitly exhaust matters related to transboundary fisheries management and lacks a comprehensive legal framework to support legal certainty of the fisheries development agenda [33]. The lack of an adequate national fisheries policy in Zambia seems to explain the reasons why the fisheries sector has received very little attention in terms of funding [16]. This shortfall has, in turn, resulted in a failure to bring about the institutional reforms necessary to enhance the utilization of the fisheries' resources both at local and international levels [14]. These claims are supported by the WorldFish Center [16] report, which revealed a low priority of data collection accorded to the Zambia fisheries.

The system of fisheries governance on the Zambezi River in Zambia is characterized by two parallel governance structures, the central government and the traditional authorities, which are often at odds with each other [53]. Tension and disagreement have often arisen between the central government and the traditional authorities over leadership roles in the governance of the fishery [26]. The main attributes of the local leadership in the area are: (i) fishing access restrictions; (ii) enforcement and punitive measures; and (iii) traditional fishing wardens [26]. The system of governance by the traditional authorities exercises authority that allows access rights for the kingship where migrant fishers get authorization from local headmen to settle in seasonal camps during the fish ban period [26]. According to a key informant from Simalaha conservancy, these conditions are likely to stymie the development of a transboundary fisheries management regime, obviously because of the existing parallel and conflicting governance structures in the fishery [26]. The contentious issues are on the aspect of a fish ban season; the traditional leadership does not fully support the idea of a fish ban due to limited livelihood options and failure by the government to recognize access rights [26].

5.2. The Zimbabwean Context

The governance of fisheries in Zimbabwe is under the Zimbabwean Parks and Wild-life Management Authority (ZPWMA). This institution falls under the Ministry of Environment and Natural Resources [14]. The Authority bears the responsibilities for wildlife (terrestrial) and fisheries management in terms of the Wildlife Act–Chapter 20:14 of 1996. The Act outlines fisheries regulations, aquaculture, and the development and control of the fishing industry. It also stipulates financial provisions, enforcement, penalties, and offences, including general provisions. Access to fishery areas in Zimbabwe is regulated through a license system [11]. The annual system of licensing stipulates where one can fish and how many gillnets a fisher can use [33]. Fish gear and mesh size restrictions are regulated to control fishing effort. The annual licenses are issued by the ZPWMA upon payment to the ZPWMA. This is done in consultation with local authorities (District Councils) [11]. This approach has often created user conflicts between government authorities and local resource users whose livelihoods depend primarily on access to the fishery resources [33]. The resource users appear to play no significant role in the management of the fisheries' resources [54], suggesting that the fisheries governance and management in Zimbabwe is a centralized 'top-down' approach. The scope of involvement by local resource users in the process of decision making with regard to management and utilization of the fisheries' resources is very low, despite the fact that the participation of resource users in management of their resources is acknowledged as a requirement for sustainable development of the fisheries' resources [54]. In 1995, the FAO recommended that active engagement of resource users and stakeholders' participation in fisheries management is among the major principles in the implementation of Code of Conduct for Responsible Fisheries [41]. Sustainability of inland fisheries' resources in Zimbabwe has received wide criticism [43,54], based on the argument that the top-down management approach has resulted in regulations that are inappropriate for local resource users [54].

Like many other countries in Southern Africa, Zimbabwe does not have a national fisheries policy [14]. This, according to Mhlanga and Mhlanga [54], explains why the country lacks appropriate interventions related to the role of the fishery sector in the national economy [14]. This suggests that the lack of a national fisheries policy in Zimbabwe has hindered institutional reforms that would have activated stakeholders' participation in decision making regarding fisheries management at a local level [14]. Viswanath et al. [55] observed that the lack of a clear fisheries policy direction in Zimbabwe has resulted in a weak management system, which is insensitive to local conditions and less likely to meet its own objectives (that is, a sustainable utilization of the resource). The principal piece of legislation governing fisheries activities (the Parks and Wildlife Act) appears to be more skewed towards management of wildlife than fisheries. As a result, fisheries are not accorded the necessary reforms to unleash their potential [14]. While Zimbabwe is a signatory to regional and international protocols on responsible fisheries, the commitment to these protocols is low and the process of institutional reforms in fisheries has stagnated owing to lack of policy direction.

5.3. The Botswana Context

The management of fisheries' resources in Botswana is under the purview of the Environment, Wildlife and Tourism Ministry [14]. The sector is run under a division within the Wildlife sector. The Fisheries Protection Act 42 of 1975 is the principal legislation governing the fisheries activities in Botswana, together with other pieces of legislation, such as the Fisheries Protection Regulations of 2016 and the Statutory Instrument of 2015 [14]. The latter regulates fishing effort with gear and mesh size restrictions [14]. Permissible fishing gears in Botswana include long lines, gillnets, and hook and line. The fish ban season is implemented for two months between January and February to protect fish breeding and recruitment during the period. However, the timing of the fish ban season remains a challenge, as it does not coincide with the fish ban season in Namibia and Zambia, where the ban is observed for three months between December to February [53]. Botswana does not have a fisheries policy on which management interventions are based [14], which suggests that management measures made without a policy may not adequately address the management concerns of the fisheries sector due to a lack of policy direction. The fisheries sector in Botswana falls under a Wildlife Management Authority whose management philosophy is more focused on conservation than sustainable exploitation of the fisheries for food security as prescribed by FAO Code of Conduct for responsible fisheries [38]. This system of governance appears to focus on the development of wildlife to sustain the tourism sector rather than the conservation of the fisheries resources for food security [14]. The problem is amplified by the lack of clear policy direction to bring about appropriate technologies and informed decision making. The major challenge is that investment in the research of the fisheries to generate the data required for development is not adequate [14], as well as not having a stand-alone policy to provide oversight and direction on fisheries management and development. The current management approach is insensitive to the access rights of fishing communities [54–56].

5.4. The Namibian Context

Governance of inland fisheries in Namibia is under the Ministry of Fisheries and Marine Resources (MFMR) [57]. The Inland Fisheries Resources Act No. 1 of 2003 is the principal piece of legislation governing the inland fisheries in Namibia. [58]. The Act is developed in the contest of the white paper on the Responsible Management of Inland Fisheries in Namibia [58]. Namibia is one of the few countries with a policy dedicated exclusively to inland fisheries. The philosophy followed is that different management approaches are devised for different rivers systems due to the diverse nature of some of these systems. Furthermore, the interest of the subsistence households on the availability of fish as food security is given priority and the need to control any commercialization of the resource. The Act provides for the conservation of aquatic ecosystems and the sustainable development of inland fisheries' resources [58]. The Namibian Fisheries Act recognizes the transboundary management of fisheries of a shared river system [58]. Furthermore, the management system provides for fisheries reserves, defined, regulated, and enforced by local resource users. A closed fishing season for the rivers systems, exclusively for the Zambezi Region is in place from the 1st of December to the end of February, similar to Zambia. The current management approach to fisheries on the Namibian side of the Zambezi River is administered by both the traditional authority and the central government [25]. The management strategies include effort restriction in the form of fishing gear restriction and type allowed, the number of gillnets allowed per fisherman, mesh size restriction, and the fishing method practiced [58,59]. Fisheries reserves are not necessarily no-take zones and may allow fishing with specific rules according to the demands of the local communities. These rules, however, must be within the framework of the Inland Fisheries Resources Act [60]. A Standing Operating Procedure (SOP) was developed, endorsed by the Ministry of Fisheries and Marine Resources, to give guidance when creating fisheries reserves [60–63]. Furthermore, the tackle box for community fisheries reserves highlight the step-by-step approach to establish community-based fisheries reserves [63]. The traditional leadership plays a vital role in the management of the fisheries resources [64] and needs to be considered for future management approaches. Regulations place emphasis on fish gear restrictions and access rights to particular fishing grounds; they do not restrict access to any fishing area during the high-water period [65–67]. However, permission is needed for fishing in secluded areas during periods of low water levels [68]. The Namibia Nature Foundation conducted numerous frame surveys in the Kavango, Kwando, Zambezi, and Chobe Rivers to gain insight into the value fish play in these communities, how fish are managed through local communities, and into the livelihood strategies communities pursue. Although the Namibian inland fisheries policy of 1995 has been reported to have a more influential profile due to its transparence attributes [12], the system of community participation in fisheries management appears to be moderated.

5.5. The Angolan Context

Inland fisheries on the Kavango–Zambezi rivers system in Angola have remained underdeveloped partly due to lack of a policy to guide governance processes. The 27-year post-civil war that destroyed infrastructure had dragged institutional processes to establish policies and regulations. [69]. The scanty information available has revealed institutional problems and processes in explaining the underdevelopment of the inland fisheries sector in Angola. Key informant interviews from both the KAZA secretariat and a fisheries official from Angola revealed that the management of inland fisheries in Angola is managed under the jurisdiction of aquatic biological resources of 2004 (LRBA), Law-A/04 of 8 October 2004 [62]. The law focuses on the protection and sustainable use of aquatic resources. The role riverine communities play in the protection of these aquatic resources is recognized. Recently, policies moved towards a more community-based attempt where communities have the right to manage their natural resources [69]. Managers still lack knowledge of community-based approaches in fisheries management. This lack of knowledge is still seen as an obstacle in establishing fishing zones that should be managed by communities for their own benefit. The Presidential declaration 139/13 of 24 September 2013 regulates the Law on Aquatic Biological Resources with regard to inland fisheries [70]. The purpose is to establish rules governing the conduct of inland fishing activities in the inland waters of the Republic of Angola.

Some regulatory mechanisms in the law are the development of management plans for all inland fisheries, the defining of fishing zones and protected areas, and the setting of fishing effort limitations, minimum sizes of fish species, prescribed mesh sizes, and fishing methods. The law further makes provision for the consultation with fishermen associations and community organizations and the devolution of power to the local level [70]. Provision is also made for closed seasons, although no current closed fishing season is in place [71]. Recent training of staff on sampling and survey protocols were done between Namibia and Angola with the aim to establish a shared database in the future for management purposes. Similar activities were performed in the establishment of fisheries reserves with the aim to have these reserves across borders, managed by communities on both sides of the river [65]. Most investment in subsistence fishery is in the coastal fisheries with very little channeled to inland fisheries. While Angola appears to have sustainable fisheries strategies and plans, these have not been implemented due to lack of a policy framework to stimulate policy debate on inland fisheries and guide governance processes [71].

6. Discussion

Classical management approaches are widely used to manage fisheries in the region, which, as shown in this paper, can be problematic in various aspects. It is argued that countries in the KAZA-TFCA have different management approaches and regulations characterized by inadequate policy [56], and that assessing several regulations, policies, and local institutions in the region is cardinal before scaling-up conservation measures [71]. This paper further argues that the implementation of a transboundary fisheries management regime throughout the KAZA-TFCA has largely failed. We hold the idea that transboundary fisheries management has shown positive results as a management concept in diverse sectors of natural resources governance, including fisheries [31,36], and theoretically, it shares a number of advantages of bottom-up management [30]. The fundamental difference in the regulatory frameworks, management approaches, and inadequate policies governing the fisheries' resources in the region has created a stalemate for the successful management of aquatic resources. This has serious policy implications for transboundary fisheries management in the region and elsewhere in the world [72]. Implementation of transboundary management as a blueprint without harmonizing the fisheries regulations, policies, and management approaches is a constraint towards conservation and a sustainable livelihood for local residents. This may further limit conservation at a larger scale because of incompatible fisheries regulations that may result into wide-spread free-riding activities [46,56].

6.1. The Dilemma of Transboundary Fisheries Management in the KAZA-TFCA

The fisheries regulations that exist across the countries in the KAZA-TFCA make the actualization of transboundary initiatives difficult. For instance, within the KAZA-TFCA, recreational fisheries in Botswana, Namibia, and Zimbabwe are allowed throughout the year, even during fish ban season, while in Zambia, recreational fishing is prohibited during the fish ban period. This conflicting regulation over the utilization and accessibility of the fishery resources during the fish ban has affected co-operation of shared management responsibilities among member countries, especially at local level [73]. Similarly, the implementation of a fish ban season of three months observed in Zambia and Namibia from December to February the following year, essentially to cover for the fish breeding season for most fish species in the Zambezi River system [24], is in conflict with the two-month ban enforced in Botswana between January and February, while Zimbabwe does not observe this ban at all [14]. The situation creates considerable challenges for transboundary fisheries management on the Kavango–Zambezi River system owing to free-riding activities by fishers in countries that do not implement a fish ban [35]. Furthermore, the efficiency of the fish ban season to allow fish breeding and recruitment is questionable because the timing does not coincide with the breeding period of most of the targeted fish species, such as the Tilapine fish species. Most of these breed around October–December. This situation is perceived to cause resentment among various stakeholders and to reduce the overall effectiveness of transboundary fisheries management at the local level [24].

Furthermore, Zambian fisheries policy emphasizes the maximum fisheries production to meet the food requirements of the growing population and to secure employment opportunities for rural communities [43]. As a consequence, many small-scale fishers who can afford entry into the fishery are allowed unfettered access, without gillnet limitations [43]. This approach may lead to over-exploitation, "Tragedy of the commons", and compromises the sustainable utilization of the fisheries' resources as prescribed by the FAO Code of Conduct for responsible fisheries [41]. This further conflicts with the fishing regulations of neighboring countries, such as Zimbabwe, Namibia, and Botswana, where fishing effort is regulated by limiting the number and size of nets a fisher is allowed to use [46]. Conversely, the Zimbabwean fisheries regulations appear to restrict and regulate the number of gillnets a fisher may use and to stipulate where one can fish [43,54]. Artisanal fishers are restricted entry to certain fishing grounds [43]. This kind of management approach appears to focus more attention on recreational fisheries and wildlife activities to support eco-tourism than on utilization of the fishery for food security. This is despite the fact that tourism conservation is likely not to create better opportunities and equal access to resources for rural riverine communities whose livelihoods depend on fishing [33].

The differences in management approaches have generally made it difficult to actualize transboundary initiatives, as different countries within the region appear to pursue diverse social economic models of development. These differences affect coordination and collaboration among participation countries at a local level [73]. For instance, the five countries in the KAZA-TFCA have pronounced policy statements in favor of transboundary fisheries management, but the existing divergent economic policies among member countries hinder meaningful implementation of equitable shared responsibilities [33,43]. Key informant interviews from both Zambia and Zimbabwean officials revealed that there are differences with regard to mesh size prescribed by Zambia fishing regulations and of Zimbabwe. These findings are further highlighted in the 2011 Zambia/Zimbabwe fisheries Frame Survey report, which showed that gillnets of mesh sizes below 63 mm (2.5 inch) were also reported to be used in Zambia. The nets increased from 51 in the 2006 Survey to 189 in the 2011 Frame Survey [43]. The use of these nets (below 63 mm) is prohibited in Zimbabwe. These differences in the regulations of inland fisheries complicate transboundary fisheries management at the local level and creates a social dilemma for a person's rational behavior, in which the absence of limits to maximize short-term personal gain may result in environmental degradation [74]. It is difficult to realize the fisher's incentive to cooperate over resource conservation as opposed to harvesting as much as possible since fish, by nature, are fugitive [44]. The fish you do not harvest today are most likely to be harvested by someone else tomorrow [74,75], leading to the tragedy of the commons.

Given the above scenario, it is apparent that a lack of compatibility of fisheries regulations between nations in the KAZA-TFCA is a huge challenge for the successful implementation of a transboundary management regime. The problem is exacerbated by inadequacies and the lack of national fisheries policies among the member countries [14,76]. This is particularly evident in the failure to optimize usage of the many dams in Zimbabwe and south-eastern Botswana for fisheries production [14]. It is acknowledged that the overriding objective of fisheries management is the biological sustenance and utilization of fisheries' resources to support the economic and social wellbeing of fishers [67]. Consequently, the development of transboundary fisheries management must be guided by a policy framework to guide the governance and utilization of the resource for food security at both national and international levels [68]. Apparently, the management of fisheries in Botswana and Zimbabwe is run under a division within the Wildlife Management Authority. The challenge with this institutional arrangement is that both wildlife terrestrial and fisheries resources are managed for conservation to sustain tourism, since recreational fisheries integrates so well with tourism [14]. This management approach denies resource users real opportunities to utilize the fisheries for food security as prescribed by FAO Code of Conduct for responsible fisheries [14,41]. The placement of the fisheries division under the wildlife sector has a negative bearing on the performance of the fisheries sector because of the frequent and unpredictable institutional changes in the wildlife sector, which is often influenced at the global level [14]. The conditions whereby fisheries management is a responsibility of the Parks and Wildlife Authorities is a compromise as these sectors are not 'development' orientated [14,68]. In other southern African countries where fisheries have a relatively established institutional profile (such as Malawi and Mozambique), transboundary fisheries management has been relatively successful [31], for instance, the establishment of a vibrant transboundary fisheries management scheme on Lake Chiuta, shared between Malawi and Mozambique. The achievement of the recently coordinated regulations in that fishery was a prerequisite to a successful implementation of a transboundary fisheries management in the lake [31]. While the idea of transboundary fisheries management has been widely recognized since the 1980s, it has recently grown in prominence through institutional reforms and collaborative initiatives [77]. For instance, a more creative partnership between the United States of America (US) and Mexico illustrates the creation of joint solutions to environmental challenges of a shared Colorado River basin [77]. In the Laurentian Lakes, where the United States of America and Canada have set up management structures to address policy and environmental issues, a harmonization of policies played a key role in establishing management structures [78]. While in the African Great Lakes region, a collaboration initiative is newer. Diverse governance systems among the riparian states sharing Lake Victoria, for example, have been among the major hindrances to the effective management of the lake ecosystems [78].

The fundamental variations in the utilization of fisheries' resources in the KAZA-TFCA show dissimilar behavior in resource exploitation and conservation, thereby making conservation prescription very difficult [35,68]. Overall, these accounts suggest how coordination and harmonization of regulations between partner states could be an essential aspect in making transboundary fisheries management sustainable on a long-term basis. According to Ostrom [75], the governance of social and ecological systems will have a positive outcome only if sufficient conditions are incorporated in the management aspects. As such, Ostrom identifies eight interrelated design principles for the effective management of resources held in common. Principle design numbers six, seven, and eight are based on the existence of a system of conflict resolution mechanism, the recognition of rights to self-organize, and a framework for co-ordination among relevant stakeholders, respectively [74,75]. These principles have the scope of application for transboundary fisheries management in achieving collective responsibilities in the KAZA-TFCA and elsewhere [40,79]. The absence of the aforementioned principles may lead to user conflicts, non-compliance to rules governing the resources, and free-riding activities [69]. The interactive effects of abrogating these principles in the management of transboundary fisheries contradicts the sustainable utilization of fisheries' resources as prescribed by FAO Code of Conduct for responsible fisheries and may weaken the initiatives of transboundary fisheries management both at local and international levels [33,80].

6.2. Prospects for Transboundary Fisheries Management in KAZA-TFCA

Several studies, so far, show that fisheries in the KAZA-TFCA have the potential to contribute to the food security and nutritional status of over one million people who regularly eat fish in the region [21,24,56]. A standard approach to support transboundary fisheries management is necessary to guarantee future prospects. FAO and SADC [81,82] call for transboundary fisheries management activities through coordinated and cooperative arrangements in the Zambezi River Basin. It is generally acknowledged that transboundary initiatives can enhance security, peace, and the long-term stability of people and resources. These goals can be actualized by recognizing regional and international protocols to which all member countries discussed here are signatories. Management of transboundary inland fisheries in Southern Africa, to a larger extent, stems from the SADC protocol of 2001 whose principals were founded on the United Nations Convention on the Law of the Sea 1982 (UNCLOS) and the principles of the FAO Code of Conduct for Responsible Fisheries (CCRF) (FAO, 1995) [41,83,84].

In light of these findings, we propose to use the FAO Code of Conduct for Responsible Fisheries (CCRF) of 1995 as a conceptual framework to secure the sustainable utilization of fisheries' resources in the KAZA-TFCA as a first step. The CCRF draws from experience and science-based evidence in designing international instruments, policies, and plans to support responsible fisheries management. It further declares that, "States should co-operate at global, regional and sub-regional [level] to promote management and conservation to ensure responsible fishing" [41,60]. The CCRF provides important guidelines for developing good management practices and policies for sustainable fisheries and aquaculture development [83]. Furthermore, the CCRF provides for community participation in the governance and management of natural resources, an aspect that offers a window of opportunity to incorporate indigenous knowledge in resource management [85]. Indigenous knowledge is context specific, and local resource users often desire to use concrete knowledge in time and space [41,68,86]. Although the CCRF is a voluntary code, its guiding principles are internationally acknowledged in the management of fisheries [70]. The CCRF is complemented by several other technical guidelines on how to implement specific provisions, for example, the precautionary approach to capture fisheries [84]. Nevertheless, designing regional and international agreements into practical strategies will require commitment and backing in many cases from interested parties, in this case, member states within the KAZA-TFCA who have already signed a memorandum of understanding for regional collaboration in the management of transboundary natural resources [23]. Regional institutions, such as SADC, are critical vehicles to influence regional stakeholders. The SADC Protocol on Shared Water Bodies and the SADC Treaty on Management of Watercourse Systems provide an opportunity for such stakeholder coordination consistent with the mission statement of the KAZA-TFCA [59].

The transboundary fisheries management challenges reviewed in this paper would be addressed by fulfilling certain key attributes, highlighted above (Table 1). For instance, (i) a lack of cooperation among member countries and stakeholders in KAZA-TFCA would be addressed by coordination and collaboration amongst the countries sharing the fisheries resources [87,88] Collaboration among member countries will create a platform for sharing knowledge, technology, expertise, and financial resources towards meeting the regional development agenda [87,89]; (ii) the inadequate institutions and inconsistence in management approaches would be addressed by fulfilling the attribute of having strong institutional frameworks. FAO and CCRF provide technical guidelines on policy development and essential institutions for fisheries management [78]. Policies are intended to guide governance processes and highlight the role and responsibilities of all stakeholders who may be key towards having strong transboundary collaborations [89].

Table 1. The key attributes essential for successful implementation of transboundary fisheries management.

No.	CCRF Attributes	Rationale
i	Co-ordination and collaboration	CCR provides policy harmonization and the integration of management approaches. In this case, countries in KAZA-TFCA can adopt to facilitate informal mechanisms for collaboration and conflict resolution in response to the objectives of transboundary cooperation.
ii	Strong institutional framework	CCRF stresses the need to develop institutional frameworks and policies which provide guidelines on the utilization of the fisheries' resources for food security, whilst taking into account compatible measures within and beyond the national jurisdiction to ensure responsible fisheries.
iii	Social-ecological approach	CCRF Promote biodiversity conservation and availability of fisheries' resources in sufficient quantities for present and future generations in the context of food security and poverty alleviation.
iv	Stakeholder's participation	CCRF emphasizes the need for community participation in the governance of fisheries' resources. The assumption is that if communities are involved in conservation, the benefits they receive will create incentives for them to become good stewards.

Table 1. *Cont.*

No.	CCRF Attributes	Rationale
v	Precautionary approach	CCRF provides guidelines to prevent and mitigate potential threats to marine and inland fisheries.

Adopted and modified from FAO [41,83].

To avoid conflicts among the stakeholders, attention has to be premised on the fact that the decision-making process incorporates all the stakeholders involved and that the strategy is multidisciplinary, i.e., involve fish traders, fishers, officers, value chain actors, and several other resource users to sufficiently integrate indigenous knowledge and create a sense of ownership and adherence [44]. Furthermore, Campbell and Olson [90–93] argued that major decisions and priorities regarding which resources to enhance for which institutions are not arbitrary, they rather mirror the interest of the most powerful groups whose power is interceded through political, economic, and social institutions. In light of this, political influence will be essential in facilitating an enabling environment for policy reforms in transitioning to CCRF [43]. Similarly, other challenges discussed in this paper would be addressed by the attributes highlighted in Table 1. Furthermore, CCRF provides for a precautionary approach towards the management of fisheries' resources, this is particularly important for KAZA-TFCA where data on which to extrapolate decisions are inadequate. Precautionary approach is widely considered as a guiding tool for policy and management decisions in times of uncertainty, as it shifts the decision-making process to anticipate, prevent, and mitigate threats [38,78]. Several studies, e.g., Coll et al. [80,81], have exalted the efficiency of CCRF in fisheries' resource management, by comparing compliance with the CCRF to changes in five ecological indicators, which quantifies the ecosystem effects of fishing. The loss in production index and the related probability of sustainable fishing index were tested in different regions. The results indicated that countries with higher levels of compliance with the CCRF experienced a decrease in production index loss and an upsurge in fisheries sustainability from the 1990s to 2000s. The study concluded that the implementation of the CCRF resulted into positive ecological outcomes. However, CCRF must not be seen as a universal panacea to deal with all the problems related to transboundary fisheries management; more studies and research are still needed to learn about better conditions leading to the implementation of a successful transboundary fisheries management.

7. Conclusions

This paper has presented a review of the fundamental differences with regard to a governance and management perspective of transboundary fisheries in the KAZA-TFCA. The study has illustrated why uniform conservation prescription matters in resource conservation. The focus of the study has been to argue that member states in the KAZA-TFCA have substantially different management approaches. With the exception of Namibia, none of the KAZA participating countries has a fully developed fisheries sector policy to guide governance roles and processes. Regulatory frameworks are constrained by inadequate institutions, which requires capacity building to strengthen coordination. This gap appears to undermine the sustainable utilization of the fisheries' resources in the region for food security, and subsequently, a transboundary management regime. They further create differences in the way the fisheries resources are accessed, managed, and utilized. The debates about fisheries governance and management are essentially to enhance livelihood opportunities for riparian communities. The study provides useful insights into the factors constraining transboundary fisheries' resources to transform the future. The findings have policy implications over the need to have a fisheries policy in transitioning towards sustainable fisheries management and enhance food security and environmental sustainability. The immediate target should aim at stabilizing the fishery by having a coordinated response involving all the partner countries and to harmonize fisheries' regulations and management approaches. If these fisheries' resources are managed sustainably, inland fisheries can contribute towards the attainment of the United Nations' Sustainable Development Goals (SDGs) of biodiversity conservation and poverty alleviation by 2030. Based on FAO reports, SDGs can be realized through poverty eradication by 2030. The first and second SDGs emphasize the need to "eradicate poverty" and "hunger" [81], which can be accomplished through improved rural development initiatives in fisheries and fish farming development. This is crucial and very urgent in southern Africa, where a United Nations (2016) report indicated that poverty is widespread, with about 40% of the population surviving on less than USD 1.95 per day in 2012.

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