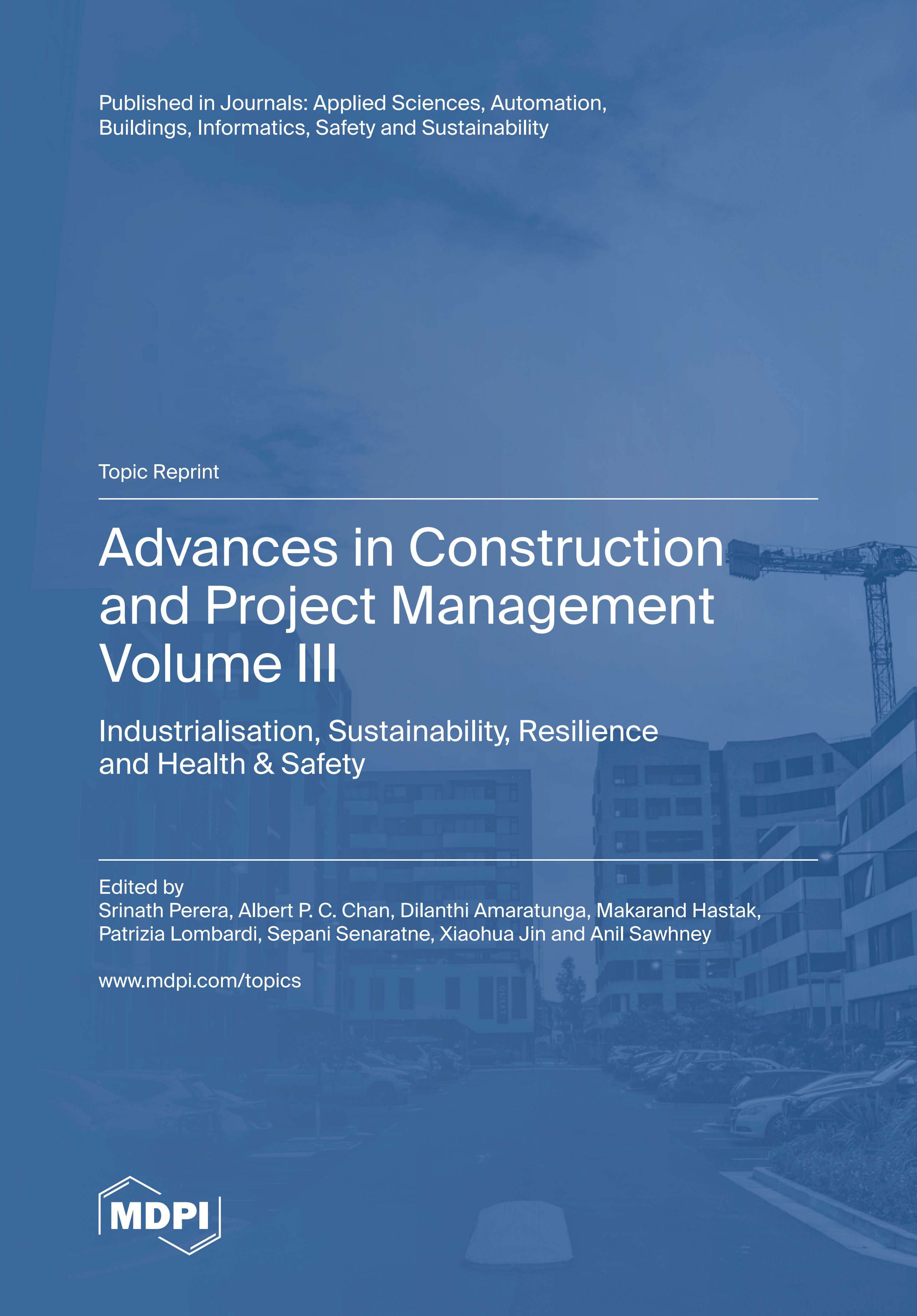

Published in Journals: Applied Sciences, Automation,
Buildings, Informatics, Safety and Sustainability

Topic Reprint

Advances in Construction and Project Management Volume III

Industrialisation, Sustainability, Resilience and Health & Safety

Edited by
Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak,
Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

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Advances in Construction and Project Management—Volume III

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This is a reprint of articles from the Topic published online in the open access journals *Buildings* (ISSN 2075-5309), *Sustainability* (ISSN 2071-1050), *Applied Sciences* (ISSN 2076-3417), *Automation* (ISSN 2673-4052), *Informatics* (ISSN 2227-9709), and *Safety* (ISSN 2313-576X) (available at: https://www.mdpi.com/topics/Construction_Management).

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

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

Volume III
ISBN 978-3-0365-7638-1 (Hbk)
ISBN 978-3-0365-7639-8 (PDF)

Volume I-III
ISBN 978-3-0365-7632-9 (Hbk)
ISBN 978-3-0365-7633-6 (PDF)

Cover image courtesy of Srinath Perera

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About the Editors

Srinath Perera

Professor Srinath Perera is chair professor of built environment and construction management and the founding Director of Centre for Smart Modern Construction (c4SMC) at Western Sydney University. He joined WSU in June 2016 after serving as professor of construction economics at Northumbria University, Newcastle, in the UK. He is a Board member and the chair of the future leaders committee of the International Council for Research and Innovation in Building and Construction (CIB, www.cibworld.org).

He is a fellow of the Royal Society of New South Wales (FRSN) and also a fellow of the Australian Institute of Building (AIB). He is a chartered surveyor and a member of the Royal Institution of Chartered Surveyors (RICS), the Australian Institute of Quantity Surveyors (AIQS) and Australian Institute of Project Management (AIPM). He has over 30 years' experience in academia and industry and has worked as a consultant quantity surveyor and project manager in the construction industry.

Professor Perera is a pioneer in the field of construction informatics integrating AI technologies to construction and project management. He co-authored a research monograph, "Advances in Construction ICT and e-Business" (2017) and two internationally recognized textbooks, namely *Cost Studies of Buildings* (2015) and *Contractual Procedures in the Construction Industry* (2017) published by Routledge. He is also the author of "Managing Information Technology Projects: Building a Body of Knowledge in IT Project Management" He has authored over 250 peer reviewed publications and his current research leads work in the areas of blockchain and IoT applications in construction, BIM, Digital Twin, offsite construction, construction business models and construction performance leading to Industry 4.0.

He recently published the *Digitalisation of Construction* report, indicating the status and future directions of digitalization of the NSW construction industry.

Albert P. C. Chan

Professor Albert P. C. Chan is currently PolyU's Dean of Students, associate director of Research Institute for Sustainable Urban Development, and chair professor of Construction Engineering and Management. He earned his MSc degree in construction management and economics from the University of Aston in Birmingham, and a PhD degree in project management from the University of South Australia. Before joining the Department of Building and Real Estate of PolyU in 1996, Professor Chan taught at the University of South Australia as a senior lecturer and deputy head of the School of Building and Planning. He was appointed by PolyU as associate head (teaching) of the Department of Building and Real Estate from 2005 to 2011, associate dean from 2011 to 2013, interim dean of the Faculty of Construction and Environment from 2013 to 2014, and head of the Department of Building and Real Estate from 2015 to 2021. He has been an Adjunct Professor in a number of Mainland and overseas universities.

A chartered construction manager, engineer, project manager and surveyor by profession, Professor Chan is devoted to a myriad of research subjects as varied as project management and project success, construction procurement and relational contracting, public–private partnerships, and construction health and safety, as manifested by his prolific research output of over 1,000 refereed journal papers, international refereed conference papers, consultancy reports, and other articles. Besides being an expert member of the Engineering Panel of the Research Grants Council, HKSAR, since 2015, Professor Chan has also served as an expert member in the Built Environment Panel of FORMAS, Swedish Research Grants Council, and the Faculty of Architectural and the Built

Environment, Delft University of Technology in the Netherlands. Professor Chan was ranked among the top 2% of Scientists in the World for three years in a row starting in 2020.

Dilanthi Amaratunga

Professor Dilanthi Amaratunga holds the chair in Disaster Risk Management at the University of Huddersfield, UK, where she leads the Global Disaster Resilience Centre. She is a leading international expert in disaster resilience, with an extensive academic career that has a strong commitment to encouraging colleagues and students to fulfil their full potential. Her research interests include disaster risk reduction in the built environment; understanding disaster risk, preparedness for response; early warning systems; disaster resilience from the perspective of the social/political, economic, and physical sciences; and compound hazards and systemic risks. She has managed the successful completion of a large number of international research projects (over GBP 20 million), generating significant research outputs and outcomes, with the engagement of many significant research collaborations around the world in partnership with key academic and other stakeholders. To date, she has produced over 500 publications, refereed papers, and reports, and has made over 100 keynote speeches in around 40 countries.

Her outstanding contributions, publications, and services to her field of expertise have been recognised with numerous international awards. Between 2016 and 2019, she was winner of the prestigious 2019 Newton Prize, which recognises the best research and innovation projects which create an impact socially and economically, between Indonesia and the United Kingdom. In 2018, she received the "His Excellency the President of Sri Lanka Award" from the President of Sri Lanka, for here contribution to Disaster Resilience in Sri Lanka. In 2018, she won the UALL International Award, which recognises innovative engagement that creates change in an international and transnational context. She is a fellow of the RICS; fellow of the Royal Geographical Society, UK; fellow of the Higher Education Academy, UK; and fellow/chartered manager of the Chartered Management Institute, UK.

Makarand Hastak

Dr. Makarand Hastak is professor and Dernlan Family Head of Construction Engineering and Management as well as professor of civil engineering at Purdue University. Prof. Hastak is recognized around the world as an expert in construction engineering and management, with specific expertise in the profitability of construction companies, disaster risk reduction, infrastructure management, project control, and risk management. He is a licensed professional engineer (PE), a construction risk insurance specialist (CRIS), and a certified cost professional (CCP). Prof. Hastak has worked on numerous projects sponsored by prestigious funding agencies. As a fellow of the American Council on Education (cohort of 2013-14), his work at Cornell University focused on hybrid RCM budgets, engaged institutions, and public–private partnerships in academia.

He is the current president of the International Council for Research and Innovation in Building and Construction (CIB) (https://cibworld.org/) and serves as the academic advisor to the CII Downstream and Chemicals Committee (DCC) as well as the Department of Building and Real Estate, Hong Kong Polytechnic University. Prof. Hastak has authored/co-authored over 200 publications and reports as well as co-authored and edited three widely used books. He served as (Editor-in-Chief of the ASCE *Journal of Management in Engineering* (2009–2016). Prof. Hastak is a founding member and the past chair of the GLF-CEM, the Global Leadership Forum for Construction Engineering and Management programs.

Dr. Hastak received his BE (civil) from Nagpur University, India, MSCE from the University of Cincinnati, and PhD (civil) from Purdue University, USA. In addition, he is a trained university planner through SCUP and has received training at Cornell University in executive leadership, financial management, and advanced strategic human resource management. He has worked at Georgia Tech, NYU, University of Cincinnati, and currently at Purdue University.

Patrizia Lombardi

Professor Patrizia Lombardi, full professor of Projects Appraisal and Planning Evaluation at Politecnico di Torino, she is currently vice-rector for Sustainable Campus Development and Community Inclusion, after having been deputy rector and Urban and Regional (DIST) Department director. Since 2015, she has been coordinating the University Green Team, dedicated to the implementation of Agenda2030, in the context of the university's third mission. She is also president of the Network of Universities for Sustainable Development (RUS), of which she has been a promoter since 2013 and advisor of a number of Industries, NGOs, European Think Thanks, Joint Research Center of the European Commission and the Italian Ministry of Sustainable Infrastructure and Mobility. At international level, she is an established figure in the field of sustainable development evaluation for over 25 years and has coordinated or served as core partner several pan-European projects. Her research concerns issues of sustainable development assessment of the built environment with reference to decision support tools, including interactive Multicriteria Spatial Decision Support Systems. She is the author of more than 240 publications (h-index 32 Google Scholar with more than 4700 citations) and member of the Editorial boards of various international scientific journals. She has received several scientific and career awards.

Sepani Senaratne

Associate professor Sepani Senaratne is currently the director of Academic Program for UG Construction Management at Western Sydney University in Australia. Sepani has more than 20 years of academic experience in the quantity surveying (QS), construction management (CM) and built environment (BE) disciplines, attached to reputable universities in Sri Lanka, the UK and Australia. Her first degree is in BSc (Honours) first-class in QS from Sri Lanka and her PhD is in CM from the University of Salford, UK. Her key research expertise is in knowledge management and project management applications in construction projects and her research interests expand to include sustainable construction, smart modern construction and cost management areas. She has over 150 publications, including several peer-reviewed journal articles, conference papers, books and reports. Sepani's research has benefited various BE industry sectors and professions such as quantity surveyors, project managers, and contractors in solving project management problems. In 2022, as co-coordinator, Sepani launched a task group in CIB (The International Council for Research and Innovation in Building and Construction) on 'TG 124 on Net Zero Carbon' to create a global discussion and research. The sustainability research and activities that she is currently conducting contribute to United Nations Sustainable Development Goals. She has received several best paper awards at international research conferences, an Emerald Award of Excellence for Highly Commended Paper in 2009 and an Outstanding Research Performances Award by the University of Moratuwa consecutively five years. She is actively serving the academic community as a paper reviewer, postgraduate thesis examiner and member of conference committees.

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Anil Sawhney

Dr. Sawhney is a construction and infrastructure sector expert, an educator, a researcher, and a ConstructionTech enthusiast. In his role at the RICS, he is involved in producing the construction and infrastructure sector's body of knowledge, standards, guidance, practice statements, education, and training. Anil is the current chair of the International Cost Management Standards (ICMS) Standard Setting Committee and the co-chair of the AECO Working Group of the Digital Twin Consortium. He is also an adjunct faculty at Columbia University, visiting professor at Liverpool John Moores University in the UK, and an adjunct faculty at the University of Southern California. Anil has gathered a rich mix of academic, research, industry, and consulting experience in the USA, India, Canada, the UK, and Australia. In 2020, he co-authored a book entitled *Construction 4.0—Innovation Platform for the Built Environment*. He is currently the co-editor of the *Construction Innovation Journal*. Dr. Sawhney serves on the international editorial board of the *ICE Infrastructure Asset Management journal and the Journal of Information Technology in Construction*.

Preface to "Advances in Construction and Project Management—Volume III"

Construction and project management are two critical areas that play significant roles in society's progress and development. Construction projects play crucial roles in shaping the built environment, with an impact ranging from towering skyscrapers to intricate transportation systems. Effective project management is equally vital in this process, ensuring projects are completed on time, within budget, and to the required quality standards.

The field of construction and project management is constantly evolving, with new technologies, processes, and best practices emerging regularly. Keeping up with these advancements is essential for professionals in these fields, allowing them to ensure that they are delivering the best outcomes for their clients and stakeholders.

This book, entitled *Advances in Construction and Project Management*, compiles a collection of chapters from experts in these fields, covering the latest developments and trends. This publication covers a wide range of topics, including sustainable construction, digital technologies, project risk management, and stakeholder engagement, among others.

Written by leading academics and industry professionals from around the world, the individual chapters provide global perspectives on the subject matter. The authors draw on their experience and research to provide practical insights and solutions to the challenges facing construction and project management professionals today.

This book constitutes an essential resource for anyone involved in the construction or project management industries, including architects, engineers, contractors, project managers, and consultants. It is also an excellent reference for students studying in the disciplines of built environment, architecture, engineering, and construction, providing them with the latest information on the subject matter.

We hope to inspire readers to embrace new technologies, processes, and best practices and continue to advance the fields of construction and project management. We would like to express our gratitude to all the authors who contributed to this book and to the readers for their interest in this important topic. We also wish to acknowledge the Centre for Smart Modern Construction (c4SMC) and their industry partners for continued support and collaborations. I would also like to thank the centre researchers, Dr Samudaya Nanayakkara, Thilini Weerasuriya and Prasad Perera, for helping in the compilation of this topics issue.

Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi,
Sepani Senaratne, Xiaohua Jin, and Anil Sawhney
Editors

sustainability

Article

Integrated Off-Site Construction Design Process including DfMA Considerations

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Abstract: Off-site construction (OSC) offers a promising means to improve the efficiency of construction projects. However, the lack of experience and knowledge regarding its use results in errors in design owing to conflicts and omissions of considerations for OSC projects. To mitigate these problems, the design for manufacturing and assembly (DfMA) is widely used to include the considerations in the OSC design process. Several studies concerning the DfMA application in OSC have been performed, but the comprehensive design process is not suggested for mitigating the aforementioned problems. This study proposes an OSC design process by integrating the fragmented DfMA considerations reported in previous studies. The considerations are identified through a systematic literature review and classified into structural and architectural types. To validate the proposed process, an OSC project design has been undertaken as a case study, wherein a significant portion of the building structure has been modified to comprise precast concrete (PC), instead of its reinforced counterpart, with a demonstrated reduction in the PC element design duration. The proposed process would guide and support the design process for reduction in the duration and errors incurred in the process. Moreover, the process can be considered a design guideline for the execution of future projects.

Keywords: offsite construction (OSC); precast concrete (PC); design process; DfMA

Citation: Hyun, H.; Kim, H.-G.; Kim, J.-S. Integrated Off-Site Construction Design Process including DfMA Considerations. *Sustainability* **2022**, *14*, 4084. https://doi.org/10.3390/su14074084

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 18 February 2022
Accepted: 28 March 2022
Published: 30 March 2022

1. Introduction

Offsite construction (OSC) methods have many benefits, such as a decrease in construction waste, duration, project cost by standardization, and cost variation, in addition to reduced effect on the construction site, as the building elements are produced in factories [1–4]. Despite its benefits, OSC has yet to become a mainstream technique, even in countries that have successfully implemented it [5–7]. Many studies have been conducted to identify the factors hindering the widespread use of OSC, and the problems related to lack of experience and knowledge of the project stakeholders have been identified as the major barriers and constraints [7–11]. These problems caused errors such as omission and conflict in design and the absence of early interventions for essential decision-making [10]. To mitigate these problems, the need for design guidelines related to the OSC process has been emphasized [5,11–13]. The design for manufacturing and assembly (DfMA) principle is widely considered to include manufacturing and assembly considerations in the OSC design process, and several studies have been conducted to incorporate the same in the downstream design processes. However, the fragmented results of the previous studies do not facilitate the development of a comprehensive design process to mitigate the problems encountered in the OSC industry.

To overcome these limitations, the objective of this study is to establish a design process for OSC projects. The process includes considerations related to the features of the OSC method, which are allocated to the sub-design phase to inform the designers of the essential considerations in the appropriate design phase. This process is expected to reduce the errors and changes in the design phase. To achieve the research objective, the following sub-objective was established. To facilitate the development of such a process, (1) this paper identifies the problems associated with the OSC industry through a literature review, (2) a systematic literature review (SLR) is conducted to identify and classify the essential considerations concerning the DfMA application in OSC projects, and (3) the considerations are allocated to the design process. The developed process is validated by performing a case study on the design of an OSC project. The scope of the process extended from the pre-design phase to construction documentation; it assumed that the project adopts a delivery method that includes OSC specialists as consultants, and the OSC method was considered in the early project planning phase.

2. Literature Review

2.1. Background of OSC

In literature, various terminologies are used to refer to OSC according to the material used or structure type, such as modular construction [14], modular integrated construction [15], prefabricated prefinished volumetric construction [16], precast construction [17], modern methods of construction [18], prefab construction [12], and industrialized building systems [19]. Moreover, OSC has been considered a promising approach for reducing the negative effects of construction at a designated site [1,3], mitigation of shortage of skilled labor [20], shortened and flexible project duration [14], reduced construction waste [2], application of environment-friendly methods [21], minimization of project cost and cost variation by elements standardization, and by producing elements in an environmentally controlled factory [4]. The benefits of OSC are attributed to the manufacturing of building elements in an environmentally controlled factory. Owing to its benefits, OSC has been implemented in many countries [2,6,9,10,22–24]. To maximize the benefits highlighted in the various project and represent characteristics of each OSC method, the various OSC methods were classified [25].

Nevertheless, OSC is yet to become a mainstream technique owing to certain constraints that overshadow its benefits during the decision-making process [8]. Therefore, the constraints should be mitigated for the widespread application of OSC projects. Many studies have been conducted to identify these constraints. Pasquire, Gibb [8] argued that the selection of the construction method was based on cost-related factors, and the other factors that were difficult to objectively quantify were rarely included in the decision process. To include these factors, the benefits of OSC were classified and a decision-making tool was developed to evaluate the potential benefits and constraints of OSC in projects, including soft issues such as health and safety. Jaillon and Poon [26] surveyed the potential benefits of the use of OSC by experienced professionals in Hong Kong. The environmental, economic, and social benefits were compared with traditional methods, and the limitations of OSC were identified, such as higher project cost, early decision and collaboration, resistance to changes in the construction industry, and difficulties in implementing design changes. Lu [9] identified the major factors driving the use of OSC in the United States; the inability to incorporate changes onsite and limited design options were emphasized as the most significant barriers. To overcome these barriers, it was recommended to train manufacturers, contractors, and designers to improve their knowledge, and collaborate with owners, designers, and contractors in the early phase to reduce the changes. Blismas and Wakefield [10] identified the drivers and constraints of OSC in Australia through qualitative surveys. Skill and knowledge were selected as the factors driving and hindering OSC. In other words, the labor shortage problem can be mitigated by adopting OSC, but the lack of specialized knowledge pertinent to OSC were identified as the greatest issues that restricted its adoption.

Previous studies to identify and overcome the constraints and barriers of OSC have reduced the gap between research and practice. In developed countries, technologies have been developed to implement OSC effectively [5]. Consequently, the number of effectively implemented OSC projects has increased [1,6,23,27]. However, the effectiveness of OSC is still viewed with uncertainty because many OSC projects have failed to meet expectations. Lee and Kim [7] identified the higher cost of OSC as a significant failure factor and derived the responsible factors for each phase of the OSC project. A sizable number of factors were concerned with workforce-related problems, such as lack of trained and experienced specialists according to the market size and maturity. Wuni and Shen [5] identified the barriers in OSC adoption through literature reviews and classified them into eight groups, including the knowledge barrier. To overcome the knowledge barrier, the role of education and academic institutions was emphasized for decision making in the early planning phase. To identify and evaluate the failure factors, Wuni and Shen [11] conducted a structured questionnaire survey among experts. Limited technical knowledge, capability, and experience were identified as among the four principal barriers. To summarize, while OSC projects have been implemented for decades, the industry continues to suffer from a lack of knowledge, experience, and availability of skilled engineers. Therefore, the barriers related to knowledge and experience should be overcome for the successful implementation of OSC.

2.2. Complexity in Design and Planning Phase of OSC Project

The decision to adopt the OSC method should be taken in the early project phase, and appropriate decisions should be taken to mitigate the risk of failure factors [10]. This requires early advice on the features of OSC from experienced and skilled specialists; several studies have been conducted to mitigate the lack of specialists and to support the early phase of construction. To determine the appropriate level of modularization in the early phase, Sharafi and Rashidi [28] identified the critical decision-making criteria through a literature review and developed a decision-making support system. Using this system, the building elements for prefabrication were selected and compared with the assessment results of the traditional onsite construction method derived from the system, and the level of modularization was evaluated. However, prefabrication of building elements increases the project complexity because the considerations for OSC such as transportation, connection methods, onsite assembly, and lifting of elements should be included in the planning and design of the project [29]. This increased complexity can be attributed to the possible occurrence of design errors, such as omissions and conflicts, and the unresolved errors are manifested as factors that lead to inefficient project execution. These include out-of-sequence deliveries, fabrication, and onsite errors [30]. Using the traditional design process for OSC projects may lead to design errors because the traditional process does not suggest how the information from the OSC stakeholders should be applied [29]. In OSC projects, changes in the planning and design are more difficult to incorporate than in the traditional construction method, and the cost is higher because the integrated prefabrication process should also be revised [31]. Therefore, to deal with significant failure factors such as poor design, inappropriate supply chain management, and late commitment, it is necessary to ensure early advice and planning to manage the entire project process smoothly [5,11,12].

Building information modeling (BIM) has been used as an effective tool to reduce errors and conflicts in OSC projects. To identify prefabrication errors, BIM was used to compare the as-built elements with the building design. Kim and Wang [32] developed a quality inspection system for precast concrete (PC) elements. The quality of the elements was assessed by comparing the BIM design with the point cloud data of the as-built component collected by laser scanning. The quality inspection data were shared with all project stakeholders through BIM. Arashpour and Heidarpour [33] used a laser scanner to identify discrepancies in the prefabricated elements by comparing them with the BIM model. To minimize geometric variability, an optimization model that included a balanced penalty and incentive scheme was used. These studies focused on the quality inspection of the fabricated elements, but a method that can be used in the design phase is required. Gbadamosi and Mahamadu [34] developed a design assessment system using BIM for OSC by following the lean construction principle. Based on the assessment factors, the design was modified and optimized for the OSC project. Alfieri and Seghezzi [35] developed a BIM-based framework, which included an architectural planning process. The framework lists the BIM tasks for a prefabricated bathroom unit according to architectural planning. Owing to the nature of OSC and its complex processes, the effect of BIM is larger than that in traditional construction methods. Abanda and Tah [36] investigated and quantitatively assessed the effect and emphasized that the lack of understanding of BIM in OSC projects hindered its use. As reported in previous research, BIM is an effective tool for sharing information between participants and finding errors in design and prefabricated elements. However, previous studies have the limitation that the comprehensive design process or design method for OSC projects was not included in the research scope.

2.3. Design for Manufacturing and Assembly (DfMA)

In OSC projects, the building is constructed by assembling discrete prefabricated elements that are integrated through standardized interfaces, rules, and specifications [37,38]. For integration, OSC projects require a high degree of planning, which has been considered a significant challenge [10]. To overcome this challenge, DfMA was considered an appropriate design method in the OSC industry. The goal of DfMA is to provide manufacturing and assembly information during the conceptualization stage of the design [13].

Many studies have been conducted to include manufacturing and assembly information in the design phase. Based on a review of related literature, Gao and Jin [39] defined the following perspectives for the adoption of DfMA in OSC: a systematic process, design evaluation model, and prefabrication technology. To integrate the information for manufacturing and assembly into the design process, a project delivery method that can involve project participants in the early design phase should be selected. Charlson and Dimka [40] identified the risks in OSC projects and suggested a procurement model for volumetric offsite manufacturing. Johnsson and Meiling [41] investigated the defects that occurred in prefabricated timber modules and demonstrated that the defects were associated with an inappropriate building system and structural design. The results of the study indicated that the structural transformation in the assembly process should be included in the structural design. Liew and Chua [42] introduced a lightweight steel–concrete composite modular system. In the design phase of the system, general considerations such as materials, structural type, height, and tolerance of units were considered. Alfieri and Seghezzi [35] included the specific considerations of OSC projects, such as prefabricated building structures and mechanical, electrical, and plumbing (MEP), into the architectural planning process. The lean principle has been adopted to reduce the non-value-adding tasks or processes. By reviewing the process of OSC projects, the constraints and limitations can be addressed in the OSC planning and design phase [34,39]. Gbadamosi and Mahamadu [34] developed a BIM-based design assessment system that integrates lean principles such as the repeatability of prefabrication and simplification of the assembly process in the assessment. To evaluate the design in terms of DfMA, Rausch and Nahangi [43] developed a simulation model based on the tolerance distribution statistical data to predict the misalignment of elements. In the system, the building design was decomposed into a subassembly, and the tolerance of connections between the elements was predicted by the model. By adopting the model in the design phase, the building design can be assessed in terms of quality, tolerance, and efficiency of onsite assembly.

Owing to the complexity of an OSC project, information management is required to facilitate communication between project stakeholders. Persson and Malmgren [44] emphasized on the need for information management in the design phase of OSC projects. Their study demonstrated that the lack of interoperability between various software packages used by manufacturers and constructors resulted in delays caused by searching for, sharing, and recreating information in the design process. The results of the case study demonstrated that knowledge of information management was required to customize the system according to the requirements of manufacturing companies and contractors. BIM has been used as an information-sharing technology in OSC projects. Abanda and Tah [36] investigated the usefulness of information management using BIM. However, the benefits of BIM and OSC were not assessed over the entire lifecycle of OSC projects. Previous studies related to DfMA have focused on specific details or aspects of OSC projects. However, to advise in the early design phase and overcome the lack of knowledge and specialists, a comprehensive design process and guidelines for OSC based on the integrated knowledge from past studies are required.

3. Method

To mitigate the lack of experience, knowledge, and specialists in the OSC industry, this research suggests a design process for OSC projects by identifying the considerations that should be integrated into the process. To integrate the fragmented considerations reported in previous studies, a method to search and filter the literature is required. Tranfield and Denyer [45] investigated the review methods that were widely used in evidence-based research, such as those in the field of medical science, and organized the reviewing methods depending on the research topic. In the research, it was emphasized that to address the research question by reviewing relevant literature, the review process should be thorough, unbiased, and rigorous. Systematic literature review (SLR) methods have been widely used for a structured review process, and the trends of studies and directions of future research were identified in various research areas by using this method. Wuni and Shen [5] adopted the SLR method to identify the barriers to the adoption of OSC. To maintain objectivity, the literature collected by using a structured query with a keyword was reviewed. The findings from the reviews were integrated using meta-synthesis. Gao, Jin [39] conducted a literature review related to DfMA by adopting SLR and classified the DfMA into three categories.

Integration of numerous studies is similar to writing a review article in that a broad literature review should be conducted from an unbiased perspective. Therefore, this study adopted the SLR method. As a first step in SLR, relevant studies were searched in Scopus as the search engine because of its wide coverage, accuracy, and ease of retrieval [5,39]. To include publications related to DfMA, keywords such as design for manufacture and assembly, DfMA, design for assembly, design for OSC, design for modular construction, and design for precast concrete were used. Then the keywords were grouped to include studies that focused on considerations after the design phase, such as transportation, element assembly, and lifting. The first group included the subcategories of the OSC method, such as offsite construction, precast concrete, modular construction, and modular integrated construction (MiC). The other group included research topics such as transportation, lifting, and onsite assembly. To search the publications, the keywords in each group were combined, such as transportation in modular construction and onsite assembly of precast concrete.

In the search results, 364 publications related to DfMA and 191 publications related to the considerations in the design phase were identified. The inclusion criteria were as follows: (1) article type of journal, (2) articles written in English, and (3) published articles, i.e., articles that were in press were excluded. Then, the articles were filtered using the following exclusion criteria: (1) general information on DfMA, (2) articles not related to the construction industry, and (3) articles focusing only on the manufacture of specific elements that are not related to the entire building design. Finally, 24 studies were filtered for a literature review to identify the considerations in OSC. Figure 1 shows the steps for developing the OSC design process.

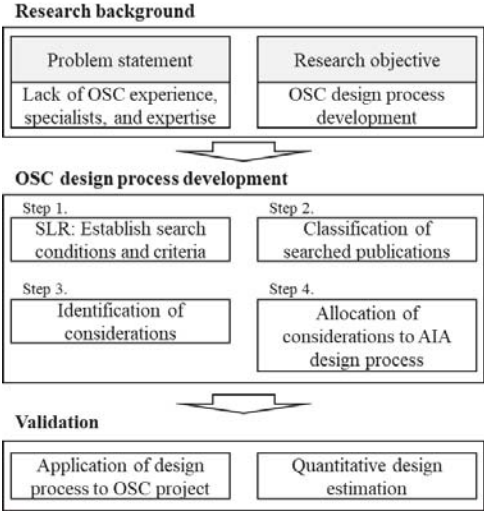


Figure 1. Steps for OSC design process development.

4. Considerations in Design Phase for OSC Project

4.1. Considerations in Structural Design

The considerations reported in the publications identified through the search criteria were classified as considerations related to (1) structural design or (2) architectural design. Table 1 shows the studies related to the considerations in structural design. In OSC projects, the size of the prefabricated elements is limited because the size should satisfy the traffic law for transportation and the element should be designed considering the efficiency of lifting and assembly. After transportation, the discrete elements are assembled onsite to construct the building structure; therefore, the structural performance of the assembled elements as the whole building structure should be ensured. To evaluate the performance, many studies have focused on various performance criteria. The origin of anti-seismic research focusing on precast concrete elements can be traced back to the early 1990s [46]. Englekirk [47] investigated the seismic performance of PC buildings and the effect of the connection design between components on the seismic performance. The assembled elements are vulnerable to lateral loads such as seismic loads, and securing the structural performance is a major consideration in OSC projects. Therefore, many studies related to the seismic behavior of an element, performance evaluation of structures obtained by the assembly of the elements, and the connections between the elements have been conducted [46]. Gu and Dong [46] suggested an assembled rebar lap splice and tested the precast and cast in situ shear walls, where the suggested splice was applied by changing the position of the splice and length of the rebar lap in PC shear walls. The test results showed that the seismic performance of the PC shear walls was equivalent to that of cast in situ shear walls. Ding and Ye [48] investigated the seismic performance of a joint between a PC column and girder by using a bolt-connecting system. The experimental results demonstrated that the joint system with bolt connection satisfied the structural requirements and improved the resistance to seismic loading. Feng and Xiong [49] suggested a numerical simulation method for the assessment of the seismic performance of dry connected PC beams and slab assemblies. Wu, Xia [50] investigated the flexural behavior of PC walls and steel shoe composite assemblies with various dry connections. The flexural behavior tests were conducted under five different scenarios, and the results showed that the performance satisfied the requirements regardless of the connection arrangement. In summary, the design of the connection system in prefabricated buildings is a major consideration in structural design because the assembled prefabricated elements are subject to brittle shear failure during earthquakes and are more sensitive to seismic loading when compared with conventional reinforced concrete (RC) structures.

Table 1. Studies related to the considerations in structural design.

	Considerations in Structural Design			
Element	**Lateral Load**	**Shear Force**	**Flexure**	**Constructability**
Joint	[48,49]	[56]	[57]	[42,52,55]
Wall, slab, and column	[46,54]		[50,51]	
Structure	[47,53]			

In addition to lateral loads, connection systems should meet other performance criteria. In the study by Jiang and Zhang [51], the out-of-plane bending performance of a PC hollow core slab with a suggested lateral joint was tested. From the test results, the relationships between the performance and effects of the rib of the slab and the number of joints on the crack of the slab were identified. While assembling the elements onsite, the temporarily connected elements should resist the loads generated during onsite construction. Araújo and Prado [52] focused on the temporary beam-to-column connection during onsite assembly to ensure construction safety. In this study, a beam-to-column connection was suggested, where the U-shaped steel corbel was embedded in the column to support the cantilevered steel tube at the beam extremity. The suggested connection system showed 60% of the theoretical strength of the corbel in the assembly phase, which ensured safety during construction.

In addition to the studies related to the structural performance of element connection systems, studies have been conducted to improve the comprehensive structural performance of whole building structures consisting of prefabricated elements. Dal Lago and Biondini [53] suggested a framework for the structural conception and seismic behavior assessment of PC structures with a cladding panel. The suggested PC structure with a cladding panel showed improved seismic behavior owing to the flexibility of the PC frame and stiffness of the panel. Vertical and horizontal wall connections are considered vital in the PC shear wall structure (PCSW). Horizontal wall connections usually ensure the normal functioning of the PCSW, and the development of a horizontal wall considering constructability and high structural performance is important for the PCSW structures. Wang, Li [54] investigated the seismic performance of precast shear wall structures with suggested horizontal wall connections, and the test results indicated a performance similar to that of the cast in situ concrete shear wall.

In the connection of a 3D volumetric modular unit, the connection system should ensure constructability in addition to satisfying the structural requirements. The lifting and assembly of units at the construction site are considered critical tasks. Therefore, the project efficiency is related to the assembly of large and heavy units. Sharafi and Mortazavi [55] suggested an interlocking system to connect the modular units and tested the structural performance of the proposed system. In addition to satisfactory structural performance, the constructability during onsite assembly was improved by automatically interlocking the units. Liew and Chua [42] suggested a connection system for a high-rise modular building and connected the units via a vertical rod and horizontal tie plate. The system was used to connect the building to an external unit. Lacey and Chen [56] suggested a connection system for modular steel units consisting of structural bolts with interlocking elements. The shear force–slip behavior of the suggested connection was improved when compared with that of the previous interlocking system. In addition to the structural performance, the limitation of small allowable tolerance was mitigated, and the constructability was improved by using bolt connections. Luo and Ding [57] investigated the mechanical performance of beam-to-column connections for steel-framed modular units. The proposed end-plate stiffener connection showed better performance than the other connection types.

In the structural design of an OSC project, discrete elements are assembled to construct a building structure. Owing to the nature of the discrete elements, it is necessary to ensure the following in the structural design phase: (1) the integrity of the elements for the composite behavior to resist various types of loads such as lateral and vertical loads, (2) meeting the structural requirements of the comprehensive building structure after element assembly, and (3) the constructability of the elements during onsite assembly.

4.2. Considerations in Architectural Design

The building design for OSC projects should be separated into elements for transportation and onsite assembly. The constraints related to the nature of the OSC project need to be included in the design. Table 2 lists the studies related to the considerations in architectural design. In modular construction, the building structure consists of 3D-volumetric units and the spaces for the facilities are generated by combining one or more units. However, it has constraints such as heavy weight of the concrete modular units and larger size than the materials used in conventional construction methods. In the study by Liew and Chua [42], the design guidelines for steel–concrete composite high-rise modular buildings were suggested to address these constraints. The steel–concrete composite units have long span, design flexibility owing to the open space framing system, and ease of assembly when compared with concrete units that require in situ grouted joints. Moreover, by using lightweight aggregate concrete, the issues related to heavy weight and fire resistance were mitigated. A high-capacity mobile or tower crane is used to assemble the modular units onsite. Hyun and Park [58] suggested an optimization model for tower crane location by considering the distance between the destination of the units and the locations of the tower crane and trailer at the construction site. The study emphasized that the weight of the units, route of transportation to the tower crane, and trailer parking location should be reviewed in the design phase, and the model can be used to find the optimized tower crane location.

Table 2. Studies related to the considerations in architectural design.

Considerations in Architectural Design				
	Design Scope			
	Site	**Building**	**Element**	**Progress Method**
Production			[42]	
Transportation			[59–63]	
Onsite assembly	[58]	[64,65]		
Information sharing				[66,67]

Prefabricated elements are usually transported by a trailer. Vibrations during transportation damage the prefabricated elements. The cost of restoring the damage is higher than that of rework in conventional construction methods [29,59]. Therefore, the need for a design procedure to consider non-traditional loads, such as transportation, lifting, and other pre-installation loads, has emerged [60]. In modular construction projects, the effects of vibration are different depending on variables such as speed, road condition, and structural type of the elements and the components of the furnished units. Innella and Bai [59] conducted an experimental study to quantify the acceleration affecting the modular units during transportation. The accelerations of the trailer and units were measured using triaxial accelerometers. Based on the results, the power spectral density, which characterizes the random vibration, was presented according to the speed and road conditions. The mechanical responses of the units during transportation can be calculated using the presented spectra. In a follow-up study, Innella and Bai [60] ascertained that the damage occurrence probability was high in the non-structural elements of modular units such as plaster board and their connections, which are subjected to long cyclic accelerations during transportation. In this study, a framework was developed to evaluate the damage levels of non-structural elements during transportation according to different parameters such as stress probability, accelerometer position, speed range, and road roughness.

The amount of dynamic loading during transportation depends on parameters such as the amount of load on the trailer, location of the center of mass, trailer suspension type, and level of damping of the vibrating part. Godbole and Lam [61] mentioned that the response behavior of buildings to the loads caused by an earthquake is similar to the behavior of the loads during transportation and investigated the effect of the parameters on the vertical motion of the trailer chassis. The authors suggested the specific vertical acceleration that the mount and its connection to the trailer should withstand and estimated the vertical accelerations that damage the components attached to the unit. In a follow-up study, Godbole and Lam [62] investigated the pounding on trailers caused by the accidental uplifting of a unit during transportation. In this study, a methodology to estimate the impact acceleration resulting from the pounding of a unit on a wooden mount and the response accelerations of the components attached to the unit at the mid-span location were predicted. The prediction results showed that a typical steel unit amplified the component acceleration response up to three times. Previous studies related to unit transportation implied that the design of prefabricated elements such as modular units should consider assembly-related constraints such as weight and size, transportation-related issues such as the deformation of structural components caused by dynamic loads, damage to the non-structural components attached to the unit caused by the transformation, and amplified impact transferred from the structural components. This is in agreement with the study by Bogue [63], who suggested a guideline to reduce damage during transportation and recommended the minimization of the use of fragile parts. These studies indicate the importance of considering assembly and transportation in the design stage of OSC projects.

In OSC projects, the work of enveloping the building structures affects the project performance because the assembled building elements are integrated through the building envelopment. Therefore, novel technologies for envelopment of prefabricated buildings are required. PC panels and cladding have been used to enclose prefabricated and conventional buildings. A prefabricated building envelope is required to be waterproof because the joints of both the prefabricated envelope and building structure, which are connected onsite, are more vulnerable to water problems than cast in situ concrete envelopment. Gorrell [64] investigated the condensation problems that caused damage to the finished materials such as insulation and gypsum boards. In this study, the examples and causes of condensation in PC cladding panels were described and reviewed, which should be included in the design phase to reduce the potential damage from condensation. Orlowski and Shanaka [65] suggested a methodology for designing waterproof seals for prefabricated buildings. They conducted a theoretical review of the generation and transfer of moisture, such as the capillary action of moisture in narrow gaps on the building surface. Then, the considerations for the application of the waterproof seal for prefabricated buildings were identified, such as fast erection time and omission of scaffolding. Based on the theoretical review and considerations, the design details of waterproof seals were suggested and applied to the joints of panelized and modular buildings.

To achieve the goal of design in OSC projects, it is necessary to facilitate collaboration between the project stakeholders. Chen and Lu [66] presented a case study of a curtain wall system designed using a DfMA-oriented approach to meet the requirements of stakeholders such as clients, manufacturers, and contractors, and a multidisciplinary team was organized for the integration of knowledge and experience. The authors recommended that the project delivery method to integrate the team, such as design–build, should be selected, and the stakeholders involved in the design phase need to be identified depending on the project objective. Yuan and Sun [67] argued that although BIM can facilitate information exchange between stakeholders, the existing BIM tools do not fully account for the prefabrication of building elements, such as element production and transportation. In the study, the DfMA approach for prefabricated buildings was integrated with a parametric design method using BIM, and the authors suggested a DfMA-oriented design team, prefabricated element manufacturing process, and a DfMA-based BIM model development and optimization process. This study described the prefabricated building design process, including the component split from conceptual building design, considering the manufacturability and constructability.

In summary, the design of prefabricated buildings should consider an intermediate process owing to the nature of the OSC project. Many researchers have focused on the transportation aspects of prefabricated units, such as element size limitation set by traffic laws, vibration during transportation, and the use of impact-resistant materials. This means that the space in a building can be separated using the prefabricated elements, and the elements must be able to cope with vibration and deformation during transportation and lifting. Moreover, to consider the assembly at the construction site, the weight of the elements and site layout for facilitating the entry of the trailer should be included in the architectural design. Finally, project delivery methods or information-sharing tools to facilitate OSC project progress are required. Therefore, to support the design process of OSC projects, design guidelines that allocate the considerations for each sub-design phase are required.

5. OSC Design Process

The objective of the OSC design process is to support the OSC project stakeholders by sharing the identified considerations for the sub-design process; thus, this process can be used as a design guideline. To develop the process, it is necessary to allocate the considerations to the appropriate design phase to prevent errors such as omissions and conflicts caused by not including the essential considerations. The process is based on the conventional design process of the American Institute of Architects (AIA). AIA provides a checklist consisting of the tasks that should be conducted in each sub-design phase based on the standard form of agreement between the project stakeholders. The scope of the checklist is from the pre-design to construction documentation phase, and the checklist specifies the stakeholders who should be consulted by the designers to conduct the specific tasks in the design phase [68]. For example, in the project programing of the pre-design phase, the architect collaborates with the consultants to determine the preliminary structural, mechanical, and electrical systems. In this phase, the decision making to determine whether the OSC method will be applied can be included by allocating the considerations related to the decision-making process. The suggested process is based on the assumption that the OSC method is considered in the pre-design phase; if it is decided to apply the OSC approach, the project stakeholders will cooperate with the architect to provide consultation for the design, production, transportation, and onsite assembly of the prefabricated elements. The considerations include those reviewed in the previous section and those related to the OSC design and planning mentioned in previous studies. Table 3 presents the OSC design process, including the considerations for the OSC project; the other tasks in the AIA process, which are similarly applicable to the OSC project, are not included in Table 3.

In the pre-design phase, the requirements of the architectural program are reviewed with the owner. Because many studies have argued the importance of the early involvement of the OSC method, the suitability of the OSC method is evaluated in this phase to maximize project efficiency. If the program is suitable for the OSC construction of buildings, such as dormitories and apartments, comprising residential units that can be standardized, the architect supports the decision-making process of the owner based on the identified benefits and constraints [5,8,10,15,16,22,24,31]. After deciding to adopt the OSC method, the architect organizes the design team, including consultants, such as structural, MEP, and special engineers. In the OSC project, the manufacturers and engineers who have experience in or knowledge of OSC are included in the special engineering group to provide advice in the early project phase [69]. At the end of the pre-design phase, the preliminary building systems are determined, and the specific method of OSC (e.g., MiC, PC) is selected based on the consultation and review of previous cases. Before the schematic design phase, site analysis is conducted and all consulting staff visit the construction site. In this phase, the information for transportation and onsite assembly, such as regulations related to traffic laws, road conditions for transport from potential manufacturing factories, pathways for trailers to approach the site, and potential location of the crane, is collected [29,58].

Table 3. OSC design process including considerations for OSC.

	OSC Design Process			
Phase	**Tasks in AIA Design Process**	**ID**	**Considerations for OSC**	**Related Studies**
Pre-design	Review owner's requirements	1	Evaluate suitability of OSC and support owner's decision-making process	[5,8,10,15,16,22,24,31]
	Organize design and consultant team	2	Include experienced manufacturer and engineer in consultant team	[69]
	Determine preliminary building system	3	Determine the specific OSC method and project delivery method	[66]
Site analysis	All stakeholders visit the construction site	4	Check the site condition for transportation and onsite assembly	[29,58]
Schematic design	Review the laws, codes, and regulations applicable to building	5	Review the laws, codes, and regulations applicable to the selected OSC method	[12]
	Present preliminary design for the owner's approval			
	Select major building systems such as structural and MEP system and determine location and space for the systems			
	Prepare basic schematic design	6	Review the design guideline for OSC	[42]
	Begin research on materials, equipment, fixtures	7	Identify materials that can resist vibration during transportation and assembly	[59,60]
	Determine structural form, design load, materials	8	Consider the load during transportation and assembly	[52,61,62,70]
Design Development	Design typical construction details and layout of building systems	9	Separate building design for element prefabrication in collaboration with designer for split element design	[67]
		10	Consider the constructability for onsite assembly	[42,55]
Construction Documentation	Prepare drawings and specifications for the construction	11	Determine specifications of elements such as size, width, height	
		12	Design the joint for discrete prefabrication of elements considering structural performance requirements and constructability	[46–51,54,56,57,64,65,71]

In the schematic design phase, laws, codes, and regulations applicable to the service of architects and necessary information for the OSC method, such as regulations for transportation and road conditions near the construction site are reviewed. Based on this review, a preliminary design is presented for the owner's approval. After obtaining approval, the tasks in the schematic design are initiated. In this phase, the major building systems to be used in the project, such as structural and MEP systems, are selected through analysis of the comparative systems, and the space and location of the systems are determined based on the requirements. The structural form and design load are determined, and the materials for the interior, exterior, and structure are studied [68]. Therefore, the load caused by transportation, lifting, and assembly should be considered in this phase [61,62,70]. Then a schematic design is prepared, which includes the features of the OSC method, such as repetitive production of elements and allowable span of space [42]. Materials that cannot resist vibrations and shocks during transportation should be excluded from the design [59,60]. In addition to consulting structural and MEP engineers, the architect draws the architectural design in collaboration with the engineers in the manufacturing unit by considering manufacturability and constructability.

In the design development phase, an approved schematic design is developed. The design documents in this phase include the typical construction details and layouts of the building systems, and they describe the size and features of the architectural, structural, mechanical, electrical, and other elements. The building design is separated into prefabricated elements, which are designed independently to determine their specifications, such as length, width, and height. In the separation process, the building parts to be prefabricated first are identified considering standardization and economic feasibility. For example, certain zones or floors in the architectural program may be excluded from prefabrication. In general, the architectural designs are reviewed for prefabrication of all structural elements. However, if some members are irregular or if the quantity is too small to be prefabricated, it can be evaluated whether the elements are to be constructed using the cast in situ concrete method, whereas non-structural elements, such as the building cladding, can be prefabricated [53]. After identifying the building parts that qualify for prefabrication, the elements of building design, such as beams, slabs, and columns, are split for prefabrication considering their transportation and assembly. Yuan and Sun [67] have recommended that the element-split designers, including the manufacturer and assembly technicians, from the construction company be included during the separation process. These personnel should cooperate with the architectural and structural designers. Additionally, appropriate communication channels must be established between these designers to obtain timely feedback from the stakeholders. The individual elements are assembled onsite; therefore, the constructability of OSC indicates the ease of assembly. In this phase, the details of the connecting system for the elements are prepared.

In the construction document development phase, drawings and specifications are prepared to describe in detail the quality level, performance criteria of materials and systems, and other requirements for the construction. In terms of structural design, the dimensions of the individual elements, such as width, height, and cross-sectional area, are determined. In addition to the size of the elements, the design and performance of the joint connecting the prefabricated elements of the PC structure should also be considered, because the structure is more sensitive to lateral loads, unlike the joint of a traditional reinforced structure. Therefore, in this phase, it should be ensured that the selected joint design can resist lateral loads such as the earthquake loads specified in the structural requirements. At the construction site, the prefabricated elements are assembled according to the joint design. The efficiency of the onsite assembly can be improved by considering the constructability when designing the joint. For example, the PC structural elements are assembled by connecting the rebar of the elements using sleeves or grouting non-shrinkage mortar to the joint, although the connection method differs depending on the joint design. Therefore, it is helpful to improve the constructability to reduce the number of rebars in the elements while preserving the structural performance [71]. After the construction documentation is complete, the manufacturer prepares the drawings for the prefabrication of the elements, and contractors prepare the shop drawings for element assembly based on the construction documentation.

6. Case Study

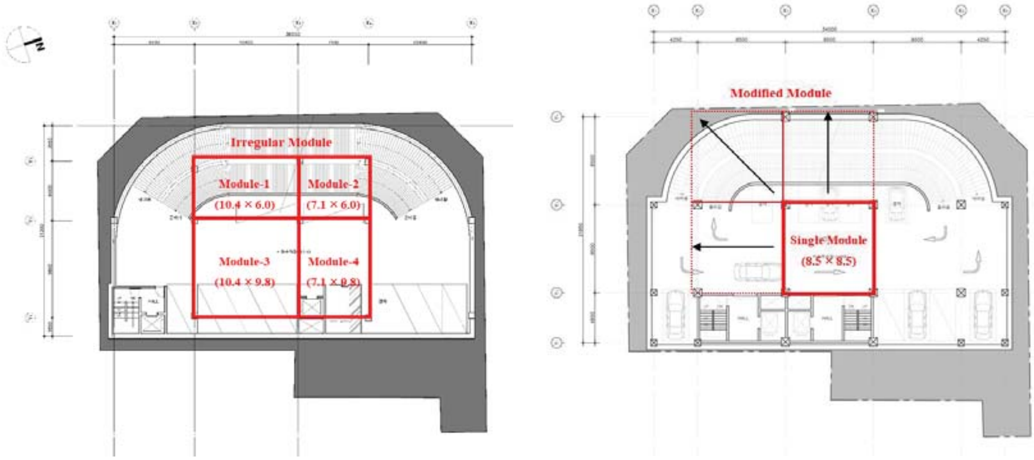
A case study was conducted based on the design of the OSC project to validate the effectiveness of the proposed OSC design process. The Korean government has increased its R&D funds to promote OSC projects. As one of the national R&D projects, the objective of this case study was to construct a complex facility in Seoul by adopting a PC construction method that consists of public housing, welfare facilities for elderly people, and offices for local facility management corporations. Project-relevant data, such as the construction cost, duration, and unpredicted errors, should be collected from the project to improve the efficiency of urban OSC projects. Table 4 presents the information on the project undertaken in the case study. This project was planned to be built using a traditional construction method and the designs of the design development phase were completed accordingly. However, the construction site was located in an urban area and, thus, the OSC method was considered to suppress the negative impact on the residential area near the site (consideration ID 1 in Table 3). Moreover, to include complex facilities, PC was considered, given that the method makes it relatively easy to construct long span area for commercial facilities compared to the other OSC methods (consideration ID 3). The previous design for the RC method was modified to that for a PC project to achieve the project objectives. Considering the situation in Korea, where the OSC method is not mature, it was decided to apply prefabrication only to the structural elements, and the other building elements, such as MEP and interior and exterior elements, were excluded.

Table 4. Case project information.

Project Information	
Location	Yeouidaebang-ro, Yeongdeungpo-gu, Seoul, Korea
Site area	1006.80 m^2
Floor area	4540.83 m^2
Floor	10 floors (Basement 3 floors)
Facilities	Public Housing, Welfare facility, Office

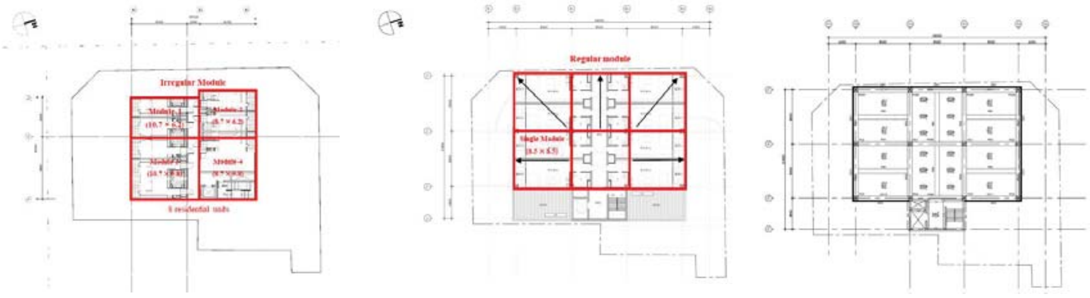
As the first step in the modification, based on the existing design, the scope to which prefabrication would be applied was established by considering the number of elements for repetitive production. The case was planned as a Rahmen structure, and slabs, columns, and girders were included in the scope. Elements that are produced in small quantities, such as the retaining walls of the basement floor, or those that are difficult to produce, such as the ramp of the basement parking lot, were excluded. In terms of standardization, an irregular architectural module was modified to reduce types of the PC elements. Figure 2 shows the architectural drawings of the basement before the modifications and the modified design. To create a regular module, the locations of the columns, cores, and ramps were adjusted. The relocated structural elements were installed at the same position on all floors, so that a regular module could be applied. The modified regular module resulted in the standardization of the elements. Figure 3 shows the floor plan before and after the modification. Figure 3b shows the architectural design of residential units that incorporate the regular design module. By using this module, the irregular shape of floor plan can be modified and the location of structural element from the basement was configured to be the same to improve the manufacturing efficiency. Figure 3c shows an erection drawing representing the standardized PC slab of the repetitive floor plan designed to minimize the element type derivations in the modification process (consideration ID 6 and 9).

When determining the column size, the generation of different column types was predicted owing to differences in the applied column loads and heights of each floor. To mitigate the reduction in manufacturing efficiency owing to the different element types, consultations were conducted with the manufacturer, and it was concluded that the length and width of the column cross sections must remain equal. The PC columns were fabricated using molds set according to the specifications of the columns, and the production cost was directly related to the repetitive use of the set mold. However, the transformation of the mold according to the change in the height of the column does not significantly affect the production efficiency, and the changes in the rebar placement specification of the column are not related to the transformation of the mold. Three types of cross-sectional column designs were created to increase the rate of repetitive use of the molds, and 20 sub-types of columns were prepared by changing the height of the column and rebar placement (consideration ID 6, 10, and 11). Figure 4 shows the examples of the types and sub-types of the columns, and Table 5 presents the specifications of the columns. The column “Sub-Types” in Table 5 indicates the number of types generated from types, and the column “Quantity” indicates the number of columns of each type considered in the building design. The number of derivations for designing the PC girders was greater than that for the columns. To mitigate the decrease in PC prefabrication efficiency caused by the increased derivations, the cross-sectional designs of the girders were limited to two types, as shown in Table 5.



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

Figure 2. Architectural building design modification: (**a**) architectural design of basement before modification; (**b**) modified architectural design of basement.



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

Figure 3. Modification for PC slab standardization: (**a**) floor plan of public housing before modification; (**b**) floor plan where regular architectural design module is integrated; and (**c**) standardized PC slab after modification.

In this case study, the PC structural elements were designed and most of the building structures were converted from RC to PC. Table 6 shows the quantities of PC and RC after the conversion. Although the quantity of PC was estimated to be 60%, a significant volume of onsite casting concrete was estimated because, in this case, topping concrete was applied to improve the integrity of the structural elements. Topping concrete was cast on the slab and joints after the installation of the elements. Thus, onsite casting of concrete and rebar placement were required. Improved integrity implies an increase in the structural performance to resist and transmit forces resulting from diaphragm action under lateral loads [72]. The method is also considered to be useful for the tolerance management problems of PC elements because the topping concrete covers all surfaces, including the joint. Moreover, the corrosion occurring in the structure can be alleviated, and problems related to water leakage can be solved (consideration ID 10 and 12). Despite the benefits of topping concrete, the increased onsite work reduces the efficiency of the OSC project. Therefore, it is necessary to develop a PC method that can mitigate problems such as corrosion, water leakage, and low integrity of structures consisting of all PC elements.

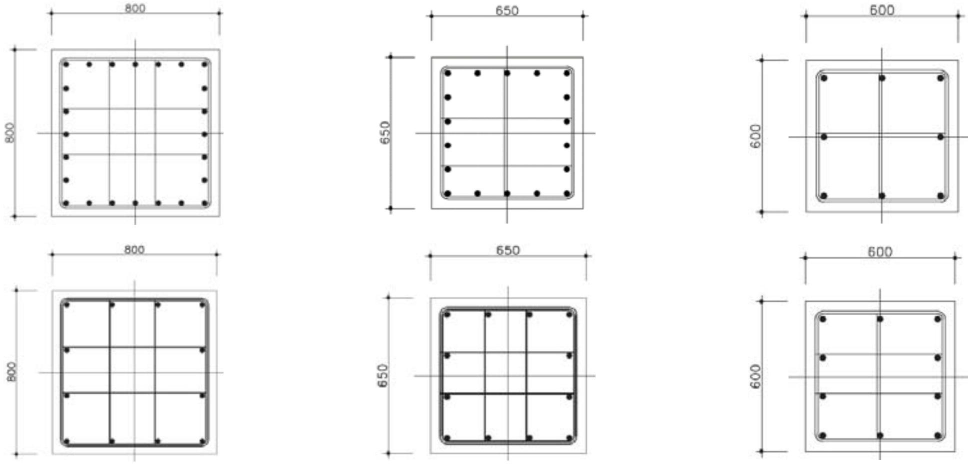


Figure 4. Examples of cross-section design of columns.

Table 5. Specification of PC columns and girders.

	Types	Size (Width × Length)	Sub-Types	Quantity
Column	Type 1	800 mm × 800 mm	8	44
	Type 2	650 mm × 650 mm	5	76
	Type 3	600 mm × 600 mm	7	38
Girder	Type 1	700 mm × 600 mm	23	262
	Type 2	480 mm × 600 mm	10	34

Table 6. Quantity calculations for PC and RC for the building in the case study.

Element	Quantity	Concrete Volume (m^3)		Quantity of Rebar Installed Onsite (kg)
		Offsite	Onsite	
Column	158	163.97	34.80	
Girder	296	590.59	320.11	40,476.15
Slab	590	508.42	448.07	27,879.93
Joint			21.66	12,866.11
Sum		1262.98 (60.4%)	824.64 (39.6%)	81,222.19

In many OSC projects, the design of prefabricated elements is undertaken during a later phase after construction documentation, which implies a high possibility of design changes. In this case study, the OSC method was applied in the design development phase, and the design modification for the PC structure was conducted based on the suggested OSC design process. In the modification process, the considerations from the design development process such as building design separation for elements produce, design considering on-site productivity, determining element specification considering manufacturing productivity, and the joint between discrete elements were included. By adopting this approach (1) design changes could be reduced, (2) the portion of standardized element can be increased using this module design, and (3) the manufacturing efficiency could be improved by considering DfMA in the early design phase and by communicating with element manufacturer. By applying the suggested design process, a significant portion of structural elements changed to PC elements. This implies that the efficiency of the design phase in the OSC project will be improved. However, a limitation of this case study is that (1) the design process from the design development phase was applied in this case study because the case study based on the existing design for RC project, (2) only the structural design was considered in the design modification, (3) the considerations that are searched using selected keyword were included, and (4) design processes such as MEP and architectural planning, such as interior and exterior planning, were not validated.

7. Discussions

The benefits of OSC have been investigated in many previous studies and projects. However, there are still barriers and limitations to the widespread use of OSC projects. The lack of expertise and knowledge of the project stakeholders were considered major barriers, which resulted in design errors such as omissions and conflicts of information related to the OSC considerations. The errors decreased the project efficiency and caused a negative perception of the OSC method. To mitigate these problems, many studies have emphasized the need for OSC design guidelines. In this research, to meet this need, the design process for the OSC project was suggested, including the considerations for each design phase. To identify the considerations, a comprehensive literature review was conducted, and the considerations were classified into structural and architectural considerations. From the review, it was identified that the structural integrity of discrete prefabricated elements should be ensured because the prefabricated components are susceptible to transfer the lateral load to the other elements. To ensure integrity, the structural considerations were sub-classified according to the element type and external forces on the elements. The other finding was that the elements should be designed considering the efficiency of manufacturing, transportation, and assembly. To improve the efficiency, the architectural considerations were sub-classified according to the scope of design, such as site, building, elements, and the downstream processes of OSC projects such as manufacturing, transportation, and onsite work. Based on the findings, the classified considerations were allocated to the related sub-design phase, which was based on the design process of the AIA.

To validate the suggested process, design modification of the OSC project was conducted as a case study with consultants from OSC engineering and manufacturing companies. In the modification, 60% of the building structure was changed from RC to PC, and 40% of the onsite casting concrete was topping concrete to improve the integrity of the elements. Using the suggested process, the separation of building design for element production was conducted with the consultants by considering DfMA. By involving consultants, the increase in cost and project duration caused by design changes can be reduced. In the case study, the element design was conducted in the schematic design phase. Given that the results of a phase affect the subsequent activities and phases, the involvement of OSC design in the early phase implies that a potential design change was mitigated. The reduction in design changes by adopting the suggested process can be considered a contribution of this research. The second contribution is that it can shorten the project period by shortening the design time for fabrication of the elements. The suggested process can also be used as an OSC project guideline because the project stakeholders lack the necessary expertise to know when and with whom the relevant information should be shared. The limitations of this research are as follows: (1) the design process was developed based on a review of selected publications, and (2) the case study focused on the structural design and excepted other design considerations such as MEP and exterior cladding planning.

8. Conclusions

OSC is considered a promising construction method owing to its various benefits, and an increasing number of projects have adopted this method. However, OSC is not a mainstream technique in the industry owing to various limitations and constraints that hinder its widespread use. The lack of expertise and knowledge of project stakeholders were identified as the major limitations. Moreover, these limitations caused errors such as omissions and conflicts in the design phase, which affected project efficiency and created a negative perception regarding the technique in the construction industry. These problems indicated the need for a design guideline.

To meet this need, this research suggested a design process for an OSC project, which included the considerations related to the features of an OSC project. To identify the considerations, a comprehensive literature review was conducted, and the identified considerations were classified into considerations for structural and architectural design. To develop the design process, the considerations were allocated to the related sub-design process based on the recommendations of the AIA. To validate the suggested process, design modification was conducted as a case study and, as a result of the modification, 60% of the structural elements were converted from RC to PC. Moreover, in the modification, the considerations to be applied at each phase were intended to be reflected in the design process of the case study as follows: (1) the structural elements were standardized by the application of module design (design phase), (2) the design method that included detailed elements without a decrease in manufacturing productivity was suggested (manufacturing phase), and (3) the topping concrete method to increase the integrity between discrete structural element was suggested (on-site assembly phase).

Through this process, the duration for building and element design could be shortened, and the errors in the design phase could be reduced by considering the features of the OSC project and consulting with an OSC engineering company. However, this study has the following limitations: (1) the design process is based on a review of selected publications, (2) the case study focused on the structural and architectural design, (3) other design considerations such as MEP and exterior cladding planning were excluded, (4) some considerations in the process were not included in the case study because it was based on the results of design development phase for RC, and (5) the effectiveness of the suggested process was not quantitatively estimated. In future work, to overcome the limitations, an additional validation will be conducted based on the quantitative project data.

Author Contributions: Conceptualization: H.-G.K.; methodology: J.-S.K. and H.-G.K.; formal analysis: H.H.; resources: J.-S.K. and H.H.; writing—original draft preparation: H.H.; writing—review and editing: H.-G.K.; funding acquisition: J.-S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by a Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure, and Transport (Grant 22ORPS-B158109-03).

Data Availability Statement: Data generated or analyzed during the study are available from the corresponding author by request.

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

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Review

DfMA for a Better Industrialised Building System

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Abstract: To improve the performance of the construction industry, innovative methods were introduced to make them better. Industrialised building systems (IBS) and prefabrication construction are the popular methods used and studied. However, these methods are still unable to meet the demands of the stakeholders. Design for manufacturing and assembly (DfMA) is a design principle that is seen as capable of improving the situation. The uptake of DfMA in the construction industry needs to be analysed to obtain a better picture of the existing condition of the method and its manner of implementation it going forward, but there are still too few studies performed on this topic. This paper gathers relevant articles from the previous studies on DfMA. With the available data, the main benefits, hindrance factors, and enabling factors for DfMA uptake in the construction industry were identified in this study. The authors also identified the research trend among the research themes and the benefits of building information modelling (BIM) integration with DfMA. By synthesising the information from previous studies, a conceptual framework was developed. Knowledge gaps and future potential research topics are also discussed in this paper, forming a simple research framework for future effort guidance. With a suitable strategy and guidelines, the application of DfMA could improve the performance of the construction industry in Malaysia and other places with similar construction environments and approaches.

Keywords: DfMA; prefabricated construction; IBS; modern method construction; BIM

Citation: Abd Razak, M.I.; Khoiry, M.A.; Wan Badaruzzaman, W.H.; Hussain, A.H. DfMA for a Better Industrialised Building System. *Buildings* **2022**, *12*, 794. https://doi.org/10.3390/buildings12060794

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 1 May 2022
Accepted: 1 June 2022
Published: 9 June 2022

1. Introduction

The construction industry is an important sector that not only directly contributes to a nation's economic growth but also indirectly through its connection to the growth of other industries [1]. The construction industry also has a high impact on a nation's environmental and social attributes. To a certain extent, the construction industry also influences the political profile [2].

"Traditional" is a word that characterises the construction industry, which has seen little evolution until recently [3]. Compared to other sectors, the construction industry, which is highly fragmented with a complicated process, a dynamic business environment, and a multi-stakeholder approach, is lagging in adopting innovation [4,5]. The cast-in-situ technique has been used in construction forever. Though the technique has survived for so long, so have the issues that come with its manual operation, non-standard method, fragmentation, and discontinuity. Typical construction methods still widely use falsework, wet trades, and scaffolding, and create lots of waste [6]. These issues reflect poorly on the environmental, economic, and social impact due to resource wastage and time overrun [7,8]. Productivity of construction, which is directly impacted by the productivity of labourers, often results in delays and wastage [9]. The productivity of the construction industry is declining while the manufacturing sector continues to increase its productivity [10].

To increase the construction industry's performance, prefabrication was introduced. Prefabrication construction is a part of the industrialised building system (IBS) [11], which includes producing building components in a controlled environment off-site or on-site to be assembled later on-site [12]. The potential of IBS in increasing the construction industry performance has been mentioned in several studies [13,14]. Based on case studies, IBS could help in reducing the time, increasing the quality, and reducing the dependency on unskilled labour [15,16]. However, the industry is still unable to tap the full potential of IBS where projects that already apply IBS still have issues with time and cost overrun and dependency on unskilled labour [17]. The lack of communication and cooperation [17–19] together with lack of knowledge and experience [20] among major stakeholders are the main issues.

Several researchers have described design for manufacture and assembly (DfMA) as a concept that could turn the IBS practice into a more efficient practice [21–23], such as in the manufacturing sector. Application of the DfMA principles would promote a design process that optimises manufacturing and assembly functions, which also leads to cost and time savings. Such a process would also have a high impact on product quality and customer satisfaction [22]. Adoption of DfMA could make construction viewed as an industrialised activity with increased productivity and predictability [21].

Prefabrication construction through DfMA has shown high potential in improving the construction industry productivity and reducing the cost of labour [23,24]. Modern prefabrication and off-site construction are currently producing complete or incomplete modules depending on the project requirements [25]. Building components could be produced like the production of cars [26].

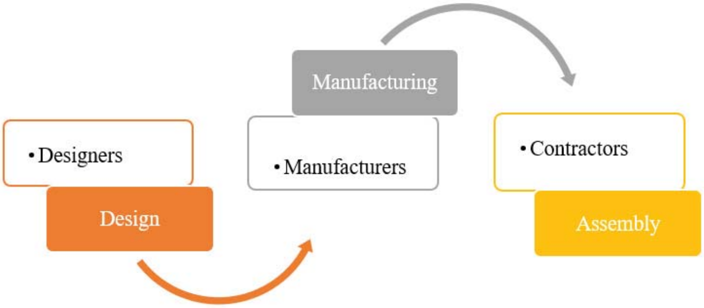
Even though the application of DfMA is not necessarily digitalised, the usage of some technologies, such as building information modelling (BIM), could help to make it more productive, similar to how other processes are made more productive through digitalization [27–29]. By using BIM, the design work and design check could be completed in less time [30]. BIM also makes the transition from the design phase to the manufacturing phase and assembly phase simple [31,32]. Integrating BIM would enhance the efficacy of DfMA.

Though there are several reviews related to DfMA studies, few are of the same theme as this current study. The article by Gao et al. [33] looked at the perspective of the construction industry in implementing the DfMA concept or principles, which are (1) a holistic design process, (2) the evaluation of the efficiency of manufacturing and assembly, and (3) DfMA as a tool of technology in the prefabrication model. The review paper by Lu et al. [34] explored the principles of DfMA and other principles that can be integrated with DfMA to make the process more beneficial, as well as in-depth comparisons of the benefits of DfMA to other concepts that have been integrated into construction practice, such as lean construction and value management. Hyun et al. [20] conducted a review on the off-site construction design process with a consideration of DfMA. However, they did not discuss the application factors of DfMA. Review articles by Musa et al. [2] and Jin et al. [35] discussed the application of sustainable industrialised building systems and off-site construction, respectively. Both articles discussed the technology for prefabrication but neither review discussed integrating DfMA in the process. These studies did not look at the strategies or integrate the factors that influence the application of DfMA in the construction industry.

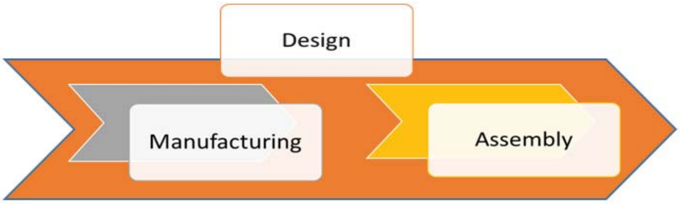
Despite the benefits of DfMA, its adoption in the construction industry is still relatively low and research linking DfMA to the construction industry is still limited [23,35]. There are too few data to influence the construction industry's players to adopt the principle. In a way, this hinders the construction industry from taking full advantage of DfMA. The objective of this study was to analyse the fragmented factors mentioned in previous studies that can influence the application of DfMA in the IBS project and the construction industry. From there, we developed a conceptual framework for DfMA application in the IBS project and the construction industry. It is hoped that this work can contribute to optimising the construction industry’s performance and add to the body of knowledge in this particular area of study.

2. Description of DfMA Principles

According to Gao et al. [23], evaluating and improving product design for manufacturing and assembly by providing input on manufacturing during the design process can be implemented through the DfMA method of analysis. DfMA is the combination of design for manufacture (DfM) and design for assembly (DfA). Where DfM focuses on minimising part counts, DfA focuses on making attachment simpler. Both are based on basic rules, past data, or simulation, with cost and time reduction along the way [23,26,36,37]. As shown in Figure 1, DfMA can be perceived as a systematic procedure that, when applied as part of the design phase, would add value to the construction and production process. Evaluation of a design for its assembly efficiency with minimal components, parts, and materials that need to be handled on-site is another way to look at DfMA.



Conventional prefabrication construction with over the wall concept



DfMA principles where the design encompasses manufacturing and assembly processes

Figure 1. Simplified DfMA principles.

Another side of DfMA that is often referred to is prefabrication, to the extent that some equate DfMA with prefabrication, where construction work is completed off-site as much as possible [23]. Another definition of DfMA according to Mesa et al. [36] is simply a principle that improves design for manufacturing, assembly, and cost, where the main product function remains intact.

In a paper by Tik et al. [37], the Royal Institute of British Architects (RIBA) defines DfMA in construction as an approach that facilitates greater off-site manufacturing and minimises on-site construction. The following are levels of off-site DfMA categorised by RIBA: (1) component manufacturing, (2) sub-assembly, (3) non-volumetric preassembly, (4) volumetric preassembly, and (5) modular building.

In the same paper, it is stated that the Singapore Building and Construction Authority (BCA) defines DfMA as where construction is designed and detailed for a substantial portion of work to be performed off-site in a controlled manufacturing environment. DfMA is a new approach that, by planning more works off-site, ensures that the manpower and time needed to construct buildings are reduced, while ensuring work sites are safe, conducive, and have a minimal impact on the surrounding living environment. DfMA is promoted in the Singapore construction industry as a way to improve productivity in a traditionally manpower-intensive industry.

DfMA Recognition

According to Tan et al. [38], several countries have either introduced the DfMA guide or emphasised DfMA's importance in construction. Such countries are the United Kingdom, Singapore, and Hong Kong governments. Other than that, two industry giants have indicated DfMA as the future of construction.

Typically, in the building design and construction process, the designer might not be able to consider all possibilities of the design solution and miss the chance to implement what should be worth having. Information from other parties is usually not there during early-stage design, which relies on the designer's knowledge and experience and may be lacking in terms of assemblies and on-site operation. DfMA as an evaluation model could help in this area [33].

The core aim of DfMA is to help designers optimise prefabricated building design and improve its one-time success rate utilising and integrating professional knowledge and information from other stages into the design stage. So, the DfMA principle should be applied at an early stage of prefabricated building design as much as possible [39].

3. Methods

Literature reviews in research form the basis of knowledge to be studied. By analysing and synthesising data from previous studies, we can improve our understanding of the knowledge under our studies [40]. This study is based on the evaluation of literature from electronic databases of Web of Science (WoS) and Scopus. These two databases are known to be reference points for academic literature reviews due to their large collection and are often seen as having a higher academic contribution [41].

After reviewing the relevant articles on DfMA application in the construction industry, several topics are investigated. The topics are: (1) the pattern of studies on DfMA in the construction industry, (2) the benefits of DfMA in the construction industry, (3) the hindrance factors on DfMA uptake in the construction industry, and (4) the enabling factors for DfMA application in the construction industry. Based on the findings from the four topics above, the trends and knowledge gap are then discussed. Science mapping is used only for the intention of depicturing the pattern of previous studies that are referred to in this current study since this work is not intended to be a bibliometric study. Figure 2 shows the overall layout of the research methodology.

Figure 2. Overall methodology.

4. Results

4.1. Pattern of DfMA for Construction Studies

Based on the scientometric review by Derbe et al. [41], this study adopted the science mapping approach using VOSviewer software (1.6.17 version, Nees Jan van Eck and Ludo Waltman, Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands) to look at the trends of research conducted under this study's topic. As a reference, several papers have used this software for studies in the field of construction and review articles [41]. The analysis using this software uses the data extracted from the related articles referred to for the current study. Using the software data mining ability, networks are visualised using science mapping that shows the linkage of research keywords and countries involved. From this network map, the evolution of a research topic can be traced and the main players can be identified.

Analysis of research keywords or phrases can reflect the researched area in a certain research domain [42]. The network of the keywords show interrelations of a certain research area [42]. In this study, the network of research keywords co-occurrence is generated based on documents referred to in this study. It can be seen here that the main keyword in this area of study is "prefabrication". Prefabrication has been studied earlier compared to DfMA, which is a relatively new research area. The bigger node size also shows that there are more studies carried out on a particular subject [42].

Figure 3 shows that referred documents on prefabrication started, on average, in mid-2019 based on the colour of the node. Documents in 2020 look at off-site construction and DfMA. In 2021, the referred documents looked at policies, engineering design, feature recognition, and sustainable development, which are also linked to prefabrication and DfMA. This shows a certain advancement of technology involved in prefabrication to have optimization in construction through DfMA. Documents related to BIM also started in 2019 but do not seem to be connected to the other keywords.

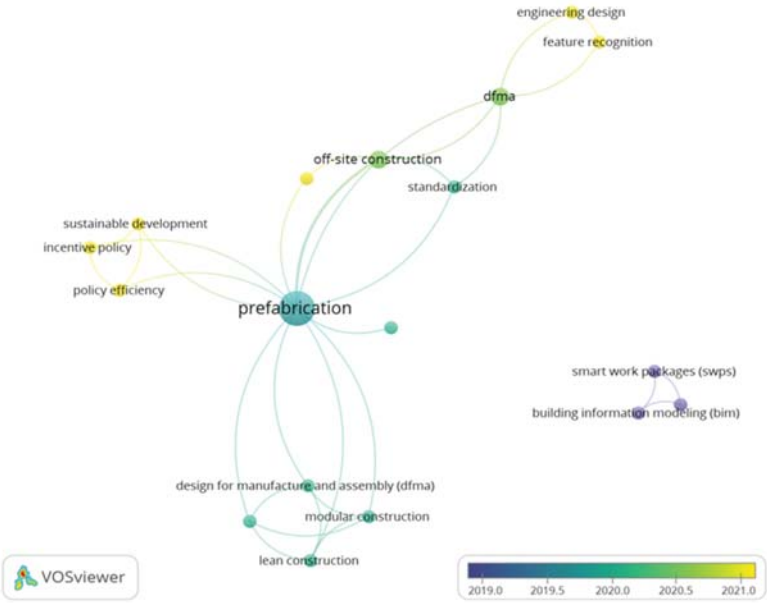


Figure 3. Science mapping of research keywords of referred papers.

Figure 4 shows the main countries involved in the research on DfMA in construction. Referred documents on this topic started around 2018 and England is the main contributor.

As can be seen on the map, most countries that contributed to this research are connected. The research also involves countries from almost all continents. There are still few countries involved in this research topic, which is also relatively still new. This could indicate the relevance of the topic for current research on construction optimization.

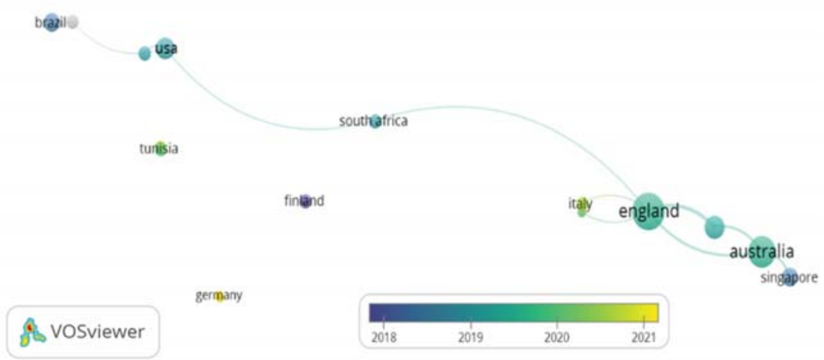


Figure 4. Countries involved in DfMA for construction research.

4.2. Benefit of DfMA in the Construction Industry

The typical benefits of DfMA in the construction industry would be reduced time, reduced cost, higher quality, and increased reliability. Reduction in time and cost is due to the reduction of waste and labour time. Waste minimization and lower labour cost occur because DfMA design principles help to ease the overall manufacturing and assembly process since it is already pre-considered in the module or part design [21].

With waste minimization and controlled working conditions, DfMA module design and prefabrication design promote sustainable, safe, and reliable construction [22]. The benefit of DfMA that was rarely discussed is the ability to point out and fix inefficient procedures and promote continuous improvement in a design [43]. Removing fragmentation and improving collaboration are other benefits that the construction industry could use [26].

In discussing the benefits of DfMA, there could be confusion about the benefits of prefabrication. DfMA is a design principle that optimises manufacturing and assembly activities. Prefabrication construction is a process performed on-site or off-site, used to produce the construction itself. The benefits shown in Table 1 are the benefits of the DfMA design principle and the benefits shown in Table 2 are the benefits of using prefabrication in construction. While the benefits of using prefabrication and off-site construction would be beneficial for a specific project, the benefits of using DfMA principles could be beneficial in the long run since they could be replicated in future projects.

The benefits of prefabrication and DfMA may look similar since both aim for the same objective. DfMA could be seen as a tool to enhance the full potential of prefabrication.

4.3. The Hindrance Factor for DfMA Application in the Construction Industry

The application of innovative concepts has its challenges. DfMA in construction is an innovative concept taken from the manufacturing sector to be adopted in the construction industry. This adoption is an effort to optimise the efficiency of the construction industry [37]. However, the benefits are not enough to convince the industry to widely implement the concept. There are challenges and hindrance factors that need to be overcome. Table 3 shows the hindrance factor or the challenges in adopting DfMA in the construction industry.

Table 1. The benefits of DfMA in construction.

DfMA Benefits for Construction Industry	Specific Benefits	Authors
Shorter construction period	Speed	Banks et al. [21]
	Reduced production time, shorter construction period	Trinder [26], Tik et al. [37]
	Faster time-to-market	Gao et al. [33]
	A drop-in assembly time	Wasim et al. [43]
	Reduction in manufacturing cycle time	Ferreira et al. [44]
Lower cost of construction	Lower cost, reducing the cost, cost saving, construction cost reduction	Banks et al. [21], Basarir and Cem Altun [45], Trinder [26], Tik et al. [37], Gao et al. [33], Wasim et al. [43]
	Enhance cost-efficiency	Chen and Lu [22]
	Decrease in parts cost	Ferreira et al. [44]
	Reduced labour on-site	Tik et al. [37]
A safer and healthier workplace	Improved safety, improved health and safety	Banks et al. [21], Trinder [26], Tik et al. [37]
	Safety enhances high-worth career	Tik et al. [37]
Higher quality in construction product	Higher quality, increasing the quality, improved quality, improvement in quality	Basarir and Cem Altun [45], Chen and Lu [22], Trinder [26], Tik et al. [37], Gao et al. [33], Banks et al. [21]
	Reduction in defects	Wasim et al. [43]
Sustainable construction	Sustainability	Banks et al. [21]
	Reduced waste, reduced construction wastage	Chen and Lu [22], Trinder [26], Tik et al. [37], Wasim et al. [43]
	Less dust and noise pollution	Tik et al. [37]
Improve design and construction reliability	Reliability, increasing the reliability, improvement in reliability	Banks et al. [21], Basarir and Cem Altun [45], Gao et al. [33]
	Reduced failures	Ferreira et al. [44]
	Allows a designer to enhance the buildability of construction products through early-stage design consideration	Gbadamosi et al. [46]
	Predict manufacturability outcomes while designing	Favi et al. [47]
	Improved the aesthetic performance	Chen and Lu [22]
	Saved interior building space	Chen and Lu [22]
	Assist designers in the selection of a variety of alternate materials for building elements, identification of design features that make the manufacturing process unfeasible or too costly	Wasim et al. [43], Favi et al. [47]
Increase productivity	Reducing number of parts, Reduction in parts count, Minimum number of parts	Basarir and Cem Altun [45], Gao et al. [33], Wasim et al. [43]
	Increase productivity, Productivity improvement	Trinder [26], Tik et al. [37]
	Remove team fragmentation and improve collaboration	Trinder [26]
	Tackle material shortages	Wasim et al. [43]

Table 2. Benefits of prefabrication and off-site construction.

Benefits in General	Benefits in Details	Authors
Better construction quality	Better building quality and high-quality control, better quality, enhanced quality, increasing on-site construction quality and efficiency, quality control, high-quality product	Musa et al. [2], Lu et al. [34], Yuan et al. [39], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]
Better efficiency	Increase in productivity, improvement in working conditions, increased material efficiency, labour productivity, more controlled conditions for weather, improved supervision of labour, easier access to tools, fewer material deliveries, decrease in disputes during construction	Musa et al. [2], Lu et al. [34], Zhang et al. [48], Bortolini et al. [50]
Reduced construction time	Reduced time, improvement of the speed of construction, shortened completion times	Zhang et al. [48], Arashpour et al. [49]
Reduce construction cost	Reduced costs, reduction of the overall cost of construction, the opportunity for producing complex building components at a lower cost, saving on-site construction labour, decreased labour	Yuan et al. [39], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]; Pan and Pan [5]
Environmental sustainability	Sustainability due to less waste, reduced damage to environment and ecosystem, less air and sound pollution, reduction of the construction waste, reduction of the environmental impacts, reduction of construction waste, reduced wastage, reducing environmental burdens, fewer job-site environmental impacts because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs, reduction of the environmental impacts to residents around construction sites	Musa et al. [2], Lu et al. [34], Yuan et al. [39], Zhang et al. [48], Bortolini et al. [50]
Better working condition	Improvement of working conditions and health and safety of the workers, safety, better worker safety, improve safety	Musa et al. [2], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]; Pan and Pan [5]
Better product sustainability	Lower maintenance and repairs, higher sustainability performance, workmanship, workflow continuity, flexible	Musa et al. [2], Zhang et al. [48], Arashpour et al. [49], Bortolini et al. [50]

Table 3. Hindrance factors for DfMA/prefabrication application.

Hindrance Factor/Challenges	Item	Authors
Awareness	Lack of awareness of the implication of using new technologies	Musa et al. [2], Trinder [26], Gbadamosi et al. [46], Charlson and Dimka [51]
	Lack of construction knowledge	Chen and Lu [22], Gao et al. [33], Gbadamosi et al. [46]
	Lack of staff training	Gao et al. [33], Charlson and Dimka [51], Lu et al. [34]
	Lack of comprehension of the requirements to fulfil off-site manufacturing business strategy	Charlson and Dimka [51]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Acceptance	Acceptance of stakeholders	Musa et al. [2], Chen and Lu [22], Pan and Pan [5], Charlson and Dimka [51], Langston and Zhang [52], Lu et al. [34]
	Dependence on conventional methods	Pan and Pan [5]
	Resistance to change, community mindset	Charlson and Dimka [51], Langston and Zhang [52], Lu et al. [34]
	Readiness	Musa et al. [2]
	Bad perception based on historic accounts	Trinder [26]
	Trapped as labour-intensive industry instead of technology-intensive	Tik et al. [37]
	Foreign workers could delay the technology engagement and development	Tik et al. [37]
Cost-effectiveness	High start-up cost	Trinder [26], Zhang et al. [48], Pan and Pan [5], Tik et al. [37], Gao et al. [33], Charlson and Dimka [51], Rosarius and de Soto [53]
	Volumetric construction needs to secure sufficient order to break even	Tik et al. [37]
	Lack of economy of scale	Shang et al. [54]
	Limited demand	Trinder [26]
Design limitation	Limited design flexibility and requires early design freeze	Trinder [26]
	Inflexible for design change, long design time, long lead time	Zhang et al. [48], Bortolini et al. [50]
	Suppliers often contribute too little during the early-stage design	Gbadamosi et al. [46]
	Order modifications that arise in the short-term lead	Rosarius and de Soto [53]
	Increase in design time	Shang et al. [54]
Logistic issues	Transportation difficulties, damage during transportation	Trinder [26], Shang et al. [54], Rosarius and de Soto [53]
	Small working area, restricted site access	Trinder [26]
	Lack of storage space	Zhang et al. [48]
	Underutilization of factory space	Pan and Pan [5]
	Transportation distance	Langston and Zhang [52], Rosarius and de Soto [53]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Contract and supply chain issues	Traditional contracting forces sequential engineering and separation of design and construction	Trinder [26]
	Early involvement of subcontractors and suppliers does face challenges in the contracting practices	Gao et al. [33]
	Unanticipated conflicts among different trades on-site	Bortolini et al. [50]
	Complex supply chain resources, such as manufacturing plants, assembly equipment, and crews, supply chain management	Bortolini et al. [50], Langston and Zhang [52]
	Payment terms; contractors only pay for products when it is delivered to the site and fully installed	Shang et al. [54]
	Adapting existing procurement models obstructs the potential benefits of using off-site technologies	Charlson and Dimka [51]
	Supply change management	Langston and Zhang [52]
Proof of concept	Inability to select the appropriate project for DfMA trials	Trinder [26]
	Few cases of DfMA application to show the actual benefits	Lu et al. [34]
	Insufficient R&D expenditures	Gao and Tian [55]
	Lack of adequate information to evaluate the potential benefits and constraints of using off-site construction	Gbadamosi et al. [46]
	Inconsistent product quality	Pan and Pan [5]
Integration difficulties	Integration difficulties between DfMA products and existing on-site assets	Trinder [26],
	Complex interfacing	Pan and Pan [5]
	High level of uncertainty when the product is not completely defined	Bortolini et al. [50]
	Information fragmentation	Li et al. [4], Pan and Pan [5]
	Scheduling complexity	Pan and Pan [5]
	Compatible building type	Langston and Zhang [52]
	Lack of suitable ecosystem, which includes guidelines, standards, and affordable technologies	Lu et al. [34]

Table 3. *Cont.*

Hindrance Factor/Challenges	Item	Authors
Guidelines, standards, and policies	New innovative solutions may sit outside current standards, leaving clients vulnerable to operational risks	Trinder [26], Lu et al. [34]
	Lack of necessary government regulatory efforts to promote prefabricated construction	Gao and Tian [55]
	No legal framework available for off-site manufacturing	Charlson and Dimka [51]
	Lack of government regulations and incentives	Langston and Zhang [52]
	Planning and building codes, lack suitable guidelines, and standards	Langston and Zhang [52]
	Some guidelines are proposed in a fragmented fashion without necessarily forming an organic whole, leading to a lack of comprehensiveness, or "easy to use" throughout the building process	Lu et al. [34]
	Available guidelines are based on manufacturing context without sufficiently considering the best fit for construction adaptation	Lu et al. [34], Tan et al. [38], Rosarius and de Soto [53]

Previous authors have discussed the hindrance factors and challenges for either DfMA or prefabrication and they are listed in Table 3 above. Noticeably, most of the challenges listed in adopting DfMA are similar to the hindrance factors for adopting prefabrication. However, there are challenges more specific to DfMA highlighted by several authors, which include:

- The multidisciplinary team does not fulfil the expectations;
- Standardisation limits design flexibility and requires early design freezes;
- Traditional contracting forces sequential engineering and the separation of design and construction;
- Staff training;
- Suppliers often contribute too little during early-stage design;
- Design involves an increase in time;
- Lack of planning and building codes;
- Lack of a suitable ecosystem that includes guidelines, standards, and affordable technologies;
- New innovative solutions may sit outside current familiar standards, leaving clients vulnerable to operational risks;
- There are too few data on the DfMA application to show the actual benefits.

The application of DfMA in the construction industry requires a paradigm shift for all stakeholders. The essential objective of DfMA needs to be properly digested and understood to garner its full potential. As described in the earlier section of this paper, DfMA is a design principle and method to optimise product manufacturing and assembly. To start the adoption of DfMA in the construction industry, available guidelines from the manufacturing industry might be the best reference. However, such guidelines need further study to better suit the construction industry. This should also include the evaluation of whether DfMA is suitable for a specific project. DfMA must not be rejected in a project just because of the perception induced by demands of off-site prefabrication. There are other options, such as on-site prefabrication and modular in situ fabrication, that could be made better with the application of DfMA principles. Understanding where DfMA is appropriate and where it is not is key.

4.4. The Enabling Factors for DfMA Application in the Construction Industry

To increase the acceptance of DfMA in the construction industry, certain enabling factors need to be considered. Enablers, such as knowledge of DfMA [21,48], supporting technologies [52,56,57], preferable government policies [55,58], and suitable procurement methods and contracts [48], could increase the interest in the application of DfMA in the construction industry.

Knowledge of DfMA is important for creating awareness and for the industry players to have an interest in it. Project owners are seen as being more interested in methods that enhance quality and reduce waste, with lesser risk and conflicts. Though the initial cost might be higher, advanced technology and integrated methods of project delivery are thought to be value-adding and forward-thinking approaches [59]. DfMA would likely match the mentioned features where DfMA focuses on enhancing the efficiency of fabrication and assembly of building parts [60].

To avoid fragmentation, projects need early engagement among all stakeholders to be successful because the earlier changes are made in the early stage of design or project inception, the less costly [61]. In construction, what has been designed will affect most of the project cost, but the cost of the design phase itself is usually less than 10% of the project cost [62]. Therefore, the application of DfMA at the design stage of a project with a full-time coordinator looking to collaborate with contractors, architects, and other consultants could help to optimise the construction project's performance [21]. Such understanding and awareness could only be achieved by knowing how things work in the construction industry and how it could benefit from DfMA.

A project involves a multidisciplinary team. Principles or methods such as DfMA intend for them to be involved from the early design stage. Only certain procurement methods could allow this. The design and building procurement method means that the appointed contractor is tasked to manage the design process and carry out the construction works. Such a procurement method is seen as the preferred method to implement prefabrication, thus implementing DfMA principles [48]. The management cost of such a practice should be considered in selecting the procurement method. Selecting those that should be on the team must be in tandem with implementing the principles or methods. The team members must be those who can make the decision making efficient [22]. The procurement method and standard form of contract is an area that needs more study in forming a stable legislation basis for the practice of DfMA or any other principles similar to it.

A redesign process that includes inventive problem solving by looking at specific design tasks and adding in solutions from an identified database of designs or technologies would make the application of principles such as DfMA work better [45]. The design process should adopt a digital and parametric platform so that it can be completed more efficiently to cope with changes. BIM is an example of such a platform that is expanding in the construction industry [22,35,41]. The inclusion of a digital system such as BIM would help in the design process [63]. To make DfMA work throughout the whole project cycle, the design process should include the delivery process and tower cranes or any other on-site machinery assembly requirements, and BIM could also help in this area [21].

BIM's ability to model and create simulations is highly beneficial in decision making [64]. Modelling and simulation would enable designers and stakeholders to evaluate the methods used in construction activities by representing the actual construction and simulating the cause and effect of a system before the actual construction is undertaken [4,65]. This could lead to producing a digital twin for a project.

BIM could also be useful in tracking the off-site manufacturing and on-site assembly by integrating it with identification and positioning technologies, such as radio frequency identification (RFID) and global positioning systems (GPSs). Information gathered in the BIM platform could then be shared with all relevant stakeholders for better management and quicker decision making [57,66]. All data collected from the various project by an organization would be beneficial in the future. Therefore, the usage of product data management (PDM) is essential in the design and manufacturing practice. This ensures the data are readily available for the next job [67]. By establishing a library of design data, the design process could be performed faster. The library should consist of proven and untested product data for future references [52,62]. With iterations of multi-criteria decision making (MCDM) involved in the design process, the library data and tools, such as the weighted sum method, analytic hierarchy process, and technique for ordered preference, could make the process easier and quicker [68].

To support the principles of DfMA, government policies, such as those in China, Singapore, and Malaysia, are important for supporting the adoption of prefabrication [35,58]. However, a high level of prefabrication might not be all good. The key is to have the optimal level that fits into the specific construction environment and considers the political, economic, social, and technological factors [6]. Policies with incentives and support have proven to be effective in increasing the uptake of new innovative methods, such as prefabrication and DfMA, as opposed to directive policies [55,58]. The type of more effective incentives and the delivery method needs more study to enable the formation of better policies regarding DfMA.

The DfMA principles, which are often linked to prefabrication, would see higher adoption when there is a higher demand for prefabrication projects. Marketing strategies for prefabrication products would therefore have an impact on DfMA adoption [48]. In creating the demand, policies and guidelines are essential. The rules, principles, and best practices of DfMA should be spread out to building designers. Pioneers in DfMA for construction, such as the Royal Institute of British Architects (RIBA), have created an overlay to their plan of work. Singapore's Building and Construction Authority (BCA) has identified DfMA as part of the strategy to increase the productivity of construction. BCA also published guidelines for prefabricated prefinished volumetric construction (PPVC) to promote the practice [33]. A flexible construction method, such as semi-modular off-site prefabrication and DfMA, would benefit smaller companies by not having to come out with a big investment of setting out large prefabrications [69]. Combining all these findings to form better guidelines for DfMA for construction is what the industry needs. This could enhance the understanding and uptake of DfMA.

The usage of manufacturing machines in construction has a considerably high investment cost. However, if a project workflow is recurring and the machines could be used across several projects, a positive return on investment is possible. In turn, this would make it highly possible to have a safer, cleaner, and quicker construction method with DfMA principles in place [70]. Data produced from academic study and actual practice could help to convince the industry players. Therefore, all the enablers need to be tabled out and studied to produce more convincing data. The enablers for DfMA can be summarised in Table 4.

Table 4. Summary of enablers for DfMA/prefabrication application.

DfMA Enabler	References	Example
Knowledge	Gao et al. [23], Trinder et al. [62], Banks et al. [21], Zhang et al. [48]	Knowledge of DfMA for all stakeholders, guidelines
Supporting organization	Gao et al. [23], Chen and Lu [22]	Supplier, designer, RIBA
Government support	Gao et al. [23], Jin et al. [35], Wang et al. [58], Lu et al. [34], Gao and Tian [55]	Policies, incentives, legislation, investment, guidelines
Stakeholders	Nguyen and Akhavian [59], Trinder et al. [62], Banks et al. [21], Chen and Lu [22]	Multidiscipline design team, clients, developers, contractors, suppliers
Technologies	Basarir and Cem Altun [45], Chen and Lu [22], Jin et al. [56], Yuan et al. [39], Banks et al. [21], Li et al. [4], Pinheiro et al. [65], He et al. [57], Merja and Harri [67], Langston and Zhang [52], Trinder et al. [62], Tan et al. [38]	BIM, RFID, GPS, PDM, MCDM, IoT
Project-specific factors	Gao et al. [33], Vaz-Serra et al. [69]	Transportation route, site storage, material

All of these enabling factors would be essential in promoting the application of DfMA in the construction industry. This could increase the demand for DfMA and, in turn, make the technology surrounding its application more affordable. With technology integrations and DfMA know-how, the construction industry would see better performance in the future in terms of quality, time, and cost.

Figure 5 shows that to improve the uptake of the DfMA principles in the construction industry, it requires a combination of the enablers listed in Table 5, including better knowledge to create awareness, supportive policies to boost demand, and good guidelines to make it easier to apply. When it comes to BIM and other related technologies, the current practice in the construction industry should not be far off from what is needed to implement the DfMA principles.

Applying collected data from Sections 4.2–4.4, the conceptual framework in Figure 6 gives an overview of the proposed direction and what is needed to make the application of DfMA in the IBS project and the construction industry more effective.

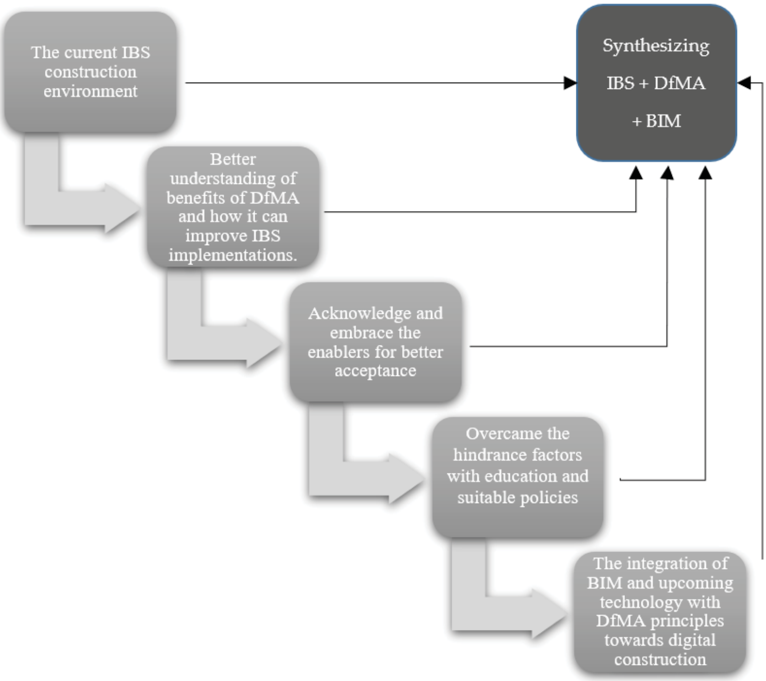


Figure 5. Synthesising DfMA principles with IBS and BIM.

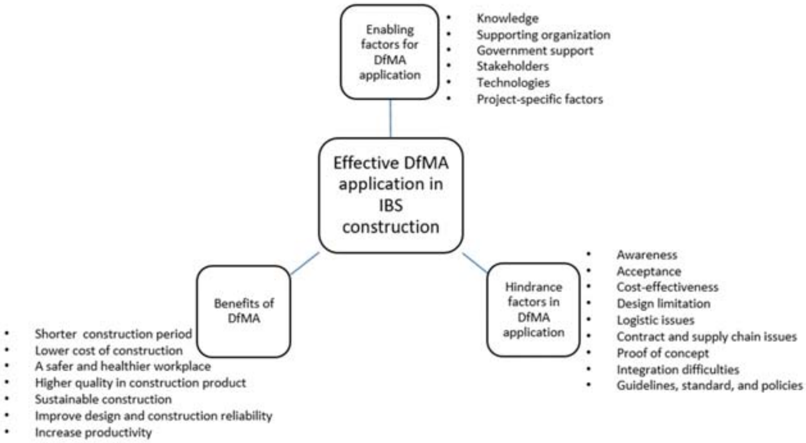


Figure 6. A conceptual framework for DfMA application.

Table 5. Summary of research themes related to DfMA/prefabrication.

Id	Research Theme	Authors
1.	DfMA/Prefabrication integration with other principles or technology 18 articles	Mesa et al. [36], Li et al. [66], Merja and Harri [67], Pinheiro et al. [65], Yuan et al. [39], Zhao et al. [10], Bensalah et al. [71], Bortolini et al. [50], Gbadamosi et al. [60], Li et al. [4], Nguyen and Akhavian [59], Tetik et al. [72], Alfieri et al. [73], Gbadamosi et al. [46], He et al. [57], Wang et al. [58], Xing et al. [74], Bakhshi et al. [28]
2.	DfMA/Prefabrication application 14 articles	Banks et al. [21], Basarir and Cem Altun [45], Chen and Lu [22], Gao et al. [23], Trinder [26], Trinder et al. [62], Tik et al. [37], Jin et al. [35], Gao et al. [33], Wasim et al. [43], Ferreira et al. [44], Lu et al. [34], Vaz-Serra et al. [69], Hyun et al. [20]
3.	Prefabrication construction method/tools 7 articles	Musa et al. [2], Orlowski et al. [75], Fardhosseini et al. [70], Pan and Pan [5], Mesa et al. [76], Favi et al. [47], Liu et al. [77]
4.	Prefabrication material 6 articles	Oktavianus et al. [78], Orlowski et al. [25] Liew et al. [79], Orlowski [80], Orlowski et al. [81]
5.	Prefabrication drivers/barriers factor 4 articles	Zhang et al. [48], Shang et al. [54], Bao et al. [82], Langston and Zhang [52]
6.	On-site construction technology based on DfMA 3 articles	Martinez et al. (2013), Li et al. [7], Rosarius and de Soto [53]
7.	Supply chain and resource management for prefabrication 2 articles	Arashpour et al. [49], Arashpour et al. [83]
8.	Policies and legislation 2 articles	Gao and Tian [55], Charlson and Dimka [51]
9.	Optimal prefabrication	Lu et al. [6]
10.	DfMA guidelines	Tan et al. [38]

5. Discussion

5.1. Research Themes, Trends, and Gaps

The research theme of each of the articles is grouped according to their research focus, as shown in Table 5. The research themes are divided into 10 groups with the largest group, containing 19 articles, discussing the integration of DfMA or prefabrication with other principles or technology. Containing 14 articles, the next highest group involves discussions of the application of DfMA or prefabrication in various capacities. These two groups combined would represent more than half of the pooled articles. This shows that the main focus of this research domain is now on the condition of DfMA or prefabrication adoption and the technology and other principles that could be integrated to make the process better.

The least studied area is the optimal prefabrication and DfMA guidelines. These two areas, from what has been discussed in the two articles, are essential in developing working policies that would make DfMA principles more appealing. Optimal publication arguments from Lu et al. [6] ensure that the practice should only be applied according to the requirements of a project and not only to make up the number of prefabrication-based projects. This would ensure the purpose of having a prefabrication-based project stay true to the cause. The guidelines discussed by Tan et al. [38] would help the construction industry to better understand the principles of DfMA and not only depend on the guidelines produced based on the manufacturing sector. The construction industry is unique and this should be considered to revamp it from all sides.

A time-based research trend was developed based on the information gathered, limited to the articles referred to in the current study. This trend will hopefully provide a better understanding of the development of research conducted on DfMA principles and prefabrication in the context of the construction industry. Figure 7 shows the current research trend and the future path of this research domain. The research trend characterises research themes that have developed over the years, forming a few dominant research areas. This research topic is relatively new and currently involves a rather small group of researchers.

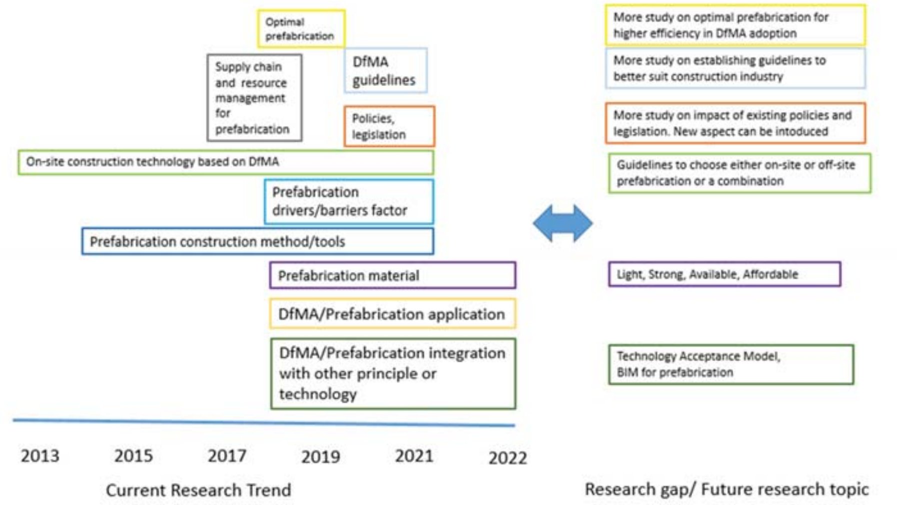


Figure 7. DfMA research framework based on trends of research theme.

From the discussions, the layout of the research theme and research trend and the research gap were identified. In Figure 7, the knowledge gaps and the potential future research topic are listed on the right and aligned with the research theme.

5.2. The Research Gap and Potential Future Research Topic

By synthesising the findings of the previous paper, this review paper can fill the research gap and provide suggestions for a future research topic. The gap is identified in several areas: (1) guidelines on DfMA application; (2) data management; (3) policies, incentives, and litigation; and (4) overall application of DfMA principles.

5.2.1. Guidelines on DfMA Application

In an effort to introduce innovative ways to increase construction performance, the risk of such innovation must be evaluated. The characteristic of a project that is suitable for on-site or off-site prefabrication needs to be set and included in the guidelines so that the innovation can be accepted and improve the industry instead of creating superficial benefits.

Construction-oriented DfMA guidelines are needed since the existing guidelines are manufacturing-based; therefore, they lack some features that fit well with the construction industry. Aspects such as natural, cultural, and geospatial data should be considered to be included in the guidelines. Technologies proposed also need to be specifically efficient for a typical project. The supply chain is of importance since construction projects usually involve lots of materials and the logistics must be taken care of. The design process usually does include the consideration of materials to be used and should be natural for the DfMA design method. DfMA usually involves modular or building components design; the integration of each part should also be considered to suit each project delivery condition. Another characteristic that should be considered is transportation. Off-site prefabricated modular or building parts transportation should be within the allowable margin of cost, time, and certain legislation restrictions. Logistic management must be efficient and reliable, taking into consideration all the different activities involved to avoid activities that do not add value to the project.

Most discussions about DfMA are focused on off-site prefabrication. There should also be guidelines for on-site fabrication and prefabrication since not all projects are suitable for off-site construction but can still benefit from DfMA design principles.

These proposed guidelines would also mean recognising which party should be included in the design team from the start of the project. They need to have a holistic view of the design that could make manufacturing and assembly better.

5.2.2. Data Management

Product data management (PDM) and BIM are tools proven to be beneficial for DfMA and the prefabrication process. However, data updating should be made automatic as the design continues so that there are no issues with inundated design data that would then defeat the purpose of PDM.

The usage of BIM in helping organise the prefabrication of creating modular and building parts has been acknowledged by several researchers. However, BIM systems are more familiar with conventional construction. Therefore, the BIM system needs to be adjusted to better suit DfMA and the prefabrication method, especially in recognising all of the jointing elements as part of the building. Even though the possible application of BIM to improvise the DfMA method of design has been mentioned by several researchers, there is still not much data that can support the claim. Hence, there is a need to further examine the adoption of BIM into the DfMA and prefabrication method.

5.2.3. Policies, Incentives, and Litigation

Studies on policies, incentives, litigation, and contractual matter regarding DfMA are still lacking. Clear related policies and strategies are available in the United Kingdom and Singapore, while Hong Kong lines up guidelines and incentives. Discussion on the right incentives needs to be lengthened to see if it benefits the right parties. Since these aspects are crucial in realising the uptake of DfMA, it is only logical that more studies need to be done, especially with the diverse aspect of construction all over the world. Procurement methods and forms of contract should also be kept updated and be suitable for the DfMA principles.

5.2.4. Overall Application of DfMA Principles

As a whole, the overall usage of DfMA in construction is relatively still new and low. Even though the concept was popularly used in the 70s, its adoption in the construction industry has only started quite recently. DfMA as design analysis is not fully applied and is not applied on all construction components. Analysis data of the benefits of DfMA are also few and cannot be definitive enough to convince further investment. The small number of studies makes the information needed to apply DfMA in the construction industry rather scarce. More studies are needed to obtain more knowledge on the practical adoption of DfMA in construction.

5.3. Limitations

This study is limited to the relevant studies on DfMA in construction based on a topic search result in the Web of Science and Scopus databases. This study is also limited to articles that have mentioned DfMA in the title, abstract, or main text. Future studies could include articles from other databases and other search criteria. It would also be beneficial for future studies to be carried out as systematic literature reviews and bibliometric studies on relevant articles.

6. Conclusions

The application of DfMA in projects using IBS has many benefits. The objective of IBS in enhancing the productivity of constructions could be achieved by implementing DfMA. More projects could be delivered on time with better construction quality. Additionally, the usage of DfMA in the IBS project could also increase the potential of making the construction industry more sustainable by reducing construction waste. Applying DfMA in the construction industry would also increase its ability to be transformed into an automated industry, especially during the manufacturing process. Enhanced with integration with technology, such as BIM and GPS, DfMA has the potential to bring the construction industry into the digital world. This will lead to more effective and sustainable constructions.

Despite the clear advantage of applying DfMA in the construction industry, more research needs to be done. In Malaysia's context, DfMA is still very vague. There is very little research performed on strategizing and developing guidelines for the application of DfMA in the construction industry. This study could help the construction industry analyse and evaluate the optimal ways of adopting new innovative solutions such as DfMA. From the previous studies, the identified benefits of DfMA should be reason enough to apply it in the construction industry. Using the data compilations presented in this study, we can identify what is required to apply DfMA in the construction industry. From the conceptual framework produced in this study, strategies and guidelines could be developed for the optimal application of DfMA.

More data collection and proper presentation of the data analysis could provide a better understanding and a strong argument for championing DfMA adoption in the construction industry. This means that more studies need to be carried out to obtain the required data. A better understanding of the benefits of DfMA and its true potential would make it more acceptable to the players and stakeholders in the construction industry.

Author Contributions: Conceptualization, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; methodology, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; validation, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; formal analysis, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; investigation, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; resources, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; data curation, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; writing—original draft preparation, M.I.A.R.; writing—review and editing, M.I.A.R., M.A.K., W.H.W.B. and A.H.H.; visualization, M.I.A.R.; supervision, M.A.K., W.H.W.B. and A.H.H.; project administration, M.A.K.; funding acquisition, M.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Kebangsaan Malaysia, grant number KK-2021-2018.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Universiti Kebangsaan Malaysia (UKM) for its financial support.

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

Abbreviation

The following abbreviation is used in this manuscript.

DfMA	Design for manufacturing and assembly
BIM	Building information modelling
IBS	Industrialised building system
RFID	Radio frequency identification
GPS	Global positioning system

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Article

Risk Network Evaluation of Prefabricated Building Projects in Underdeveloped Areas: A Case Study in Qinghai

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Abstract: Prefabricated building projects (PBPs) face more risks than traditional construction projects, especially in underdeveloped areas. This study takes Qinghai Province as a study case. Social network analysis (SNA) is adopted to develop a risk network of PBPs, and nine core risk factors and five key risk relationships are identified. Risk effect detection reveals the effectiveness of risk response strategies. The research shows that PBPs in underdeveloped areas are still in the early stage of development, and developers generally lack a leading role. There are prominent problems in the design stage of PBPs, so the stakeholders pay special attention to them. In underdeveloped regions, the development of PBPs must rely on the strong promotion of the government. Limited by natural and economic conditions, the market mechanism of PBPs in underdeveloped areas is not perfect, and policy regulation greatly affects the spread of the risk network. Therefore, local governments need to actively introduce corresponding supportive policies and mobilize the enthusiasm of stakeholders. This is the first study to consider the risk within the life cycle of PBPs in underdeveloped plateau areas. This study expands the research system of risk management of PBPs and provides valuable risk response strategies for the stakeholders.

Keywords: prefabricated building project; risk management; social network analysis; underdeveloped areas; Qinghai Province

Citation: Wang, Q.; Gong, Z.; Liu, C. Risk Network Evaluation of Prefabricated Building Projects in Underdeveloped Areas: A Case Study in Qinghai. *Sustainability* **2022**, *14*, 6335. https://doi.org/10.3390/su14106335

Academic Editors: Albert P. C. Chan, Srinath Perera, Xiaohua Jin, Patrizia Lombardi, Dilanthi Amaratunga, Anil Sawhney, Makarand Hastak and Sepani Senaratne

Received: 14 April 2022
Accepted: 18 May 2022
Published: 23 May 2022

1. Introduction

Compared with traditional buildings, prefabricated building projects (PBPs) can reduce construction energy consumption by 20%, conserve construction materials by 60%, save labor by 40%, and shorten the construction period by one-third [1]. Therefore, PBPs have significant advantages in protecting the environment and conserving resources [2,3], which are regarded as the key to the industrialization and upgrading of the construction industry [4,5]. During China's "13th Five-Year Plan" period, the national prefabrication rate is required to reach 15% [6]. In 2020, the national prefabrication rate reached 20.5% [7], and the work target of the "13th Five-Year Plan of Action for Prefabricated Buildings" has been completed.

However, the development of PBPs in China shows obvious regional distribution characteristics of "strong in the east and weak in the west". The plateau areas in western China are restricted by natural and economic conditions [8]. Therefore, unlike the rapid development of PBPs in eastern, coastal China, PBPs in the western plateau develop slowly [7]. Qinghai Province is one of the typical underdeveloped plateau regions in China [9]. By the end of 2021, the new PBPs area in Qinghai Province has reached 1,557,900 square meters in the past five years [10], and the prefabrication rate is still less than 10%. The low degree of industrialization [11] and the prominent contradiction between economic development and the ecological environment [12] restrict the development of these regions [13]. Furthermore, the promotion and construction costs of PBPs are much higher than traditional buildings [14], and the climate and geological conditions in the plateau region have greatly increased labor costs and material transportation costs [15]. There are also problems in respect of unsound policies and inconsistent design standards. In short, the unique characteristics of construction projects, such as large construction investment, long periods, complex natural and technical conditions, and unpredictable external environmental impacts [16], expose them to many risks [17].

Due to the changes in construction methods, PBPs face more risks than traditional construction projects [18], especially in underdeveloped plateau areas. In order to control the risk factors that hinder the success of PBPs to the greatest extent, improve the risk management level of projects effectively, reduce project losses, and promote the development of PBPs, experts and scholars in the construction project industry have been keen on risk management research.

When exploring the risks of PBPs in China, “imperfect policies and regulations” [1,19] have been listed as the primary risk many times, reflecting the importance of policies. In terms of supply chain management risks of PBPs, “poor planning of resources and schedules”, “poor control of working flows”, and “poor information sharing” were the three major challenges in Hong Kong [20], and “component supply” [21] also required attention. The “economic situation” ranked first in the cost and schedule risk of PBPs in North America [22] and the investment risk of PBPs in China [23]. The construction cost risk of PBPs in South Korea mainly came from the design stage and construction stage [24]. Furthermore, the core stakeholders of a project in Nanjing were developers and contractors [25].

In previous studies, the content of risk management of PBPs has great regional differences. The core risks faced by PBPs in different regions were different, so there was no universal risk response strategy. In addition, the risk stages of each study were also different. Some studies only focused on the risk factors of a single construction stage, while others integrated risk across the life cycle of PBPs.

These studies provide diversified perspectives and personalized cases for the risk research of PBPs. However, most studies were carried out in countries with relatively developed economies and prosperous construction industries [20,22,24,26–28], which could not provide specific management ideas and development strategies for the risk management of PBPs in underdeveloped areas in China. The PBPs are in a complex social network environment, and various risk factors will also change due to different stakeholders. In addition, the current risk management system of PBPs in China is not perfect. Most of the existing research on risk assessment of PBPs regard risk factors as isolated points, and there are many studies on the influence of independent risk factors [29–33]. These studies did not consider the complex relationships among risks and the perspective of interrelationships among risk factors.

Therefore, exploring the relative importance of risk factors is significant for developing PBPs in underdeveloped areas. This paper takes Qinghai Province as a study case to develop and analyze the risk network of PBPs and control core risks and key relationships to block the spread of risks. The research can provide valuable information for developing PBPs in underdeveloped plateau areas.

2. Literature Review

2.1. Development of PBPs in China

The concept of PBPs first appeared in China in the 1950s [34]. In the 1980s, China began to promote industrialized buildings, and PBPs gradually developed [5]. However, by the 1990s, the development of PBPs remained stagnant due to the constraints of the technical level, economic conditions, and people’s cognition [26]. Although China introduced PBPs decades ago, the application of PBPs still faces major problems [31]. Since the General Office of the State Council issued a policy on vigorously developing PBPs in 2016, China’s PBPs have developed rapidly. The PBPs are very attractive to China’s construction industry [14] because they conform to the construction concept of “sustainable green development" [35]. With the increasing demand for PBPs in China's construction industry, the central government has promulgated many policies to promote the development of PBPs [34]. However, the development of PBPs in China, including related technical levels, is still in its infancy [23], resulting in a relatively low proportion of PBPs in the existing building stock [36].

Many researchers have explored the reasons that hinder the development of PBPs from finding effective solutions. Lu et al. [37] developed a PBP analysis framework with 13 unfavorable factors to study the optimal level of prefabrication and clarify the prevailing misconception that "the higher the prefabrication level, the better". Xie et al. [28] used the importance–performance analysis (IPA) to explore the sustainability importance and performance levels of PBPs from three dimensions (economic, social, and ecological sustainability) and proposed key sustainability criteria. Hong et al. [38] established a framework for cost-benefit analysis of PBPs and suggested that future development should focus on providing financial support for advancing technology development, optimizing structural integrity, and increasing market maturity. Liang et al. [39] used the fuzzy analytic hierarchy process (fuzzy AHP) to develop a performance evaluation model, which provided reliable support for the decision-making stage of PBPs. These studies used different methods and provided suggestions for promoting the development of PBPs from different dimensions but ignored the geographical situation. The economic level and natural conditions of different regions are quite different. For example, PBPs are better developed in the eastern provinces of China and lag behind in the western and northwestern provinces [40]. Even though the implementation of some PBP incentive policies is not effective [41], the government plays a leading role in the promotion of new things [42]. Therefore, relying on policies to promote the development of PBPs is still considered a strong strategy in less developed regions [43].

2.2. Risk Management of PBPs

The Project Management Institute [44] defines risk as "an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives." Construction is a highly risk-prone industry [45], and the risks of PBPs are more prominent than those of traditional buildings [30]. No project is risk-free [46], but effective risk management can minimize the impact of risk [47]. Therefore, many researchers believe that it is necessary to take risk management as an important part of project management in PBPs [48].

The construction goals of PBPs are wider and longer than those of traditional construction. In addition, PBPs have the typical expression of economic externality. The long-term benefits of PBPs are difficult to quantify and cannot be directly reflected, making risk management more difficult for stakeholders [30]. The high initial investment is one of the most significant risks of PBPs [29]. The PBPs face the uncertainty of future investment income and the possible loss of investment principal. The PBPs will face serious risks if risk management measures are inadequate [49]. Li [23] used structural equation modeling (SEM) to explore the factors of an investment risk evaluation system from the policy, market, technology, economy, and management perspectives, and proposed a method that can evaluate the investment risk. Li et al. [30] constructed a risk identification feedback graph and a risk flow chart using the system dynamics method to comprehensively identify investment risks that projects in China may face, and identify four key risk factors. Ye et al. [35] established a dynamic evolution model of PBP cost risk based on the dynamic Bayesian network (DBN) and studied the construction cost risk evolution and transfer mechanism of PBPs. Rose [27] used an interactive research approach to conduct a case study of a Swedish PBP and proposed solutions for three major risks. Xia et al. [26] analyzed the risks faced by PBPs using EPC from the perspective of general contractors, conducted an empirical study in Nanjing, China, and found that construction and design are the main factors that determine the level of project risk.

In addition to the risks at various stages, the overall risks in the life cycle of PBPs are also worthy of attention. Yuan et al. [19] established a risk network containing 41 factors based on the life cycle theory and proposed ten challenges that must be solved for PBPs.

Wang et al. [36] identified 77 risk factors covering the life cycle of PBPs using an important performance analysis method and revealed eight key risks. Luo et al. [20] explored the supply chain risks of the identified 30 PBPs in Hong Kong using social network analysis (SNA), and finally came up with three main challenges and gave specific response strategies. Identifying the risks in PBPs accurately and proposing strategies for different types of risks is a common research process in the current risk management of PBPs [46,47].

3. Methodology

SNA originated from sociological research [50]. SNA is a quantitative analysis method that uses graph theory and mathematical methods to quantitatively analyze the relationship between actors (nodes) in the network. The whole network analysis is suitable for exploring the overall characteristics of the network relationship structure, and the ego-network analysis is applied to quantify the impact of the attributes, positions, and degrees of individuals in the network [51]. Combined with the characteristics of multiple parallel processes, complex stakeholder relations, and emphasis on the integration of PBPs, SNA has its unique advantages over classical risk network research methods such as interpretative structural modeling (ISM) and the bayesian network (BN). This study constructs and evaluates the risk network of PBPs in Qinghai Province based on SNA, and follows a classical risk management framework [19,20,44]. The research framework is shown in Figure 1.

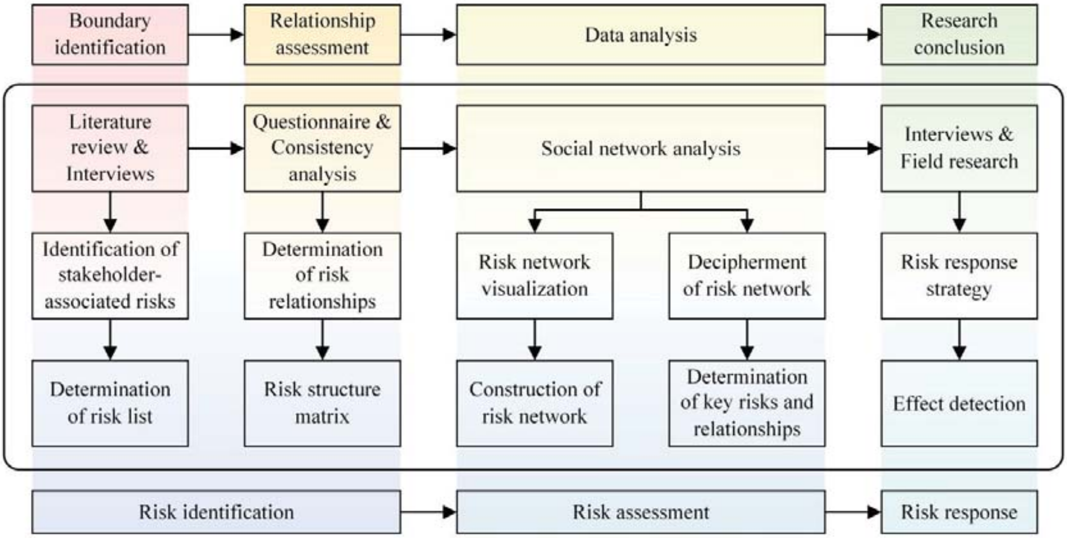

Figure 1. Research framework.

In the risk identification stage, boundary identification is the first step. The main stakeholders and key risk factors are explored to determine the risk list by combining literature review and expert interviews. Then, the relationship between risks is determined through a questionnaire survey and consensus analysis, thus building a risk network adjacency matrix. In the risk assessment stage, a risk network model is constructed for PBPs in Qinghai Province, and the relationship between the risk factors is revealed based on SNA to identify the core risk. The risk network model and field investigations are analyzed comprehensively in the risk response stage. Then, the actual risk response strategy is put forward according to expert suggestions. Finally, the effect of various indicators of the risk network is evaluated to test the criticality and effectiveness of the risk response strategy.

The respondents who filled out the questionnaire and were interviewed were the same experts in the research process. This study followed the principle of stakeholder sampling [52], and experts were selected and invited. Based on our stakeholder analysis (Section 4.1.1), six stakeholder groups (Developer, Designer, Contractor, Manufacturer, Government, and Facility) were surveyed in Qinghai Province. A total of 12 experts (two people in each stakeholder group) in the field of PBPs in Qinghai Province were contacted through the internet and recommendations from cooperative schools and enterprises. One of the experts was not willing to be interviewed, so 11 experts were finally interviewed. The background information of the 11 experts is shown in Table 1. Experts meet the following requirements:

- They have more than six years of work experience in PBPs in Qinghai Province.
- They participated in and completed at least two PBPs in Qinghai Province.
- They have senior titles or hold senior positions in their organizations.

Table 1. Profiles of respondents.

Experts		Position	Years of Working in PBPs	Number of PBPs	Professional Title
Developer	1	Technology	6–10 years	At least 5 projects	Intermediate title
	2	Research	6–10 years	At least 5 projects	Intermediate title
Designer	1	Management	More than 20 years	2 projects	Senior title
	2	Technology	11–15 years	2 projects	Senior title
Contractor	1	Management	16–20 years	2 projects	Senior title
	2	Technology	6–10 years	At least 5 projects	Intermediate title
Manufacturer	1	Management	More than 20 years	At least 5 projects	Senior title
	2	Technology	6–10 years	At least 5 projects	Intermediate title
Government	1	Management	More than 20 years	3 projects	Senior title
	2	Administration	11–15 years	4 projects	Intermediate title
Facility	1	Management	6–10 years	At least 5 projects	Intermediate title

Before the first face-to-face interview, the research background, purpose, and risk factors collated from a literature review were emailed to experts. Short interviews with experts were completed by phone and email. Experts were invited to review the representativeness of risk factors and judge whether they fit the actual situation in Qinghai Province. Some experts had proposed new risk factors and given reasons. Then, the questionnaire was designed according to the compiled list of risk factors (Section 4.2) and the special data form [52] required for SNA. Two points should be noticed when designing the questionnaire:

- The relationship between risks may be mutual, but the effects may be different. For example, risk A directly affects risk B, but risk B does not directly affect risk A.
- It is necessary for respondents to theoretically judge 1600 groups (40×40) of relations to obtain the data in the matrix form. However, overwork may lead to unclear thinking and judgment of respondents, resulting in larger errors.

Based on the above key points and design skills, the questionnaire consists of the introduction, basic information, the judgment of the interaction between risk factors, and thanks. The binary matrix is used to quantify the relationship between the risks of each group, and the judgment of the risk relationship is the core part of data collection. The risk factors of the line and the column are compared. If the respondents think that the line risk factor directly affects the column risk factor, “1” will be filled at the intersection of the line and column; otherwise, respondents will fill “0”. The questionnaire has eliminated the intersection of risk factors that almost have no mutual influence, and the respondents only judge the possible relationship, thus improving the quality of the questionnaire.

We made an appointment with each expert before the one-on-one interview and informed them that the interview was expected to take 60–90 min. The first face-to-face interview was mainly divided into three processes:

- General Introduction. Experts were provided with the background, purpose, and refined list of risk factors.
- Questionnaire. Experts were invited to fill out the questionnaire on-site.
- Semistructured interview. Experts talked about their opinions and suggestions on the development of prefabricated buildings in Qinghai Province.

Each interview took an average of 70 min, and the interview time was adequate and effective [19]. After obtaining the consent of experts, interview processes were recorded to ensure the completeness of the materials.

During the risk response phase, a second interview was conducted to invite the above 11 experts to propose some targeted risk response strategies based on our research findings. Because of the experience of the first interview, the second interview process went smoothly. After the expert interview, field research was conducted at a national prefabricated construction industry demonstration base in Qinghai Province to ensure the strategy was on the ground. The views and demands of managers and operational workers were adopted to help refine the risk response strategy.

4. Risk Identification

4.1. Boundary Identification

4.1.1. Critical Stakeholders

Freeman [53] defines "stakeholders" as individuals and collectives that can influence the realization of or be affected by organizational goals. In the PBP, stakeholders are individuals or organizations that work hard to achieve the project goals or are affected by the construction process of the project. PBP risks run through the life cycle of the project that involves many stakeholders, and different stakeholders have different priorities [54] that should be taken into account.

As shown in Figure 2, core stakeholders and the relevant statistics are selected from 10 papers related to stakeholders of PBPs [19,20,25,36,55–60]. Since the focus of this research is not on the project contracting model, the main contractor and subcontractors are collectively referred to as contractors. The transportation of prefabricated components in Qinghai Province is arranged by manufacturers, and there is almost no independent transporter. Therefore, component manufacturers and transporters are collectively called manufacturers. Finally, six types of stakeholders are selected as the core stakeholders of the life cycle of PBPs in Qinghai Province: developer, designer, contractor, manufacturer, government, and facility, as shown in Table 2.

Table 2. Core stakeholders of PBPs in Qinghai province.

ID	Stakeholder	Position
1	Developer	Responsible for project development, decision making, and integrated management
2	Designer	Responsible for the design task of the whole process of the project
3	Contractor	Responsible for site construction and coordinated management
4	Manufacturer	Responsible for the production and transportation of components
5	Government	Formulate relevant policies and approve and supervise projects
6	Facility	Daily management and regular maintenance of PBPs

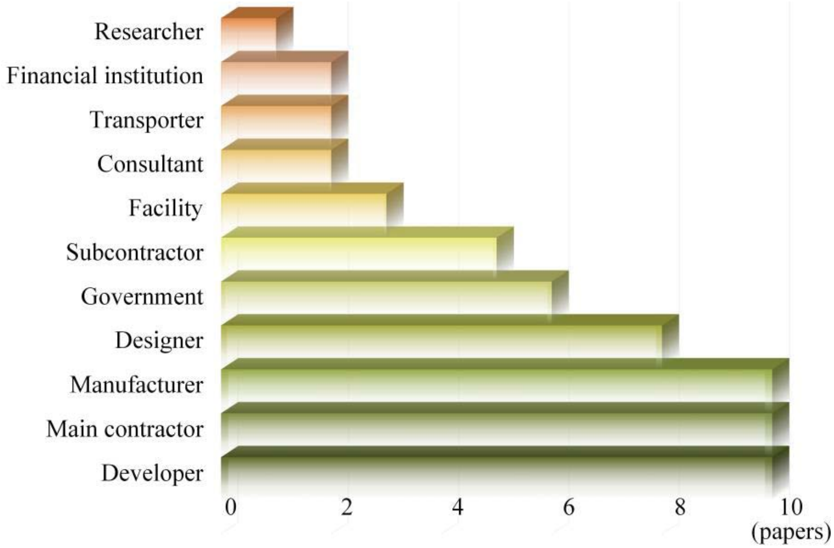

Figure 2. Literature statistical analysis for stakeholders.

4.1.2. The Life Cycle

PBP's management focuses on integrated management [61]. Therefore, the analysis of PBP risk needs to be based on the life cycle theory [52,62]. The life cycle of construction projects covers the stages of planning, design, construction, operation, and demolition, and there are interactions between different stages. Compared with the traditional construction method, the new component supply stage of the PBP will affect the realization of the project goal to a greater extent.

At present, the development of PBPs in underdeveloped areas is in the primary stage, and it does not involve the operation and maintenance stage and the demolition and recovery stage. However, it is still necessary to consider the risks of the two stages for ensuring the integrity of the research [63] and provide some forward-looking and instructive suggestions to promote the development of PBPs in underdeveloped regions.

According to the literature review and expert interviews, the life cycle of PBPs is divided into seven stages: feasibility study stage, design stage, component supply stage, construction stage, acceptance stage, operation and maintenance stage, and demolition and recovery stage.

4.2. Risk List

The risk factors involved in 20 highly relevant papers were reviewed and supplemented by experts. Finally, a risk list of PBPs containing 40 factors was determined. This process was widely used in previous studies [19,20,64]. Furthermore, according to experts' suggestions, six risk factors (R7, R8, R22, R23, R39, and R40) that were not covered much in references were included in the list of risk factors. Risk factors have been classified based on stakeholder perspective and life cycle theory, as shown in Table 3.

Table 3. Risk list of PBPs.

Risk ID	Risk	Classification		References
		Stakeholder	Life Cycle	
R1	Market demand fluctuation	Developer/Designer/Contractor/Manufacturer	Feasibility study	F1, F2, F3, F4, F16, F17, F18
R2	Underestimate cost	Developer		F1, F2, F5, F18
R3	Difficulties in financing			F1, F4, F6, F8, F14, F16, F17
R4	Low communication efficiency between partners	Developer/Designer/Contractor/Manufacturer	Feasibility study/Design/Construction/Component supply	F3, F4, F6, F7, F8, F9, F10, F11, F12, F14, F15
R5	Low level of decision-making	Developer	Feasibility study	F5, F6, F9, F10, F11, F15, F18, F20
R6	Lack of professional consultants			F5, F6, F17, F18
R7	Low material reuse		Demolition and recovery	F6, F15
R8	Difficult to recycle resources			F6, F15
R9	Low level of information technology	Designer	Design	F5, F10, F15, F17
R10	Design changes frequently			F2, F3, F4, F7, F8, F12, F20
R11	Lack of standardized design system			F1, F3, F4, F5, F10, F11, F12, F14, F16, F17, F19
R12	Imperfect design paper			F2, F3, F4, F5, F7, F8, F10, F14, F17, F19
R13	Inadequate design review			F3, F4, F7, F8, F12, F17
R14	Unreasonable construction scheme	Contractor	Construction	F2, F3, F5, F7, F9, F10, F14, F16, F19, F20
R15	Lack of skilled labor			F1, F2, F4, F6, F7, F14, F17, F18, F20
R16	Frequent personnel flow			F5, F13, F19, F20
R17	Safety accidents			F5, F7, F15, F20
R18	Labor disputes			F3, F5, F7, F8
R19	Mechanical failure			F3, F4, F7, F12, F17, F18
R20	Irresistible force			F3, F5, F7, F8, F17, F20
R21	Lack of management experience			F2, F3, F4, F6, F8, F10, F14, F16, F18, F19
R22	Turnover of own funds			F4, F5
R23	Project scope changes			F2, F8
R24	Immature key technologies			F1, F6, F10, F14, F15, F18
R25	Unreasonable storage of components			F12, F13, F14, F17
R26	Installation error of prefabricated components			F2, F7, F12, F14, F17
R27	Delayed payment		Acceptance	F3, F4, F7, F9
R28	Construction quality accident			F2, F3, F18, F20

Table 3. *Cont.*

Risk ID	Risk	Classification		References
		Stakeholder	Life Cycle	
R29	Delayed delivery of components to the site	Manufacturer	Component supply	F2, F3, F4, F7, F8, F12, F13, F17
R30	Unclear prefabricated components			F7, F12, F13
R31	Problems in factory management			F2, F3, F7, F17
R32	Poor quality of prefabricated components			F2, F4, F7, F8, F14, F15, F17, F18, F20
R33	Does not meet shipping standards			F4, F11, F15, F17, F20
R34	Transportation damage of components			F2, F7, F14, F15, F17, F20
R35	Policy changes	Government	Feasibility study	F3, F4, F7, F15, F16, F17, F18
R36	Imperfect regulations and standards			F1, F2, F3, F4, F14, F15, F16, F17, F18, F20
R37	Lack of financial support policies			F1, F2, F4, F6, F14, F16, F17, F18, F20
R38	Complex or inefficient approval procedures			F6, F7, F9, F13, F18
R39	Lack of experienced facility companies	Facility	Operation and maintenance	F19, F20
R40	Lack of reasonable and scientific maintenance			F2, F13, F19

Note: F1 = [31]; F2 = [19]; F3 = [65]; F4 = [66]; F5 = [67]; F6 = [68]; F7 = [20]; F8 = [69]; F9 = [70]; F10 = [32]; F11 = [33]; F12 = [71]; F13 = [72]; F14 = [18]; F15 = [73]; F16 = [23]; F17 = [36]; F18 = [30]; F19 = [74]; F20 = [75].

5. Construction of Risk Network

5.1. Consistency Analysis

"Consistency analysis" explores the consistency of different experts' answers to the direct relationship between risk factors [76]. Then, the risk network of PBPs is constructed according to the final consistent answers of experts, and the steps are shown in Figure 3. First, the "Respondent–Answer" binary matrix is constructed using the 11 valid questionnaires recovered in the data sorting part. Then, the consistency matrix is calculated in the software operation part to obtain analysis results using Ucinet 6.0. Finally, in the result-analysis part, the ratio of the first largest to the second largest eigenvalue is 9.196, and the ratio is greater than three, proving that the answer data have a single answer mode. The analysis results can be used to construct an adjacency matrix of the risk factor relationship of PBPs.

5.2. Risk Network Model

The adjacency matrix of the PBP risk relationship is imported into NetDraw, and a risk network model composed of 40 nodes and 129 directed arrow lines is obtained, as shown in Figure 4. Each risk factor is represented by a node (square). Different patterns in the node represent different stakeholders, and different colors represent different stages of the entire life cycle of the risk node. The arrow tail of the connection between the two nodes is the sender of the risk factor, and the arrow is the receiver of the risk factor.

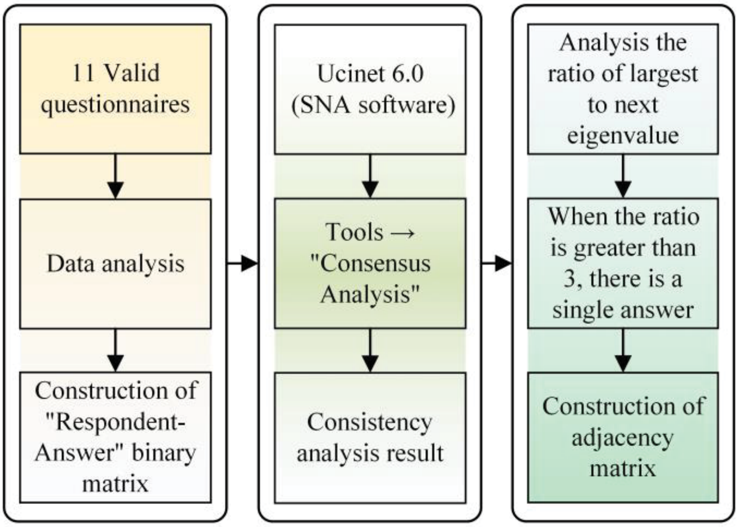

Figure 3. Consistency analysis process.

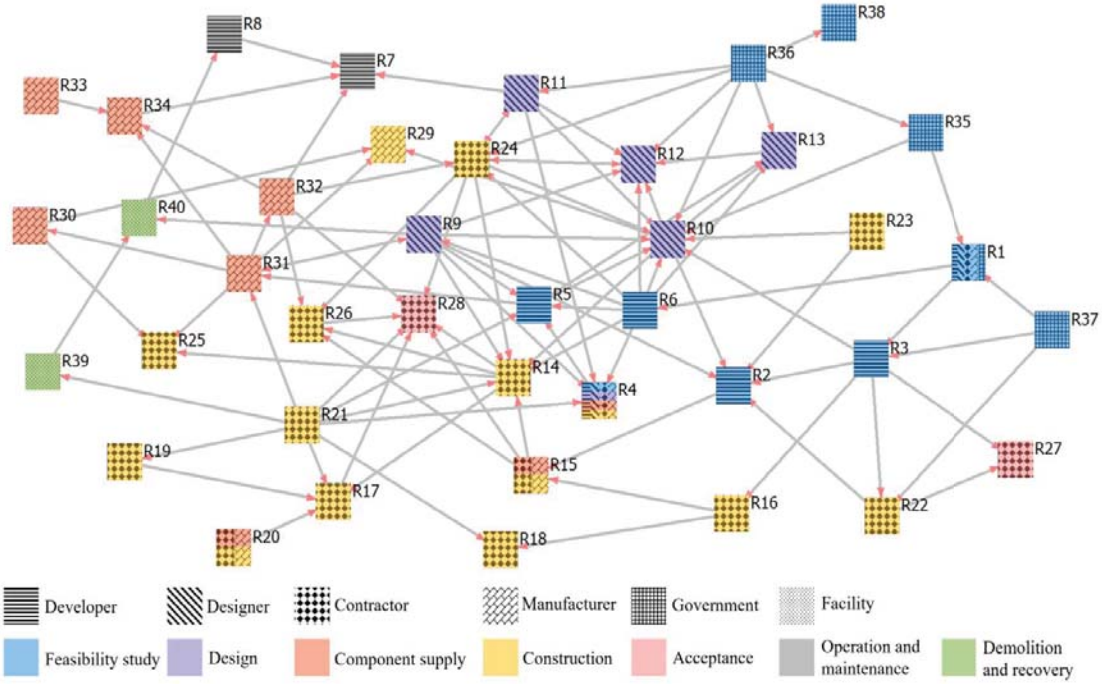

Figure 4. Risk network model.

6. Key Risk Analysis

6.1. Key Risk Factor

6.1.1. Whole Network Analysis

The whole network analysis can comprehensively study the whole network relationship and reveal various structural characteristics [77]. According to the block model theory of White et al. [78], the most basic characteristics of a network can be shown by the relationships between various point sets, and these relationships can be reflected by the image matrix of the block model. In the whole network analysis, the block model theory can be used to make the relationship of the entire risk network clearer. Following the block model construction ideas of Wasserman and Faust [79], the block model is constructed and analyzed for the risk network of PBPs. In Ucinet 6.0, the CONCOR algorithm is used to block the risk network nodes of PBPs. The block matrix is shown in Table 4. Furthermore, the density matrix of the risk network block model is shown in Table 5.

Table 4. Block matrix of risk network.

Block	Risk Factor
1	R1, R37, R3
2	R16, R2, R22, R27
3	R9, R5, R23, R6, R35, R36
4	R24, R13, R12, R10, R11
5	R4, R18, R19, R40, R39, R31
6	R28, R15, R17, R20, R14, R26, R21
7	R8, R33, R32, R7, R34, R38
8	R25, R29, R30

Table 5. Density matrix of risk network block model.

Block	1	2	3	4	5	6	7	8
1	0.500	0.417	0.056	0.067	0.000	0.000	0.000	0.000
2	0.000	0.167	0.000	0.000	0.042	0.071	0.000	0.000
3	0.056	0.083	0.133	0.500	0.139	0.048	0.000	0.000
4	0.000	0.050	0.000	0.500	0.033	0.114	0.033	0.067
5	0.000	0.000	0.056	0.000	0.033	0.024	0.083	0.167
6	0.000	0.000	0.024	0.000	0.119	0.286	0.000	0.048
7	0.000	0.000	0.000	0.033	0.000	0.048	0.167	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.333

The high network density of the whole network indicates the close links between network members, thus resulting in the strong impact of the network on the attitude and behavior of the actors [80]. The whole network density of the risk network is calculated to be 0.0647. The value greater than 0.0647 in Table 5 is replaced by 1, and the value less than 0.0647 is replaced by 0 to obtain the image matrix of the risk network block model, as shown in Table 6.

Based on the descriptive analysis and classification research of various positions in the network structure from the study of Burt [81], it can be analyzed from Table 6 that: ① Block 2, Block 4, and Block 6 have both transmitting and receiving relationships, and are closely related to each other, indicating that they are in the primary position. ② Block 5 has both transmitting and receiving relationships, and the internal connection is not close, implying it is in the broker position. ③ Block 1, Block 3, Block 7, and Block 8 have only transmit or receive relationships, showing that they are in isolated positions. To sum up, the nodes in the core position of the network should have many external connections and close internal connections. Therefore, Block 2, Block 4, Block 5, and Block 6 are the core positions in the risk network.

Table 6. Image matrix of risk network block model.

	Block 1	**Block 2**	**Block 3**	**Block 4**	**Block 5**	**Block 6**	**Block 7**	**Block 8**	**Transmit**	**Relations with Oneself**
Block 1	1	1	0	1	0	0	0	0	2	1
Block 2	0	1	0	0	0	1	0	0	1	1
Block 3	0	1	1	1	1	0	0	0	3	1
Block 4	0	0	0	1	0	1	0	1	2	1
Block 5	0	0	0	0	0	0	1	1	2	0
Block 6	0	0	0	0	1	1	0	0	1	1
Block 7	0	0	0	0	0	0	1	0	0	1
Block 8	0	0	0	0	0	0	0	1	0	1
Receive	0	2	0	2	2	2	1	2		
Relations with oneself	1	1	1	1	0	1	1	1		

6.1.2. Ego-Network Analysis

The ego-network analysis mainly measures the importance of a single risk factor in the risk network, which helps to identify key risk factors. Generally, brokerage roles, node degree centrality, and node betweenness centrality analyses are used for individual network analysis. The top 20% risk factors in the three analysis methods are taken as the key factors, and the union is taken as the list of key risk factors in the ego-network analysis.

1. Brokerage Roles Analysis

The brokerage roles analysis focuses on the characteristics of the ego-network. The broker occupies an essential position in the network because they often hold the secrets between multiple groups [82]. Gould and Fernandez [83] classified brokers into five categories: Coordinator, Gatekeeper, Representative, Consultant, and Liaison.

The frequency of the brokers in a node is proportional to the influence of the node and the complexity of the network. Based on the PBP risk network constructed above, the nodes are classified from the perspective of stakeholders and the life cycle (Table 3). Five types of brokerage roles analysis are obtained using Ucinet 6.0. The risk factors for the top eight brokerage roles with the consideration of 20% of the 40 risk factors are shown in Table 7.

Table 7. The risk factors for the top eight brokerage roles.

Rank	**Risk ID**	**Based on the Stakeholder Perspective**					**Based on the Life Cycle Perspective**					**Total**
		Coordinator	**Gatekeeper**	**Representative**	**Consultant**	**Liaison**	**Coordinator**	**Gatekeeper**	**Representative**	**Consultant**	**Liaison**	
1	R10	2	8	4	3	14	2	8	4	7	10	31
2	R14	6	12	0	0	0	6	9	0	0	3	18
3	R24	0	12	0	2	4	0	8	0	2	8	18
4	R31	0	12	0	1	4	0	9	0	2	6	17
5	R9	0	2	0	1	7	0	2	0	1	7	10
6	R3	1	1	4	0	3	2	0	7	0	0	9
7	R6	2	0	6	0	0	2	0	6	0	0	8
8	R5	0	0	4	1	2	0	0	4	1	2	7

The above eight risk factors act as 118 brokerage roles, accounting for 74.68% of all brokerage roles (40 risk factors act as a total of 158 brokerage roles). R10 (design changes frequently) plays all brokerage roles in both dimensions and ranks first in number. Both R3 (difficulties in financing) and R5 (low level of decision making) play the role of four types of brokerage roles in a certain perspective, but the number of R5 is small with little influence. R14 (unreasonable construction scheme), R24 (immature key technologies), R31 (problems in factory management), R9 (low level of information technology), and R6 (lack of professional consultants) all play three types of brokerage roles in at least one perspective. Among them, R6 only plays two types of brokerage roles from the perspective of stakeholders, and the number of R6 is small. Considering the types and number of brokerage roles, R10, R14, R24, R31, R9, and R3 are key risk factors.

2. Node Degree Centrality Analysis

The node degree centrality is proportional to the importance of risks in the risk network [84]. The influence between risk factors is directional. In the digraph, the degree of each point can be divided into "out-degree" and "in-degree". The "out-degree" of a risk factor is large, and the "in-degree" is small, showing that the risk has a large influence on other risks, and there are many uncontrollable factors. Such risk factors easily become risk sources and should be avoided from the source. The "in-degree" is large, and the "out-degree" is small, indicating that the risk factor is easily affected by other risk factors, but it is not easy to cause new risks. The degree difference equals the "out-degree" minus the "in-degree". A large degree difference means that the impact of the risk on other risks is significant, while the impact on itself is relatively small. The top eight risk factors based on node degree centrality are shown in Table 8.

Table 8. The top eight risk factors based on node degree centrality.

Risk ID	Out-Degree	In-Degree	Normalized Out-Degree	Normalized In-Degree	Degree Difference
R21	9	0	23.077	0	9
R6	8	1	20.513	2.564	7
R9	8	2	20.513	5.128	6
R36	6	0	15.385	0	6
R32	5	1	12.821	2.564	4
R31	6	3	15.385	7.692	3
R3	5	2	12.821	5.128	3
R11	5	2	12.821	5.128	3

The "in-degree" of R21 (lack of management experience) and R36 (imperfect regulations and standards) are both 0, which are trigger nodes and the source of affecting the transmission of risk relationships, and they need to be controlled and contained from the source of risk. The "out-degree" and "in-degree" of other nodes are all greater than 0, which are path nodes. The node degree difference of R6 (lack of professional consultants) and R9 (low level of information technology) is relatively high, indicating that they have a greater impact on other risk nodes, but they are not easily affected. R6 and R9 belong to risk sources, which need attention. The node degree difference of R32 (poor quality of prefabricated components), R3 (difficulties in financing), and R11 (lack of standardized design system) is small, but the "out-degree" is still greater than the "in-degree", and they tend to be risk sources. The "in-degree" of R31 (problems in factory management) is the largest among the top eight nodes, indicating that this risk is vulnerable to other risks.

3. Node Betweenness Centrality Analysis

The node betweenness centrality can reflect the control ability of each risk node in the network to risk transmission and act as an "intermediary" connecting each node. The centrality is proportional to the "mediation effect" and the control power. The top eight risk factors ranked by node betweenness centrality are shown in Table 9.

Table 9. The top eight risk factors ranked by node betweenness centrality.

Rank	1	2	3	4	5	6	7	8
Risk ID	R24	R10	R31	R5	R11	R4	R12	R14
Node Betweenness Centrality	113.333	97.167	96.833	91.667	78.000	67.000	63.167	52.333

In Table 9, the node betweenness centrality of the eight risks is large, and the influence on other risk nodes is relatively strong. The eight risks can be listed as key risks. The node betweenness centrality of R24 (immature key technologies) is greater than 100, indicating that R24 belongs to the super influential node, and the risk control of this node should be paid special attention.

Table 9 shows that the key risk factors obtained from the brokerage roles analysis are: R10, R14, R24, R31, R9, and R3; from the node degree centrality analysis are: R21, R6, R9, R36, R32, R31, R3, and R11; from the node betweenness centrality analysis are: R24, R10, R31, R5, R11, R4, R12, and R14. The union of key risk factors from three dimensions is taken as the final key risk list for ego-network analysis, containing 14 risk factors: R3, R4, R5, R6, R9, R10, R11, R12, R14, R21, R24, R31, R32, and R36.

6.2. Key Risk Relationship

The directed arrow between nodes represents the interaction relationship in the risk network, and the key risk interaction relationship is identified by line betweenness centrality analysis. Line betweenness centrality measures the control advantage of the relationship between two nodes in the whole network [51]. The betweenness centrality of a line is proportional to the ability to control risk transmission and the importance of the control. The line betweenness centrality of the risk network can be calculated by Ucinet 6.0. There are 101 lines (relationships) greater than 0, and the top 20 (20% of the 101 lines) are shown in Table 10.

Table 10. The top 20 relationships according to line betweenness centrality analysis.

Rank	Relationships	Betweenness Centrality Analysis
1	R5→R31	89.333
2	R4→R5	89.000
3	R24→R11	87.000
4	R12→R24	85.167
5	R11→R4	76.000
6	R1→R6	52.667
7	R31→R9	45.333
8	R10→R12	44.667
9	R9→R40	34.333
10	R2→R15	31.000
11	R31→R32	28.667
12	R10→R14	28.500
13	R35→R1	27.500
14	R3→R10	25.500
15	R13→R12	24.667
16	R6→R9	24.000
17	R32→R24	23.333
18	R40→R8	22.333
19	R10→R2	22.000
20	R14→R17	22.000

The betweenness centrality of the above 20 relationships is relatively large, indicating that the ability to "control information" is strong. The above 20 relationships have a greater impact on the structure of the entire risk network and should be controlled as key risk relationships. In addition, there are 15 relationships among 14 key risk factors in Table 10, indicating that the key risk factors in the above analysis have a great control advantage in the risk network.

7. Risk Control and Effect Detection

7.1. Core Risk Identification

Identifying core risks relies on the results of ego-network analysis and whether the key risk factors are in the core block of the whole network. The key risk in the core block is the core risk. The identification process of the core risk factors is shown in Figure 5.

The whole network analysis shows that only Block 2, Block 4, Block 5, and Block 6 are at the core position in the risk network. R3 belongs to Block 1; R5, R6, and R9 belong to Block 3; and R32 belongs to Block 7. Therefore, the core risks consist of R4, R10, R11, R12, R14, R21, R24, R31, and R36 (Table 11).

7.1.1. Communication

R4 (low communication efficiency between partners) is a core risk throughout the main stage of PBPs, involving many stakeholders led by developers. During the promotion of PBPs in underdeveloped areas, the communication between partners does not belong to the technical or economic aspects, which can easily lead all stakeholders to ignore the importance and influence of this risk.

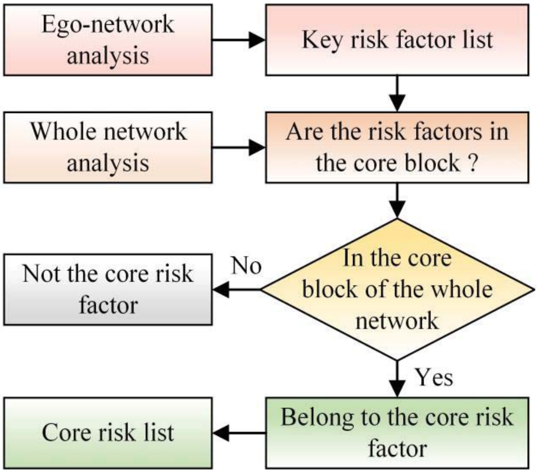

Figure 5. The identification process of the core risk factors.

Table 11. Core risk factors of PBPs in Qinghai Province.

Risk ID	Risk	Classification	
		Stakeholder	**Life Cycle**
R4	Low communication efficiency between partners	Developer/Designer/ Contractor/Manufacturer	Feasibility study/Design/ Construction/Component supply
R10	Design changes frequently	Designer	Design
R11	Lack of standardized design system		
R12	Imperfect design paper		
R14	Unreasonable construction scheme	Contractor	Construction
R21	Lack of management experience		
R24	Immature key technologies		
R31	Problems in factory management	Manufacturer	Component supply
R36	Imperfect regulations and standards	Government	Feasibility study

7.1.2. Design

The stakeholders involved in R10 (design changes frequently), R11 (lack of standardized design system), and R12 (imperfect design paper) are mainly designers, and they are relatively single from the perspective of the life cycle. R10, R11, and R12 are concentrated in the design stage. Many experts highlight the above design risks in field research.

- R10 is mainly caused by the developer's insufficient experience and incomprehensive overall control of the PBP, leading to the heavy task of design changes.
- R11 mainly stems from the fact that underdeveloped areas did not adjust the relevant design standards for PBPs to local conditions and lacked a specific and unified design system during construction.
- R12 and R11 are closely related. The lack of a targeted standard design system results in problems for designers, such as insufficient construction drawings and undetailed component drawings. Therefore, many risks in the design stage have seriously hindered the development of PBPs.

7.1.3. Construction

R14 (unreasonable construction scheme), R21 (lack of management experience), and R24 (immature key technologies) are mainly concentrated in the construction stage.

- At present, there are few PBPs and few contractors with rich experience in underdeveloped plateau areas. Therefore, lack of management experience is one of the core risks.
- Compared with the developed areas in the east, the theoretical and technical aspects are still backward. Some key technologies of PBPs are not mature enough. There are generally problems such as large errors in on-site installation components and insufficient node processing.
- When formulating the construction scheme, the contractor follows the experience of traditional construction projects and copies the construction mode of PBPs in other regions but fails to adjust the construction scheme to local conditions, thus leading to an unreasonable construction plan.

7.1.4. Component Supply

R31 (problems in factory management) is mainly caused by the problems of component manufacturers (which contains PC components and steel structures), including unreasonable production line scheduling, long-term storage of components, and a small supply radius of factory components. In fact, there are fewer component factories in less-developed areas. At present, there are only two large component manufacturers in Qinghai Province, which has almost formed a monopoly in the market. Qinghai Baoheng Green Building Industry Co., Ltd., Haidong, China mainly produces PC components, and Qinghai Xikuang Hangxiao Steel Structure Co., Ltd., Xining, China mainly produces steel structure components. From a long-term perspective, this is detrimental to the development of the PBP market. Additionally, these two large-scale manufacturers are currently facing a situation of "no order to do".

- The current PBP market in underdeveloped areas is oversupplied. Although the production line operation of steel structure components is slightly better than that of PC components, it is still not optimistic.
- The transportation distance of PC components is limited and even cannot be transported to other provinces. However, since the production line of PC components is generally not interrupted, there is a conflict in production line scheduling, leading to the long-term stacking of components.

The PBP market environment in underdeveloped areas is not very friendly to manufacturers, and factory management naturally faces many problems. It is necessary to control such risks to find a balance between market supply and demand.

7.1.5. Policy

R36 (imperfect regulations and standards) is mainly due to the lack of comprehensive policies, regulations, and standards in underdeveloped areas. Although the local government strongly supports the development of PBPs and promulgates many supporting policies, there are still two problems.

- The relevant construction departments are actively promoting PBPs, but the funds are difficult to implement. Compared with other plain areas, the plateau area has higher construction costs, such as artificial construction costs, material transportation costs, and mechanical maintenance costs. Therefore, financial support is particularly important.
- The relevant regulations and standards are not targeted enough, and the operability and supervision ability of policies are poor. When learning from the experience of PBPs in developed areas, it is easy to ignore whether certain aspects apply to local development. For example, it is difficult to achieve a high prefabrication rate in the short term under the current situation.

7.2. Risk Response Strategy

There are usually four risk response strategies: risk avoidance, risk mitigation, risk transfer, and risk acceptance. Given the above nine core risk factors and five key risk relationships, 11 experts have been interviewed again, and specific measures have been put forward accordingly. Then, field research has been conducted on a national prefabricated construction industry demonstration base in Qinghai Province and improved various strategies according to the research situation.

7.2.1. Core Risk Factors

1. For R4, the risk mitigation strategy is adopted.
    - With the help of building information modeling (BIM) technology, developers can establish a network information management platform for PBPs that includes all stakeholders to strengthen project progress management, expand information sharing channels, and improve communication efficiency among all parties.
    - The government should speed up the implementation of the engineering, procurement, and construction (EPC), and strengthen the connection between design, construction, manufacturer, and management personnel. By doing so, the efficiency of information transmission is improved, the common goals of all stakeholders are promoted, and inefficient communication and ineffective management are avoided.
2. For R10, the risk mitigation strategy is adopted.
    - Designers should fully understand the needs of developers in the early stage of design and keep in touch with all participants at any time to reduce design changes caused by information asymmetry.
    - Designers can visualize the design scheme through BIM technology and try to standardize and modularize the design drawings to avoid excessive design changes.
3. For R11, the risk avoidance strategy is adopted.
    - Designers can use BIM to create a component library for checking collisions and optimizing the design. Then, a standardized design system can be gradually built.
    - The government can actively promote the creation of a standardized design system for PBPs, encourage relevant enterprises to formulate design standards, and prepare for the formation of a complete standardized design system for PBPs.
4. For R12, the risk avoidance strategy is adopted.
    - Designers need to improve their professional ability, master the specifications of PBP design drawings, and use BIM technology appropriately to improve the design level to ensure the accuracy and completeness of drawings.

   - Designers can establish a drawing control system, complete the design according to laws, regulations, and industry standards, and focus on reviewing drawings involving project quality and safety. According to the characteristics of PBPs, the drawing control system can ensure the design quality effectively.

5. For R14, the risk mitigation strategy is adopted.
   - When formulating construction schemes, contractors should strengthen communication with developers to clarify their goals. The scheme should also be dynamically adjusted according to the construction progress to reduce rework during the construction process.
   - Contractors should be involved in the design of the project scheme at the design stage, which can improve the constructability of the design scheme.
6. For R21, risk mitigation and risk transfer strategies are adopted.
   - Contractors should use reasonable construction technology and scientific management methods to implement the construction scheme seriously, report and solve problems found on-site promptly, and do a good job in construction organization and coordination.
   - Contractors should pay attention to management innovation, establish a management system in line with PBPs, and strengthen mechanism innovation in quality management and progress management.
   - According to the actual situation of the contractor, the developer can reasonably transfer the construction risk through subcontracting and engineering insurance.
7. For R24, the risk avoidance strategy is adopted.
   - Contractors should strengthen the technical training of construction personnel of PBPs and build a skilled prefabricated construction team.
   - The government can organize colleges and universities, scientific research institutes, and relevant large enterprises to pool scientific research resources and promote industry–university–research cooperation. Furthermore, the bottleneck of key technologies in PBPs should be broken in plateau areas, and especially research on prefabricated structural systems should be strengthened to promote the development of key prefabricated technologies in a large-scale and systematic manner.
8. For R31, the risk mitigation strategy is adopted.
   - Manufacturers should actively adjust component production tasks and innovate the industrial structure according to the market environment to optimize factory management.
   - Manufacturers can build a factory information management system combined with emerging technologies to provide a collaborative work platform for all stakeholders, efficiently assisting in information management, production scheduling, and on-site assembly tasks for components.
9. For R36, the risk mitigation strategy is adopted.
   - The government should establish and improve relevant laws and regulations as soon as possible, gradually standardize the PBP market, and improve the whole-process supervision mechanism to reduce construction risks.
   - The government should formulate policies scientifically based on the actual local conditions. PBPs in underdeveloped areas are still in the promotion stage, and financial subsidies need to be implemented. Dynamic adjustments will be made later according to the development situation.

7.2.2. Other Key Relationships

Since the core risk factors can be controlled to a certain extent through the above risk response strategies, the related key relationships are no longer considered. The list of other key risk relationships is shown in Table 12, and the specific response strategies are as follows.

Table 12. List of other key risk relationships.

Rank	Relationships		Betweenness Centrality Analysis
6	R1→R6	Market demand fluctuation → Lack of professional consultants	52.667
10	R2→R15	Underestimate cost → Lack of skilled labor	31
13	R35→R1	Policy changes → Market demand fluctuation	27.5
16	R6→R9	Lack of professional consultants → Low level of information technology	24
18	R40→R8	Lack of reasonable and scientific maintenance → Difficult to recycle resources	22.333

1. For R1→R6, risk mitigation and risk transfer strategies are adopted.
    - The government can issue relevant policies to strongly support the development of consulting companies whose main business is PBP professional consulting.
    - Universities and enterprises should strengthen the training of BIM talents, which can improve the ability of practitioners to use information technology to solve engineering problems and cultivate more talents for the PBP consulting industry in underdeveloped areas.
2. For R2→R15, the risk avoidance strategy is adopted.
    - Developers should fully consider the particularity of plateau projects and appropriately increase the cost budget of PBPs.
    - Contractors should keep the labor cost of PBPs and market conditions abreast in underdeveloped areas and try to maintain long-term cooperation with experienced and reliable construction teams.
3. For R35→R1, the risk mitigation strategy is adopted
    - The government should guide relevant enterprises to establish a unified, fair, and open construction market, break down regional barriers, remove unreasonable local market access restrictions, and minimize market downturns caused by excessive market demand fluctuations.
    - The government should actively evaluate the support policy of PBPs, consider the factors such as construction cost and market promotion comprehensively, and continue or increase the policy support of credit financing appropriately. The government should also actively promote the prefabrication of public buildings to increase the production orders of components, offset the impact of high costs, and expand market applications.
4. For R6→R9, the risk avoidance strategy is adopted.
    - The government can support enterprises in carrying out professional training by pretax exemption or by setting up special funds. Furthermore, support funds can be weighted towards the development of higher education, encouraging colleges and universities to open related majors or courses, which can cultivate more professional talents.
    - The government needs to actively guide relevant enterprises to create an integrated cooperation platform based on BIM, which will help designers achieve “forward design”. In addition, the platform is conducive to information sharing and resource integration in the industrial chain, thus improving the information technology level of the PBP industry.
5. For R40→R8, the risk mitigation strategy is adopted.
    - Developers and facilities can introduce BIM technology into the operation and maintenance stage of PBPs to achieve information sharing throughout the life

cycle. BIM technology can monitor the usage and safety performance of PBPs in real-time and provide data support for the recycling and utilization of PBP resources in the future.

- Facilities need to strengthen training in the maintenance of PBPs for ensuring reasonable and safe construction of PBPs.

7.3. Risk Effect Detection

Core risk factors play an essential role in different dimensions of the risk network. Removing these core nodes and lines can effectively reduce the overall complexity of the network. To test the effectiveness of the above risk response strategies, the methods proposed by Yu et al. [52] and Yang et al. [85] are adopted to eliminate all core risks and relationships and construct a new risk network (Figure 6). Then, the network integrity, network cohesion, and network reachability are measured to analyze their impact on the network.

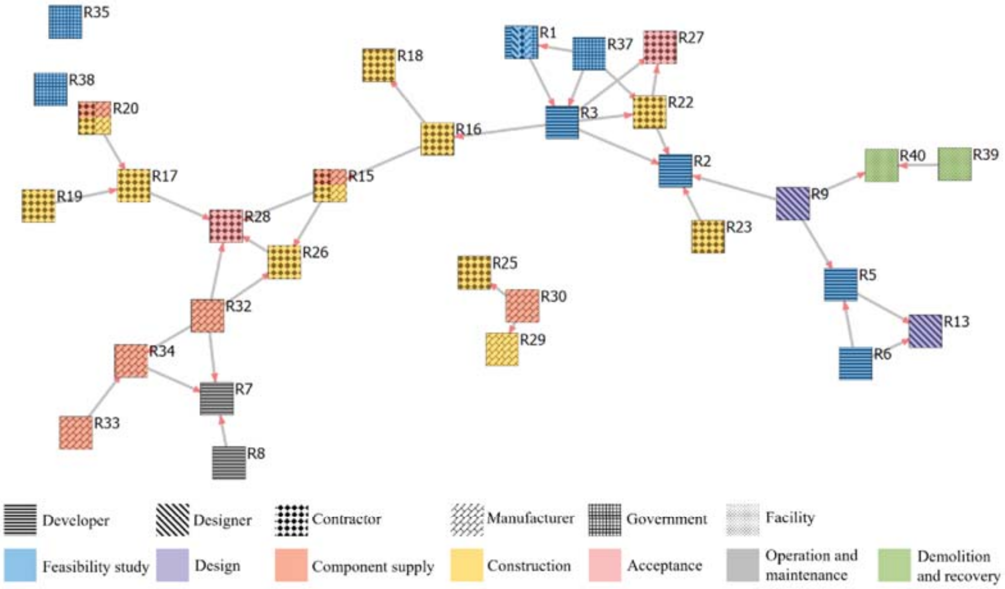

Figure 6. Risk network model after taking risk response strategies.

If all proposed risk response strategies are implemented effectively, core risks and key relationships in the risk network can be eliminated. The calculation results show that the number of risk factors is reduced from 40 to 31, and the number of risk relationships is reduced from 129 to 35. Compared with Figure 4, the risk network in Figure 6 becomes sparse, and the risk relationship is significantly reduced, indicating that the tightness between nodes in the network is significantly reduced. The specific indicators are analyzed as follows.

1. Network integrity. The whole network density can reflect the completeness of the network [80]. High network density is proportional to the connections between nodes and network integrity. After controlling the risk, the whole network density decreases from 0.0647 to 0.0376, reduced by 41.89%. The network density is significantly reduced, and the integrity of the risk network structure is weakened.
2. Network cohesion. The average distance and cohesion index of each node in the network are large, showing that the whole network is cohesive and the network structure is strong [79]. The average distance of each point decreases from 2.92 to

1.65, decreasing by 43.49%, and the cohesion index decreases from 0.151 to 0.049, decreasing by 67.55%. The results indicate that the network structure is no longer solid, and the risk control measures block the influence between risks.

3. Network reachability. Analyzing network reachability can explore the ways of risk transmission and determine the impact of risk transmission. The value is proportional to the number of ways that the risk spreads and the reachability, thus affecting the degree of the impact. The statistical number of reachable matrices before and after the risk control is shown in Table 13. Before the risk control, the reachable number between risks in the reachability matrix is 486, accounting for 31.53% of the maximum reachable number (40 × 39 = 1560). After the risk control, the reachable number between risks in the reachability matrix is 60, accounting for 6.45% of the maximum reachable number (31 × 30 = 930), which is much lower than before. The results indicate that the risk control is effective. It can block the reachability between a large number of risks.

Table 13. The statistical number of reachable matrices before and after the risk control.

Risk ID	Before the Risk Control	After the Risk Control	Risk ID	Before the Risk Control	After the Risk Control	Risk ID	Before the Risk Control	After the Risk Control
R1	29	9	R15	5	2	R29	0	0
R2	6	0	R16	7	4	R30	2	2
R3	27	8	R17	1	1	R31	22	0
R4	22	0	R18	0	0	R32	22	4
R5	22	1	R19	2	2	R33	2	2
R6	23	2	R20	2	2	R34	1	1
R7	0	0	R21	26	0	R35	30	0
R8	1	1	R22	8	2	R36	31	0
R9	22	4	R23	23	1	R37	30	10
R10	22	0	R24	22	0	R38	0	0
R11	22	0	R25	0	0	R39	3	1
R12	22	0	R26	1	1	R40	2	0
R13	22	0	R27	0	0	Total	486	60
R14	4	0	R28	0	0			

In addition, R35 and R38 become isolated nodes, and the subgroup consisting of R25, R29, and R30 are also independent of the main risk network. Therefore, these nodes can be treated separately. In summary, after removing the core risk nodes and key relationships, the complexity of the entire risk network is significantly reduced, indicating that the above risk response strategies are very effective.

8. Discussions

This study follows the classic risk management framework and builds a risk network model for PBPs, which provides response strategies for stakeholders to control the risks of PBPs in the life cycle. Few studies combine the two dimensions of stakeholders and the life cycle for risk analysis of PBPs. However, risks exist at every stage and are closely related to every stakeholder. Compared with other studies, the interaction between risks has been considered in this paper to identify and analyze risks effectively. However, this study has been conducted in an underdeveloped plateau region, and the value for promotion and application in other areas needs to be improved.

Through an in-depth investigation into the underdeveloped plateau area of Qinghai Province, the developers of PBPs, as the core stakeholders, did not show a strong "existence" and did not play a leading role in this study. The results are different from some previous studies. In previous studies, developers and contractors are the core stakeholders of the risk management of PBPs [20,24,25]. Among the core risk factors identified in this study, the risks involved by designers and contractors, respectively, account for more than 33%.

Except for the construction stage, the design stage occupies most of the risks, which is closely related to the particularity of underdeveloped plateau areas. Consistent with the research conclusions of Jiang et al. [43] and Wuni et al. [32], the design stage should receive the attention of the stakeholders of the PBP to reduce problems in the component production and construction stages. When dealing with risks, the government and other core stakeholders are not at the same level in promoting the development of PBPs. Many risk issues need to be solved by the government's policy of regulation or incentives in China's underdeveloped areas [29,31,86], which is different from other studies conducted in developed regions [67]. Therefore, it is significant to explore specific and effective PBP policies in further research. In addition, the lack of the facility is also a problem worth considering. Underdeveloped areas lack professional operation and maintenance teams or enterprises, developers, and contractors, making the public generally have "worries" about the maintenance of PBPs.

9. Conclusions

The SNA is adopted to develop a risk network of PBPs, and nine core risk factors and five key risk relationships are identified. Finally, the effectiveness of relevant risk response strategies through risk effect detection is shown. The main conclusions are as follows:

1. Developers of PBPs in underdeveloped areas fail to play a leading role. Among the nine core risks, developers are only involved in one risk, showing that developers have not yet fully understood the PBPs, resulting in insufficient awareness of developers in the entire construction process.
2. There are prominent problems in the design stage of PBPs. Stakeholders should focus on the design stage of PBPs. While other regions are already advancing the technical breakthroughs in the construction stage, the PBPs in underdeveloped areas are still in the early stage of development, where many design problems still need to be solved. Additionally, these regions lack a unified design system, and there is a phenomenon of "each speaks its own words".
3. In less-developed regions, the development of PBPs must rely on the strong promotion of the government. The market mechanism of PBPs in underdeveloped areas is not perfect, the supply and demand risks are relatively large, and policy regulation greatly affects the spread of the risk network. Therefore, in underdeveloped areas, local governments need to actively introduce corresponding supporting policies to strengthen market cultivation and industrial chain integration and mobilize the enthusiasm of stakeholders.

This is the first study to consider the risk within the life cycle of PBPs in underdeveloped plateau areas, providing theoretical support for the development of PBPs in similar regions. The risk interdependence has been considered, the limitations of traditional risk analysis have been overcome, and the research system of risk management of PBPs has been expanded in this paper. In practice, this study provides valuable risk response strategies for the stakeholders and a reference for the government to formulate targeted incentive policies, thus helping to improve the risk management level of PBPs in underdeveloped areas. The government of underdeveloped areas should actively introduce various policies to improve developers' willingness and the dominant consciousness of PBPs. Furthermore, the design specifications should be standardized and unified to effectively reduce the bottleneck problem in the design stage of PBPs.

Limitations and further research on this topic area should mainly focus on the following two aspects:

1. Although the risk network model of this study can reflect the relationship between risks, it ignores the intensity of the impact. There are solid or weak relationships between risk factors, and the quantitative evaluation of the risk relationship will be realized in future research.

2. The risk strategy proposed in this study is subjective, and some empirical analysis may be required for the actual effect of risk control. In the future, case studies will be conducted on more suitable PBPs to improve risk management strategies.

Author Contributions: Conceptualization, Z.G. and C.L.; methodology, Q.W.; software, Q.W.; investigation, Z.G. and Q.W.; writing—original draft preparation, Q.W.; writing—review and editing, Z.G.; supervision, C.L.; funding acquisition, Z.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Department of Qinghai Province (grant number 2018-ZJ-734) and the Qinghai Provincial Key Laboratory of Plateau Green Building and Eco-community (grant number KLKF-2021-005).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

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

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Design and Implementation of Quality Information Management System for Modular Construction Factory

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Abstract: Modular construction has been gaining increasing attention from industry and academia as a solution to the limitations of the traditional on-site orient production systems in the construction industry. Various attempts have been made to improve modular construction performance. However, while previous studies have attempted to enhance the productivity of modular construction, attempts to improve the efficiency of quality management in modular construction have been limited. Moreover, the quality management practices in a modular factory still rely on document-oriented quality information management, which is inefficient. Therefore, this study aims to develop a quality information management system to improve quality information management during module manufacturing. Accordingly, quality information during module manufacturing has been standardized using integration definition for process modeling, and system functions are defined using standardized quality information. The developed modular factory quality information management system includes module information and production-type management, material management, and module production management. The practicability and validity of the developed system were examined by accredited tests and certification laboratory and modular construction experts. The developed system is expected to contribute to improving the existing inefficient quality management process of module manufacturers by providing an integrated and systematic method to manage quality information generated during manufacturing.

Keywords: modular construction factory; quality management; quality information management system; off-site construction

Citation: Shin, J.; Choi, B. Design and Implementation of Quality Information Management System for Modular Construction Factory. *Buildings* **2022**, *12*, 654. https://doi.org/10.3390/buildings12050654

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 28 April 2022
Accepted: 12 May 2022
Published: 13 May 2022

1. Introduction

Quality management refers to all management activities aimed at achieving the intended use of a product and satisfying user requirements. It seeks to maintain and improve quality by preventing defects. This is achieved by identifying and managing the causes of defects in manufacturing. Construction quality management can be defined as the management of construction according to the design documents and contract with the owner [1]. Construction quality management failures affect various parts of a construction project. Further, construction work that does not adhere to the proposed design often leads to reconstruction, which negatively affects the cost and construction period [2]. In addition, insufficient quality management in construction works can lead to poor construction and, consequently, large-scale casualties [3].

With construction projects becoming larger, more complex, and more advanced, the importance of quality information for effective project management has increased. The accumulation of quality information can lower the defect rate in construction projects by increasing the efficiency of quality management. A reduction in the defect rate positively affects cost and schedule in construction projects by decreasing the rework rate [4]. Further, with construction projects growing in size and complexity, the amount of quality information to be managed has also increased. Quality information is generated in all phases of construction projects, such as during contract change, design change, and nonconforming construction management, in addition to physical inspections for building components, such as construction and material inspections [5]. The construction industry introduced (and continues to utilize) information technology to effectively manage large amounts of quality information [6,7]. For example, technologies such as continuous acquisition and life-cycle support (CALS) and project information management system (PIMS) have been widely adopted in the construction industry.

Meanwhile, modular construction has emerged to overcome the limitations of the existing site-oriented construction method [8]. As a type of off-site construction (OSC), it involves modularizing a building into a panel- or volumetric-type unit (Lawson et al., 2014). It combines the existing construction method of site-oriented operation with the production methods of the manufacturing industry [9,10]. Specifically, modular construction involves transporting and installing building modules manufactured in a factory to the site. The current site-oriented construction method exhibits low productivity; it is difficult to utilize production automation equipment owing to the narrow workspace [11,12]. Further, because most construction activities are performed outdoors, site-oriented construction methods are greatly affected by weather conditions [13]. In contrast, it is easy to use automated facilities in a modular construction factory, and the influence of weather conditions is not significant because the main processes are performed indoor factories [14,15]. Furthermore, modular construction can reduce construction time by simultaneously executing module manufacture in the factory and on-site construction processes, such as excavation and foundation construction [9,16]. Therefore, modular construction can improve productivity by approximately 60% compared to the site-oriented construction method [17]. In addition, modular construction is receiving a lot of attention as the future of construction technology because it is better than site-oriented construction work in terms of safety, waste reduction, and quality [17,18]. Modular construction can be considered as a process between manufacturing and construction. Unlike general manufacturing, which focuses on mass production of small items, modular construction is a project-based production system. However, modular construction's factory-based production system is also different from that of general construction. Owing to such unique characteristics of module manufacturing, various attempts have been made to find better methods of improving the performance of module manufacturing. Goh and Goh [19] proposed a method to improve the productivity of modular construction by applying lean production. Accordingly, they suggested implementing total quality management (TQM), utilizing the E-Kanban Just-in-Time system, multi-skilled labor, and using robots. A comparative analysis of the productivity of the existing and new methods through simulation confirmed that the cycle time was reduced by up to 81.27% and the work in progress by up to 74.30% using the proposed method. Lee and Lee [20] developed a BIM-based digital twin framework and proposed a method for optimizing the transportation of modules from the factory to the site. The developed framework improved the productivity of the modular project by automatically identifying potential risk factors in the transportation process and providing an optimal transport route.

Although studies on modular construction are continuously being conducted, research on its quality management aspect is insufficient. Most of the research to date has focused on improving the productivity of modular construction. Goh and Goh [19] mentioned the need for TQM during the manufacturing process in module factories. However, they could not suggest a specific quality management plan for improving productivity. Although the importance of quality information in the construction industry is increasing, utilizing quality information in modular construction has not been researched. The main difference between modular construction and site-oriented construction is the factory manufacturing method employed in the former. Characteristically, the manufacturing industry repeatedly produces products according to a set production line [21]. Further, it is easy to manage and utilize quality information because related information is also generated sequentially according to a set manufacturing process [22,23]. In contrast, it is difficult to collect and utilize quality information in site-oriented construction work due to complexity and uncertainty, such as sudden actions of workers and changes in the weather [24]. Therefore, quality information can be better utilized in modular construction than in site-oriented construction. Despite the potential of using quality information in modular construction, studies on the management and utilization of quality information have not yet been conducted. In this study, interviews with experts working at module manufacturing factories were conducted to elucidate the quality information management status at the manufacturing stage in a module factory. The interviews were conducted thrice, targeting two different modular construction companies. The two companies are leading modular construction companies in South Korea. Two interviewees with more than ten years of experience in modular construction participated in the interviews from each company. The first one was a paper-based interview focusing on the basic procedures of quality management in module manufacturing factories. Based on the responses from the first interview, a second in-person interview was conducted to clarify the current problems in quality management processes in module manufacturing factories. The last interview was conducted to confirm the issues in the quality management processes of module manufacturing factories identified herein. Both manufacturers managed the quality information generated during the module manufacturing process by relying on documents. Document-oriented quality information management is associated with various problems, such as the loss of written documents and duplicate documents, resulting in inefficient quality management. In addition, large amounts of quality documents were produced during one modular construction project. Because many projects were simultaneously conducted, the amount of documents generated within the module manufacturing company was high. However, there was no method of systematically storing and managing quality information during module manufacturing. Notably, quality information cannot be utilized properly if a separate quality information management plan is not prepared.

This study aims to develop a web-based quality information management system to improve quality information management in the module manufacturing process. Using it, module manufacturers can break away from the existing document-centered quality information management. It facilitates effective management and utilization of the quality information generated during module manufacturing. Regarding system development, this study analyzed module manufacturing in detail. Afterwards, quality information generated in each subdivided task was classified according to its characteristics. Because there is no research on the utilization of quality information in module manufacturing, this study will elucidate the quality information generated in the module manufacturing process. Furthermore, the system can positively affect the module quality level as well as improve the quality control work efficiency.

2. Methods

The quality information management system was developed in the following order: (1) collection of quality data generated during manufacturing in a modular factory, (2) standardization of quality information, (3) defining the system function, (4) system development, and (5) system verification. Figure 1 shows a schematic of the system development process.

1. Data collection was performed to identify key quality information in the module manufacturing process, and key quality information generated at each stage of the process was derived.
2. To integrate the various types of quality data generated in module manufacturing into a single management system, information standardization was performed using integration definition for process modeling (IDEF0).
3. The overall system design direction was determined based on the previous content, and the main functions of the system were defined accordingly.
4. A quality information management system was developed according to the defined functional contents.
5. The usefulness of the developed system was validated by accredited certification laboratory test and modular construction experts.

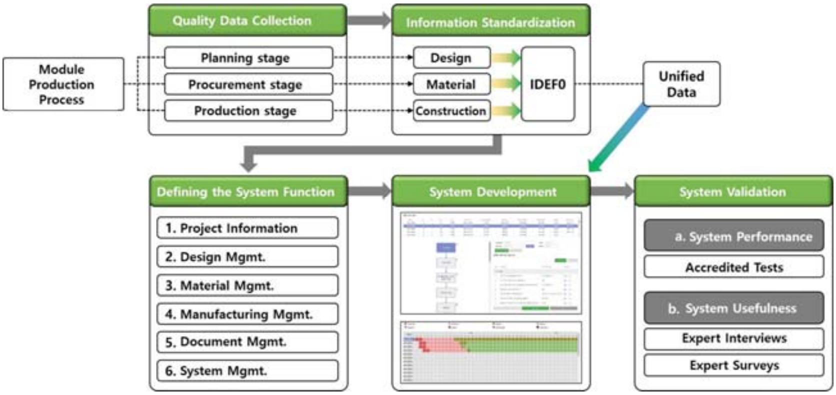


Figure 1. Framework of the development of quality information management system for modular factory.

3. Design of Quality Information Management System

3.1. Module Production Process Analysis

An abundant amount of quality information is generated during module manufacturing. It is generated from all activities that can affect modular quality, such as physical inspection and testing of building components, as well as approval management of material suppliers, management of manufacturing personnel, and management of design documents. Module manufacturing in the factory is conducted in connection with various tasks, such as design, production, and procurement. Quality information generated in the module production stage is also directly or indirectly influenced by quality information generated in other tasks. For example, information related to the main materials and production of the module may vary depending on the quality information generated in the design phase. Thus, the relationship among different types of quality information is complicated because quality information is generated in all tasks during module manufacturing, and the generated quality information affects other information. Therefore, to effectively manage quality information, it is necessary to identify and classify the types and characteristics of tasks that generate quality information during module manufacturing. To elucidate the role of quality management during module manufacturing, we conducted an analysis of modular manufacturers' documents related to quality management, a literature review, and expert interviews. Figure 2 shows a schematic of the quality management process during module production.

The quality management process in module production can be divided into a pre-preparation stage and a module assembly stage based on the time point in module assembly. The former can be further divided into planning and procurement stages. The planning stage starts with the distribution of the completed design documents. A basic management plan for module production is established based on the contents in these documents. The module production management plan refers to the overall management plan for quality management, production management, material import, etc. The initial plan becomes more detailed, according to the actual production environment, as production progresses. After the planning stage, the procurement stage proceeds according to the basic management plan. This phase primarily involves bringing in the main materials selected in the planning stage. The main tasks include selection of material suppliers, making material purchase requests, and material ordering. The factory production stage primarily involves inspection of incoming materials and construction works. After the inspection of the final activity, the module production quality management process is completed by shipping the finished module.

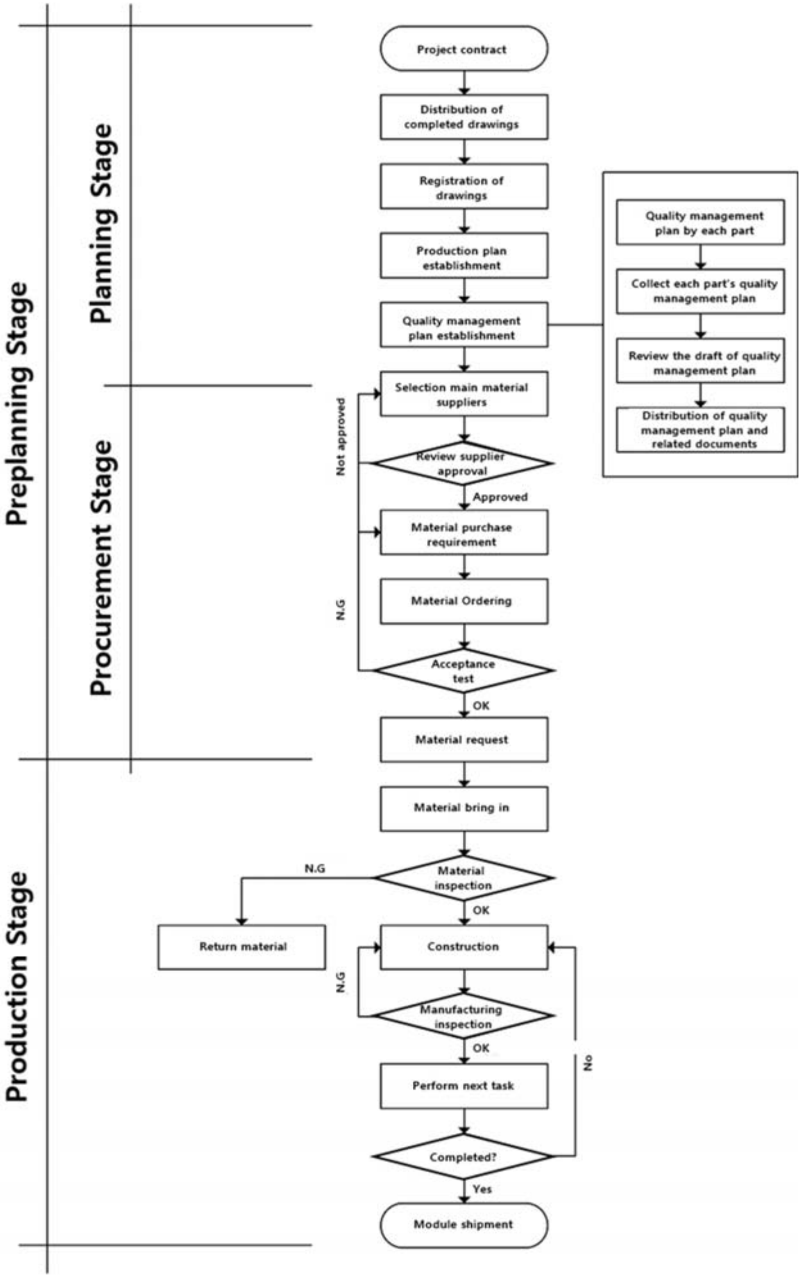


Figure 2. Quality management process in module production.

3.2. Standardization of Quality Information

As previously mentioned, quality information is generated at each stage of module manufacturing. Quality information has different characteristics according to the objective of quality management activities at each stage. Information standardization is required to manage information with different attributes in an integrated way through a single platform [25,26]. It refers to standardizing different types of quality information generated in each process of module production into a specific data format. Quality information in the module manufacturing process is sequentially generated according to the module manufacturing process. IDEF0, one of the process modeling techniques, can comprehensively represent the input and output information, control (i.e., a set of conditions required for a function), and mechanism (i.e., means or resource required to transform input to output) of each function according to the workflow. It is considered an easy and effective method of expressing complicated processes and functions [27]. Therefore, many studies have used IDEF0 for information system development [28]. Gingele et al. [29] applied IDEF0 to the quality management practices of manufacturers and demonstrated that IDEF0 is also effective in dealing with the international standard for quality management systems (ISO 9001). In this study, the quality information of the module manufacturing process was standardized through the IDEF0 method. For effective information standardization, the division between each stage of the module manufacturing process must be distinct. If the stage division of the production process is unclear, determining which information is input/output at which stage in detail and how it is influenced by other information becomes difficult. This study analyzed the object of quality management activities at each stage of the module production process to clarify the information standardization results. Accordingly, it was confirmed that the manufacturing plan establishment process was centered on design, a procurement stage focused on materials, and a factory manufacturing stage focused on construction. Therefore, information standardization was conducted by dividing the factory manufacturing stage into tasks related to design, materials, and construction [30,31]. Table 1 shows the quality information for each production task identified through information standardization.

3.2.1. Standardization of Design Information

Figure 3 shows the standardization result of design quality information during module manufacturing. Design-related quality control tasks can be expressed in the following steps: (A01) preparation of design documents, (A02) review of design (draft), and (A03) preparation of factory production drawings. The design document preparation stage requires basic project information, such as the owner requirements and the project outline. Specifically, in the design document preparation stage, information on the area and height of the modular building, the type of interior/exterior material of the building, etc., is input. Further, basic design document details, such as design drawings, specifications, structural calculations, and bill of quantities, are generated by the design team led by the architect. The basic form of each manufactured module is determined according to the information generated in the design document preparation stage. When completed, the relevant departments, such as the engineering and manufacturing teams at the manufacturer, review the prepared design documents. This review stage involves examination of discrepancies between the contents of the design documents and interference in construction to determine the probability of presence of defects based on the design documents. During design review, new design document information is generated depending on the number of revisions. Information about the production drawing for manufacturing the module is generated from the reviewed design documents by the manufacturer's engineering and manufacturing teams. Factory-manufacturing drawings are created at a more detailed level than the previously created design drawings in that they are created to ensure constructability and precision in the manufactured module. The more accurate the factory manufacturing drawings are, the less the defects in the module manufacturing process and risk of reconstruction.

Table 1. Quality information generated during each production task.

Division	Input	Output	Control	Mechanism
A. Design	1. Contract agreements 2. Owner's requirements 3. Basic project information	1. Design drawing 2. Specifications 3. Structural calculations 4. Bill of quantities 5. Factory production drawings	1. Contract document 2. Relevant regulations 3. Design work procedure 4. Document management procedure	1. Plant manager 2. Design team 3. Owner 4. Production team 5. Engineering Team
B. Material	1. Owner's requirements 2. Basic project information 3. Schedule 4. Required quantity 5. Supplier approval request 6. Material performance test results 7. Application for bringing in material	1. Material supply plan 2. Review result of supplier approval request 3. Purchase order 4. Acceptance inspection result document 5. Material approval documents 6. Invoice for incoming materials 7. Material inspection result document	1. Contract document 2. Design drawings 3. Specification 4. Project Schedule 5. Bill of quantities 6. Relevant regulations 7. Document management work procedure 8. Inspection and test plan	1. Owner 2. Plant Manager 3. Production team 4. Material Supplier
C. Construction	1. Contract Agreement 2. Owner's requirements 3. Basic project information 4. Material supply plan 5. Production manpower status 6. Status of major facilities 7. Request for inspection and test	1. Construction and production plan 2. Project schedule 3. Inspection and test plan 4. Inspection Checklist 5. Inspection result document 6. Test result document	1. Contract document 2. Design drawings 3. Specification 4. Bill of quantities 5. Material supply plan 6. Document management work procedure 7. Relevant regulations	1. Owner 2. Plant Manager 3. Production team

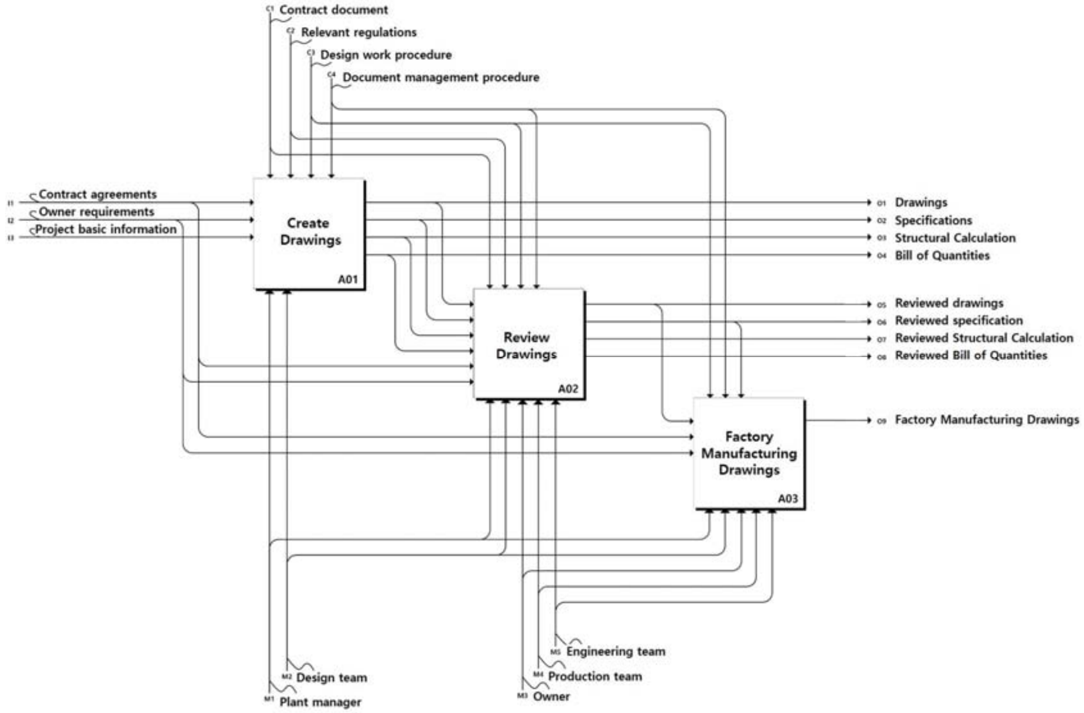


Figure 3. IDEF0 modeling results for quality management in design.

3.2.2. Material Information Standardization

Figure 4 shows the standardization of quality information on materials during module manufacturing. Material-related quality management tasks can be expressed in the following steps: (B01) establishment of material supply plan, (B02) approval of material suppliers, (B03) acceptance inspection of materials, and (B04) inspection of imported materials. The first three are conducted in the pre-preparation stage before module production, and B04 is conducted during the module production stage. Generally, the material supply plan is established according to the basic project information, such as the requirements of the owner and the project outline. The type of material for manufacturing the module depends on the design drawings and specifications. Even if the material type has been determined, the material import schedule will depend on the overall module manufacturing schedule. Therefore, establishing a supply plan for equipment and material follows the initial stage of design and manufacturing. In it, basic information on imported materials, such as item, specification, unit, quantity, and import schedule, is created. Depending on the equipment and material supply plan, major equipment and materials that require supplier approval are selected. Major equipment and material are those that directly affect the performance of modular buildings, such as concrete and structural steel. Supplier approval involves reviewing and determining whether the supplier can supply the materials required in the design documents. Therefore, different qualification certificates and information on material performance certification that can prove stable delivery on the part of the material supplier are primarily managed in this stage. After supplier approval, the materials go through a pre-acceptance inspection before entering the factory. Acceptance inspection is a repeat inspection before entering the factory to check the performance of key materials, where the final performance suitability of the purchased material is judged. It mainly involves checking whether the conditions of incoming materials and suppliers match the supporting documents. If there is no major problem in the material performance, the material that has passed the acceptance inspection is brought into the factory. The imported materials go through a material inspection process before being utilized in module manufacturing. Here, a checklist containing the main inspection items for each material is used, and whether the material is damaged or matches the order information is determined. Further, information such as incoming invoice information and material inspection results is generated.

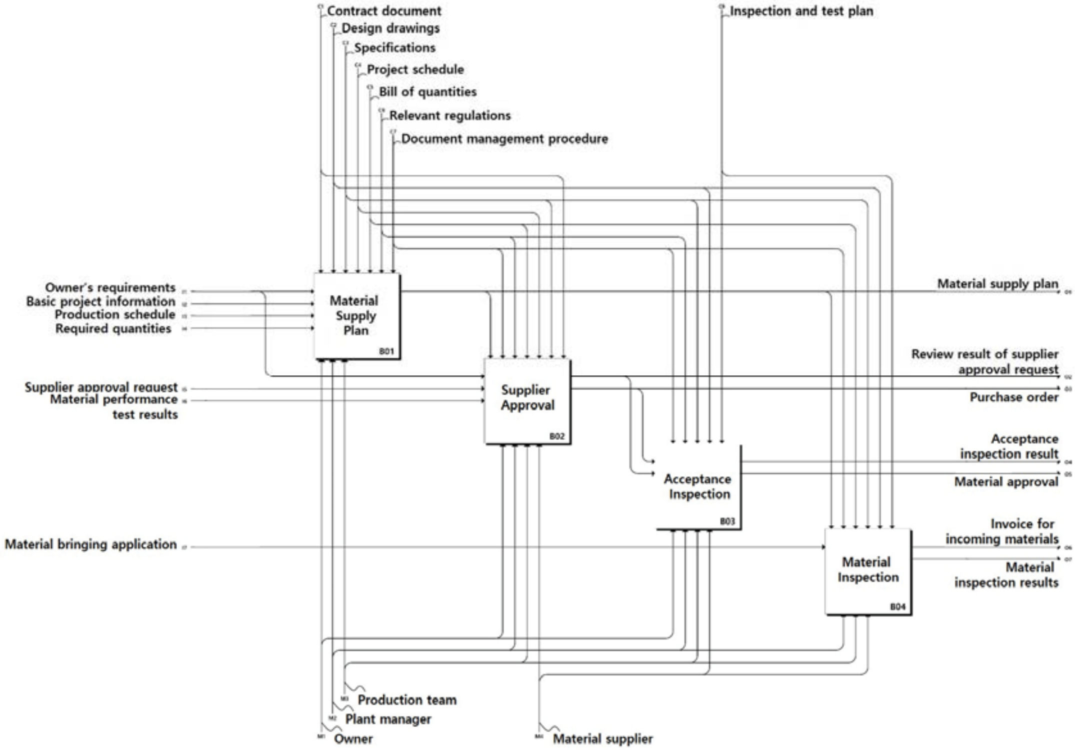


Figure 4. IDEF0 modeling results for quality management in material management.

3.2.3. Standardization of Construction Information

Figure 5 shows the results of standardization of construction quality information during module manufacturing. Construction-related quality management tasks can be represented as follows: (C01) production plan establishment, (C02) inspection and test plan establishment, and (C03) construction inspection and test steps. C01 and C02 are conducted in the pre-preparation stage before factory production. C03 is performed at the module manufacturing stage. Generally, the module manufacturing plan depends on basic project information on the owner's requirements, construction outline, etc. The module production plan can be established after the basic design document is prepared. A module manufacturing plan is established based on the contents of the prepared basic design documents, considering the status of the workers and the equipment that can be used in the factory. In the production plan establishment stage, what production line and equipment to use in the factory manufacturing process, how many workers to employ, how to plan the movement line, how to set the production schedule for each stage of construction, etc., are decided. Therefore, information about the production schedule and construction and manufacturing plans is generated. After the module manufacturing planning stage, an inspection and test plan is established according to the established manufacturing schedule. Inspection and testing are conducted for the main processes that affect the performance and quality of the module. In the inspection and test plan establishment stage, the process that requires inspection and testing is selected, and the inspection and test method, schedule, and main items of the selected process, are determined. Based on the relevant regulations and project specifications, some tests and inspections are planned to be conducted by accredited laboratories, while the others are planned to be performed at the factory. This process generates information on construction inspection checklists and quality test plans for the critical processes. At the module manufacturing stage, construction inspection and quality testing are conducted in accordance with the established plan. Construction inspections and tests are based on the main inspection items, methods, and procedures determined during the inspection and test plan establishment stage. In this step, information is generated on the quality performance of each module, such as the construction inspection and test report or results of quality tests reported by accredited laboratories.

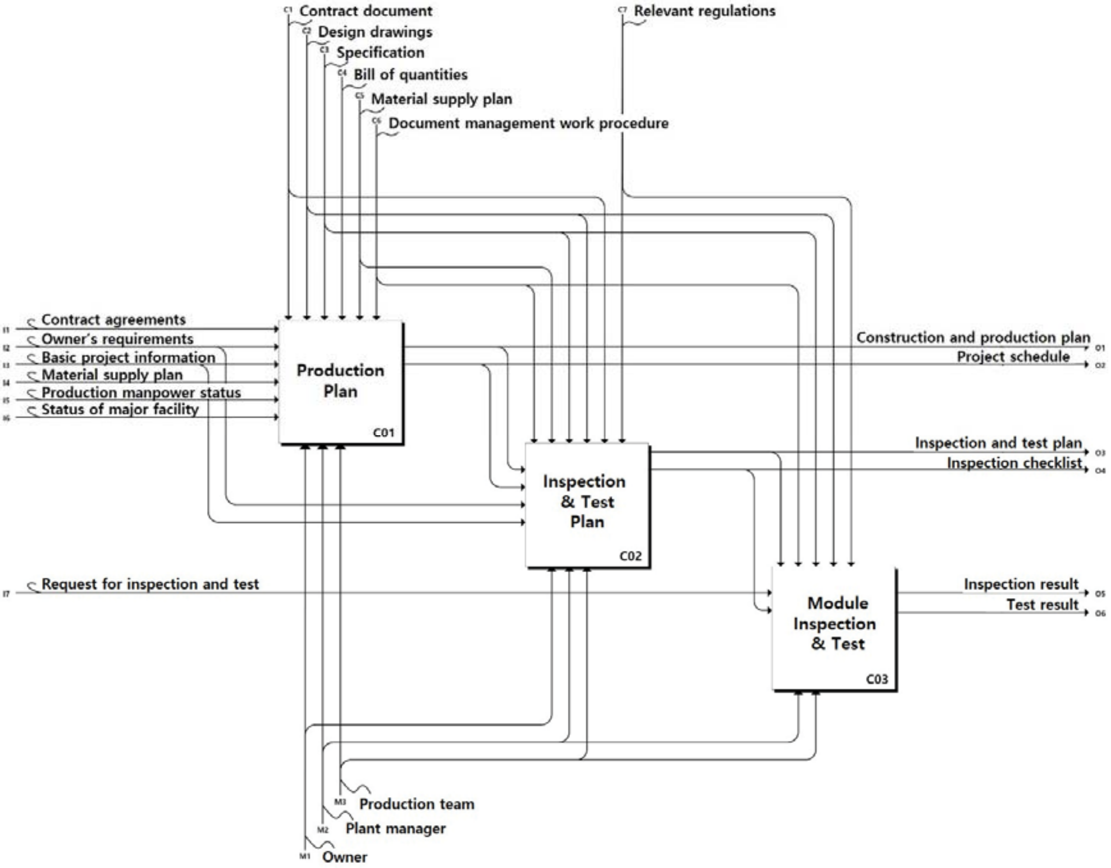


Figure 5. IDEF0 modeling results for quality management in construction.

3.3. Defining the Main Functions of the System

System function definition aims to facilitate system development by clarifying the purpose of the function, standard operation method, and scope of the development work [32]. By defining key functions before system development, unnecessary functions in the development process can be eliminated, and the usability of the system can be improved [33]. The system function is defined after defining the main function, which comes after the basic function is defined. The menu of the development system was configured according to the function definition result. The system configuration menu is shown in Table 2.

Table 2. Modular Factory Quality Information Management System Menu.

Main Menu	Sub Menu	Purpose of Development
1. Basic Project Information	1-1. Basic information and General Items	Project basic information management Manufacturing module information management per project
	1-2. Project module information	
	1-3. Module-type management	
	1-4. Production process management by module type	
2. Design management	2-1. Design document review	Design document management Design document establishment/revision management
	2-2. Factory manufacturing drawing review	
3. Material management	3-1. Equipment and material supply plan	Material-related document management Material acceptance and inspection management
	3-2. Inspection and test report	
	3-3. Supplier approval	
	3-4. Incoming material inspection	
	3-5. Management of nonconforming material	
4. Manufacturing management	4-1. Manufacturing inspection management	Module manufacturing inspection and test management
	4-2. Nonconforming manufacturing management	
	4-3. Module inspection progress	
	4-4. Test management	
5. Document management	-	Management of documents related to quality control
6. System management	6-1. User management	System database management
	6-2. Test equipment management	
	6-3. Project management	
	6-4. Checklist management	
	6-5. Admin menu	

The system basic function aims to manage basic information, such as project basic information. The general information of the modular project can be managed through the project basic information management function. Specifically, information such as project outline, quality policy, quality management procedure, and module information can be managed. Module information includes where each module is installed in a building (i.e., building, floor, and room number) and how it is manufactured. The user can more intensively manage the module information through the independent module information management function. On the other hand, general project information, such as construction outline, quality policy, and quality management procedures are all composed at a basic level. Therefore, it would be more efficient to manage the general project information as a single function.

The main function of the system is to manage the quality information related to design, materials, and construction in module factory production according to the information standardization result. The design management function aims to manage the quality information related to the design of the modular project. Design-related quality information includes the revision history of design documents, review opinions, and special matters in the review and revision stage. The design management function allows for efficient tracking and management of design document information. It involves separating basic design documents and factory manufacturing drawings according to the type of design documents, thus improving the identification of design quality information. System users can systematically manage design document information through the design management function. Furthermore, it is possible to prevent problems related to the quality of design documents, such as discrepancies between design documents, because sharing work contents with other fields is simplified.

The material management function aims to manage material information used in module manufacturing and quality information related to material supply. It separates detailed functions for material supply planning, supplier approval, and material inspection. To track and manage material-related quality information easily, the revision history information of each material supply plan is included. The source approval function handles information about the qualifications of major material suppliers. Therefore, information such as the quantity of each material brought in, specifications, suppliers, and various supporting documents related to material performance, are included. The material inspection function manages quality inspection information for materials brought into the modular factory. It uses the existing checklist in the system database. Accordingly, a function for editing the material checklist should be separately prepared to increase the system usability. In addition, nonconformities that occur during material inspection should be managed through a separate and independent function to effectively utilize material defect information in future projects.

Manufacturing management targets module manufacturing inspection and test information management. The module manufacturing inspection function manages inspection information for each module manufacturing process. Further, manufacturing inspection utilizes the checklist included in the system database in advance, and the user can edit the checklist, similar to in the material inspection function. Meanwhile, when a large number of modules are manufactured, determining the inspection progress of each module may be difficult. Accordingly, a function should be prepared to provide information on the module inspection progress of the entire modular project, see Table 2—Modular Quality Information Management System Configuration Menu.

4. Development of Quality Information Management System for Modular Construction Factory

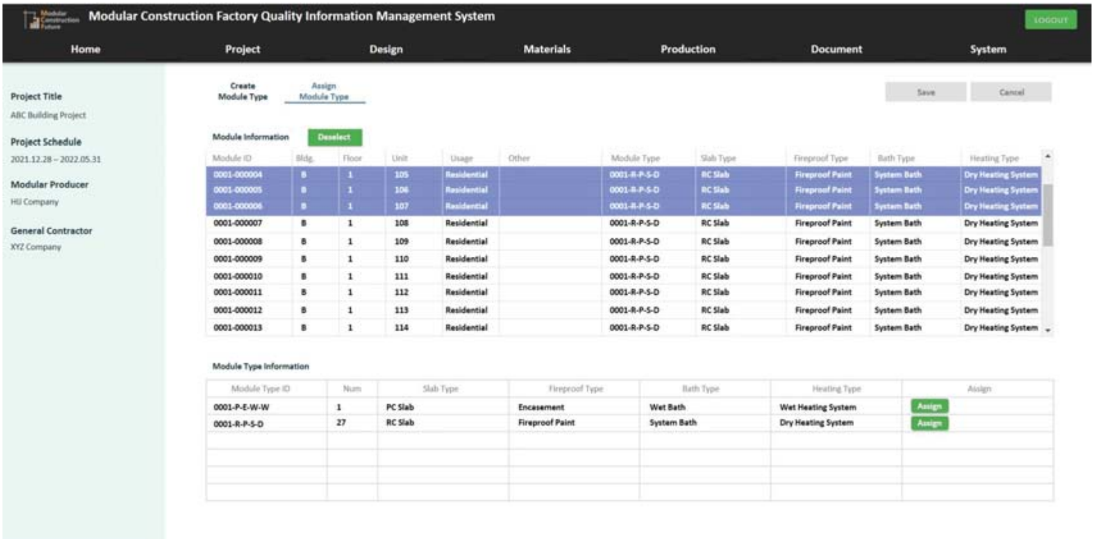
4.1. System Overview

The developed system was planned to be web-based to increase the user's system accessibility. It consists of a client that needs and a server that provides information. A MySQL server was used for the modular factory quality information management system. MySQL is advantageous because it can be used on various operating systems, such as Unix, Linux, and Windows. The MySQL server was used to prepare for future server migration and system expansion. For system deployment and server operation, Docker—an open-source virtualization platform based on containers—was used. A container packages and isolates software, such as libraries, system tools, code, and executable files, for system operation. Using Docker can reduce the hardware resources required for server operation, thereby reducing the server operation burden on the host.

4.2. Main System Features

4.2.1. Module Information and Production Type Management

To reduce the defect rate in the module manufacturing process, it is important to clearly identify the target defect and its cause. In large projects where many identical modules are built, it is difficult to identify and track individual modules. The developed system manages module information by dividing it into information about each module and information about the module type. Module information was divided based on module ID, building, floor, room number, and use to prevent duplicate management of modules. Generally, modules manufactured in a modular project are constructed differently, depending on the structural systems, material type, and construction methods applied to each module. Therefore, changes in module types lead to changes in key quality check items for the module manufacturing process. Therefore, the modular factory quality information management system was developed to classify and manage module types to effectively manage module production inspection information. Therefore, 86 modular building projects undertaken in Korea from 2003 to 2020 were analyzed to identify and predefine the different types of modules. First, the module types were classified by examining the commonly applied construction methods regardless of the module type and analyzing the construction methods involving different construction processes. Therefore, depending on the type of slab construction method (wet or dry floor), type of fireproof construction (fireproof painting, fireproof spraying, or encasement fireproofing), type of toilet construction (wet or dry toilet), and heating construction (wet or dry heating), 24 module types were predefined. In addition, because the predefined module types may not be comprehensive, the developed quality information management system also includes a function to create and manage module-type information. The user can set the types of slab construction, fireproof construction, toilet construction, and heating construction for each module using the module type management function. Information on the module type is registered in the system according to the set construction method, and the module manufacturing process and main inspection items of each process are determined for each registered module type. In addition, by designating module type information to each previously created module, inspection items and contents for each module can be used in the production inspection step. Figure 6 shows the process of assigning the created module type to the created module information.



Project Title
ABC Building Project

Project Schedule
2021.12.28 – 2022.05.31

Modular Producer
HU Company

General Contractor
XYZ Company

Module Information

Module ID	Bldg.	Floor	Unit	Usage	Other	Module Type	Slab Type	Fireproof Type	Bath Type	Heating Type
0001-000004	B	1	105	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000005	B	1	106	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000006	B	1	107	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000007	B	1	108	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000008	B	1	109	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000009	B	1	110	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000010	B	1	111	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000011	B	1	112	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000012	B	1	113	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System
0001-000013	B	1	114	Residential		0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System

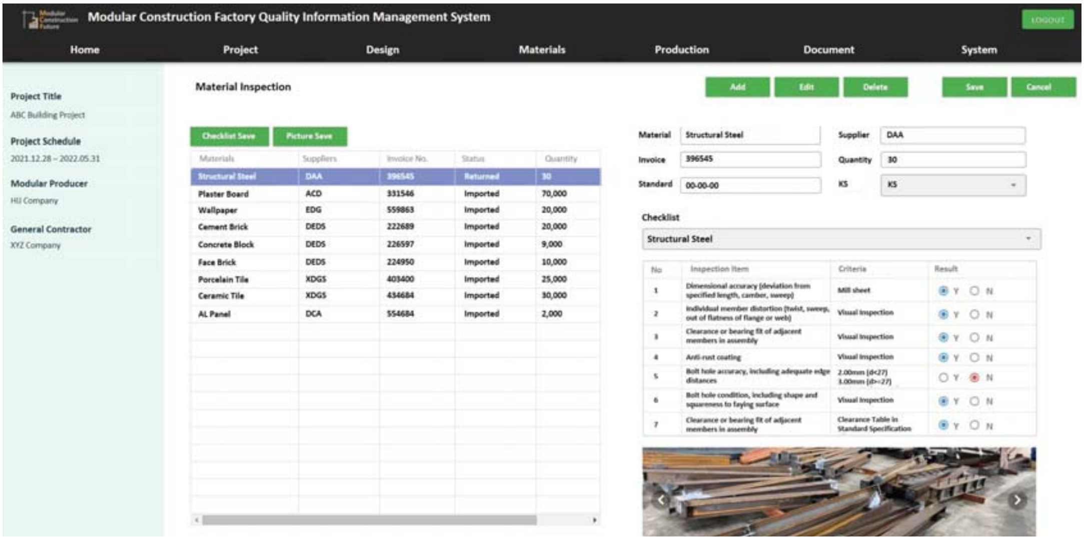
Module Type Information

Module Type ID	Num	Slab Type	Fireproof Type	Bath Type	Heating Type	Assign
0001-P-E-W-W	1	PC Slab	Encasement	Wet Bath	Wet Heating System	Assign
0001-R-P-S-D	27	RC Slab	Fireproof Paint	System Bath	Dry Heating System	Assign

Figure 6. Module type information designation function.

4.2.2. Material Management

The quality information management system can track and manage material quality information from the initial planning stage to the final construction stage. Specifically, the material management function manages material quality information in the factory pre-production stage through equipment and material supply plan management, inspection, and test plan management, supplier approval, and incoming material inspection functions. The equipment and material supply plan management and inspection and test plan management functions were developed to manage material-related information in the planning stage. Users can manage the establishment/revision history of each plan through equipment and material supply plan management and inspection and test plan management functions and share the review with other stakeholders. The supply approval function was developed to manage in detail the main equipment and material information selected in the planning stage. The supplier approval function manages basic material information such as material items and specifications and information on documents related to supplier approval. Specifically, the source approval function works by inputting information about the main material and uploading/downloading the source approval application document. The incoming material inspection function manages the factory inspection information of key materials, and it is presented in Figure 7. The incoming inspection of each material is performed using the checklist for each material stored in the system database. The user can add or edit the contents of the material inspection checklist through the system management function of the quality information management system. Nonconformities identified during the inspection of incoming materials are managed separately in the management of nonconforming equipment function. In it, information such as nonconforming material nonconformity, nonconforming action details, and quantity of nonconforming material, is managed.



Project Title
ABC Building Project

Project Schedule
2021.12.28 – 2022.05.31

Modular Producer
HIJ Company

General Contractor
XYZ Company

Materials	Suppliers	Invoice No.	Status	Quantity
Structural Steel	DAA	396545	Returned	30
Plaster Board	ACD	331546	Imported	70,000
Wallpaper	EDG	559863	Imported	20,000
Cement Brick	DEDS	222689	Imported	20,000
Concrete Block	DEDS	226597	Imported	9,000
Face Brick	DEDS	224950	Imported	10,000
Porcelain Tile	XDGS	403400	Imported	25,000
Ceramic Tile	XDGS	434684	Imported	30,000
AL Panel	DCA	554684	Imported	2,000

Material: Structural Steel
Supplier: DAA
Invoice: 396545
Quantity: 30
Standard: 00-00-00
KS: KS

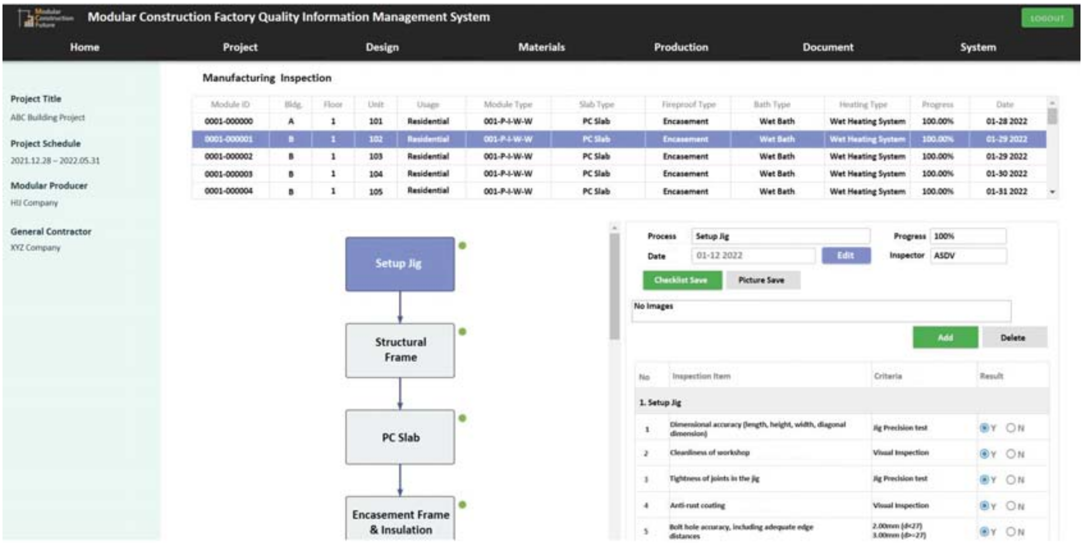
Checklist: Structural Steel

No	Inspection Item	Criteria	Result
1	Dimensional accuracy (deviation from specified length, camber, sweep)	Mill sheet	● Y ○ N
2	Individual member distortion (twist, sweep, out of flatness of flange or web)	Visual inspection	● Y ○ N
3	Clearance or bearing fit of adjacent members in assembly	Visual inspection	● Y ○ N
4	Anti-rust coating	Visual inspection	● Y ○ N
5	Bolt hole accuracy, including adequate edge distances	2.00mm (d<27) 3.00mm (d>=27)	○ Y ● N
6	Bolt hole condition, including shape and squareness to faying surface	Visual inspection	● Y ○ N
7	Clearance or bearing fit of adjacent members in assembly	Clearance Table in Standard Specification	● Y ○ N

Figure 7. Material inspection information management function.

4.2.3. Module Manufacturing Management

The module production management function can manage test information and production inspection information generated during the production of each module. Module test management was developed to manage various test information to ensure module performance, such as fire resistance, waterproofness, and airtightness. The user can manage information such as test types, standards, and scores through the module test management function. Module manufacturing inspection management was developed to manage manufacturing inspection information for each process according to each module type. As mentioned above, the developed system includes data on the manufacturing process and a step-by-step inspection checklist according to 24 predefined module types. Similar to material inspection management, the checklist for manufacturing inspection can be added and edited by the user. Production inspection is conducted on the entire module input in the module information management function. The module manufacturing inspection management function is shown in Figure 8. The information of all modules included in the project and information of the module selected for inputting the current inspection result are displayed at the top of the production inspection function screen. The process status of the module is displayed on the left side of the screen. The diagram schematizes the production process and inspection progress of the module. When all inspection items in the process are completed, the inspection items in the next process are displayed. The manufacturing inspection status indicator appears in the upper-right corner of the diagram, and the process under inspection is displayed in black; when all inspection items are completed without nonconformity, in green; and when one or more nonconformities occur, in red. The user can check the production and inspection status of individual modules through the module manufacturing inspection management function.



Manufacturing Inspection

Project Title
ABC Building Project

Project Schedule
2021.12.28 – 2022.05.31

Modular Producer
HIJ Company

General Contractor
XYZ Company

Module ID	Bldg.	Floor	Unit	Usage	Module Type	Slab Type	Fireproof Type	Bath Type	Heating Type	Progress	Date
0001-000000	A	1	101	Residential	001-P-I-W-W	PC Slab	Encasement	Wet Bath	Wet Heating System	100.00%	01-28 2022
0001-000001	B	1	102	Residential	001-P-I-W-W	PC Slab	Encasement	Wet Bath	Wet Heating System	100.00%	01-29 2022
0001-000002	B	1	103	Residential	001-P-I-W-W	PC Slab	Encasement	Wet Bath	Wet Heating System	100.00%	01-29 2022
0001-000003	B	1	104	Residential	001-P-I-W-W	PC Slab	Encasement	Wet Bath	Wet Heating System	100.00%	01-30 2022
0001-000004	B	1	105	Residential	001-P-I-W-W	PC Slab	Encasement	Wet Bath	Wet Heating System	100.00%	01-31 2022

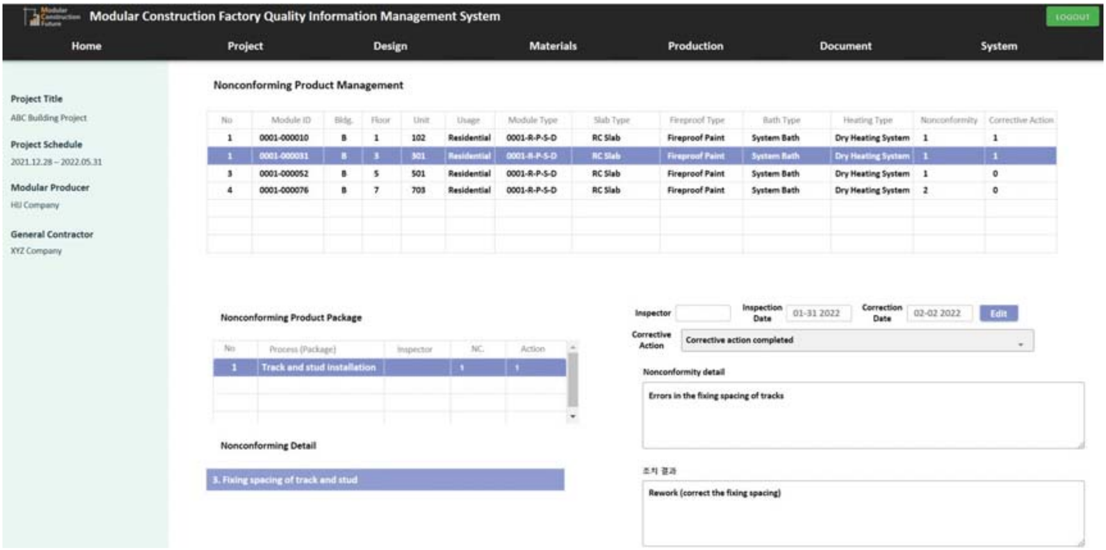
Process: Setup Jig
Progress: 100%
Date: 01-12 2022
Inspector: ASDV

No Images

No	Inspection Item	Criteria	Result
1. Setup Jig			
1	Dimensional accuracy (length, height, width, diagonal dimension)	Jig Precision test	● Y ○ N
2	Cleanliness of workshop	Visual Inspection	● Y ○ N
3	Tightness of joints in the jig	Jig Precision test	● Y ○ N
4	Anti-rust coating	Visual Inspection	● Y ○ N
5	Bolt hole accuracy, including adequate edge distances	2.00mm (d<27) 3.00mm (d>=27)	● Y ○ N

Figure 8. Module production inspection management.

Nonconformities that occur during manufacturing inspection are separately managed through the management of the nonconformity manufacturing function. The quality information management system recognizes a process as nonconforming when one or more of the checklist items used for manufacturing inspection indicate nonconformity. Each item in the checklist has an error tolerance for determining nonconformity. These tolerances are determined by the type of work, relevant regulations, and specifications. The developed system is designed to accept error tolerance inputs from users. When users upload inspection checklists based on the inspection and test plan, they are asked to determine the error tolerance for each item in the checklist based on the type of work, relevant regulations, and specifications. Then, the users refer to the error tolerances in the system when conducting inspections and tests during manufacturing. The information of the module in which the nonconformity occurred is displayed at the top of the screen of the nonconformity production management function. In it, detailed information about the process in which nonconformities occurred is displayed on the left side of the screen, and the reason for nonconformity and measures to be taken are displayed on the right side. The nonconforming product management function is shown in Figure 9.



Project Title
ABC Building Project

Project Schedule
2021.12.28 – 2022.05.31

Modular Producer
HU Company

General Contractor
XYZ Company

Nonconforming Product Management

No	Module ID	Bldg.	Floor	Unit	Usage	Module Type	Slab Type	Fireproof Type	Bath Type	Heating Type	Nonconformity	Corrective Action
1	0001-000010	B	1	102	Residential	0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System	1	1
1	0001-000031	B	3	301	Residential	0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System	1	1
3	0001-000052	B	5	501	Residential	0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System	1	0
4	0001-000076	B	7	703	Residential	0001-R-P-S-D	RC Slab	Fireproof Paint	System Bath	Dry Heating System	2	0

Nonconforming Product Package

No	Process (Package)	Inspector	NC.	Action
1	Track and stud installation		1	1

Nonconforming Detail

3. Fixing spacing of track and stud

Inspector:
Inspection Date: 01-31 2022
Correction Date: 02-02 2022
Corrective Action: Corrective action completed

Nonconformity detail
Errors in the fixing spacing of tracks

조치 결과
Rework (correct the fixing spacing)

Figure 9. Management of nonconforming module information.

Although the module manufacturing inspection management function provides information on the manufacturing inspection status of each module, it is difficult to determine the overall module manufacturing inspection status in a modular project that manufactures multiple modules. This difficulty is exacerbated when modules of multiple projects are produced in one factory. To resolve this, a function to visualize the overall module production inspection process of the project was developed for the quality information management system. The module inspection status management function is shown in Figure 10. It displays the overall module production inspection status of the modular project, inspection history of individual modules, and Takt Schedule Chart. In the module inspection status management function, the inspection status information of the entire project module is displayed at the top of the screen, and the inspection history information of the selected module is displayed at the bottom. The detailed production process for each module depends on the previously set module type. To determine the inspection status of all modules irrespective of module type, this study investigated the common processes in all module types. Accordingly, the module manufacturing process could be divided into eight main processes: structure assembly, slab construction, fireproof construction, wall construction, toilet construction, ceiling construction, floor heating construction, and final finishing construction. Therefore, the bar chart displaying the module inspection status is composed of eight steps. The production inspection status management function intuitively describes the overall production and inspection status of the project module to the user. The production inspection status management function is also useful in terms of schedule management; the user can check the module production status through the information provided and adjust the production schedule accordingly. The module manufacturing inspection status management function facilitates the tracking and management of the quality information of each module by displaying the detailed inspection history of each module along with the status diagram.

Project Title
ABC Building Project

Project Schedule
2021.12.28 – 2022.05.31

Modular Producer
HU Company

General Contractor
XYZ Company

Figure 10. Information management in the production inspection status.

5. System Evaluation

System evaluation is critical for determining the practicability of a system [34]. It provides feedback on functional improvement and supplementation. In this study, system evaluation was conducted to verify the usefulness of the development system and to confirm its practicability. It can be divided into system performance evaluation in terms of implementation of system functions and system usability evaluation and in terms of implemented system functions according to the purpose of evaluation [35]. The usability of the developed system can be measured through system performance and system usability evaluations. Further, it is necessary to verify whether the system developed is practically helpful for quality control in module production. Therefore, this study conducted a system evaluation targeting modular experts.

5.1. System Performance Evaluation

The system performance evaluation aims to evaluate whether the system can normally provide the functions required by the user under the planned operating environment [36]. In this study, validation and verification test (V&V test) by accredited testing and certification laboratory was implemented for objectively evaluating system performance. The certified performance test was conducted for all major functions except for the system management function. The accredited performance test was conducted in accordance with ISO/IEC 25023:2016, an international software quality standard. It was developed to quantitatively evaluate the quality of a system using the ISO/IEC 25023:2016 standard [37], and it provides a test method and performance criteria suitable for the function to be evaluated [38]. The performance test of the modular factory manufacturing quality information management system was conducted by checking whether the main functions of the system operate normally according to the defined operation method. Table 3 shows the official performance test results of the developed quality information management system. The test system execution result matched the expected result, and the system function operates normally and as planned.

Table 3. Developed system performance test results.

No	Detail Function	Expected Result	Implementation Result	
			Input/Save	View
1	Design management	- Stable upload/download of basic design drawings and factory manufacturing drawing documents. - The history of establishment and revision of basic design drawings and factory manufacturing drawings is normally reflected in the system.	Expected result Satisfaction	Expected result Satisfaction
2	Material management	- Product name, specification, and verifying document information are normally reflected in the system - Stable linkage with nonconforming material management function. - Stable linkage with nonconforming material management function.	Expected result Satisfaction	Expected result Satisfaction
3	Module information management	- A unique module number (module ID) is generated, and basic information for each module (building/floor/room number, usage) is not duplicated. - The entered module information is normally registered in the system.	Expected result Satisfaction	Expected result Satisfaction
4	Module type management	- All types of process diagrams are implemented normally. - All types of inspection checklists are normally viewed. - Module information and manufacturing type information designation works normally.	Expected result Satisfaction	Expected result Satisfaction
5	Production inspection management	- All module information registered in the system and the inspection process of each module are displayed on the screen. - The status indicator of the inspection process works normally. - Stable linkage with nonconforming product management functions.	Expected result Satisfaction	Expected result Satisfaction
6	Module production inspection status	- The module inspection status is normally displayed according to the entered manufacturing inspection result. - The detailed history of the selected module is displayed normally.	Expected result Satisfaction	Expected result Satisfaction

5.2. System Usability Evaluation

System usability evaluation aims to determine the usability of the system from the user's point of view [39]. It can be used to judge the usefulness and reliability of various objects, such as general devices, web search engines and maps, application software, and systems [40]. System usability evaluation is divided into analytical and empirical evaluation according to the evaluation subject. The former is also called predictive evaluation because it is conducted by experts and predicts problems that may occur when using the system. It includes list test, rehearsal test, model analysis, and simulation. An empirical evaluation is conducted by real system users. An empirical evaluation is mainly conducted in the form of post-evaluation for a certain period after the system is launched.

In this study, heuristic evaluation, one of analytical evaluation methods, was conducted to check the usability of the developed quality information management system. It is mainly performed to evaluate system usability in terms of user interface and design of the developed system [41]. As a representative method, it is used for system usability evaluation due to cost and time advantages and efficiency [42]. It is conducted by three to five experts writing an evaluation sheet on the Nielsen [43]'s 10 principles of the heuristic.

The questionnaire was developed based on a Likert 5-point scale (1 point: disagree, 5 points: agree). The heuristic evaluation items were reconstructed according to the characteristics of the modular factory quality information management system and existing heuristic evaluation studies. Accordingly, a survey with 21 evaluation questions to evaluate seven items of system status visibility, match the system and real world, evaluate user control and freedom, consistency and standard, error prevention, recognition rather than recall, and aesthetic and minimalist design was developed. A questionnaire response sheet with questions was also developed. Table 4 shows the contents of the developed questionnaire response sheet. The heuristic evaluation of the developed quality information management system was conducted by two experts in the software field and three experts in modular architecture. For the evaluation, the characteristics of the development system and the main purpose of each evaluation item were first explained to the survey respondents. To help them understand the system, the system user manual and main function demonstration video were provided. For the analysis of the evaluation results, they were explained for negative responses or non-evaluable items. All items were found to be generally excellent (mean = 4.43, SD = 0.610), particularly the match between the system and real-world items (mean = 4.68, SD = 0.471). However, the user control–freedom item received a relatively low evaluation (mean = 4.06, SD = 0.524).

Table 4. Contents of the questionnaire for heuristic evaluation.

Heuristic Evaluation Items	Evaluation Questions
Visibility of system status	Can the user know at a glance the current state of the system and what operations are currently available just by looking at the screen?
	Are the current states clearly marked, such as icons, images, or hypertext?
	Is it clearly indicated which location the user has currently selected?
Match between system and the real world	Are the terms used in the input window frequently used by users?
	Does the form on the document that users work on match the form on the computer?
	Are highly related items appearing on the same screen?
User control and freedom	Is there an undo function for each action?
	Can the user go back to the previous menu item and change a selection already made?
	Is the button to the home page on each screen prominently displayed?
Consistency and standards	Are the names of the same menu items presented consistently within a system?
	Is the length of the term appropriate?
	Do all pages have titles and headers that describe their content?
Error prevention	Is it possible to simultaneously input letters and numbers in one field in the input window?
	Are the buttons that are not currently applicable are dimmed or not shown at all?
	Does the system warn the user of the consequences before executing a function that could have serious consequences?
Recognition rather than recall	Are the infrequently used but essential tasks easy to remember in order?
	Do the menu items provide multiple steps for the user to remember with ease?
	Are the names of the buttons clear and easy to understand?
Aesthetic and minimalist design	Are the buttons refraining from overly detailed expressions in the button design?
	Is it refraining from using too many colors?
	Are colors used to make it easier to distinguish between text and background color?

5.3. System Utility Evaluation

System usability evaluation aims to determine whether the efficiency of the production quality management work in the modular construction factory is improved by the developed system [44]. To derive meaningful evaluation results, practical application is necessary. However, this is difficult because the application is in the precommercial stage. Therefore, this study evaluated the usefulness of the system by interviewing modular construction experts. Five modular construction experts and five research and development experts on modular construction participated in the system utility evaluation. All modular construction experts have more than seven years of experience in module manufacturing (mean = 10.6, SD = 2.65). Moreover, all research and development experts have more than four years of experience (mean = 6.4, SD = 1.62) in modular construction research. Prior to evaluation, each expert received a preliminary explanation on the system function configuration and key functions (i.e., project module information management, module type management, production process management by type, supply source approval, material incoming inspection, nonconforming equipment management, manufacturing inspection management, nonconformity production management, and module inspection status), and watched a demonstration video. After performing the system function according to the directed request, the usefulness of the main function of the system was evaluated using a 7-point Likert scale (1 point: not very useful, 7 points: very useful). In addition, opinions on system improvement were collected using open-ended questions.

The evaluation revealed that the system was generally useful for most functions (mean = 6.01, SD = 0.641), and production inspection management was evaluated as the most useful (mean: 6.4, SD = 0.490). It received a high evaluation in terms of practical utility because manufacturing inspection is repetitive and frequently occurs during quality control activities in the module factory. The module inspection status was evaluated to be the second most useful (mean = 6.3, SD = 0.458), presumably because it helps to intuitively determine the overall project progress status in connection with process management. In addition, two additional functions were developed based on expert opinions on system improvements. First, to improve the linkage with existing quality management work, a function was added to automatically output the results of incoming material and manufacturing inspection in the form of an existing quality result report. This is expected to increase the utility of the developed system in the quality control of the current module factory. In addition, the improvements to the developed system can allow it to be used flexibly according to project conditions by allowing users to add and modify module types and checklists, depending on project characteristics in module-type management and varied-checklist management.

6. Conclusions

The importance of quality information in the construction industry is increasing due to the increase in the scale and complexity of construction projects. Although the usefulness of quality information is greater for modular construction because it has the characteristics of a manufacturing industry, studies on quality information management during factory production have rarely been conducted in contrast to the case of site-oriented construction. In this study, we developed a quality information management system that can effectively manage and utilize quality information generated during manufacturing in a modular factory. The module manufacturing process was analyzed to determine the characteristics of modular construction in the system function. To manage the quality information generated in each quality management process in an integrated system, information standardization was conducted using IDEF0. From the information standardization, the system function was defined and system development conducted. The developed quality information management system efficiently manages the quality information generated during manufacturing in the factory. Representative functions of the developed modular quality information management system include module information and production-type management, material management, and module production management. Using the module information and production type management function, the utilization of the module production quality information can be improved. Using the material management function, it is possible to track the quality information of the materials used to manufacture the module. Using the module production management function, the production inspection information for each module and the production status of all modules can be interpreted.

The developed quality information management system can improve the inefficiency in the quality management process of module manufacturers by providing an integrated and systematic method to manage quality information generated during manufacturing. The developed system can prevent the generation of redundant quality information and improve identification and traceability by recording quality information management history. Furthermore, the information provided by the developed system, such as production inspection status information, can be utilized in tasks other than quality management (e.g., production schedule management). Therefore, if the development system is applied, the overall efficiency of quality management tasks in the module manufacturing process can be increased. In this study, performance and usability evaluation were performed to confirm the practicability of the module factory manufacturing quality information management system. The evaluations were conducted through a V&V test and heuristic evaluation, respectively. The performance evaluation indicated that all functions of the developed quality information management system operated normally as predefined. The evaluation of the usability and usefulness of the system revealed that the developed system had excellent usability, and its practical usefulness was also judged to be high. However, accurately reflecting the positions of all practitioners in the evaluation of system usability by interviewing experts had limitations. Accordingly, future research should evaluate the usefulness of the development system based on the results of practical application over a duration. In addition, it is necessary to prepare a plan to maximize the advantages of the system from the practitioner's point of view and to compensate for the disadvantages of the system. The system performance can be improved by incorporating the suggestions of practitioners. The improved system will have a positive effect on the quality of the manufactured module as well as on the quality control.

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

Funding: This research was supported by the Housing Environment Research Program funded by the Ministry of Land, Infrastructure, and Transport of the Korean Government [21RERP–B082884-08, 2021].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

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

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sustainability

Article

Coordination of Prefabricated Construction Supply Chain under Cap-and-Trade Policy Considering Consumer Environmental Awareness

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Abstract: The construction industry accounts for over one third of excessive CO_2 volume, so it is essential that this amount be curbed. Prefabricated construction has superior strengths in terms of both the environment and economy, but low carbon is not one such strength. Meanwhile, the increasing number of consumers with environmental awareness makes it necessary to investigate consumer preferences and behaviors. Therefore, we firstly built a prefabricated construction supply chain consisting of a prefabricated company (leader) and a manufacturer, using the Stackelberg model. To regulate and mitigate carbon emissions, this study investigated the implementation of a cap-and-trade policy. Consumer environmental consciousness was considered from preferences on improving the prefabricated rate and carbon reduction. This study provides decision-making suggestions, not only from a pricing point of view but also for green production, i.e., the prefabricated rate and carbon reduction. We find that consumer environmental consciousness and the cap-and-trade policy improve decision making. To effectively limit the manufacturer's emissions, we suggest governments set a cap below a certain threshold. However, under the policy, the prefabricated company has free-rider behaviors and gains greater profits as the leader, which results in an unfair profit distribution. Hence, for the sake of optimizing the supply chain's profits, the cost-sharing contract and the two-part tariff were discussed. Both contracts achieved Pareto improvement, while the two-part tariff contract realizes coordination and reaches the desired level under a centralized system. Numerical analysis also verified the theoretical feasibility.

Keywords: prefabricated construction; cap-and-trade policy; consumer environmental awareness; two-part tariff contract; supply chain management

Citation: Jiang, W.; Yuan, M. Coordination of Prefabricated Construction Supply Chain under Cap-and-Trade Policy Considering Consumer Environmental Awareness. *Sustainability* **2022**, *14*, 5724. https://doi.org/10.3390/su14095724

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 1 April 2022
Accepted: 4 May 2022
Published: 9 May 2022

1. Introduction

The construction industry emits a large quantity of carbon dioxide, accounting for 40% of total energy consumption [1]. More seriously, it is reported that carbon emission of buildings across the world will reach 42.4 billion tons in 2035 [2]. Hence, it is imperative to reduce carbon emissions in construction.

A prefabricated construction supply chain (PCSC) is when an off-site factory manufactures the construction components, then transports them to the designated location, before a prefabricated company eventually assembles all the components on site [3]. Based on the construction characteristic, it is obvious that prefabricated construction is superior to conventional methods in terms of waste reduction [4], efficiency [5], and environmental sustainability [6]. Therefore, prefabricated buildings are vigorously promoted in countries worldwide [7,8]. Various policies have been established to promote large-scale prefabricated construction [9,10]. To sum up, prefabrication was a revolution in construction and has become the main method within in the industry. However, prefabricated construction does not significantly reduce carbon emissions, and investigations into controlling greenhouse gas and decision-making problems in PCSC are inadequate.

The Kyoto Protocol (1997) put forward four policies to reduce and regulate carbon emissions. A cap-and-trade policy, one of the policies, represents the purchasing of credits or selling redundant carbon credits within the limit of a carbon cap [11]. There are advantages, such as cost effectiveness, emission reduction reliability, and green technology incentives [12,13]. In supply chain management, the cap-and-trade policy achieves substantial emission reductions [14]. However, the influence of the policy on PCSCs is not extensively studied. Therefore, to limit and regulate the carbon emissions in prefabricated construction, we built a PCSC consisting of a manufacturer and a prefabricated company (PC), where the manufacturer was subject to the policy and traded carbon credits in the trading market.

As the environment increasingly deteriorates, consumers' environmental awareness (CEA) achieves an increasingly significant status. CEA refers to the consumer that has the awareness of protecting the environment and tends to purchase environmentally friendly products [15]. This study analyzed CEA from two aspects: carbon reduction and the prefabricated rate. First, low-carbon products attract consumers who pay attention to carbon emissions, and consumers are willing to pay a premium for enterprises' carbon reduction [16]. Second, consumers also pay attention to the improvement in the prefabricated rate. Prefabricated construction is environmentally friendly, with the aforementioned superiorities, and policies have been implemented to improve the prefabricated rate [8]. However, under the double pressures of the government and consumers, studies that simultaneously discusses CEA with regard to consumers' preferences on the prefabricated rate and carbon reduction are lacking. Generally speaking, demand will improve by reducing carbon emissions, but also by enhancing the prefabricated rate [17]. Costs of assembly and using low-carbon technology have increased, so this study explored the proper decision-making to minimize the costs. In addition, we solved another manufacturer's dilemma regarding the cost of carbon reduction and the revenues (or cost) from the trading market.

First of all, we built a PC-Stackelberg PCSC. The PC made an order to the manufacturer, and shouldered the assembly work. Next, the manufacturer produced the prefabricated components in the factory. Under the cap-and-trade policy, the manufacturer sells or buys carbon credits according to the emission volume and the cap. We solved members' decision making using centralized and decentralized systems. Finally, a cost-sharing contract and a two-part tariff contract were introduced to coordinate the PCSC. There were two essential problems that remained to be solved:

(1) When considering the two preferences and a cap-and-trade policy simultaneously, what are members' optimal decisions? How will the policy and preferences affect decisions and profits?

(2) After introducing two contracts into this PCSC, do the mechanisms achieve coordination, and what is the difference between them?

Through exploring and answering the above problems, this study could enrich the scenarios of cap-and-trade policies applied to the PCSC and could also provide enlightenments and suggestions for policymakers, who could establish market-friendly carbon allowances, and for stakeholders to make optimal pricing and production decisions in the PCSC. Finally, this study contributes to the literature through introducing two contracts, which improve collaboration and unfair profit distribution.

The remainder of this paper is organized as follows: Section 2 surveys the related literature. Section 3 presents the model formulation and assumptions. Section 4 investigates the decentralized model with the cap-and-trade policy and derives the optimal decisions and profits. In Section 5, we discuss the centralized model with the cap-and-trade policy and derive the whole supply chain's optimal decisions and profits. Section 6 examines the effect and differences after introducing the two contracts. Section 7 shows the numerical analysis based on the theoretical results. In Section 8, we present the concluding remarks, limitations, and future prospects.

2. Literature Review

Our study investigates a PCSC considering CEA under the cap-and-trade policy, so the literature reviewed here primarily relates to three research streams: (1) the operational decisions under cap-and-trade policy; (2) the operational decisions under CEA; (3) models for PCSCs.

2.1. The Operational Decisions under Cap-and-Trade Policy

The cap-and-trade policy is accepted as one of the most effective market-based mechanisms to curb carbon emissions from firms, so much of literature has been devoted to investigating operational decisions among agents in different supply chains. Under the cap-and-trade policy, Benjaafar et al. [11] developed relatively simply models to discuss operational decision-making about procurement, production, and inventory management. Xu et al. [14] investigated firms' decisions in a make-to-order supply chain, where manufacturers produced substitutes (complements).

Cao et al. [18] studied the government's policy-making problems and then explored the optimal responses under carbon subsidy and cap-and-trade policies. Wang and Han [19] considered the dual mechanisms of cap-and-trade and subsidies/penalties with stochastic returns. The realization of low-carbon supply chain not only belongs to manufacturers but also other members. Wang et al. [20] assumed that a manufacturer directly participates in carbon emission reduction, while a retailer has to invest in low-carbon promotion. Under certain conditions, a joint emission reduction model is an optimal choice for a supply chain. In the cap-and-trade mechanism, many studies are based on the linear demand function. Wang et al. [21] additionally explored the decisions on green technology innovation using a stochastic model. Qi et al. [22] considered whether decision makers have different risk preferences under cap-and-trade policy with stochastic demand. Entezaminia et al. [23] developed a new joint production and trading control policy for unreliable manufacturing systems, considering the stochastic and dynamic context. In summary, the cap-and-trade policy is an effective mechanism in reducing and regulating enterprises' emissions; thus, it will be considered to promote the green development of prefabricated construction.

2.2. The Operational Decisions under Consumer Environmental Awareness

Consumer's attitudes towards protecting the environment have significant impact on consumption [24]; evidence has shown that consumers state a preference for green products, and thus companies must consider producing environmentally friendly products [25]. Papers devoted to studying the CEA are numerous. Zhang et al. [26] confirmed that order quantity of the green products increased with CEA. Giri et al. [27] compared two models with and without consumer green preference. Hong and Guo [28] reported that retailer and manufacturer shoulder environmental responsibilities when considering CEA. Wang and Hou [29] noted that consumer green preference significantly influenced the product green level in a supply chain. Heydari and Rafiei [30] investigated the integration of environmental and social responsibilities.

One option to enable consumers to act with environmental awareness is buying low-carbon products, so consumers with CEA would purchase low-carbon products; that is, they have a preference for low carbon. Chen et al. [31] studied two rival manufacturers' optimal decisions with different market power structures, considering low-carbon preference. Ji et al. [32] discussed consumer's low-carbon preference in retail-channel and dual-channel supply chains. Improving low-carbon preference always brought an increase in carbon reduction [33] and profits [34]. Under the cap-and-trade policy, Zhang et al. [35] reached the same conclusion. Tong et al. [36] also proved this in a retailer-led supply chain. Although some scholars have considered more than one preference [37–39], most studies only consider CEA in carbon reduction. Nevertheless, enhancing the prefabricated rate is environmentally friendly. Moreover, some policies incentivize consumers to purchase high-prefabricated-rate buildings [40,41], which influences PCSC members' decision making.

We seek to address decision-making problems with CEA with regard to two preferences: the low-carbon preference and the high-prefabricated-rate preference.

2.3. Models for PCSC

Supply chain management in the construction industry improves enterprises' performance [42]. Countries all over the world have started to promote prefabrication in construction to improve buildability, quality, and efficiency as well as to reduce construction waste [43]. Supply chain management is critical to the successful delivery of prefabricated construction projects because supply chains are complex, involving multiple processes and stakeholders [44]. Therefore, the study of prefabricated construction with supply chain management resulted in the concept of PCSC.

Research topics of PCSC are classified into precast production, storage and inventory, delivery and transportation, and performance of the entire supply chain [45]. First, from the perspective of precast production, Zhai et al. [46] focused on how the production contractor prefers informing the prefab factory (PF) an earlier due date, which leads PF to compress its production process. Second, to mitigate conflicts, the production contractor requires the transportation company to store and deliver due to limited warehouse space; Zhai et al. [3] developed models with a buffer space hedging strategy in PCSC under different power structures. Further, Zhai et al. [47] extended the model into multi-period hedging. Jiang and Wu [48] proposed an algorithm to minimize total tardiness and earliness of delivery of PCSCs and achieved the optimization of precast component production. Third, from the perspective of the performance and coordination of PCSCs, Isatto et al. [49] analyzed the way commitments are demanded, bound, and fulfilled by members using a language-action perspective, which successfully coordinated PCSC.

However, research on reducing carbon emissions and cap-and-trade policy in PCSCs is limited. As one of three major sources of carbon emissions, it is significant to reduce global greenhouse gases in the construction industry [50]. Yu et al. [51] discussed a construction manufacturer's carbon reduction decision. Reducing carbon emissions in PCSCs plays an important role in the realization of low-carbon construction. In addition, it is beneficial to accelerate the development of prefabricated construction. Jiang et al. [48] proposed a joint carbon reduction model in a PCSC under the cap-and-trade policy. To optimize operational strategies and enrich the research context in prefabricated construction, this study will investigate PCSC decision making and coordination under cap-and-trade policy and CEA.

3. Model Description and Assumptions

This study investigates a two-echelon PCSC composed of a manufacturer and a PC. The manufacturer is in charge of producing the prefabricated components, and the PC takes the responsibility of assembly. In reality, the relationship between the PC and the manufacturer is a make-to-order relationship [14]; thus, in the Stackelberg model, we assume that the PC is the leader and the manufacture is the follower, which is practical in real cases. The two members will work under the following procedures: the manufacturer receives the company's order Q and manufactures using low-carbon technology. The manufacturer can produce revenue or expense through the carbon trading market according to the cap E. Then, the PC relays the prefabricated components to the manufacturer with the wholesale price w. Finally, the assembled product sells to the public as the sale price p. Because of the increasing number of consumers with CEA, this study considers two preferences from consumers: (1) low-carbon manufacturing, where the manufacture achieves the carbon reduction V by low-carbon investment, and a greater reduction will attract consumers with CEA; (2) high-prefabricated-rate buildings, where the prefabricated rate r is decided by PC, and the assembly cost is related to the rate. The higher rate also attracts consumers with CEA.

Parameters and variables are specified in Table 1.

Table 1. Parameters and variables.

	Parameters		
a	potential market demand	b	consumer's sensitive coefficient to price
h	consumer's sensitive coefficient to prefabricated rate	d	consumer's sensitive coefficient to carbon reduction
C	unit cost of production for manufacturer	k	green technology investment cost coefficient of manufacturer
ε	the cost coefficient of assembling prefabricated components	E	initial carbon allowance set by the government
e	enterprise's initial carbon emissions	P_e	unit price of carbon credits (carbon trading price)
K	a fixed fee	π_j^i	profit function for supply chain member i in model j
	Decision variables		
v	total carbon reduction $v \geq 0$	w	wholesale price, unit price of prefabricated components $p < w < C$
β	margin revenue	r	prefabricated rate $0 \leq r \leq 1$
p	unit product price set by prefabricated company	φ	cost allocation coefficient $0 < \varphi < 1$

The subscript $i \in \{PC,\ M,\ SC\}$ represents the PC, manufacturer, and supply chain, respectively. The $*$ in the superscript represents the optimal solution. Superscript $j \in \{N,\ GO,\ CS,\ TT\}$ represents the following four scenarios: decentralized system, global (centralized) optimal supply chain system, cost-sharing contract, and the two-part tariff contract.

For the convenience of calculation and practice in reality, the following assumptions are proposed, and symbols are defined as follows:

(1) Both subjects in the PCSC are rational with symmetrical information, so both of them will maximize their own profits.

(2) Based on the market linear demand function proposed by Ferguson and Toktay [52], additionally, with consumer's preferences [53], the equation is as follows:

$$Q(p, r, v) = a - bp + hr + dv \tag{1}$$

where a denotes the potential market demand, which is sufficiently large, p denotes the sale price, r denotes the prefabricated rate, and v is carbon reduction. The quantity Q increases with r and v, and the preference coefficients are h, d; Q decreases with p, and the price sensitivity is b.

(3) p can be expressed as

$$p = \beta + w \tag{2}$$

Equation (2) shows that if w (set by manufacturer) increases, p will be increased accordingly [36,54]. Therefore, PC will determine a final sale price by determining an optimal marginal revenue β. In addition, $p > w > C > 0$, ensuring a positive marginal profit.

(4) $C_v = \frac{kv^2}{2}, C_r = \frac{\varepsilon r^2}{2}$. The first function denotes the cost of emission reduction for the manufacturer, and the second denotes the cost of assembly for the PC. If enterprises improve the prefabricated rate and carbon reduction, the costs are higher accordingly [31,55].

(5) $P_e[E - (e - v)]$ denotes the profit and loss function for manufacture under the cap-and-trade policy, where E denotes the initial carbon allowance set by the government and e denotes the initial carbon emission discharged by manufacturer. After introducing low-carbon technologies, the carbon reduction is achieved. If the emission is still more than E, they can only purchase carbon credits in the carbon trading market for a unit price P_e or they can sell their extra carbon credits as profits.

(6) $b > d$, $b > h$, $k > d$, $\varepsilon > h$. The first and second assumptions represent price sensitivity having a greater influence on demand, which is common in reality. The last two

assumptions are reasonable, denoting that the cost coefficient is greater than the sensitivity. Thus, $bk > d^2$, then $2bk - d^2 > bk > hk$, so $\varepsilon(2bk - d^2) > h^2k$ and $2\varepsilon(2bk - d^2) > h^2k$, and the sharing rate should satisfy $0 < \varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon - h^2k}$.

4. The Decentralized Model with Cap-and-Trade Policy

The profit function of the manufacturer can be expressed as

$$\pi_M^N(w, v) = (w - C)Q + [E - (e - v)]P_e - k\frac{v^2}{2} \tag{3}$$

The first term denotes that the revenue of prefabricated components sold to PC where $w > C$ guarantees the manufacturer's profit. The second term represents the revenue (or cost) received from carbon trading market. This study will discuss the cap for government. The third term is the cost of technology for reducing carbon emissions. The manufacturer will make decisions through $\underset{(w,v)}{max}\ \pi_M^N(w, v)$.

The profit function of the prefabricated company can be expressed as

$$\pi_{PC}^N(p, r) = (p - w)Q - \varepsilon\frac{r^2}{2} \tag{4}$$

The first term represents the revenue from selling products, where $p > w$, and the second term is the cost of assembling prefabricated components. The PC will make decisions through $\underset{(p,r)}{max}\ \pi_{PC}^N(p, r)$.

Through the decentralized Stackelberg model, two members' optimal decisions are expressed in Proposition 1.

Proposition 1. *(1)* $p^{N*} = \frac{\varepsilon X}{N} + \frac{\varepsilon X(2bk - d^2)}{bkN} + C$, $r^{N*} = \frac{hX}{N}$; *(2)* $w^{N*} = \frac{\varepsilon X}{N} + C$, $v^{N*} = \frac{d\varepsilon X + P_eN}{kN}$.

The proof is provided in Appendix A. Where $X = ak - bkC + P_ed > 0$ and $N = 2\varepsilon(2bk - d^2) - h^2k > 0$.

From Proposition 1, in the case of the decentralized model, there exists optimal decisions for the manufacturer. Proposition 1 shows that the initial carbon emission has no impact on members' decisions, because the initial carbon emission only affects the carbon trading quantity for the manufacturer, and the cap-and-trade policy influences members' decisions through the trading price.

The optimal profits under a decentralized system can be derived with the above optimal solutions, which are expressed as Equations (5)–(7):

$$\pi_{PC}^{N*}\left(p^{N*}, r^{N*}\right) = \frac{\varepsilon X^2}{2kN} \tag{5}$$

$$\pi_M^{N*}\left(w^{N*}, v^{N*}\right) = \frac{(P_eN)^2 + (2bk - d^2)\varepsilon^2X^2}{2kN^2} + P_e(E - e) \tag{6}$$

$$\pi_{SC}^{N*} = \pi_{PC}^{N*} + \pi_M^{N*} = \frac{(P_eN)^2 + \varepsilon X^2[\varepsilon(2bk - d^2) + N]}{2kN^2} + P_e(E - e) \tag{7}$$

Results indicate that the initial emission allowance affects only the manufacturer's profits.

Regarding the PC's optimal prefabricated rate and sale price (denoted by r^{N*}, p^{N*}), we explore how the cap-and-trade policy, cost coefficient, and preference of carbon reduction influence the PC's decisions, and we obtain the following proposition:

Proposition 2. *(1)* $\frac{\partial r^{N*}}{\partial P_e} > 0$, $\frac{\partial r^{N*}}{\partial d} > 0$, $\frac{\partial r^{N*}}{\partial k} < 0$; *(2)* $\frac{\partial p^{N*}}{\partial P_e} > 0$, $\frac{\partial p^{N*}}{\partial d} > 0$, $\frac{\partial p^{N*}}{\partial h} > 0$, $\frac{\partial p^{N*}}{\partial k} < 0$, $\frac{\partial p^{N*}}{\partial \varepsilon} < 0$.

The proof is provided in Appendix A.

Based on Proposition 2, when the trading price increases, the PC will increase the prefabricated rate, as an increase of P_e motivates the manufacturer to further reduce to avoid the trading cost, which makes demand increase; thus, PC has the motivation to increase the rate and sale price. Hence, the introduction and implementation of a cap-and-trade policy is beneficial to improve the prefabricated rate. However, if the manufacturer spends more on low-carbon technology, then the PC has a lower marginal revenue, leading a decrease in the sale price; then, the PC will decrease the prefabricated rate to lower the investment on assembly technology. Hence, if the two preferences are enhanced, the PC should enhance the sale price and prefabricated rate, and thus the construction industry should increase the publicity of prefabricated buildings. Higher CEA is beneficial to decision making, which is beneficial to the economy and the environment.

Regarding the manufacturer's optimal carbon reduction and wholesale price (denoted by v^{N*}, w^{N*}), we explore how the PC's cost coefficiency and preferences will influence the manufacturer's decisions; thus, we obtain the following proposition:

Proposition 3. *(1)* $\frac{\partial v^{N*}}{\partial P_e} > 0, \frac{\partial v^{N*}}{\partial h} > 0$, $\frac{\partial v^{N*}}{\partial \varepsilon} < 0$; *(2)* $\frac{\partial w^{N*}}{\partial P_e} > 0$, $\frac{\partial w^{N*}}{\partial h} > 0$, $\frac{\partial w^{N*}}{\partial \varepsilon} < 0$, $\frac{\partial w^{N*}}{\partial k} < 0$.

The proof is provided in Appendix A.

Proposition 3 is similar to Proposition 2. First, when the preference increases, the demand increases, so the PC orders more and increases the sale price, and the manufacturer has the motivation to reduce carbon emissions. At the same time, the manufacturer enhances the wholesale price to ensure profits. However, when the assembly cost improves, the PC's marginal revenue decreases, which influences the PC's order quantity from the manufacturer; thus, the manufacturer cuts the wholesale price to ensure the order. Accordingly, the manufacturer lowers carbon reduction to decrease the cost. In all, it is intuitive that the cost of the technology investment should be controlled, and members should improve independent research and the efficiency of the technology. Implementing cap-and trade policy and improving CEA are effective to improve the level of green production and pricing decisions, which is economically and environmentally friendly.

We obtain the optimal member's decentralized decisions, then analyze the factors influencing decisions. Next, we will explore members' profits using the following proposition:

Proposition 4. *(1)* $\frac{\partial \pi_{PC}^{N*}}{\partial P_e} > 0$, $\frac{\partial \pi_{PC}^{N*}}{\partial k} < 0$; *(2)* $\frac{\partial \pi_{M}^{N*}}{\partial P_e} = \frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2} + E - e$, $\frac{\partial \pi_{M}^{N*}}{\partial \varepsilon} < 0$.

The proof is provided in Appendix A.

From Proposition 4, it is intuitive and easily understood that when firms increase the costs of assembly or low-carbon technology, the PC and manufacturer simultaneously have lower revenues. However, there is a difference between the PC and manufacturer for carbon trading price P_e. The initial carbon cap only influences the manufacturer's integrated cost. If the government enhances the trading price to regulate the carbon emissions, the PC will achieve higher profits without expenditure because the manufacturer is motivated to spend on green technology, which is a "free-rider" behavior. However, the manufacturer has three cases, including the situation in which the profits decrease. This implies that the policy is more beneficial to the PC because of the 'free-rider' behavior.

From the government's point of view, we suggest the government set the carbon cap $E < e - \frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2}$. Only in this way, when the government increases the intensity of punishment will it have an impact on manufacturers, because $\frac{\partial \pi_{M}^{N*}}{\partial P_e} < 0$, and manufacturers will take green measures to minimize costs and to ensure profits. The volume of carbon emission reduction should be at least $\frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2}$.

5. The Centralized Model with Cap-and-Trade Policy

In a centralized system, the PCSC is regarded as a whole entity, so the PC and the manufacturer changes the goal to maximization of the global profit instead of personal interest. Based on this, w will be internalized for the whole supply chain, so it is not necessary to make a decision on w. Instead, we should solve optimal v, p and r.

The total profit can be expressed as below:

$$\pi_{GO}^{N}(p,r,v) = (p-C)Q + [E-(e-v)]P_e - k\frac{v^2}{2} - \varepsilon\frac{r^2}{2} \tag{8}$$

Two members are chasing a global optimal system, so the whole PCSC makes decisions based on $\underset{(p,r,v)}{max}\ \pi_{GO}^{N}(p,r,v)$.

Proposition 5. *(1)* $r_{G0}^{N*} = \frac{hX}{Z}$, $p_{GO}^{N*} = \frac{\varepsilon X}{Z} + C$; *(2)* $v_{G0}^{N*} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k}$.

where $Z = \varepsilon\left(2bk - d^2\right) - h^2k$ and $Z > 0$. The proof is provided in Appendix A.

Taking optimal solutions into (1) and (8), we obtain global optimal profit under a centralized system:

$$\pi_{GO}^{N*}\left(p_{GO}^{N*}, r_{GO}^{N*}, v_{GO}^{N*}\right) = \frac{\varepsilon X^2}{2kZ} + \frac{{P_e}^2}{2k} + P_e(E-e) \tag{9}$$

Members' optimal solutions under different model systems have different results, so we compare and analyze the two results, and we obtain the following proposition:

Proposition 6. *(1)* $v_{GO}^{N*} > v^{N*}$, $r_{GO}^{N*} > r^{N*}$; *(2) if* $\varepsilon > \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} \le p^{N*}$; *if* $\frac{h^2k}{2bk-d^2} < \varepsilon < \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} > p^{N*}$; *(3)* $\pi_{GO}^{N*} > \pi_{SC}^{N*}$.

The proof is provided in Appendix A.

In Proposition 6, comparing decisions under the two systems, the profit under the centralized model is more beneficial, so it is important to integrate supply chain members as a whole from the economic perspective. However, it is surprising that although green production decisions perform better in a centralized system, the centralized system is better for the environment because the PC decreases the sale price.

The global optimal profit of the PCSC is denoted as π_{GO}^{N*} under a centralized system, and we denote π_{SC}^{N*} as the PCSC's profits under decentralized system ($\pi_{SC}^{N*} = \pi_{PC}^{N*} + \pi_{M}^{N*}$). Although we know $\pi_{GO}^{N*} > \pi_{SC}^{N*}$, we will explore the differences between the two systems faced with the cap-and-trade mechanism; thus, the proposition is as follows:

Proposition 7. $\frac{\partial\pi_{GO}^{N*}}{\partial P_e} = E - e + \frac{P_e\left(2b\varepsilon - h^2\right) + d\varepsilon(a - Cb)}{Z}$, $\frac{\partial\pi_{SC}^{N*}}{\partial P_e} = E - e + \frac{N(d\varepsilon X + P_eN) + 2bdk\varepsilon^2X}{kN^2}$; $e_{GO} - E_{GO} < e_{SC} - E_{SC}$.

The proof is provided in Appendix A. From the supply chain's perspective, we denote two thresholds when $\frac{\partial\pi_{SC}}{\partial P_e} = 0$: $e_{GO} - E_{GO}$ under a centralized system and $e_{SC} - E_{SC}$ under decentralized system, which represent the maximum emissions for the supply chain.

Proposition 7 suggests the government set the cap $E < e - \frac{P_e\left(2b\varepsilon - h^2\right) + d\varepsilon(a - bC)}{2bk\varepsilon - d^2\varepsilon - h^2k}$; that is to say, if the government raises the trading price, the cap will serve as a punishment mechanism because the manufacturer's profit will decrease when the trading price raises. Furthermore, $e - E$ represents the carbon emission in excess of quota E. Furthermore, the thresholds of the two systems have $e_{GO} - E_{GO} < e_{SC} - E_{SC}$, implying that the government execute a more stringent and rigorous cap under the centralized model. However, this exerts greater pressures on the manufacturer, as only the manufacturer shoulders the responsibility of reduction. It is difficult to reach a steady supply chain and to achieve centralized system.

First, when two enterprises make decisions independently, the manufacturer undertakes the whole burden of carbon emission reduction, and the PC acts as a leader that derives greater profits, resulting in an unfair profit distribution, which makes the PCSC unstable. Second, regarding the supply chain as a whole leads to better response and profits; thus, it is necessary to promote collaboration in the PCSC. These two problems will be addressed in the following section by introducing coordination contracts into the PCSC.

6. The Coordination Contracts

In this section, we investigate two contracts: (1) a cost-sharing contract; (2) a two-part tariff contract [28]. For each contract, there are mainly three decision stages. In the first stage, one of the members designs a contract and determines the optimal contract parameters. The other member decides to accept or reject the offer. If accepting, in the second stage, the PC decides on their decision variables, considering the reaction function of the manufacturer. In the third stage, the follower decides on their decision variables, finally the market outcomes are realized.

6.1. The Cost-Sharing Contract

Under a cost-sharing contract, the PC shares part of the cost of emission reduction $\varphi\frac{kv^2}{2}$; thus, the remainder of the cost for manufacturer is $(1-\varphi)\frac{kv^2}{2}$. Similarly, we solve this problem using a Stackelberg model and backward induction. Under the cost-sharing contract, the PC is a leader, and the manufacturer is a follower. PC decides the p, r, φ, and the manufacturer decides v and w. Hence, objective functions under the cost-sharing contract are $\underset{(p,r,\varphi)}{max}\ \pi_{PC}^{CS}(p,r,\varphi)$ and $\underset{(w,v)}{max}\ \pi_{M}^{CS}(w,v)$, which can be expressed as below:

$$\pi_{PC}^{CS}(p,r,\varphi) = (p-w)Q - \varepsilon\frac{r^2}{2} - \varphi\frac{kv^2}{2} \tag{10}$$

$$\pi_{M}^{CS}(w,v) = (w-C)Q + [E-(e-v)]P_e - (1-\varphi)\frac{kv^2}{2} \tag{11}$$

Proposition 8. *(1)* $r^{CS*} = \frac{h(4X-P_ed)}{4N-d^2\varepsilon}$, $p^{CS*} = \frac{12b\varepsilon X+P_edh^2-7P_ebd\varepsilon-3d^2\varepsilon(a-bC)}{b(4N-d^2\varepsilon)} + C$, $\varphi^* = \frac{d\varepsilon X-P_eN}{d\varepsilon(3X-P_ed)+P_eN}$; (2) $v^{CS*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)}$, $w^{CS*} = \frac{\varepsilon(4X-P_ed)}{4N-d^2\varepsilon} + C$.

The proof is provided in Appendix A.

Proposition 8 shows that there are optimal decisions under the cost-sharing contract. The PC should cover less than half of the cost as the sharing rate is $\varphi < \frac{1}{2}$. Bringing these optimal solutions into Equations (10) and (11), we have the maximum profits for the PC and manufacturer under the cost-sharing contract.

$$\pi_{PC}^{CS*}\left(p^{CS*}, r^{CS*}, \varphi^*\right) = \frac{4(\alpha-bC)\varepsilon X + 2P_ed\varepsilon(a-bC) + {P_e}^2\left(4b\varepsilon-h^2\right)}{2(4N-d^2\varepsilon)} \tag{12}$$

$$\pi_{M}^{CS*}\left(w^{CS*}, v^{CS*}\right) = \frac{[d\varepsilon(dP_e-2X)-2P_eN]^2 + \varepsilon^2\left(bk-d^2\right)[4k(a-bC)+3P_ed]^2}{k(4N-d^2\varepsilon)^2} + P_e(E-e) \tag{13}$$

After introducing the cost-sharing contract, members of the PCSC obtain optimal decisions. When we compare decisions under the two systems (with and without a cost-sharing contract), we obtain the following proposition:

Proposition 9. *(1)* $r_{GO}^{N*} > r^{CS*} > r^{N*}$; *(2)* $w^{CS*} > w^{N*}$, $v_{GO}^{N*} > v^{CS*} > v^{N*}$; *(3)* $Q_{GO}^{N*} > Q^{CS*} > Q^{N*}$.

The proof is provided in Appendix A.

Proposition 9 illustrates that, compared with the decentralized model, the manufacturer has lower carbon emissions and has higher wholesale prices under the contract. The PC improves the prefabricated rate under this contract. In addition, a greater demand is also achieved. Therefore, the introduction of this cost-sharing contract is beneficial to pricing and production. However, compared with the centralized model, we find the cost-sharing contract is no longer more beneficial, and optimization should be further proposed and studied, as the cost-sharing contract does not reach the level of the centralized model.

With greater v and r, the cost of carbon reduction and assembly will be increased. The profits of the PC, manufacturer and PCSC under the cost-sharing contract are denoted as $\pi_{PC}^{CS*}, \pi_{M}^{CS*}, \pi_{SC}^{CS*}$, respectively. Whether the cost-sharing contract achieves Pareto improvement is related to whether the profits under the cost-sharing contract are greater than under the decentralized system. We obtain the following proposition:

Proposition 10. *(1)* $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$*; (2) if* $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-d^2\varepsilon(\Theta+1)}$, $\pi_{M}^{CS*} \geq \pi_{M}^{N*}$*; if* $P_e < \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-d^2\varepsilon(\Theta+1)}$, $\pi_{M}^{CS*} < \pi_{M}^{N*}$*; (3)* $\pi_{SC}^{CS*} > \pi_{SC}^{N*}$.

The proof is provided in Appendix A. Where $\Theta = d\varepsilon\left[\frac{d}{2N} + \frac{8N}{2d\varepsilon^2(2bk-d^2)}\right] - 4 > 0$.

Proposition 10 illustrates that with this cost-sharing contract, both the PC and manufacturer are willing to cooperate with each other to achieve greater profits when $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$; thus, an improved and stable PCSC is realized. However, when $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$, the trading price is too high if emissions exceed the cap. Hence, the manufacturer must spend more on the low-carbon investment to avoid buying credits with a high trading price. At the moment, the cost-sharing contract is beneficial to the manufacturer, because the PC shares some of the cost of the carbon reduction technology.

When $P_e < \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$, the trading price is rational, and the manufacturer can undertake the cost. Furthermore, the greater investment in the technology promotes increased carbon reduction, and the manufacturer can gain revenues from the trading market and does not need the cost-sharing contract. The above results also suggest that when there is a cost-sharing contract, the policymaker should make the trading price satisfy $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$.

Certain key lessons can be derived from this. Leaders are often concerned about the loss of profit owing to the introduction of a cost-sharing contract. However, we prove that the contract not only not decreases the pricing and production, but also increases the profit. Finally, a better performance is achieved than in the decentralized model.

The cost-sharing improves the performance of members; however, it does not reach the level of the centralized system. Hence, we will investigate another coordination mechanism, called the two-part tariff contract.

6.2. The Two-Part Tariff Contract

The cost-sharing contract achieves Pareto improvement but does not optimize the PCSC. We use a linear two-part tariff contract to optimize the decentralized supply chain [39,56]. In a linear two-part tariff contract, the PC commits to pay a fixed fee to the manufacturer, because the objective of the contract is to incentivize the manufacturer to reduce the wholesale price. We assume that the PC offers a lump-sum payment K to the manufacturer as compensation for the lower values of wholesale price; thus, the profit functions for the PC and manufacturer are $\underset{(p,r,K)}{max}\ \pi_{PC}^{TT}(p,r,K)$ and $\underset{(w,v)}{max}\ \pi_{M}^{TT}(w,v)$. Again, the PC is dominant in the model. The Equations are as follows:

$$\pi_{PC}^{TT}(p,r,K) = (p-w)Q - \varepsilon\frac{r^2}{2} - K \tag{14}$$

$$\pi_M^{TT}(w,v) = (w - C)Q + [E - (e - v)]P_e - k\frac{v^2}{2} + K \tag{15}$$

In order to achieve the level under the centralized model and ensure collaboration of the two members, we obtain the following proposition:

Proposition 11. $K_l < K < K_u$, $K_l = \frac{X^2\varepsilon^2\left[2bh^4k^3 - 2h^2k\varepsilon\left(4b^2k^2 - d^4\right) + \varepsilon^2\left(2bk - d^2\right)^2\left(3d^2 + 2bk\right)\right]}{2k(ZN)^2}$, $K_u = \frac{X^2\varepsilon^2\left[2bk^2\left(2b\varepsilon - h^2\right) - d^4\varepsilon\right]}{2kNZ^2}$, $w^{TT} = C$, $r^{TT} = r_{GO}^{N*}$, $p^{TT} = p_{GO}^{N*}$, $v^{TT} = v_{GO}^{N*}$.

The proof is provided in Appendix A.

From Proposition 11, the two-part tariff contract achieves coordination and optimization. Surprisingly, the wholesale price has been slashed, but the two-part contract still exists, as it guarantees $\pi_M^{TT} > \pi_M^{N*}$ and $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$. The premise of a feasible coordination is that profits are higher than in the decentralized system. Under the contract, the sum of members' profits is optimal and equal to that under the centralized model, which is $\pi_{PC}^{TT*} + \pi_M^{TT*} = \pi_{GO}^{N*}$; thus, the contract only changes the profit distribution between them. However, in reality, the applicability of the two-part tariff contract is a challenge, because the manufacturer may not be willing to cut the wholesale price to the production cost, and it requires the PC's bargaining ability. Compared with the cost-sharing contract, the two-part tariff performs better because it fully coordinates the channel when $K_l < K < K_u$, while the cost-sharing contract does not.

7. Numerical Analysis

In this section, we present the numerical analysis to illustrate the theoretic results obtained above and the impact of carbon trading price and cap on the operational decisions of stakeholders. We assume $a = 1000$, $b = 8$, $C = 40$, $h = 6$, $d = 0.8$, $k = 1$, $\varepsilon = 300$, $e = 80$. Similar numerical studies are widely used in the literature, such as Xu et al. [14] and Kuiti et al. [39].

7.1. Carbon Reduction Level and Prefabricated Rate

Figures 1–3 show that carbon reduction level, prefabricated rate, and optimal sale price all increase with the trading price, which has been theoretically proven in Propositions 2 and 3. Our observations suggest that a higher trading price incentivizes the manufacturer to emit less carbon, as it can benefit from a surplus in the trading market, and the PC is motivated to enhance the prefabricated rate and sale price. Therefore, the cap-and-trade policy is beneficial to the members' operational decisions. Moreover, from the comparisons, we find that prefabricated rate and carbon reduction under a centralized model (two-part tariff contract model) are greater. Although the cost-sharing contract achieves greater values in all decisions than the decentralized model, the cost-sharing contract in our study does not perfectly coordinate the PCSC, as the values cannot reach the level of the centralized model. From Figure 3, the sale price is the lowest in the centralized model. This can be explained as follows: as a dominant leader, the PC decides the sale price in order to obtain greater profits in decentralized system; however, when it comes to centralized system, the PC has to lower price to maximize the profits of the whole PCSC instead of just itself, which has been shown in Proposition 9.

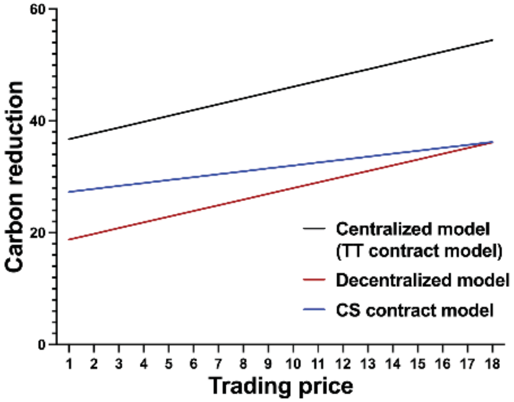

Figure 1. Impact of trading price on emission abatement level.

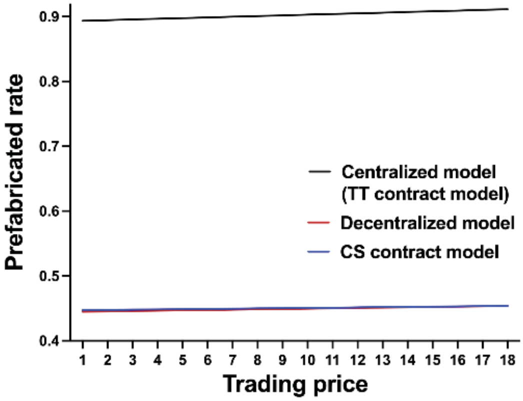

Figure 2. Impact of trading price on prefabricated rate.

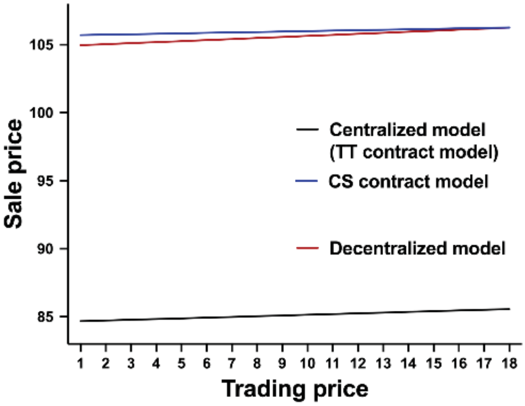

Figure 3. Impact of trading price on sale price.

7.2. Decentralized and Centralized Model Comparisons

Figure 4 presents the impact of trading price on the PC's profits, which increase with the trading price. However, the PC's profits are independent of the cap, showing the same conclusion as Proposition 4. Moreover, the manufacturer's profit initially decreases and then increases after the trading price reaches a certain threshold value when the cap is at a low level. However, when the trading price is at a high level, it will motivate the manufacturer to reduce emissions to avoid cost, so profits will gradually increase. Furthermore, Figure 4 also illustrates that the manufacturer's profits increase with cap, as more surplus could result in revenues. Compared to the manufacturer, the PC gains greater profits as the leader, but when the cap is extremely high, the direct revenues of the manufacturer from the external trading market are extremely high, and thus the profit of the PC is no longer greater.

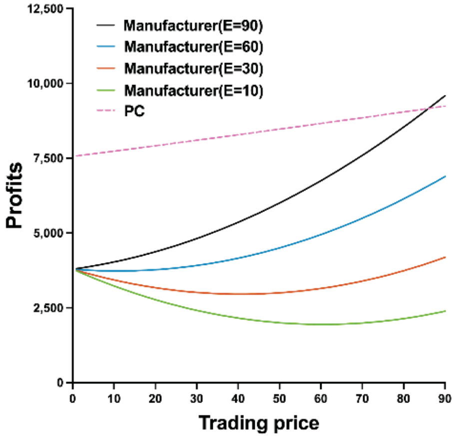

Figure 4. Impact of trading price and cap on two members' profits.

Figure 5 illustrates that the PCSC's profits have similar trends as the manufacturer, because the cap E is not in the PC's profit function; this is a "free-rider" behavior, as proven in Propositions 6 and 7. The centralized model performs better, as shown in Figure 5.

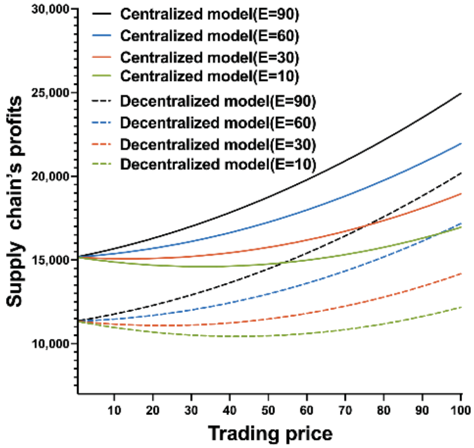

Figure 5. Impact of trading price and cap on PCSC's profits.

7.3. The Cost-Sharing Contract's Profit Analysis

Figure 6 shows that the cost-sharing contract is preferable for the PC. Although the PC takes on part of the cost of carbon reduction, the profit still increases. However, in Figure 7, for the manufacturer, when the trading price is over a certain threshold, the cost-sharing contract performs better than the decentralized model, which implies that the cost-sharing contract cannot perfectly coordinate the PCSC. Similarly, the PC as the leader obtains greater profits more obviously, and the line trend of profits is similar to 7.2. Figure 8 shows that the cost-sharing contract achieves Pareto improvement, because the supply chain's profits are greater than decentralized model, but the improvement is not significant.

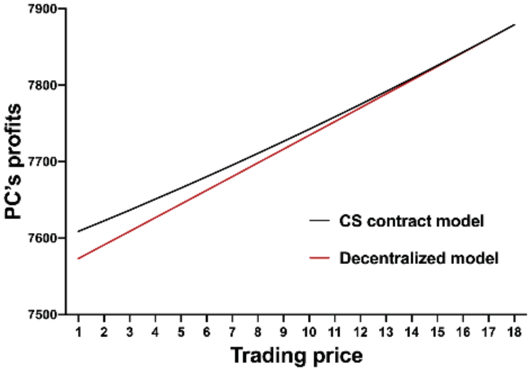

Figure 6. Impact of trading price between cost-sharing contract.

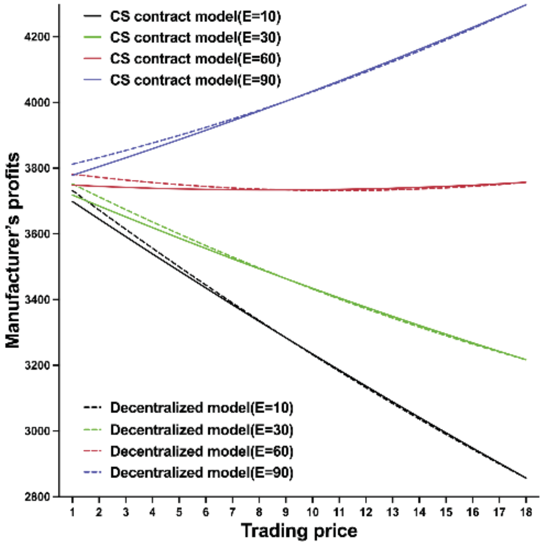

Figure 7. Impact of trading price and cap on manufacturer's profits.

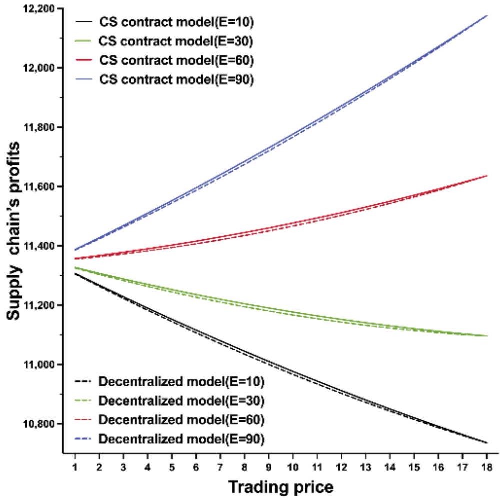

Figure 8. Impact of trading price and cap on the PCSC's profits.

7.4. The Two-Part Tariff Contract's Profit Analysis

Figure 9 presents the PC's profits with the upper bound (K_u) and lower bound (K_l) of the fixed fee, varying with the carbon trading price. With the upper bound, the PC shares the greatest fixed fee, and the PC's profits are equal to those under the decentralized model; thus, the manufacturer achieves the greatest profits with K_u. With the lower bound, the PC achieves the greatest revenues, so the manufacturer wins the minimum fixed fee. Therefore, the fixed fee varies from K_l to K_u. In addition, Figure 10 also shows that the trading price is not always beneficial to the manufacturer, and under a low carbon cap, the manufacturer's profits decrease with the trading price. Moreover, operational decisions in the two-part tariff contract reach the level of centralized approach; thus, the supply chain's profits are equal to the centralized model, which optimizes the supply chain's profits. Comparing the two-part tariff contract to the cost-sharing contract, we can conclude that members win more profits under the two-part tariff contract, and the PCSC achieves coordination optimization; however, profit allocation between the two members depends on the leader.

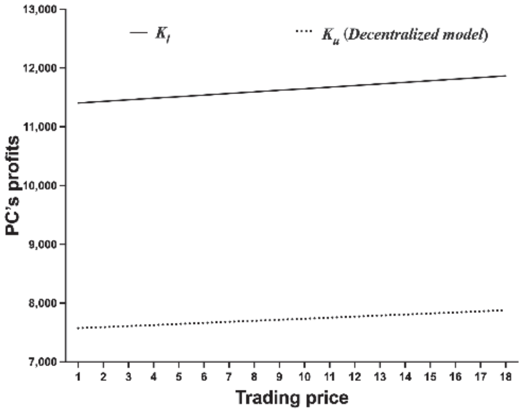

Figure 9. Impacts of trading price on two-part tariff contract.

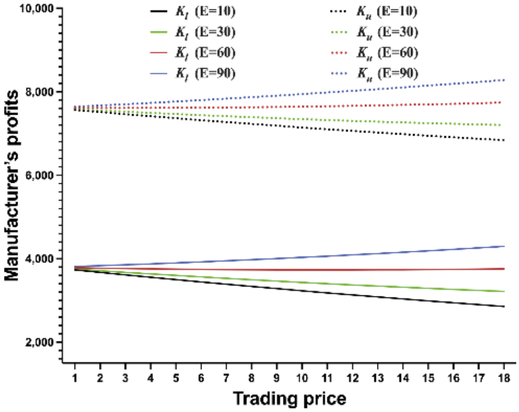

Figure 10. Impacts of trading price and cap on two-part tariff contract.

8. Conclusions

In this paper, we build a PCSC consisting of a manufacturer and a PC. This study is aimed at solving issues regarding decision making and coordination of the PCSC using the Stackelberg model and backward induction under different systems, where the PC is the leader. The cap-and-trade policy is implemented to limit emissions in prefabricated component manufacturing. In addition, with the increasing CEA, we consider the consumer's preferences in terms of prefabricated rate and carbon reduction. Furthermore, sensitivity analysis is carried out to analyze mutual influences. Finally, we take a cost-sharing contract and a two-part tariff contract to coordinate the PCSC. Managerial findings are obtained as follows:

(1) In the PCSC, we determine the members' optimal decisions. The trading price promotes carbon reduction, prefabricated rate, and pricing decisions. Therefore, the cap-and-trade policy has a positive effect on the PCSC from economic and environmental perspectives, and the policy is beneficial to the development of prefabricated construction. Moreover, enhancing consumer preferences promotes pricing and green production, and thus it is beneficial to guide consumers to improve the CEA to protect the environment. Additionally, the publicity of prefabricated buildings should be strengthened.

(2) In the Stackelberg model, the PC is dominant, so it gains more profits than the manufacturer. For two members, the PC's profits increase with the trading price; however, this is essentially a 'free-rider' behavior, because the cap-and-trade policy only affects the manufacturer. Profits of the manufacturer are complicated, which relates to the cap. The government policymaker should set the cap below a threshold, so the policy works as a punishment mechanism that regulates the manufacturer's emissions. The centralized models perform better, achieving greater profits and environmental benefits.

(3) To coordinate the PCSC, this study designs and compares two contracts (the cost-sharing contract and two-part tariff contract). First, all decisions under the cost-sharing contract are improved over the decentralized system, but it does not achieve the same level as under the centralized system, indicating that the contract only achieves Pareto improvement. Moreover, when the cap is high, the manufacturer will prefer the decentralized system to obtain revenues in the trading market, while the cost-sharing contract is redundant. Next, we investigate the two-part tariff contract: members also win more profits than in the decentralized system. Furthermore, decisions reach the level of the centralized system, and the contract only changes the profit distribution; thus, the contract achieves coordination and optimization. Nevertheless, it is worth noting that the manufacturer's wholesale price is slashed under the two-part tariff contract, so it give the PC (leader) high bargaining power.

This study has several limitations, and opportunities exist to extend this research in the future. First, the model in our study considers one prefabricated company and one manufacturer, but multiple manufacturers are more realistic in the construction industry, so the investigation should consider the lateral competition. Second, this study assumes a deterministic demand, so another extension is to use the stochastic model to analyze the effect of cap-and-trade policy and preferences on the PCSC. Finally, the process of assembling prefabricated parts also emits greenhouse gas. Therefore, the PC shoulders the responsibility of emission reduction; a new profit function of PC could be adopted in the future research.

Author Contributions: Formal analysis, W.J. and M.Y.; Project administration, W.J.; Writing—original draft, M.Y.; Writing—review & editing, W.J. and M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Youth Foundation for Humanities and Social Sciences of Ministry of Education of China (No. 19YJC630063), Sichuan Science and Technology Program (No. 2020YJ0365), National Natural Science Foundation of China (No. 71972136), and Key research base of humanities and Social Sciences of Sichuan Province-Research Center of Sichuan County Economy Development: No. xy2020035.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are contained within the article.

Conflicts of Interest: All authors declare that they have no conflict of interest.

Appendix A

Proof of Proposition 1. Through backward induction, the manufacturer first determines the optimal emission reduction amounts v and w. The Hessian matrix $\begin{vmatrix} -k & d \\ d & -2b \end{vmatrix}$, only when $2bk - d^2 > 0$, is a negative definite matrix; in this case, there are optimal solutions for the manufacturer: $w^N = \frac{k(Cb+a-b\beta+hr)-d(Cd-P_e)}{2bk-d^2}$, $v^N = \frac{d(Cb+a-b\beta+hr)-2b(Cd-P_e)}{2bk-d^2}$. As derivatives of β, r in $\pi_{PC}^N\left(v^N,\ w^N\right)$, we obtain a Hessian Matrix $\begin{vmatrix} -\frac{2b^2k}{2bk-d^2} & \frac{bhk}{2bk-d^2} \\ \frac{bhk}{2bk-d^2} & -\varepsilon \end{vmatrix}$. $N > 0$, hence, there are optimal solutions of β and r, and we get $\begin{cases} r^N = \frac{bhk\beta}{\varepsilon*(2bk-d^2)} \\ \beta^N = \frac{-Cbk+P_ed+k(a+hr)}{2bk} \end{cases}$. The optimal β, r under the decentralized system are: $r^{N*} = \frac{hX}{N}$, $\beta^{N*} = \frac{\varepsilon X\left(2bk-d^2\right)}{bkN}$. Substituting r^{N*}, β^{N*} to other variables, the optimal solutions of $w^{N*}, V^{N*},\ p^{N*}, Q^{N*}$ are

$$w^{N*} = \frac{\varepsilon X}{N} + C, v^{N*} = \frac{Xd\varepsilon + P_eN}{kN},\ p^{N*} = \frac{\varepsilon X}{N} + \frac{\varepsilon\left(2bk - d^2\right)X}{bkN} + C,\ Q^{N*}\frac{b\varepsilon X}{N}.$$

□

Proof of Proposition 2. As $N = 2\varepsilon\left(2bk - d^2\right) - h^2k > 0$, $2bk - d^2 > 0$, $r^{N*} = \frac{hX}{N}$ with $r^{N*} \in (0,1]$, we get $X > 0$. Therefore, $\frac{\partial r^{N*}}{\partial P_e} = \frac{hd}{N} > 0$; $\frac{\partial r^{N*}}{\partial d} = \frac{P_eN+4d\varepsilon X}{N^2} > 0$; $\frac{\partial r^{N*}}{\partial k} = \frac{-h*\left(P_edN+2d^2\varepsilon X\right)}{kN^2} < 0$. Because $3bk - d^2 > 2bk - d^2 > 0$, then $\frac{\partial p^{N*}}{\partial P_e} = \frac{d\varepsilon\left(3bk-d^2\right)}{bkN} > 0$; $\frac{\partial p^{N*}}{\partial h} = \frac{2h\varepsilon X\left(3bk-d^2\right)}{bN^2} > 0$; $\frac{\partial p^{N*}}{\partial d} = \frac{\varepsilon\left[2h^2kdX+4bdk\varepsilon X+P_eN\left(3bk-d^2\right)\right]}{bkN^2} > 0$; $\frac{\partial p^{N*}}{\partial \varepsilon} = \frac{-h^2X\left(3bk-d^2\right)}{bN^2} < 0$; $\frac{\partial p^{N*}}{\partial k} = \frac{-d\varepsilon\left[h^2kdX+2bkd\varepsilon X+P_eN\left(3bk-d^2\right)\right]}{bk^2N^2} < 0$. □

Proof of Proposition 3. $\frac{\partial v^{N*}}{\partial P_e} = \frac{1}{k} + \frac{d^2\varepsilon}{kN} > 0$; $\frac{\partial v^{N*}}{\partial h} = \frac{2hd\varepsilon X}{N^2} > 0$; $\frac{\partial v^{N*}}{\partial \varepsilon} = -\frac{dh^2X}{N^2} < 0$; $\frac{\partial w^{N*}}{\partial P_e} = \frac{d\varepsilon}{N} > 0$;$\frac{\partial w^{N*}}{\partial h} = \frac{2hk\varepsilon X}{N^2} > 0$; $\frac{\partial w^{N*}}{\partial \varepsilon} = \frac{-h^2kX}{N^2} < 0$; $\frac{\partial w^{N*}}{\partial k} = \frac{-d\varepsilon\left[2d\varepsilon*(a-bC)+P_e\left(4b\varepsilon-h^2\right)\right]}{N^2}$

First, $a - bC > a - bp > 0$ with $p > w > C$. Second, $2\varepsilon\left(2bk - d^2\right) - h^2k > 0 \Leftrightarrow k\left(4b\varepsilon - h^2\right) -2d^2\varepsilon > 0 \Leftrightarrow 4b\varepsilon - h^2 > \frac{2d^2\varepsilon}{k} > 0$; we get $4b\varepsilon - h^2 > 0$; then, $2d\varepsilon(a - bC) + P_e\left(4b\varepsilon - h^2\right) > 0$, so $\frac{\partial w^{N*}}{\partial k} < 0$. □

Proof of Proposition 4. $\frac{\partial \pi_{PC}^{N*}}{\partial P_e} = \frac{d\varepsilon X}{kN} > 0$; $\frac{\partial \pi_{PC}^{N*}}{\partial k} = -\frac{d\varepsilon X\left[d\varepsilon X+P_ek\left(4b\varepsilon-h^2\right)\right]}{(kN)^2}$; Proposition 3 proved $4b\varepsilon - h^2 > 0$; thus, $\frac{\partial \pi_{PC}}{\partial k} < 0$, $\frac{\partial \pi_M^{N*}}{\partial \varepsilon} = \frac{-h^2\varepsilon\left(2bk-d^2\right)X^2}{N^3} < 0$;

$\frac{\partial \pi_M^{N*}}{\partial P_e} = \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2} + E - e$; then, the sign of $\frac{\partial \pi_M^{N*}}{\partial P_e}$ depends on the values between $\frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$ and $E - e$. There are three conditions: (1) if $e - E > \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, then $\frac{\partial \pi_M}{\partial P_e} < 0$; (2) if $e - E < \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, then $\frac{\partial \pi_M}{\partial P_e} > 0$; (3) if $e - E - \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, P_e and r are irrelevant. □

Proof of Proposition 5. In the decentralized model, $N = 2\varepsilon\left(2bk - d^2\right) - h^2k > 0$, which can be transformed to $\varepsilon > \frac{h^2k}{2(2bk-d^2)}$, so $\varepsilon > \frac{h^2k}{(2bk-d^2)} > \frac{h^2k}{2(2bk-d^2)}$. The second derivative of v is $\frac{\partial^2 \pi_{GO}^N}{\partial v^2} = -k < 0$, so when $\frac{\partial \pi_{GO}^N}{\partial v} = 0$, the optimal solution is: $v_{GO}^N = \frac{dp-Cd+P_e}{k}$.

The Hessian Matrix of p and r is $\begin{vmatrix} \frac{-2b+d^2}{k} & h \\ h & -\varepsilon \end{vmatrix}$ with $Z = \varepsilon\left(2bk - d^2\right) - h^2k > 0$ as the evidence that there are optimal solutions for p and r; then, we get $\begin{cases} p_{GO}^N = \frac{Cbk-Cd^2+P_ed+ak+hkr}{2bk-d^2} \\ r_{GO}^N = \frac{h*(p-C)}{\varepsilon} \end{cases}$, so we have: $r_{G0}^{N*} = \frac{hX}{Z}$; $p_{GO}^{N*} = \frac{\varepsilon X+CZ}{Z} = \frac{\varepsilon X}{Z} + C$; $Q_{GO}^{N*} = \frac{b\varepsilon X}{Z}$.

Bringing the p^{GO*}, r^{GO*} into v^{G0}, we get $v_{GO}^{N*} = \frac{Xd\varepsilon+P_eZ}{kZ} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k}$. □

Proof of Proposition 6. $N - Z = \varepsilon\left(2bk - d^2\right) - h^2k$ with $2bk - d^2 > 0$, then $N > Z$. r, v have the same numerator but different denominators under the two models, so $v_{GO}^{N*} > v^{N*}$; $r_{GO}^{N*} > r^{N*}$.

p_{GO}^{N*} and p^{N*}: $p_{GO}^{N*} - p^{N*} = -\frac{\varepsilon X\left(2bk-d^2\right)\left[\varepsilon\left(bk-d^2\right)-h^2k\right]}{bkZN}$. The value of $\varepsilon\left(bk - d^2\right) - h^2k$ is unknown, so $p_{GO}^{N*} - p^{N*}$ has three possibilities: (1) if $\varepsilon\left(bk - d^2\right) < h^2k < \varepsilon\left(2bk - d^2\right)$, then $\frac{h^2k}{2bk-d^2} < \varepsilon < \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} > p^{N*}$; (2) if $\varepsilon\left(bk - d^2\right) - h^2k > 0$, then $\varepsilon > \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} < p^{N*}$; (3) $\varepsilon\left(bk - d^2\right) - h^2k = 0$, $p_{GO}^{N*} = p^{N*}$. However, order quantity and profit are: $Q_{GO}^{N*} > Q^{N*}$. $\pi^{N*} - \pi_{GO}^{N*} = -\frac{\varepsilon^3X^2\left(2bk-d^2\right)^2}{2kN^2Z} < 0$, so $\pi_{GO}^{N*} > \pi^{N*}$. □

Proof of Proposition 7. $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} = E - e + \frac{P_e}{k} + \frac{d\varepsilon X}{kZ}$. When $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} < 0$, $e^{GO} - E^{GO} > \frac{P_e\left(2b\varepsilon-h^2\right)+d\varepsilon(a-Cb)}{2bk\varepsilon-d^2\varepsilon-h^2k} > 0$, when $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} \geq 0$, $e^{GO} - E^{GO} \leq \frac{P_e\left(2b\varepsilon-h^2\right)+d\varepsilon(a-Cb)}{2bk\varepsilon-d^2\varepsilon-h^2k} \leq 0$. Decentralized system: $\frac{\partial(\pi_M^{N*}+\pi_{PC}^{N*})}{\partial P_e} < 0$, let $e^{SC*} - E^{SC*}, e^{GO*} - E^{GO*}$ as decentralized and centralized thresholds, the difference of two thresholds is $e^{GO*} - E^{GO*} - \left(e^{SC*} - E^{SC*}\right) = \frac{d\varepsilon X}{k}\left(\frac{1}{Z} - \frac{1}{N} - \frac{2bk\varepsilon}{N^2}\right) = -\frac{d\varepsilon^2X}{kZN^2} * \left[d^2Z + \varepsilon\left(d^2 - 2bk\right)^2\right] < 0$. □

Proof of Proposition 8. From assumptions, $\varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}$, and $\frac{2bk-d^2}{2bk} - \left(1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}\right) = \frac{h^2d^2k}{2bk(2bk\varepsilon-h^2k)} > 0$, so $Y = 2bk(1 - \varphi) - d^2 > 0 \Leftrightarrow \varphi < \frac{2bk-d^2}{2bk} < \frac{1}{2}$. Taking (1) and (2) into (7), the manufacturer first determines the optimal V and w under the cost-sharing contract. The Hessian matrix is $\begin{vmatrix} -k(1-\varphi) & d \\ d & -2b \end{vmatrix}$ and $2bk(1 - \varphi) - d^2 > 0$, so there are optimal w and v under the cost-sharing contract when $\frac{\partial \pi_M^{CS}}{\partial v} = 0$, $\frac{\partial \pi_M^{CS}}{\partial w} = 0$, and the solutions are: $v^{CS} = \frac{2b(Cd-P_e)-d(Cb+a-b\beta+hr)}{-Y}$, $w^{CS} = \frac{d(Cd-P_e)+k(\varphi-1)(Cb+a-b\beta+hr)}{-Y}$. Substituting w^{CS}, v^{CS} into (7), we find β and r's partial derivatives, and we can obtain the Hessian matrix: $\begin{vmatrix} -\frac{b^2k\left[d^2\varphi+2Y(1-\varphi\ )\right]}{Y^2} & \frac{h\left[bd^2k\varphi+bk*(1-\varphi\ )Y\right]}{Y^2} \\ \frac{h\left[bd^2k\varphi+bk*(1-\varphi\ )Y\right]}{Y^2} & -d^2h^2k\frac{\varphi}{Y^2}-\varepsilon \end{vmatrix}$. If $\frac{(b^2d^2h^2k^2\frac{\varphi}{Y^2}+b^2k\varepsilon)\left[d^2\varphi+2Y*(1-\varphi\ )\right]}{Y^2} - (hbk)^2\left[\frac{d^2\varphi+(1-\varphi\ )*Y}{Y^2}\right]^2 > 0$, then optimal decisions for the PC exist.

Obviously $\frac{d^2\varphi+2Y(1-\varphi\ )}{Y^2} > \frac{d^2\varphi+Y\ (1-\varphi\ )}{Y^2}$ with $Y > 0$ and $\varphi \in [0,1]$, so we compare $b^2d^2h^2k^2\frac{\varphi}{Y^2} + b^2k\varepsilon$ with $(hbk)^2\frac{d^2\varphi+(1-\varphi)*Y}{Y^2}$: $\left(b^2d^2h^2k^2\frac{\varphi}{Y^2} + b^2k\varepsilon\right) - (hbk)^2 * \frac{d^2\varphi+(1-\varphi\ )*Y}{Y^2} = \frac{b^2kY\left[\varepsilon Y-h^2k(1-\varphi)\right]}{Y^2}$, $\varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}$, thus $\varepsilon Y - h^2k(1-\varphi) > 0$; then, the revenue of the PC is a concave function, so there is optimal β and r. With v^{CS}, w^{CS}, we can obtain $\beta(v^{CS}, w^{CS})$ and $r^{CS}(v^{CS}, w^{CS})$. Substituting the above variables into (7), the PC determines the optimal φ^*. Similarly, we get $\varphi_1 = \frac{d\varepsilon X-P_eN}{d\varepsilon(3X-P_ed)+P_eN}$, $\varphi_2 = \frac{-Cbdk\varepsilon+4P_ebk\varepsilon-P_ed^2\varepsilon-P_eh^2k+adk\varepsilon}{-Cbdk\varepsilon+4P_ebk\varepsilon-P_eh^2k+adk\varepsilon}$. Substituting φ_2 into $w^{CS}(\beta^{CS}, r^{CS})$ and $v^{CS}(\beta^{CS}, r^{CS})$, we find $w = C - \frac{P_e}{d} < C$ and $v = 0$; manufacturer has no motive to produce and cooperate, so only φ_1 exists.

Then, we have: $\varphi^* < \frac{Z}{2bk\varepsilon-h^2k}$, that is, $P_e > \frac{(a-bC)d\varepsilon\left(-2h^2k-3d^2\varepsilon+4bk\varepsilon\right)}{-2h^4k+4h^2(3bk-d^2)\varepsilon+2b(8bk-5d^2)\varepsilon^2}$, $\beta^{CS*} = \frac{\varepsilon(3X-P_ed)\left(2bk-d^2\right)+2bk\varepsilon X-P_edN}{bk(4N-d^2\varepsilon)}$; $r^{CS*} = \frac{h(4X-P_ed)}{4N-d^2\varepsilon}$; $w^{CS*} = \frac{4\varepsilon X-P_ed\varepsilon}{(4N-d^2\varepsilon)} + C$; $v^{CS*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)}$; $p^{CS*} = \frac{12b\varepsilon X+dh^2P_e-7P_ebd\varepsilon-3d^2\varepsilon(a-bC)}{b(4N-d^2\varepsilon)} + C$; $Q^{CS*} = \frac{b\varepsilon(4X-P_ed)}{4N-d^2\varepsilon}$. □

Proof of Proposition 9. (1) Comparisons with decentralized model:

The denominator of φ^* is $d\varepsilon(3X-P_ed)+P_eN = 3dk\varepsilon(a-Cb)+P_e\left(4bk\varepsilon-h^2k\right)$, as we have proven $a-bC>0$, $4bk\varepsilon-h^2k>0$; that is, $d\varepsilon(3X-P_ed)+P_eN>0$. $\varphi^* \in (0,1)$, then, $d\varepsilon X > P_eN > 0$ and $2d\varepsilon X + 2P_eN - P_ed^2\varepsilon > 0$. In addition, $d\varepsilon(3X-P_ed)+P_eN = d\varepsilon(4X-P_ed)+(P_eN-d\varepsilon X) > 0$, then $d\varepsilon(4X-P_ed) > d\varepsilon X - P_eN > 0$, which means $4X - P_ed > 0$. As $Q^{CS*} = \frac{b\varepsilon(4X-P_ed)}{4N-d^2\varepsilon} > 0$, and then $4N - d^2\varepsilon > 0$.

$\beta^{CS*} - \beta^{N*} = \frac{\varepsilon d\left(2bk-d^2\right)(d\varepsilon X-P_eN)+Nd(d\varepsilon X-P_eN)}{bkN(4N-d^2\varepsilon)} > 0$, $w^{CS*} - w^{N*} = \frac{d\varepsilon(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$. Therefore, $p^{CS*} > p^{N*}$, $r^{CS*} - r^{N*} = \frac{hd*(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$, $v^{CS} - v^N = \frac{2N(d\varepsilon X-P_eN)+d^2\varepsilon(d\varepsilon X-P_eN)}{kN(4N-d^2\varepsilon)} > 0$, $Q^{CS*} - Q^{N*} = \frac{b\varepsilon d(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$.

(2) Comparisons with centralized model: $r^{cs*} = \frac{h(4X-P_ed)}{4N-d^2\varepsilon} < \frac{4hX}{4N-d^2\varepsilon}$ and $N - d^2\varepsilon - Z > 0$ in proof of Proposition 10; thus, $4N - d^2\varepsilon - 4Z > 0$, so $\frac{4hX}{4N-d^2\varepsilon} = \frac{4hX}{4N-d^2\varepsilon} < \frac{4hX}{4Z} = \frac{hX}{Z} = r_{GO}^{N*}$, that is $r^{cs*} < r_{GO}^{N*}$. Similarly, $w^{CS*} < w_{GO}^{N*}$, which leads to $p^{CS*} < p_{GO}^{N*}$, $Q^{CS*} < Q_{GO}^{N*}$. While for the carbon reduction, $v_{GO}^{N*} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k} > \frac{Xd\varepsilon}{kN} + \frac{P_e}{k}$ because $N > Z$, so we compare $\frac{Xd\varepsilon}{kN} + \frac{P_e}{k}$ with $v^{cs*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)}$. $\frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)} - \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} = \frac{-(d\varepsilon X-PN)\left(2N-d^2\varepsilon\right)}{kN(4N-d^2\varepsilon)}$, $2N - d^2\varepsilon > N - d^2\varepsilon > 0$ as $N > 0$, thus $\frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)} - \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} < 0$, so $v^{CS*} < \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} < v_{GO}^{N*}$. □

Proof of Proposition 10. $\pi_{PC}^{CS*} - \pi_{PC}^{N*} = \frac{(Xd\varepsilon-P_eN)^2}{2kN*(4N-d^2\varepsilon)} > 0$, so $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$. $\Theta = \left[\frac{d}{2N} + \frac{8\mathrm{N}}{(2bk-d^2)*2\varepsilon^2d}\right]d\varepsilon - 4 > \frac{8Nd\varepsilon}{(2bk-d^2)2\varepsilon^2d} - 4 = \frac{8Z}{2\varepsilon(2bk-d^2)} > 0$.

$\Delta M = \pi_M^{CS*} - \pi_M^{N*} = \frac{2N^2\left(2d\varepsilon X+2P_eN-d^2\varepsilon P_e\right)^2+N^2\varepsilon^2\left(2bk-d^2\right)(4X-P_ed)^2-N^2d^2\varepsilon^2(4X-P_ed)^2}{2k(4N-d^2\varepsilon)^2N^2} - \frac{[\varepsilon^2X^2\left(2bk-d^2\right)+N^2P_e{}^2]*\left(4N-d^2\varepsilon\right)^2}{2kN^2(4N-d^2\varepsilon)^2}$. Through the squared difference, we achieve the following simplification: $\Delta M = \frac{(d\varepsilon X-P_eN)*\left\{2\varepsilon^2dN\left(2bk-d^2\right)(4X-P_ed)-(d\varepsilon X-P_eN)\left[\left(2bk-d^2\right)d^2\varepsilon^2+8N^2\right]\right\}}{2k(4N-d^2\varepsilon)^2N^2}$. As $d\varepsilon X - P_eN > 0$ and $2k\left(4N-d^2\varepsilon\right)^2N^2 > 0$, the sign of ΔM depends on $H = 2\varepsilon^2dN\left(2bk-d^2\right)(4X-P_ed) - (d\varepsilon X-P_eN)\left[\left(2bk-d^2\right)d^2\varepsilon^2+8N^2\right]$. When $H > 0$, the contract achieves Pareto improvement, and members in the PCSC are willing to accept the cost-sharing contract.

As Proposition 9 has proven, $d\varepsilon X - P_e N > 0, 4X - P_e d > 0$, then $H > 0 \Leftrightarrow \frac{4X - P_e d}{d\varepsilon X - P_e N} \geq \frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d} \Leftrightarrow \left\{3d + \left(N - d^2\varepsilon\right) * \left[\frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d}\right]\right\} P_e \geq (ak - Cbk)\Theta$, with $\Theta > 0$; thus, the right-hand side of the inequality sign is greater than 0. As and $Z > 0$ and $\varepsilon - Z = 2\varepsilon\left(bk - d^2\right) > 0$, that is, $N - d^2\varepsilon > 0$, then $3d + \left(N - d^2\varepsilon\right)\left[\frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d}\right] > 0$, $P_e \geq \frac{(a - bC)\Theta k d\varepsilon}{N(\Theta + 4) - (\Theta + 1)d^2\varepsilon}$. With $P_e \geq \frac{(a - bC)d\varepsilon\left(-2h^2k - 3d^2\varepsilon + 4bk\varepsilon\right)}{-2h^4k + 4h^2(3bk - d^2)\varepsilon + 2b(8bk - 5d^2)\varepsilon^2}$ in the proof of Proposition 8, $P_e \geq \frac{(a - bC)\Theta k d\varepsilon}{N(\Theta + 4) - (\Theta + 1)d^2\varepsilon}$, which means $\Delta M \geq 0$, so $\pi_M^{CS*} \geq \pi_M^{N*}$. □

Proof of Proposition 11. The first order proposition is given by $\frac{\partial \pi_{PC}^{TT}}{\partial p} = a - bp_{GO}^{N*} + dv_{GO}^{N*} - b\left(p_{GO}^{N*} - w^{TT}\right) + hr_{GO}^{N*} = 0$. $\frac{\partial \pi_{PC}^{TT}}{\partial r} = h\left(p_{GO}^{N*} - w\right) - r_{GO}^{N*}\varepsilon = 0$. We use the r_{GO}^{N*}, p_{GO}^{N*}, v_{GO}^{N*} equal to the solutions to solve the w^{TT}, so we have $w^{TT} = C\pi_M^{TT} > \pi_M^{N*}$; then, we obtain the lower bound:

$$K_l = \frac{X^2\varepsilon^2\left[2bh^4k^3 - 2h^2k\varepsilon\left(4b^2k^2 - d^4\right) + \left(d^2 - 2bk\right)^2\left(3d^2 + 2bk\right)\varepsilon^2\right]}{2k(ZN)^2} > 0,\ \pi_{PC}^{TT} > \pi_{PC}^{N*};$$

and we obtain the upper bound: $K_u = \frac{X^2\varepsilon^2\left[2bk^2\left(2b\varepsilon - h^2\right) - d^4\varepsilon\right]}{2kNZ^2} > 0$. $K_u - K_l = \frac{\left(2bk - d^2\right)^2 X^2\varepsilon^3}{2kZN^2} > 0$. Hence, $K_l < K < K_u$. □

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The Monetary and Non-Monetary Impacts of Prefabrication on Construction: The Effects of Product Modularity

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Abstract: Prefabrication is rapidly increasing in construction, and previous research has identified various impacts of prefabrication on projects. Modular product architecture is a great enabler for prefabrication; however, practitioners would benefit from more explicit knowledge on the impacts of prefabricated product types with different levels of product modularity. This study investigates the connection between the modularity level and the monetary and non-monetary impacts of prefabricated products. First, the literature on prefabrication and modularity is used to form three propositions which are related to product modularity and the benefits of prefabrication. The level of modularity is considered with two dimensions: the proportion of modules and the module description detail. Second, four prefabricated products are analyzed to test the propositions. The analysis revealed that (1) the level of modularity adopted in the product is directly proportional to the benefits. More specifically, (2) a higher proportion of modules in a project product contributes to higher cost-benefits. On the other hand, (3) prefabricated products with highly detailed module descriptions seem to lead to higher non-monetary benefits, such as better ergonomics and work satisfaction. The study reveals new empirical evidence on the relationship between product modularity and the benefits of prefabricated products. Cost-benefit analysis revealed that even though some prefabricated products could have higher direct costs, the total cost can still be lower than conventional construction when also considering the indirect benefits. Practitioners can utilize the findings when selecting modular and prefabricated products that best fulfil their project objectives.

Keywords: prefabrication; product modularity; choosing-by-advantage; cost-benefit analysis; multiple case study

Citation: Chauhan, K.; Peltokorpi, A.; Lavikka, R.; Seppänen, O. The Monetary and Non-Monetary Impacts of Prefabrication on Construction: The Effects of Product Modularity. *Buildings* **2022**, *12*, 459. https://doi.org/10.3390/buildings12040459

Academic Editor: Srinath Perera

Received: 20 February 2022
Accepted: 23 March 2022
Published: 7 April 2022

1. Introduction

An increase in prefabrication is a key driver for increasing performance in the construction sector [1,2] and many studies have discussed the positive impacts of prefabrication on reducing waste (e.g. [3]), shortening schedules [4], improving safety [5], reducing defects [6], and lowering greenhouse gas emissions [7]. Even though the implementation of prefabrication in a construction project impacts multiple factors [7], empirical research has focused mostly on a single product type or a single impact factor. Multiple impacts have not been thoroughly evaluated and compared between different product categories.

The majority of previous studies have classified prefabricated products into four categories: (1) component manufacturing and sub-assembly, including factory-made products, such as windows, bricks, and tiles; (2) non-volumetric off-site construction, including products that do not create usable space, such as structural frames and wall panels; (3) volumetric off-site construction, including pre-assembled units that create usable spaces, such as modular bathrooms, plant rooms, and shower rooms; and (4) modular buildings, including volumetric space units that also include the structure and exteriors, such as schools, motels, and prison blocks [8–10]. These categories, however, differ significantly in their scope, scale, and other main characteristics, and choosing a prefabricated product among these for a project is typically exclusionary. Thus, practitioners need suitable decision-making frameworks to compare prefabricated products and comparative information on their overall impacts.

Current research on the impacts of prefabricated products argues that a higher level of off-site construction typically provides more delivery, cost and quality benefits to projects but diminishes the flexibility and innovativeness [8–10]; however, the level of off-site construction does not fully consider the product architecture. We argue that the level of product modularity should also be considered when assessing different prefabrication products and their suitability for a project. Product modularity, where the required functions are assigned to specific physical components [11], often enables a higher level of off-site construction [10]. Some of the benefits of modularity, such as a reduction in CO_2 emissions, reduction in waste and minimizing the energy losses could help the construction industry to contribute to the circular economy [12]; however, empirical research on assessing prefabricated product types together with their level of modularity is scarce. As modularity is one essential characteristic of prefabricated products, practitioners could benefit from more precise knowledge on the combined impacts of the prefabricated product type and the level of product modularity on a construction project's performance.

This paper aims to increase the knowledge of prefabrication's multifaceted impacts on construction when modularity is considered a characteristic of the prefabricated product. The study addresses the following research question: How do the prefabricated product type and product modularity level affect the multiple dimensions of construction performance? Regarding the performance measurement, both the positive and negative impacts, as well as monetary and non-monetary impacts, are considered (see, e.g., [13]. Additionally, the level of modularity is considered using Hvam et al.'s [14] modularity framework.

The paper is structured as follows. First, the theoretical background introduces the literature on prefabricated product types and modularity assessment frameworks. Then, as a synthesis of the literature, three propositions on the connections between the level of prefabricated product modularity and project impacts are derived. The method section describes the impact evaluation method adopted in this study and the overall design for empirical research to test the developed propositions. We selected four prefabricated products for the empirical analysis, two representing volumetric products and two non-volumetric products with different modularity levels. The analysis and results section focuses on revealing the patterns between the product characteristics and project performance. The following section discusses the findings in light of the previous literature. The final section summarizes the theoretical contributions and implications for practice and suggests avenues for further research.

2. Theoretical Background

This section reviews the relevant literature on prefabricated product types and their impacts and product modularity. Based on the literature analysis, we then elaborate on our three propositions.

2.1. Multiple Impacts of Prefabrication

Most previous research on prefabrication has emphasised the importance of prefabrication and discussed prefabrication as an immediate solution to improve the construction industry's productivity. Prefabrication can affect the following project factors: cost (e.g., [15]), time [4], waste [16], safety [5] and defects [10].

The impact on cost is the most controversial topic in the prefabrication literature, as prefabrication has been shown to be more cost-efficient than on-site construction due to reduced labor and material costs and less construction waste [17]. Boyd et al. [18] highlighted 30% savings from off-site construction; however, prefabrication implementation also increases capital costs [19] through investments in new machinery and factories (e.g., [20,21]). Costs are also increased due to additional transportation costs [17], complex techniques, and the requirement for highly skilled workers [22].

Regarding the factors lowering the total costs, numerous studies have indicated that a shorter on-site construction schedule is a major attraction for implementing prefabrication [23–25]. In traditional construction, major delays occur because of subcontractor work, disputes with stakeholders, delayed decision making between the client and consultant, slow information flow between several subcontractors and project team members, poor site management and poor weather conditions [26]. Most of these delay factors could be avoided with prefabrication. For instance, all the prefabricated components can be manufactured in the factory, which would be independent of the weather conditions. Additionally, compared with conventional construction, prefabrication creates less noise and waste, which lowers the chance of a dispute with a construction site's neighbourhood.

Waste reduction is one major objective in implementing prefabrication, and it concerns the different types of waste, such as material waste, defects, waiting times and overproduction [3,27–29]. The major characteristics of prefabrication for waste minimisation include having a factory-controlled process, which is material and resource-efficient by nature, the capability to assemble repetitive units in a controlled environment and minimising waste because of less weather intrusion and site theft when compared with conventional construction.

The safety improvements in prefabrication have been well presented in previous research. Fortunato et al. [30] explained the four causes of risk in traditional construction: falls, overexertion/repetitive motion/working in an awkward position, becoming caught in equipment/objects/materials, and being struck by an object/equipment. The use of prefabrication decreases these risks because of the better ability to perform complex assemblies at the ground level or off-site, the ability to have fewer workers on-site, easier monitoring of hazardous activities, less involvement of the contractor and subcontractors and an overall safer working environment [5,31]. The Construction Industry Report [31] noted that 73% of prefabrication users adopt safety measures, including safety personnel appointments and the development and implementation of a health and safety plan. In contrast, only 48% of non-prefabrication users have adopted similar measures.

Better quality in construction could also be achieved by implementing prefabrication [17,32,33]. In the prefab manufacturing plant, quality can be checked in multiple stages. For example, the first stage would be before the prefabrication process, where the project manager would conduct material quality checks to confirm that all the materials meet specific quality standards. Second, quality checks can be employed before the unit's installation, where the project team could also ask for the approval of each unit and still then check the quality after the installation of the units. Thus, better quality can be achieved in a prefabrication process than in a conventional one [6].

2.2. Prefabricated Products and Their Impacts

Most previous researchers have classified prefabricated products into four categories based on the degree of product standardization and off-site production [8–10]. Table 1 presents these categories.

Table 1. Prefabricated Product Categories.

	Category	Definition	Examples	Impacts	Sources
1.	Modular buildings	Pre-assembled volumetric units that form a complete building or part of the building. Consist of the highest level of off-site production and standardization.	Motels, prison blocks, residential buildings, and houses.	Speeds up the construction schedule by up to 50%, more cost-efficient than panelized homes, and better safety and productivity.	[10,34]
2.	Volumetric pre-assembly	A specific part of the building that encloses usable spaces but does not constitute the whole building.	Modular bathrooms, plant rooms, and shower rooms.	Reduction in self-weight, less complex for maintenance, and overall cost reduction.	[21,35]
3.	Non-volumetric pre-assembly	Pre-assembled elements that do not create usable spaces.	Wall panels, structural frames, and bridge units.	Improves the structural performance, reduces ergonomic risk, and reduces cost and time.	[36–38]
4.	Component manufacture and sub-assembly	Typically, always made in a factory and never considered for on-site construction.	Bricks, tiles, and windows.	Impacts from traditional construction.	[8]

In the current paper, our focus is on volumetric and non-volumetric pre-assembly.

- Volumetric pre-assembly: Volumetric products are manufactured for usable space and are then installed with or onto a building or structure. They include, for example, prefabricated bathroom units (PBUs), machine rooms, and hospital patient rooms.
- Non-volumetric pre-assembly: This category includes the pre-assembly of non-volumetric items, that is, they cannot be used as usable spaces. Examples include precast concrete elements, mechanical, electrical, and plumbing (MEP) corridor elements, and water pipe modules. Most previous studies on prefabrication impacts have focused on non-volumetric products. For instance, Hong et al. [15] utilized a precast balcony, precast staircase, and prefabricated air conditioning panel to evaluate cost impacts. Some studies have evaluated specific non-volumetric product impacts, such as cross-laminated timber (CLT) wall lateral behavior [36]; however, multiple impacts have not yet been studied.

2.3. Product Modularity

In addition to the level of prefabrication, product modularity is another aspect to consider when analyzing industrialized products and their impacts on construction. Ulrich [11] mentioned that the most important character of a product's architecture is modularity which is related to functionality, and a modular structure contains modules with standardized interfaces and interactions [39]. Modularization is the activity in which module structuring takes place [40]. The same product can be formed with different modularization strategies.

The generic benefits of modularity have been extensively discussed in the literature. They include cost savings, product variety, and the enhanced flexibility and simplification of complex systems [12]). Wuni and Shen [41] argue that modular integrated construction (MiC) transforms fragmented site-based building construction into the production and assembly of value-added prefabricated modules; however, previous studies have not evaluated the benefits of prefabricated product types in construction projects when taking the level of modularity into account. To fill this research gap, as a first step, evaluating the modularity of prefabricated products is necessary. Thus, this study adopted Hvam et al.'s (2017) framework for product modularity assessment.

2.4. Modularity Framework to Assess Prefabricated Products

Hvam et al. [14] suggested a modularity assessment framework for classifying products based on their modularity level (Figure 1). The framework is based on two dimensions: (1) the proportion of the modules in the end product and (2) the degree of detail for the modules contained in the end product.

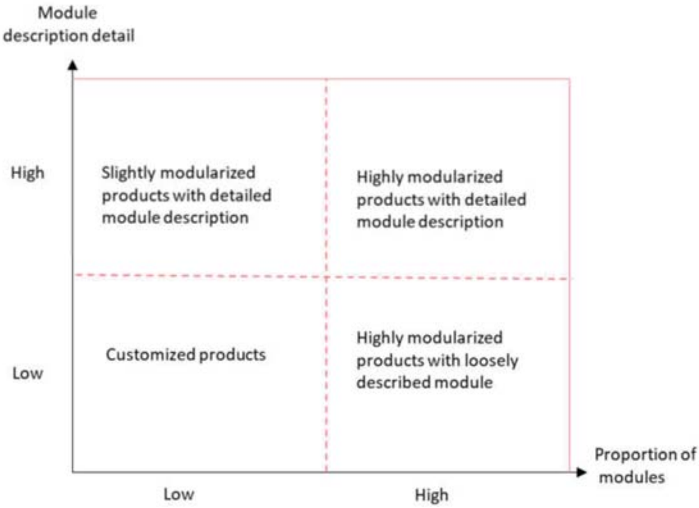

Figure 1. Modularity assessment matrix [14].

To estimate the proportion of modules, the product modules should first be defined. Two hundred modules are part of the product containing self-contained functionality [11,40]. The modules can be designed independently, yet when combined into the final product, they function together as a whole [42]. The module proportion as a percentage contained in the end product, such as in a whole building, can be crudely estimated and for renovation projects, it would be reasonable to proportionate the share of modules only to the renovated part of the building. The analysis aims to estimate the product's approximate rather than precise placement in the low–high axis.

The second dimension of the matrix is the module descriptions. According to Hvam et al. [14], this specifies "the degree of detail of modules contained in the product—as opposed to the degree of detail of the product itself" (p. 5). Based on Mikkola [43], the degree of modularity depends on the components used, their interfaces, characteristics, and the opportunity for replacement. Hvam et al. [14] explain that the more concrete the module's form, function, and interfaces are, the higher its product placement. For instance, if the overall product is loosely defined, but the used modules have detailed predetermined designs, the product could be placed at the top of the matrix [44]. Similarly, if the product is fully customized for a specific construction project and its requirements, the module description detail level is typically low.

Based on the framework, any product could be located in one of the four corners. The estimation for both dimensions could be completed mostly subjectively without using any specific formula or equations. Thus, the exact location of the product is not the goal, but the ability to compare different products is. The highest modularity level is materialized when the whole end product consists of modules with a high degree of detail.

2.5. Connecting the Level of Modularity in Prefabricated Products to Project Performance

This section aims to synthesize the literature on prefabrication in construction and product modularity and develop propositions on the impacts of prefabricated and modular products on project performance. The extensively discussed benefits of modularity include simplifying the designs, lead time reductions, and the standardization and prefabrication of subsystems [10]. Outside of construction, modularity is also a major means for increasing competitiveness [10,39]; however, the degree of modularity depends on the components adopted, their interfaces, and the opportunity for modular replacement [43]. Based on the previous literature, we suggest the following:

1. P1: The level of modularity of the prefabricated product adopted in a construction project is directly proportional to the extent of the gained benefits.
   Proposition 1 suggests that prefabrication impacts can be increased by increasing the proportion of modular prefabricated products in the end product, by increasing the degree of detail in the modular prefabricated products, or by both. This improvement should be possible even without moving from one prefabricated product type to another. When considering the proportion of modules in a building, one can argue that this proportion is typically highly dependent on the prefabricated product type. The use of modular building production methods means the proportion of modules is high. On the other hand, using non-volumetric pre-assembly products implies that much of the assembly and fitting and finishing work involves no prefabricated modules (e.g. [10]). Therefore, when we adopt a particular prefabricated product type in the project, our specific attention should be placed on the impacts of the degree of detail on the benefits. Hvam et al.'s [14] framework emphasizes the product's detailed module description, with projects benefiting from detailed information for all stages of the project design and installation process [45]. Baldwin and Clark [42] further mention that products do not benefit from modularization principles unless such products are composed solely of modules that are described in detail. In the construction context, we argue that description details are often defined at the project level, leading to prototype problems, at least if the repetition does not allow for a steep learning curve inside the project. Therefore, we argue that predefined detailed module descriptions should benefit the project when using certain prefabricated product types. These arguments lead to the second proposition:
2. P2: Prefabricated products with detailed module descriptions are more beneficial than those with less detailed ones.
   Gosling et al. [46] highlighted module description-related problems in prefabricated buildings, such as incorrect specifications, a lack of assembly alignments, the on-site coordination of deliveries and trades, and information flow issues. These mostly non-monetary problems could be resolved by providing detailed module descriptions, for instance, correct module forms, functions, and specifications. Therefore, we argue that implementing prefabricated products with highly detailed module descriptions should eventually provide more non-monetary benefits, such as worker satisfaction, benefits from earlier project completion, and better safety and ergonomics [13]. Based on these arguments, we propose the following:
3. P3: Higher module description detail leads to higher non-monetary benefits. We next present our research method to validate and elaborate on the defined propositions empirically.

3. Method

Our research's main objective was to create new knowledge regarding prefabricated products' specified impacts when modularity is taken into account and to create new knowledge on the connections between prefabricated product types, the level of modularity, and their multiple impacts on projects. This requires an in-depth analysis of multiple product types implemented in real projects. According to Yin [47], a multiple case study is a suitable approach to investigate this kind of problem. Furthermore, multiple sources of evidence can be used to increase reliability and because our research considers the non-monetary benefits of prefabrication, multiple sources of information were necessary for the analysis. Thus, this research was conducted based on a multiple case study analysis.

3.1. Case Selection

Seawright and Gerring [48] have suggested seven case-selection strategies: typical, diverse, extreme, deviant, influential, most similar, and most different. In this research, we employed the most different procedure to determine the impacts of different prefabricated products via a cross-case analysis. By selecting different prefabrication cases in terms of their modularity dimensions, we could examine the relationship between the product characteristics and the multiple impacts. We chose a case involving volumetric prefabricated products (prefabricated machine room) and three cases involving non-volumetric prefabricated products (bathroom pipe module, MEP corridor elements and water pipe modules).

4. Prefabricated machine room: This case is an office building project in which a prefabricated machine room was designed, produced, and installed. The machine room included all the technical equipment inside a single steel frame with exteriors and a roof. The room included pre-assembled automation and control systems, heat distribution and recovery systems, refrigeration appliances, water, and electricity supply systems. The data originated from an interview with the project manager, product description reports, and a site visit report.
5. Bathroom pipe module: This case implemented the prefabricated bathroom pipe module product consisting of water pipes, sewer pipes, and toilets. This product is manufactured based on the bathroom size, and its weight is about 55 kg. The bathroom pipe module has been implemented in several projects in different parts of the world. For this study, we have analyzed the impacts of this product in a residential renovation project in the middle of Finland, which consists of a five-story building, 4 staircases, and 52 apartments. Each apartment consists of a bathroom with a 3 m^2 area. The case is analyzed based on the cost data, interview with the product developer, product description reports, and experiences shared by site managers and engineers.
6. Mechanical, electrical, and plumbing corridor elements: This case adopted prefabricated MEP corridor elements installed in an office building. The MEP contractor had implemented similar prefabricated MEP racks with heating, cooling, ventilation pipes, and electric wires in several projects. The data originated from project reports, site visit reports, and an interview with the project manager.
7. Water pipe modules: We analyzed prefabricated domestic water pipe modules installed in a plumbing renovation project. The project involved 6 buildings and 164 apartments. The case was investigated based on a site visit, interviews with the contractor's and client's representatives, and a focus-group discussion (FGD) with an installer and site engineers.

3.2. The Modularity of the Selected Cases

Hvam et al.'s [14] framework was adopted to evaluate the modularity of the selected case products (Figure 2). Placement of the model's products is not based on any particular formula but on subjective and relative placement within the dimensions.

1. Bathroom pipe modules: This renovation project implemented prefabricated bathroom pipe module products. Other parts of the building were designed and renovated following traditional methods. The module producer described the specifications, forms, and functions of the bathroom pipe modules and components in detail. In summary, the solution was placed in the top left quadrant of the matrix.
2. Machine room: This solution included a single module designed and installed in the project. Even though the module was rather large, it was only a small share of the whole office building project. According to the project manager, the module was quite complex to install. As a project-specific and unique product, the description detail regarding the product was not great initially. Thus, even though the machine room was prefabricated, the product was placed in the bottom left area of the matrix.
3. Mechanical, electrical, and plumbing corridor elements: This case implemented prefabricated MEP corridor elements, including a MEP rack with heating, cooling, ventilation, and electrical systems. The solution covered quite a large part of the whole office building project; however, the modules were designed for this specific building without major design and interface standardization. Therefore, it was placed on the bottom right quadrant of the matrix.

4. Water pipe modules: The solution was based on a commercial pipe module product developed by a Finnish company. The standard pipe design was utilized and fitted to the building. The pipe modules were installed in stairwells and apartments. Based on the site measurements, pipes were pre-cut in the factory and then delivered to the site. As the project's scope focused on a domestic water system renovation, a large proportion of the project was implemented through the modules. During the site visit, the site manager mentioned that the product was easier to install as its specifications and forms were described in detail. In summary, the product was placed in the top right area of the modularity matrix.

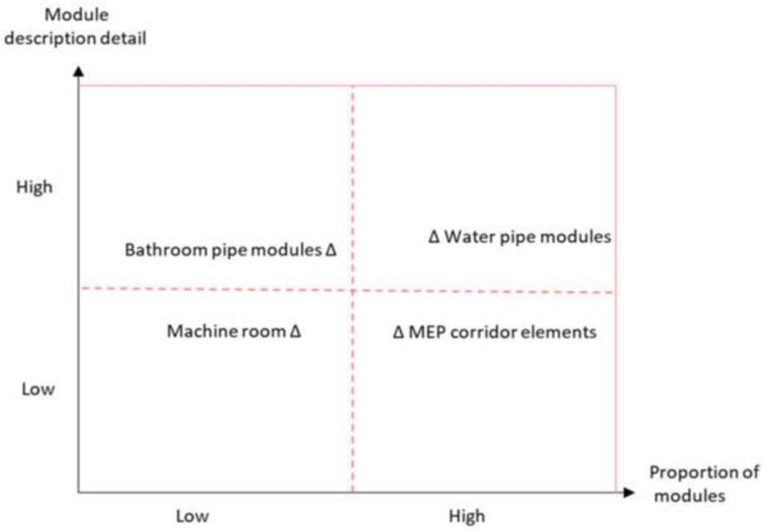

Figure 2. Approximate modularity of the selected cases.

3.3. Data Collection and Analysis

After selecting the cases, data were collected for within- and cross-case analyses [10], with the identified quality, delivery, cost, and flexibility as the competitive priorities to consider while evaluating the production system. Thus, to evaluate the impact of prefabrication, we used the choosing-by-advantage (CBA) method developed by Suhr [49], as it has been found to be the most appropriate method for choosing alternatives [50]; however, Suhr [49] did not provide clear guidelines regarding a monetary factor analysis. Consequently, Chauhan et al. [13] argued that CBA would be more effective if the cost components could be evaluated based on a cost–benefit analysis to account for indirect monetary effects. Thus, this study combines CBA with a cost–benefit analysis of cost components (Figure 3).

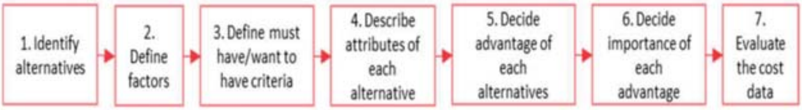

Figure 3. The choosing-by-advantage steps, according to Arroyo et al. [50].

The CBA process we adopted began by defining the prefabrication solution and any on-site alternatives, identifying the most probable impacts of the solution or factors likely to affect production, defining assessment criteria to compare alternatives, describing each factor's attributes and the advantages of each attribute, and marking the least preferred attributes. The most challenging stage was deciding on the importance of advantages (IoAs). Based on public documents, interviews, and observations, each advantage's IoA points were agreed upon in an FGD session. The FGD included 17 leading Finnish architecture, engineering and construction (AEC) companies representing different construction, design, building product, and IT companies.

We then followed the European Commission [51] guidelines to carry out a cost–benefit analysis by comparing the total costs of conventional construction with the total costs of prefabrication. We first evaluated the total cost of conventional construction and the direct costs of the prefabricated products. We then identified all the benefits and disadvantages of the prefabricated products and converted these impacts into costs. Then, cost–benefit ratios were calculated for each case.

3.4. Within- and Cross-Case Analyses

As an outcome, the CBA analysis enabled us to compare the traditional and prefabricated solutions in all four cases and conduct a cross-case analysis of the relative impacts of the four analyzed case products.

A cross-case analysis helps to identify patterns by looking at the data in divergent ways and increasing the probability of capturing novel findings [47]. Following Yin [47], we first conducted a within-case analysis by comparing each solution with its alternative in traditional on-site construction using a cost–benefit analysis and CBA to determine a performance measurement. Then, the four cases and their performances were compared for different dimensions (product category, level of modularity, and the monetary and non-monetary impacts of the products) to test and elaborate on our propositions.

4. Analysis and Results

4.1. Within-Case Analysis

For our in-depth case analysis, CBA was used, where the monetary factors were analyzed based on a cost–benefit analysis.

4.1.1. Case I: Bathroom Pipe Module

1. Choosing-by-advantage.

The CBA results for the bathroom pipe module are presented in Table 2. According to the on-site interviews and discussions, the major identified non-monetary benefits were being easier to install, having a shorter project schedule, and a higher quality; however, the design uncertainty and availability of the installers were found to be the advantages of the conventional method.

From the perspective of the product manufacturers, the installation process of the bathroom pipe module product is 2–3 times shorter than in conventional construction and the product is light and easy to install on the bathroom wall. In the traditional method, the installer needs to spend more time connecting small parts required for the final product.

In this project, bathroom renovation time was reduced by 5–15% compared with the conventional method. Overall, the project team estimated that the whole site schedule was reduced by a week. Additionally, earlier completion of the bathroom helped subcontractors arrange bathroom workers to be involved in other activities, which helped maintain the streamlined workflow. Noise and dust were also reduced, which made the circumstances better and easier for the workers and neighbors.

The quality of the prefabricated bathroom module was significantly higher than in the conventional renovation method. Pipes used to manufacture this product were breakable in several parts that would make it easier to identify possible problems with the pipe and leakage of the system. The product is sealed with soundproof and odor-proof materials, which directly benefits the customer. Additionally, the manufacturer assumes that the need for maintenance would be significantly lower than in the traditional method.

Despite the huge advantages of the bathroom pipe modules over traditional construction, some limitations were identified. For example, the product manufacturers mentioned that obtaining initial information about the installation could be a hurdle, as the design often contains uncertainty. Additionally, the installation requires more experienced people than in the conventional method.

Table 2. Choosing-by-Advantage for Bathroom Pipe Module (EUR 1000).

Factors	**Alternative 1: Bathroom Pipe Module**	**Imp**	**Alternative 2: Conventional**	**Imp**
Installation	Att: Easier to install Adv: 2–3 times easier than conventional	60	Att: Difficult to install Adv:	
Project schedule	Att: Fast to construct Adv: 5–15% faster than conventional	58	Att: Slower when constructed on-site Adv:	
Quality	Att: Higher quality, less maintenance Adv: 2–3 times higher quality then conventional	60	Att: Lower quality, requires more maintenance Adv:	
Design uncertainty	Att: No access to the original source for design Adv:	-	Att: Installed in the actual location Adv: Lower uncertainty with design	40
Availability of installer	Att: Sometimes difficult to find experienced installers Adv:	-	Att: All the subcontractors are following the traditional mechanism Adv: Easily available installer	25
Total IofAs		178		65

Key: Att = attributes; Adv = advantage, Imp = importance, IoAs = importance of advantages.

2. Cost–benefit analysis

The cost–benefit analysis for prefabricated bathroom modules versus traditional on-site construction is presented in Table 3. The direct costs (raw materials, labor, and module installations) were about 3% lower than in the conventional renovation method.

The project received benefits from several indirect cost factors. For instance, each staircase was completed 1.5 weeks earlier, and a total of 15% of time was saved compared with the conventional method. This resulted in 2% savings. Additionally, based on the cost data, several additional works were reduced by implementing this product, such as the transportation of smaller parts, fixing the installation, and maintaining a smooth workflow. This resulted in about 5% savings.

Table 3. Cost–Benefit Analysis for a Prefabricated Bathroom Pipe Module (EUR 1000).

Total Project Cost (Conventional) = 396	
Total Cost of a Conventional Renovation of Pipe Module= 374	
Monetary factors	Cost of bathroom pipe module compared with conventional construction
Direct cost (material, labor, transportation, and installation)	−10
Indirect costs	-
Project schedule	−9
Additional work	−18
Total cost	337
Project-level benefit–cost ratio = in total project cost = 396/359=1.10 > 1	

Based on Hvam et al.'s [14] modularity assessment framework, this case project belongs to the top left quadrant as the module of this product was described in detail.

The FGD was organized to evaluate the IofA points for non-monetary factors. The FGD participants mentioned that the detailed product description of the modules was a major factor for them while choosing modular bathrooms over the traditional ones and the difference in importance of the advantage points between the modular and conventional methods of the bathroom was 113.

4.1.2. Case II: Machine Room

1. Choosing-by-advantage

Based on the non-monetary advantages and disadvantages, CBA was applied, as presented in Table 4. The identified non-monetary factors for the machine room included the space, project schedule, customer value, installation, maintenance working conditions, and design flexibility.

According to the project manager, about 18% of the room space was saved compared to conventional construction, requiring less maintenance and heating. These impacts were analyzed as non-monetary impacts, as accurate cost effects were hard to estimate. The project was completed one week faster than conventional implementations, benefiting everyone (contractor, owner, customer). Additionally, a single supplier designed the machine room, therefore, lifecycle support and resolving later issues were improved.

However, a key drawback was its challenging installation. Once installed, it limited workforce mobility during the next project phase. Designing the prefabricated machine room was also more complex than in conventional construction.

Based on the FGD, space was considered the most important advantage factor (70 points), whereas design flexibility was the least important, with 55 points given to its alternative (i.e., conventional).

Table 4. Choosing-by-Advantage for the Machine Room.

Factors	Alternative 1: Machine Room	Imp	Alternative 2: Conventional	Imp
Space	Att: Requires less space, meaning less maintenance and heating Adv: 18% space saved compared with conventional	70	Att: Requires more space Adv:	
Project schedule	Att: Faster to construct, less uncertainty Adv: 1 week faster than conventional	40	Att: Slower to construct Adv:	
Customer value	Att: Maintenance service included Adv: Less downtime for customer	60	Att: More downtime for customer Adv:	
Installation of new machines	Att: Might be complex to install Adv:	-	Att: Easier to install Adv: Easier to install	40
Maintenance work conditions	Att: Limited space blocks worker mobility Adv:	-	Att: No disturbance to worker mobility Adv:	30
Design flexibility	Att: Design should be fixed earlier Adv:	-	Att: Easier to make changes according to space users Adv: Easier to design	55
Total IofAs		170		125

Key: Att = attributes; Adv = advantage, Imp = importance, IoAs = importance of advantages.

2. Cost–benefit analysis

The machine room cost–benefit analysis is presented in Table 5. The direct cost was 19% higher than for on-site construction. The direct costs included MEP-related and installation costs. The increase was mainly due to the additional cost required at the installation location, where the floor preparation costs were higher.

Major savings came through indirect costs. According to the project manager, about 18% of the typical machine room space was saved due to the more compact prefabricated version, equating to 28% cost savings. The installation process was completed about one week faster, which resulted in a 4.8% saving through general condition costs and project administration costs and about 0.8% coordination cost savings; however, some indirect costs were higher, such as the additional design cost, at about 1.6% more than for conventional design.

Table 5. Cost–Benefit Analysis for a Prefabricated Machine Room (EUR 1000).

Total Project Cost = 4900	
Total Cost of Conventional Construction = 124	
Monetary Factors	Cost of the machine room
Direct cost (material, labor and installation)	+24
Indirect costs	-
Space (−18%)	−35
Schedule (−1 week)	−6
Co-ordination	−1
Design work	+2
Total cost (direct + indirect)	108
Project-level benefit–cost ratio = 4900/4884 = 1.00 > 1	

This case product is estimated to be in the bottom left quadrant of Hvam's modularity assessment framework. Compared to the other case, this product was less modular and had less description of the product module.

4.1.3. Case III: Water Pipe Modules

1. Choosing-by-advantage

Table 6 shows the CBA analysis for the pipe modules. Implementation of the water pipe modules allowed residents to stay in situ during the renovation, which was a huge advantage.

The renovation of each staircase was completed two weeks earlier than with conventional methods, directly benefitting the customer. Additionally, the water pipe modules were manufactured in a factory, with staged quality inspections that also involved the insulation, pipe bracket, and high-quality surface inspections. Furthermore, the installers mentioned that the pipe module documentation was better than for conventional installations.

However, prefabricated product surface scratching was reported as a common problem during installation, which is not an issue for conventional installations. In addition, the pipe modules were installed as a visible element in the stairways and lobbies, which would not fulfil the aesthetic requirements in all buildings. Additionally, the manufactured modules have very strict tolerances, which might require additional on-site fitting work when combined with the looser tolerances of the renovated building.

Overall, the FGD viewed customer value as the most important factor (85 points), while pipe scratching was the least important factor, with 65 points awarded to conventional construction.

Table 6. Choosing-by-Advantage for Water Pipe Modules.

Factors	Alternative 1: Pipe Modules	Imp	Alternative 2: Conventional	Imp
Customer value	Att: No need to evacuate Adv: More customer-friendly compared with conventional	85	Att: Requires evacuation Adv:	-
Project schedule	Att: Faster to construct Adv: 2 weeks per floor faster than conventional	75	Att: Slower to construct Adv:	-
Quality	Att: Standard materials are connected Adv: Easier to detect leakages and connect materials	70	Att: No standard materials are connected Adv:	-
Documentation	Att: Well documented Adv: Better pipe documentation	65	Att: Poorly documented Adv:	-
Pipe scratching	Att: Higher possibility of being scratched Adv:	-	Att: Lower possibility of scratching Adv:	65
Design	Att: Not suitable for all buildings Adv:	-	Att: Suitable for all buildings Adv: More suitable than prefabrication	55
Total IofAs		295		120

Key: Att = attributes; Adv = advantage, Imp = importance, IoAs = importance of advantages.

2. Cost–benefit analysis

The cost–benefit analysis of the water pipe modules is presented in Table 7. According to the site manager, the direct cost was the same as for conventional construction. Major savings came through indirect costs. The implementation allowed residents to stay in their apartments during the entire renovation period; approximately EUR 350,000 of the additional budget would have been needed to evacuate the apartments for conventional renovation. Additionally, based on the site manager's assumption, each staircase was completed two weeks faster than for conventional construction.

Table 7. Cost–Benefit Ratio for Water Pipe Modules (EUR 1000).

Total Project Cost = 2924	
Total cost of conventional construction = 2624	
Monetary Factors	Cost of pipe modules
Direct cost (material, labor and installation)	Same as in conventional construction
Indirect costs	
Evacuation cost	−350
Schedule (general condition cost + administration cost)	−49
Project schedule (capita cost and profit margin and others)	−147
Total cost (direct + indirect)	2078
Project level benefit–cost ratio = 1.26>1	

This case belongs to the top right quadrant of the modularity assessment framework. Where the case contains a high number of modules, and the modules are described in detail. This case product was the most attractive product for construction stakeholders who participated in the FGD session, where the IofA difference was 175, which is the highest compared with other cases.

4.1.4. Case IV: Mechanical, Electrical, and Plumbing Corridor Elements

1. Choosing-by-advantage

The CBA for the MEP corridor elements is shown in Table 8. According to the project manager, the project was completed four weeks earlier than for conventional construction. He further assumed that the quality of these elements was better than for conventional products (better heat and noise insulation, easier to install). The installers confirmed the ease of installation enabled physical movements during the installation task.

However, one issue concerned later design changes being difficult; thus, in following the CBA guidelines, points were given to the on-site product alternative. Other FG site managers mentioned corridor elements requiring large wall openings, which increased the on-site theft risk. In addition, some subcontractors were not familiar with the prefabricated corridor elements; it was difficult to motivate them to install these elements as it lowered the subcontractors' and workers' piecework pay.

In summary, the FGD session found that the schedule was the most important non-monetary factor (60 points). In contrast, a design change was considered the least important factor, with 55 points assigned to the conventional route.

Table 8. Choosing-by-Advantage for Mechanical, Electrical, and Plumbing Corridor Elements.

Factors	Alternative 1: MEP Corridor Elements	Imp	Alternative 2: Conventional	Imp
Schedule	Att: Fast to construct Adv: 4 weeks faster than conventional	60	Att: Slow to construct Adv:	
Quality	Att: Better soundproofing, better insulation assembly quality Adv: Less sound is transmitted, better insulation	55	Att:Non-standardized environment, disruptions in workflow Adv:	
Ergonomics	Att: Allows for movement and stretches Adv: More comfortable to install	40	Att: Poor assembly ergonomics Adv:	
Material risk	Att: Elements required large holes in walls Adv: Transportation holes might ease stealing from site		Att: Easier to keep site locked Adv:	25
Design change	Att: Difficult to change the design Adv:		Att: Easy to modify spaces for rental users Adv: Easier to change the design	55
Subcontractor motivation	Att: Lower motivation of subcontractor Adv:		Att: Conventional method has beenin practice for a long time Adv: Higher subcontractor motivation	30
Total IofAs		155		110

Key: Att = attributes; Adv = advantage, Imp = importance, IoAs = importance of advantages.

2. Cost–benefit analysis

The cost–benefit analysis for MEP corridor elements is presented in Table 9. In this project, the direct cost was found to be 11% lower than for conventional construction. The material costs for the prefabricated products were higher, but the labor cost was reduced significantly due to factory installation.

Indirect cost benefits arose from the implementation. For example, MEP corridor elements were installed in 28 days on-site, which was 4 weeks shorter than conventional construction, saving around 20% in general costs compared to conventional installations.

During the site visit, the project manager mentioned that, due to prefabrication, 2–3 days were saved in subcontractor coordination meetings, resulting in about a 1% saving compared to conventional construction. In addition, about 1% of the cost was eliminated in material pickups by utilizing corridor element prefabricated products.

Regardless of the indirect cost benefits, prefabrication required additional design costs, with about a 7.3% cost increase. A highly skilled designer was required to make detailed fabrication-level designs. In addition, more coordination was needed between the designer and contractor.

Table 9. The Cost–Benefit Analysis of Mechanical, Electrical, and Plumbing Corridor Elements (EUR 1000).

Total Project Cost = 4200	
Total Cost of Conventional Construction is 110	
Monetary Factors	**Cost of Prefabricated MEP Corridor Elements**
Direct cost (material, labor and installation)	−12
Indirect costs	-
Design	+8
Project schedule (4 weeks)	−23
Meetings	−1
Material pickup	−1
Total cost	81
Project-level benefit–cost ratio=4200/4171 = 1.01 > 1	

This case belongs to the bottom right quadrants of the modularity assessment framework, where the end product is estimated to be highly modular but with less description of the modules. Even though the modules were less described, the MEP prefabrication was prioritized over its traditional counterparts; however, compared with other case products, this one was less prioritized with an IofA 45.

4.2. Cross-Case Analysis and Validation of the Propositions

After the in-depth within-case analyses, a cross-case analysis was conducted to identify common patterns in the cases. We focused on the connections between the level of modularity and the impacts of the prefabricated products. We first compared the cases regarding their monetary and non-monetary factors (Table 10 and Figure 4).

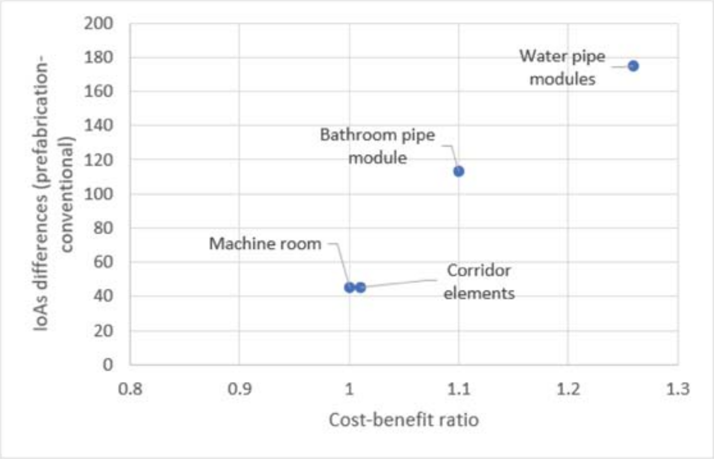

Figure 4. Cost advantage analysis.

Table 10. Cross-Case Analysis of Selected Cases.

Case Product	Product Category	Position in Modularity Assessment Matrix	Impacts on Monetary Factors (Project Level (B/C))	Impact on Non-Monetary Factors (IoA Differences)
Bathroom pipe module	Volumetric	Top left	1.10	113
Machine room	Volumetric	Bottom left	1.00	45
MEP corridor elements	Non-volumetric	Bottom right	1.01	45
Water pipe modules	Non-volumetric	Top right	1.26	175

Based on the analysis, all cases' cost-benefit ratios were above one, which means they were all economically beneficial for implementation. The advantage point difference between the prefabrication and conventional method was also positive in all cases; thus, prefabrication is more beneficial from the non-monetary "value" perspective compared with the traditional method.

When considering the project-level cost–benefit aspect and advantage points, the machine room was the least beneficial solution among the cases. It was also characterized by the lowest relative proportion of modules and low module description detail. The corridor element had similar non-monetary advantages but slightly better cost–benefits. The water pipe modules dominated the machine room in both dimensions. As the water pipe modules had the highest level of modularity and the machine room the lowest, the findings provide indicative support for proposition 1, stating that the level of modularity is directly proportional to the extent of the gained benefits.

The second and third propositions were related to the connections between the module description detail and prefabrication impacts. As the water pipe modules had the highest project benefits, the findings also support proposition 2 about more benefits arising from detailed modular product descriptions. Additionally, the bathroom pipe module's and the water pipe module's highly detailed module descriptions seem to be connected to their better non-monetary impacts. Thus, this finding strongly supports proposition 3 regarding the higher non-monetary benefits of prefabricated products with detailed module descriptions.

5. Discussion

Implementing prefabricated products impacts multiple direct and indirect factors [7] that affect productivity in the construction industry [52]; however, the effects of prefabricated product types and modularity on construction projects have not yet been discussed in the literature.

Based on the findings, several contributions can be made to the existing literature on prefabrication and modularity in construction. First, we argue that the level of modularity of the prefabricated product adopted in a construction project is, on average, proportional to the extent of the gained benefits. Many previous works discuss the benefits of modularity (e.g., [10,12]), and modularity is further discussed as one of the major means of increasing firm competitiveness [39]. Our analysis indicates that construction projects with a higher proportion of modules have a higher project-level cost–benefit ratio than projects with a lower share of modules. This was especially evident when comparing our water pipe module case with the other cases. More specifically, the finding indicates that a high proportion of modules in a project is especially recommended if the major objective of prefabrication is to gain remarkable cost benefits. Previous research has indicated that the need for complete modular product architecture increases if low costs are prioritized [1]. This research extends that knowledge by stating that a complete modular product architecture contributes to higher benefits resulting mostly from advantages in indirect cost factors, such as schedule and quality issues, while the impacts on direct costs are more mixed.

Second, the analysis reveals that detailed descriptions of prefabricated modules are connected to their non-monetary benefits, which, in the analysis, were defined using the CBA approach. Baldwin and Clark [42] explained how products would be more beneficial if the product modules were described in detail. In our analyses, cases with highly predetermined module descriptions (i.e., water pipe modules and bathroom pipe modules) had more non-monetary benefits, such as time-related, ergonomics, and safety, than those with less detailed descriptions (MEP corridor elements and a machine room).

The observation regarding the non-monetary impacts can be extended to the discussion on the productization of the modules. Both the bathroom and water pipe modules products represented solutions owned and developed by a company that aimed to use the same detailed solution in multiple projects. Conversely, the machine room and MEP corridor elements were designed directly to meet the specific project's needs. Therefore, it can be argued that product ownership and usage in multiple projects support the notion of taking non-monetary impacts into account. Furthermore, this indicates that product ownership and design reuse can support learning and continuous improvement. In other words, project-specific solutions tend to focus on cost benefits, and they may encounter potential challenges with other impacts, such as those related to lower work satisfaction or negative on-site surprises. In conclusion, selecting prefabricated product types for a project should be made carefully based on the project's priorities.

This research adopted the CBA approach to evaluate multiple impacts of prefabricated products in construction. The analysis revealed that the CBA approach is a suitable method to compare prefabricated products with conventional construction, especially when indirect costs at the project level are also considered in the cost part of the analysis. The CBA approach embedded in the cost–benefit analysis is especially fruitful when comparing complex products with multifaceted impacts on many different project stakeholders and it would be more effective to evaluate the production systems based on the competitive priority factors of cost, quality and flexibility [10].

6. Conclusions

This research analyzed the impacts of modular and prefabricated products based on multiple case analyses. The cases included a volumetric product (prefabricated machine room) and three non-volumetric products (bathroom pipe module, MEP corridor elements and water pipe modules). Hvam et al. [14] proposed a modularity assessment framework based on the proportion of modules and module description detail. We used this framework to develop three propositions for prefabrication impacts and tested the propositions via the empirical analysis of four cases.

The cross-case analysis revealed that prefabricated products that form a high proportion of the project are more cost-beneficial than products that form only a low proportion of the project. The implication is that practitioners who aim to maximize project cost-efficiency should consider utilizing prefabricated solutions for a major part of the whole project. In renovation projects, these solutions are typically non-volumetric elements, but in new buildings, they may belong to any prefabricated product category from non-volumetric elements to fully modular buildings.

The study also revealed that prefabricated products often have many non-monetary benefits. These more hidden or soft benefits, such as worker satisfaction, safety, and ergonomics, may be easier to materialize if the used product is not only designed for the project at hand but has a longer development and improvement history in multiple past projects. Thus, we recommend that practitioners favor productized standard solutions with existing detailed designs if they want to tackle these non-monetary impacts in their projects. On the other hand, if project-specific solutions are used, the project team should be aware of the potential pitfalls and invest in competency and resources to avoid issues in the design and execution stages.

This study investigated four case solutions, and therefore the generalizability of the findings is rather limited. Further research is required to analyze more diverse cases of implemented prefabricated products with high-level modularity and compare the benefits with the low-level use of modular products. Moreover, the impacts of the prefabricated products should be evaluated in different project stages and from different stakeholder perspectives. An analysis of planned impacts and realized impacts would also reveal the most suitable measurement methods in each project stage.

Author Contributions: Conceptualization, K.C. and A.P.; methodology, K.C. and A.P.; data curation, R.L.; A.P. and K.C.; writing—original draft preparation, K.C.; writing—review and editing, A.P.; R.L. and O.S.; supervision, A.P.; project administration, A.P. and O.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Building 2030 Esivalmistuksen pilotointi project 4106599.

Informed Consent Statement: Informed consent was obtained from all respondents interviewed in the study.

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

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Experimental Investigation of Seismic Performance of a Hybrid Beam–Column Connection in a Precast Concrete Frame

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Abstract: Prefabricated beam–column connections are the most vulnerable components of prefabricated buildings during earthquake events. The seismic performance of the beam–column connection is functional as the critical component plays a key role in structural safety. This study aimed to develop a novel hybrid prefabricated concrete (HPC) connection, combining with wet and dry connection techniques, to enhance the seismic performance of prefabricated concrete frames. A quasi-static experimental investigation was carried out to examine the seismic performance of the proposed connection. Two full-scale prefabricated connection specimens utilizing the proposed HPC connection and another code-defined monolithic prefabricated concrete (PC) connection were tested under cyclic loading, keeping the axial load on the column constant. The ductility, stiffness degradation, energy dissipation capacity, post-tensioned force, and residual displacement were obtained based on the experimental output. The results indicated that the HPC connection developed had high construction efficiency and better seismic performance than the conventional PC connection. The strength and energy dissipation capacity were significantly improved by up to 52% and 10%, respectively. The cracking and stiffness degradation were well-controlled.

Keywords: beam–column connection; seismic performance; hybrid connection; energy dissipation capacity; post-tensioned

Citation: Chen, W.; Xie, Y.; Guo, X.; Li, D. Experimental Investigation of Seismic Performance of a Hybrid Beam–Column Connection in a Precast Concrete Frame. *Buildings* **2022**, *12*, 801. https://doi.org/10.3390/buildings12060801

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 13 May 2022
Accepted: 8 June 2022
Published: 10 June 2022

1. Introduction

Prefabricated reinforced concrete structures have many advantages, such as high-level quality control, efficient construction, relatively low cost, etc. [1–3]. However, the applications of prefabricated buildings in seismic regions are limited due to the possibly weak beam–column connections [4,5]. Compared to cast in situ buildings, the beam–column connections in prefabricated buildings are more susceptible to brittle shear failure in earthquake events, which easily leads to the progressive collapse of the structure. In the 1988 Armenian earthquake, poor beam–column connections contributed to the collapse of numerous precast frame buildings [6]. Similar seismic hazards, including damage to or collapse of various precast structures, were identified in the 2012 Emilia-Romagna (Italy) earthquake due to inefficient connections [7]. Therefore, it is necessary to develop an efficient and reliable connection form for prefabricated concrete structures.

To achieve this goal, various dry and wet connections have been proposed depending on whether post-pouring concrete is used. Dry connections refer to bolting, welding, and post-tensioned techniques without concrete pouring [8]. The dry connection, unlike the wet connection, provides the optimum speed in precast construction and allows the replacement of damaged members after earthquake events [9]. A series of experimental studies conducted in recent decades have significantly improved our understanding of the seismic performance of buildings with dry connections. Rodríguez and Matos [10] proposed a dry connection using welded reinforcement and conducted cyclic load tests. The results indicated that the welded reinforcement connection could lead to brittle failure under cyclic loading. Deng et al. [11] designed a composite dry connection with bolts, seat angles, and post-tensioned high-strength steel strands parallel to the beam. The results showed that the connection had sufficient energy dissipation capacity and ductility. Lago et al. [12] proposed a dry prefabricated frame structure connection to couple the reinforcement of columns and beams and demonstrated its efficiency in reducing seismic drifts. Gennaro et al. [13] tested an isolated single dowel connection and a refined one in a pushover experiment. Ding et al. [14] put forward a dry connection with a bolt and claimed that the energy dissipation capacity of the proposed connection could be improved significantly with a higher strength grade for the bolt.

Compared to cast in situ reinforced concrete structures, prefabricated reinforced concrete structures with dry connections have insufficient ductility and energy dissipation capacity [15,16]. As the deployment of prefabricated buildings with dry connections is not considered suitable in highly seismic regions, solutions with wet connections have been developed involving in situ concrete pouring. Choi et al. [17] proposed a wet precast connection system using steel plates inside the connection to improve the structure performance. Parastesh et al. [18] developed a new wet precast connection and proved its effectiveness in providing considerably higher ductility and energy dissipation capacity compared to similar monolithic connections. Chen et al. [19] put forward a novel assembling method for precast reinforced concrete shear walls using wet connections. They demonstrated that the proposed system could prevent cracking efficiently and provide satisfactory seismic performance under sustained stress [20,21]. However, wet connections require long waiting times for the in situ casting and, hence, may lead to congestion and inefficiency in construction [22–24].

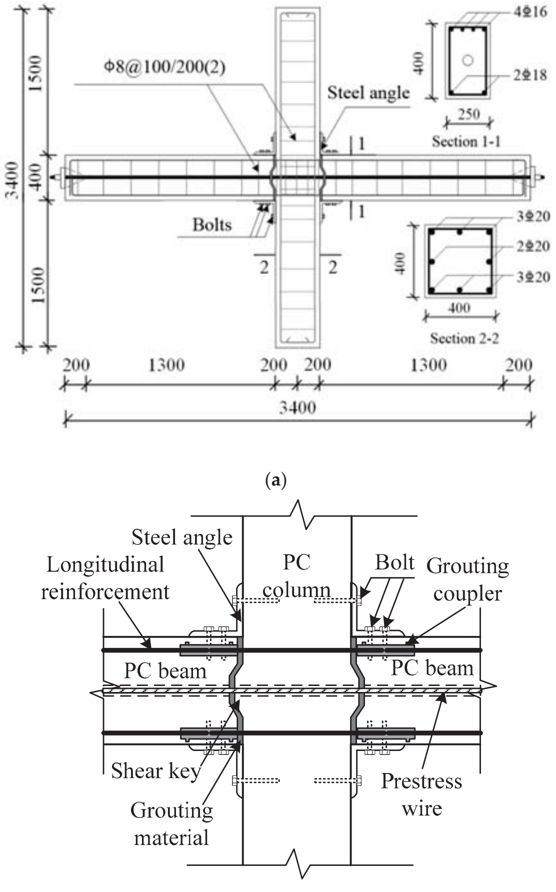
To address the limitations of dry and wet connections, hybrid connections combining dry and wet connection techniques have been proposed. Senturk et al. [25] made use of different steel angles and plates in the beam–column connection to facilitate the connection of prefabricated members. These hybrid steel–concrete connections exhibited adequate ductile behavior under cyclic loading. Moghadasi et al. [26] used hybrid connections of steel and concrete in full-scale H-subframes and concluded that this new type of hybrid connection benefited from more rotational ductility than the conventional type. Song et al. [27] proposed hybrid unbonded post-tensioned prefabricated concrete connections for seismic regions and demonstrated their excellent stiffness and energy dissipation capacity compared to conventional cast in situ systems. Wang [28] experimentally tested hybrid connections with partially unbonded longitudinal rebars (PDLRs). The results showed that the tendons were associated with more limited cracking, higher load-carrying capacity, and less energy dissipation in comparison to conventional prefabricated beam–column connections. Huang et al. [29] proposed a new self-centering hybrid connection with variable friction dampers to achieve a self-centering capacity and satisfactory energy dissipation. Hybrid connections with different types of energy dissipators, such as metallic yielding devices [30], friction devices [31], bracing systems [32], and smart materials [33], have been evaluated as well.

While most of the existing prefabricated buildings with hybrid connections have been demonstrated to have the same level of seismic performance as similar monolithic connections, they generally require complex assembly techniques or customized member or minor casting. In order to optimize these hybrid connections and achieve the goal of rapid fabrication and cost efficiency, this study aimed to develop a novel hybrid connection using grouting couplers, steel angles, and prestress wires. First, the developed hybrid connection is described conceptually. Then, the experimental investigations of two full-scale connection specimens under cyclic loading are described. The seismic performance of these connections is then identified in terms of strength, ductility, stiffness degradation, energy dissipation capacity, post-tensioned force, residual displacement, and strain. Finally, the seismic performance of the developed hybrid connection is summarized and discussed.

2. Experimental Process

2.1. Conceptual Design of Hybrid Connection

Two frame connections were designed based on the Chinese Code for Seismic Design of Buildings (GB 50011-2010): a novel HPC connection and another monolithic PC connection. The cross-section of the column member was 400 × 400 mm and its height was 3000 mm, while the cross-section of the beam member was 250 × 400 mm and its length was 3400 mm, as shown in Figure 1. For the HPC connection, the grouting couplers were fixed with steel rebars and embedded in the prefabricated beam members. Three 1860 grade high-strength prestress wires with a diameter of 15.2 mm were placed in the corrugated duct, which had a diameter of 50 mm. Steel angles of L160 × 160 × 10 were used in the beam–column connection regions. All the steel angles were bolted using high-strength bolts, 20 mm in diameter.

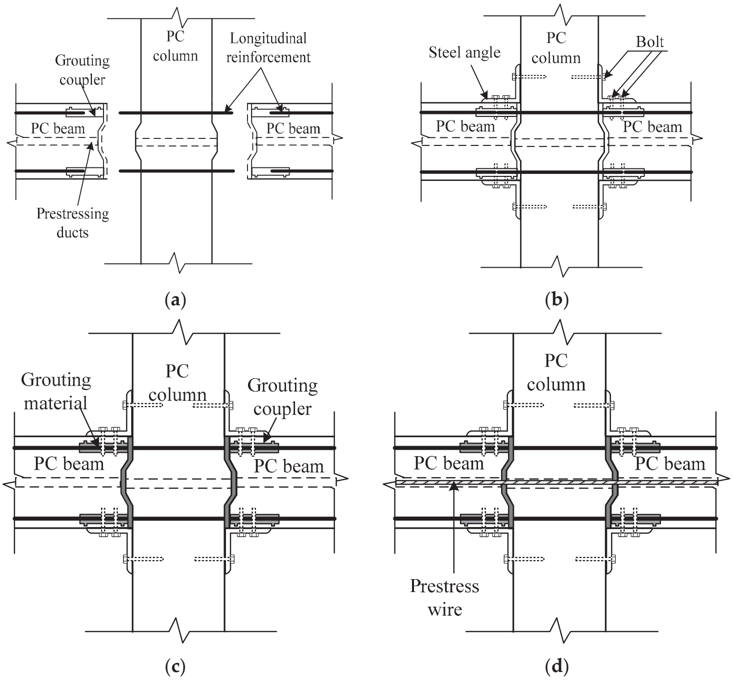


(**a**)

(**b**)

Figure 1. Design dimensions and reinforcement of the HPC connection: (**a**) details of the dimensions and reinforcement of the HPC connection; (**b**) details of the HPC connection.

The detailed procedures for the proposed HPC frame connection are illustrated in Figure 2. Specifically, the prefabricated beam and column members were located and assembled with steel angles (Figure 2a,b), and then the longitudinal rebars in the beam members could be connected using grouting non-shrinkage high-strength mortar into the corrugated duct (Figure 2c). Finally, the prestress wires were tensioned in the corrugated duct and anchored at the tendons (Figure 2d). The specific post-tensioning construction of the tendons is shown in Figure 3. The post-tensioned techniques consisted of three steps: embedding of the corrugated duct and tensioning and anchoring of the prestress wires.



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

(**c**) (**d**)

Figure 2. Assembly process for the HPC connection: (**a**) locations of the beam and column; (**b**) connection assembly; (**c**) grouting curing; (**d**) prestress tension.

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

Figure 3. Post-tensioning tendon construction: (**a**) embedding corrugated duct; (**b**) prestress wire tensioning; (**c**) prestress wire anchorage.

As the control, the code-defined monolithic PC connection was designed following the Technical Specification for Prefabricated Concrete Structures (China JGJ 1-2014). The design dimensions and reinforcement of the PC connection are illustrated in Figure 4. The dimensions of PC frame connection were the same as the HPC frame connection. The significant difference between the two connections was the post-casting belt in the beam and connection core zone. The assembly process of the PC connection is shown in Figure 5. The longitudinal rebars at the bottom of the beam members were connected first with grouting couplers (Figure 5a), and then the secondary pouring of concrete was performed in the connection core zone after the upper longitudinal rebars were bounded (Figure 5b). Next, the upper prefabricated column was installed and fixed with the grouting couplers. Finally, the shrinkage-resistant high-strength grouting material was poured at the interface between the column and the connection (Figure 5c).

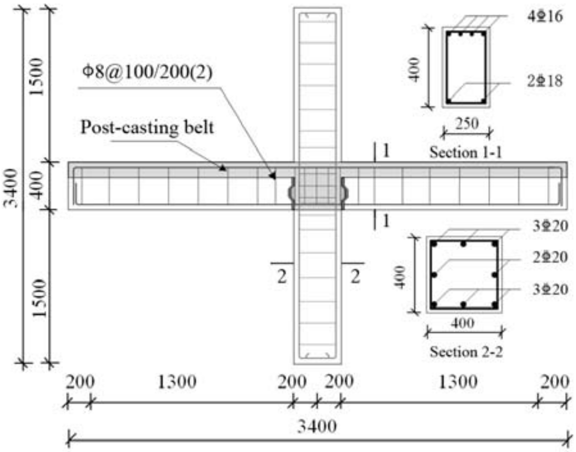
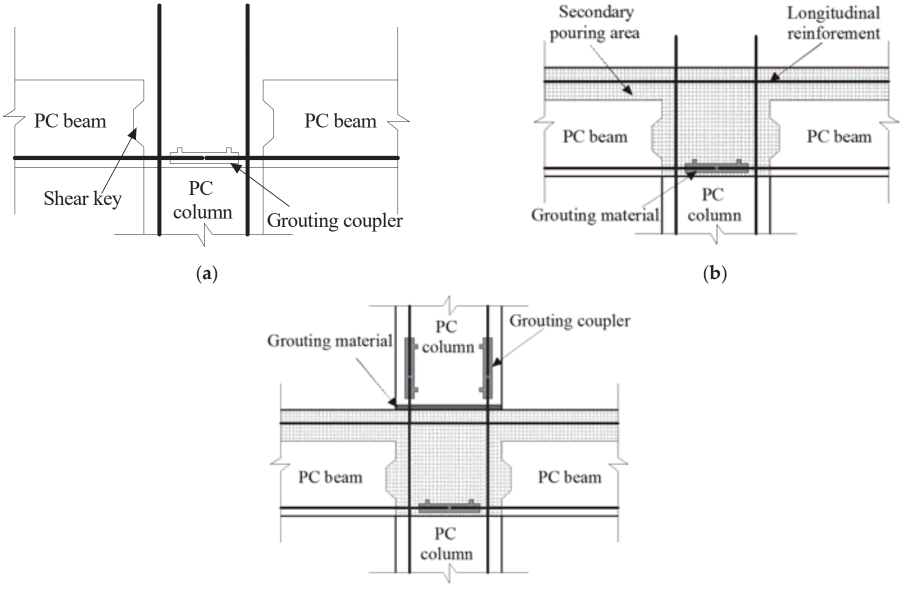


Figure 4. Design dimensions and reinforcement of PC connection.



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

(**c**)

Figure 5. Assembly process for PC connection: (**a**) locations of beam and column; (**b**) secondary pouring; (**c**) grouting curing.

2.2. Material Properties

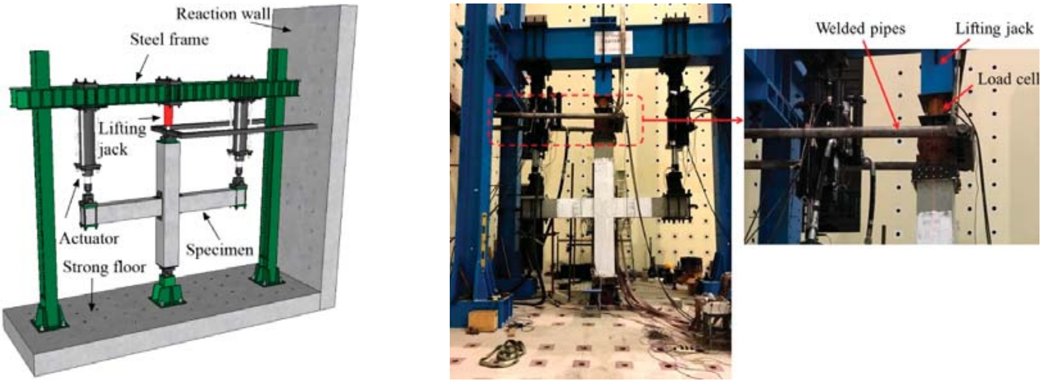
Following the Standard for Test Methods for Mechanical Properties of Ordinary Concrete (China GB/T50081-2002), tests were carried out on each group of three 150 mm × 150 mm × 150 mm cubic concrete blocks. The compressive strengths of the prefabricated concrete, cast in situ concrete, and high-strength grouting material were identified as 40.8, 40.3, and 61.3 MPa, respectively. Table 1 lists the mechanical properties of the steel bars, including the yield strength, ultimate strength, and elastic modulus. The yield and ultimate strengths of the Q235 steel plate were 281.5 MPa and 347.0 MPa, respectively.

Table 1. The mechanical properties of the steel bars.

Diameter (mm)	8	18	20	Φ^{s} 15.2
Area (mm^2)	50.2	254.3	314	139
Yield strength (MPa)	310	402	403	1720
Ultimate strength (MPa)	404	540	530	1912
Elastic modulus (MPa)	2.01×10^5	2.11×10^5	1.99×10^5	1.95×10^5

2.3. Test Setup and Loading Program

Figure 6 shows an illustration and photographs of the test setup for the connection specimens. Each of the test connection specimens was subjected to cyclic loading that simulated earthquake loading. The prefabricated column was pinned to the strong floor and steel frame. The end of the beam was connected to the steel frame by steel links that permitted rotation and free horizontal movement in the beam, but restricted vertical movement. A 1000 kN capacity lifting jack was connected on top of the column to apply the constant axial load. Two 500 kN capacity vertical actuators were installed on the beam end to apply the displacement-controlled cyclic load.



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

Figure 6. Illustration and photographs of the experimental setup: (**a**) illustration of the experimental setup; (**b**) photographs of the experimental setup.

The axial compression load on the top of the column was set as 0.2. Two vertical actuators asymmetrically applied cyclic load at both beam ends, while the axial load on the column remained constant. The displacement-controlled cyclic loading history is shown in Figure 7. The applied loads and displacement response were accurately measured by transducers in the hydraulic servo-control actuator. Moreover, strain gauges attached on the longitudinal steel bars, stirrups and steel angles in the connection were used to monitor the rebar strain during the test. The tests of the specimens were terminated when the bearing capacity decreased to 85% of the peak load.

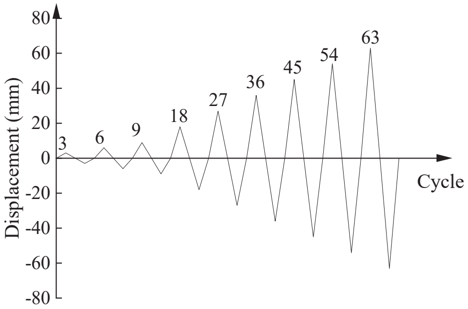
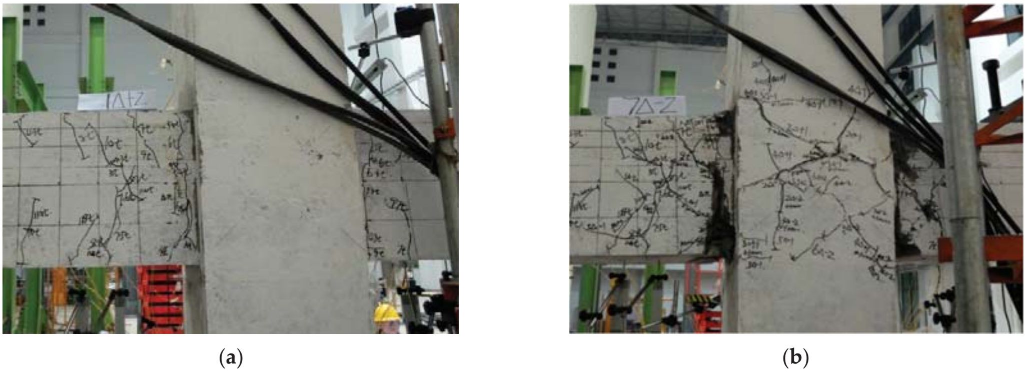


Figure 7. Cyclic displacement-controlled loading history.

3. Experimental Results

3.1. Crack Pattern and Failure Mode

The crack patterns and failure modes of these specimens are illustrated in Figures 8 and 9, respectively. For the PC connection, a flexural crack 0.02 mm in width developed at the intersection of the beam and column regions (i.e., the potential plastic hinge), with the displacement of vertical actuators reaching 3 mm. When the yielding of the longitudinal rebar initially appeared, with a displacement of up to 9 mm (i.e., Δ_y = 9 mm), several flexural cracks 0.15 mm in width propagated through the plastic hinge (Figure 8a). Then, a few diagonal cracks appeared in the connection core zone, with the vertical displacement reaching 3Δ_y, and they further propagated along the diagonal directions. When the displacement increased to 5Δ_y, the concrete started to spall off at the bottom of the beam and the shear cracks along the diagonal direction expanded to 2.3 mm. Finally, the concrete at the top of the beam began to become crushed with the stirrups exposed, and an obvious diagonal compression structure at a displacement of 7Δ_y was formed (Figure 8b). At this stage, the connection experienced a substantial reduction in strength, until it reached 85% of the peak load.



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

Figure 8. Crack pattern and failure mode of the PC connection: (**a**) crack at the beam end; (**b**) failure mode of the PC connection.


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

Figure 9. Crack pattern and failure mode of the HPC connection: (**a**) opening of crack; (**b**) closure of crack; (**c**) failure mode.

For the HPC connection, the first flexural crack of 0.01 mm in width formed at the intersection of the beam and column, with the displacement reaching 6 mm. When the longitudinal rebar yielded at the displacement of 10 mm (i.e., $\Delta_y = 10$ mm), a few vertical cracks appeared at the top and bottom of the beam with 0.05 mm widths (Figure 9a). At the displacement of $3\Delta_y$, the cracks at the interface of the beam connection were partially closed due to the retraction of the prestressed steel strand (Figure 9b). It should be noted that the cracks in HPC connection underwent opening and closure under cyclic loading due to the post-tensioned wires. Two diagonal cracks appeared gradually in the connection core zone at a displacement of $5\Delta_y$. The shear crack expanded along the diagonal direction by only approximately 0.75 mm. Another obvious difference between the HPC and PC connections was that the cracking of the HPC connection was narrower, which highlighted the contributions of the post-tensioning technique to cracking control. The connection failed at the displacement of $7\Delta_y$ due to a small amount of spalling of concrete in the connection core zone and the bucking of the steel angles (Figure 9c).

3.2. Hysteresis Curve

The shear force versus displacement of hysteresis loops of the HPC and PC connection is shown in Figure 10. During the initial cycles, the PC connection performed an elastic behavior in hysteresis loops. With the displacement in the loading cycles up to 9 mm, the connection attained the initial yield with the corresponding shear force reaching 105.2 kN. In the subsequent loading cycle corresponding to 18 mm, the connection reached the maximum capacities of 115.3 kN in the positive loading direction and 140.6 kN in negative loading direction, respectively. Afterwards, the connection experienced the stiffness degradation and performed a significant pinching behavior. The test was terminated at the displacement of 63 mm, and the connection reached the residual capacity of 90.3 kN.

The shear force versus displacement hysteresis loops for the HPC connection can be compared as a further analysis. In the positive loading direction, the initial yield of the HPC connection occurred at the displacement of 10 mm, with the shear force reaching 112.6 kN. The maximum capacities—175.6 kN in the positive and 176.1 kN in the negative loading directions—were reached at displacements of 45 mm and 36 mm, respectively. In the positive direction, the maximum capacity of the HPC connection was 52% larger than that of PC connection, while the difference in the negative direction was 25%. Before reaching the maximum capacities, hardening phenomena in the shear force were identified, which implied contributions from the steel angles to the bearing capacity. These phenomena suggested that the hybrid connection improved the seismic performance in view of the bearing capacity. Steady energy dissipation in the HPC connections was observed from the hysteresis loops. After attaining the highest bearing capacity, the stiffness degradation of the connection lasted until the final residual capacity of 142.5 kN, which corresponded to 63 mm.

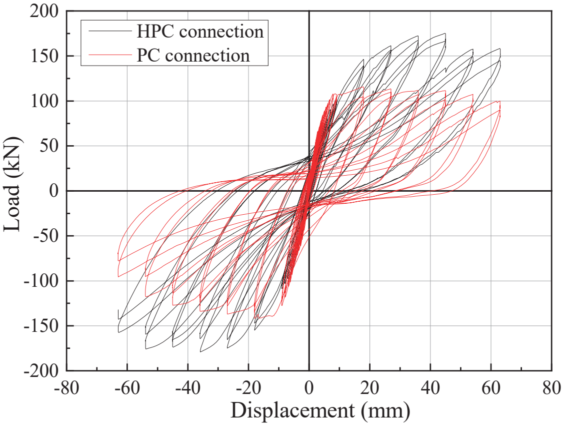


Figure 10. Hysteresis curves.

3.3. Envelope Curve

The envelope curves of the HPC and PC connections are shown and compared in Figure 11. Before the yielding of the longitudinal rebar in the beam member, the bearing capacities of these connections increased almost linearly with the increasing loading. Then, the bearing capacity of the PC connection decreased slightly, and the descending trend in the negative bearing capacity was faster. However, the bearing capacity of the HPC connection continued to increase obviously after the yielding of the rebar. The post-yielding behavior of the HPC connection indicated the significant contributions of the steel angles and post-tensioned wires to the improvement of the bearing capacity and the stiffness of the connection. After reaching the peak load, mild degradation of the bearing capacity was observed, as opposed to a more obvious decrease in the negative bearing capacity. In the final loading stage, the yielding of the steel angles and the longitudinal rebar in the plastic hinge occurred in the HPC connection, but the yielding did not appear in the prestressed strand. As long as the strands remained elastic, the HPC connection was able to keep self-centering upon the unloading process.

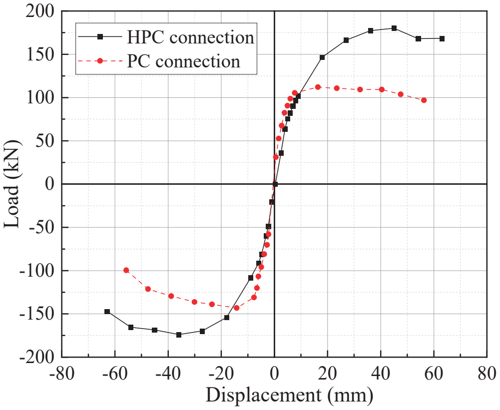


Figure 11. Envelope curves.

3.4. Ductility and Stiffness Degradation

Ductility is another vital parameter for seismic capacity that reflects the plastic deformation ability of the structure in the post-yielding stage. The ductility coefficient μ can be quantified as the ratio of the ultimate displacement Δ_u to the corresponding yielding displacement Δ_y; i.e., $\mu = \Delta_u/\Delta_y$. Specifically, the yielding displacement for each connection can be identified by using the equivalent energy method. The ultimate displacement corresponded to the 85% peak load. The ductility coefficients of each connection are listed in Table 2. It can be seen that the ductility coefficient of the HPC connection (6.20 on average) was generally higher than that of the PC connection (5.02 on average).

Table 2. Ductility coefficients of the connections.

Specimen	**Load Cycle Direction**	Δ_y	Δ_u	μ	$\overline{\mu}$
HPC connection	+	8.5	56.2	6.61	6.20
	−	−9.5	−55.1	5.80	
PC connection	+	5.8	33.7	5.81	5.02
	−	−6.7	−28.5	4.23	

The stiffness degradation behaviors in the HPC and PC connections are shown and compared in Figure 12. With the increase of the displacement level, the stiffness of these connections gradually decreased and then tended to remain steady. The stiffness degradation curves for the HPC and PC connections show analogous trends, but the stiffness degradation rates were different. The stiffness degradation rate of the PC connection, due to the cracking and spalling of the concrete, was obviously higher than that of HPC connection, especially in the post-yielding stage. During the loading process, the initial stiffness of the PC connection was higher than that of the HPC connection. After the connection yielding, the HPC connection could provide more stiffness than the PC connection, which demonstrated that the prestressed strands could affect the overall stiffness degradation of the connection.

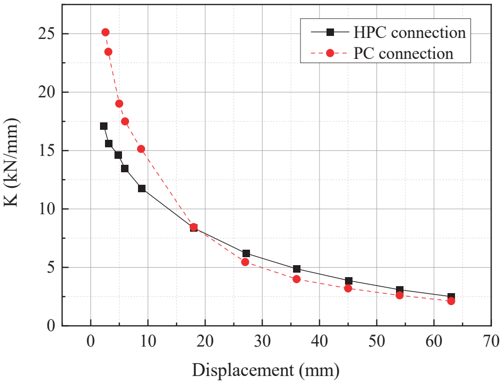


Figure 12. Curves for the stiffness degradation.

3.5. Energy Dissipation Capacity

The energy dissipation capacity of the connections was obtained based on the areas enclosed by their hysteresis curves. The cumulative energy dissipation versus the displacement is shown in Figure 13. Obviously, the energy dissipation characteristics of the two specimens show nonlinear increasing trends, varying with the increasing displacement. At the initial loading stage, the energy dissipation of the HPC connection was limited. With increasing displacement, the energy dissipation capacity of the HPC connection sharply increased with the development of plastic deformation in the steel angles and rebars. The results indicated that the PC connection had slightly higher (10% on average) energy dissipation compared to the HPC connection.

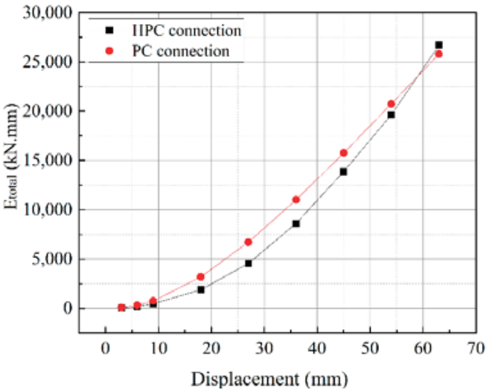
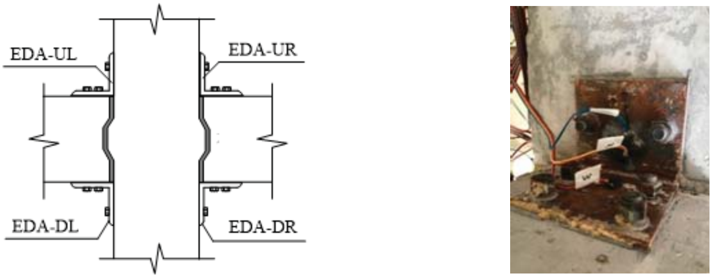


Figure 13. Energy dissipation with displacement.

4. Discussion

4.1. Energy Dissipation of Steel Angles

The steel angles play a critical role in transferring the column load and moment to the beam. In order to understand the contributions of the steel angles to the bearing capacity and energy dissipation capacity, three strain gauges were distributed for each steel angle, as shown in Figure 14. Consequently, the tensile strength–displacement curves of the steel angles at the four measured points were obtained, as shown in Figure 15. The tensile strength at the bottom steel angles is generally higher than that at the upper steel angles. Specifically, the tensile strength of EDA-UR can reach 542.3 kN compared to a value of 366.9 kN for EDA-DR. The corresponding deformation of the steel angles is 1.75 mm. It was found that the stiffness of the steel angles reduced gradually and Bauschinger effects appeared with the strain hardening, which demonstrated the anticipated inelastic behavior of the steel angles [34]. Furthermore, the plumpness of the hysteretic curve can be used to calculate the energy dissipation of the steel angles [35]. It can be concluded that all the steel angles had good plumpness in their hysteretic curves and presented excellent energy dissipation capacities.



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

Figure 14. Illustration and photograph of strain gauges: (**a**) strain gauge position; (**b**) photograph.

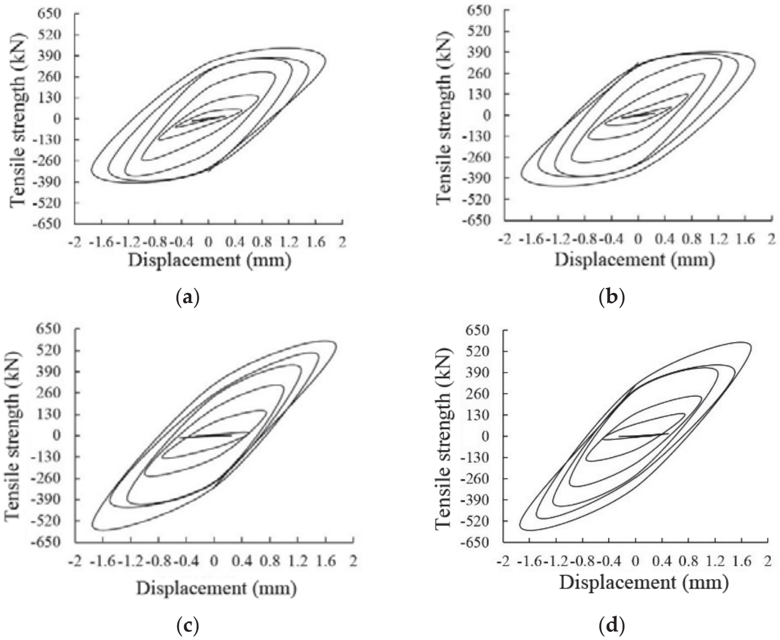


Figure 15. Displacement-strain curves for the steel angles: (**a**) EDA-UL; (**b**) EDA-UR; (**c**) EDA-DL; (**d**) EDA-DR.

The energy dissipation results for the upper steel angles (EDA-U) at each loading step are listed in Table 3. It can be seen that the contribution of the steel angles to the total energy dissipation in the connection increased slightly, up to 18.7%, before connection yielding. Then, the percentage for the contribution of the steel angles to connection energy dissipation showed a rapid increase and even reached 84.2%, with this proving to be the dominant role of the steel angles in the energy dissipation in the connection. Table 3 reinforces the earlier observation that more energy can be dissipated with the use of thicker steel angles [36].

Table 3. Energy dissipation capacities of the steel angles.

Δ (mm)	EDA-U (kN·mm)			E_0 (kN·mm)	PP (%)
	+Δ	−Δ	Total		
3	1.18	0.95	2.13	37.63	5.7
6	9.12	8.87	17.99	142.48	12.6
9	28.66	26.53	55.19	294.63	18.7
18	181.15	179.89	361.04	1411.11	25.6
27	333.58	278.88	612.46	2679.8	22.9
36	985.95	927.31	1913.26	4052.54	47.2
45	1626.52	1889.08	3515.60	5263.25	66.8
54	2362.64	2451.58	4814.22	5766.37	83.5
63	2831.15	3104.83	5935.98	7047.28	84.2

4.2. Variation in Prestressing Force

The prestressing force at the PT tendon versus the displacement of vertical actuator is shown in Figure 16. The initial prestressing force after the prestressing wires were tensioned was 361.3 kN. Due to the anchorage retraction at the initial loading steps and limited cracking in the high-strength grouting material, a loss in the prestressing force occurred, with its maximum value reaching 19.2 kN, only 5.31% of the initial value. Thus, the prestressing force varied within the elastic range (up to 170.1 kN) during the cyclic loading process. It was demonstrated that the prestressing force remained elastic, with negligible losses in the prestressing force during the cyclic loading steps. This ensured the connection had sufficient stiffness and restoring capacity to undergo large nonlinear displacements without crushing of the concrete [12,37].

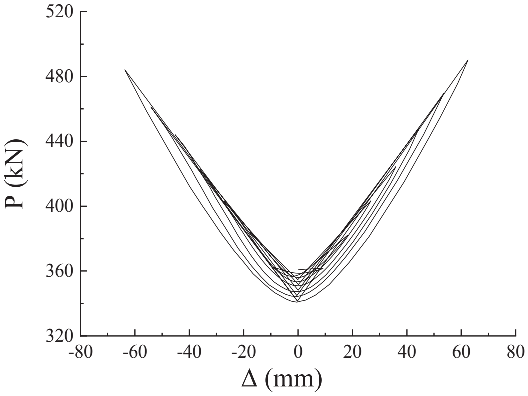


Figure 16. Prestressing force.

4.3. Deformation Capacity

The deformation capacity can be evaluated in terms of the residual displacement and residual rotation at the beam end. The residual deformation rate α_{rd} can be calculated as follows:

$$\alpha_{\mathrm{rd}} = \frac{\Delta_{\mathrm{rd}}}{\Delta_{\max}} \tag{1}$$

where Δ_{rd} and $\Delta_{\max}$ are the residual displacement and maximum displacement, respectively, applied at the beam end. The residual rotation rate β_{rd} can be obtained as follows:

$$\beta_{\mathrm{rd}} = \frac{\theta_{\mathrm{rd}}}{\theta_{\max}} \tag{2}$$

where θ_{rd} and $\theta_{\max}$ are the residual rotation and maximum rotation of the connection, respectively.

Table 4 lists the residual displacement and residual rotation results for the HPC connection. It can be seen that both residual displacement and residual rotation increased slightly and reached the maximum values of 9.5 mm and 0.56%, respectively. Correspondingly, the residual displacement and residual rotation were constricted to within 0.21 and 0.153, respectively. The limited residual displacement and rotation may be attributable to the pretension force and its restoring characteristics [38].

Table 4. Residual displacement and rotation in the HPC connection.

Δ (mm)	Δ_{rd} (mm)	Δ_{max} (mm)	θ_{rd} (%)	θ_{max} (%)	Δ_{rd}/Δ_{max}	θ_{rd}/θ_{max}
3	0.5	3.2	0.04	0.53	0.16	0.083
6	1.1	6.3	0.10	1. 07	0.17	0.097
9	1.8	9.5	0.17	1.60	0.18	0.106
18	3.3	17.9	0.31	2.13	0.18	0.144
27	4.2	27.8	0.39	2.67	0.15	0.148
36	7.3	36.4	0.48	3.20	0.20	0.150
45	9.5	45.5	0.56	3.66	0.21	0.153

Figure 17 shows the relationship between the residual displacement Δ_{rd} and maximum displacement Δ_{max} for these two specimens. Compared with the HPC connection, the PC connection showed a significant increase in the residual displacement, and its maximum value could reach 24.8 mm. The corresponding maximum residual deformation rate was 0.55, which was more than twice that of the HPC connection. These results indicate that the HPC connection exhibited lower residual deformation, which can minimize concrete cracking and spalling [39,40].

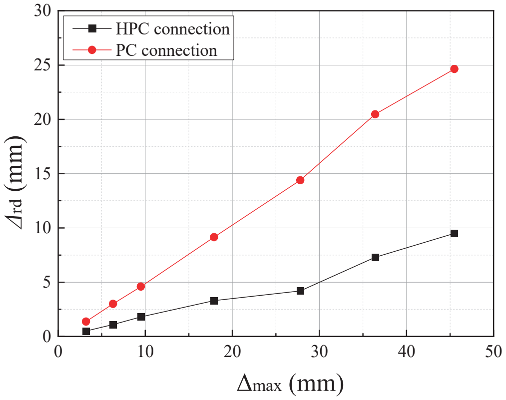


Figure 17. Displacement residual deformation rate.

4.4. Applied Element Method Simulation

Numerical simulation is another efficient method used to address the problem of progressive collapse of buildings and to study the seismic performance of novel connections. Compared with the most commonly used method, the finite element method (FEM), the applied element method (AEM) can facilitate faster dynamic analysis by using the normal and shear springs to connect rigid elements in the structural model [41]. The AEM has been efficiently used in a collapse analysis for prototype reinforced-concrete (RC) frame buildings subjected to a set of 22 ground motion records [42] and in the seismic assessment of a typical four-story building for two earthquake magnitudes (0.15 g and 0.3 g) [43], among other settings. In the future, progressive collapse analyses of frame buildings with novel hybrid connections could be performed using AEM analysis. Consequently, the collapse mode, collapse direction, and damage level could be obtained. Moreover, the effectiveness of the novel hybrid connection in precast buildings in seismic regions could be demonstrated and optimized further.

5. Conclusions

A novel prefabricated hybrid connection system was developed for prefabricated beam–column connections in prefabricated concrete frame structures in seismic areas. Experimental tests were conducted on two full-scale prefabricated beam–column connections, a hybrid connection and a monolithic connection, under displacement-controlled cyclic loading. A variety of parameters for the specimens, including the hysteresis behavior, envelope loop, PT tendon resultant, residual displacement, energy dissipation capacity, ductility, and stiffness degradation, were obtained. Some major conclusions can be drawn as follows:

1. The proposed HPC connection exhibited lower cracking development, stiffness degradation, and residual displacement owing to prestressing strands, while the prestressing force remained elastic.
2. The strength and energy dissipation capacity of the HPC connection increased rapidly, and both were larger than those of the PC connection (up to 52% and 10%, respectively) during the post-yielding stage. It was demonstrated that the steel angles played a critical role in improving the seismic performance of the connections.
3. The grouting technique could efficiently realize the continuation of beam reinforcement with the minimum of cast in situ work. Thus, the proposed HPC connection has great potential for deployment in seismic regions, demonstrating excellent seismic performance and efficient construction techniques.

Author Contributions: W.C.: methodology, conceptualization, writing—review & editing, funding acquisition; Y.X.: experiment, writing—original draft; X.G.: supervision, investigation, review & editing; D.L.: methodology, writing—review & editing, correspondence. All authors have read and agreed to the published version of the manuscript.

Funding: The research reported in this paper was supported by the Scientific Research Founding of Key Laboratory of Building Collapse Mechanism and Disaster Prevention, China Earthquake Administration (Grant No. FZ211106).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

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

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sustainability

Article

Eco-Economic Performance Estimation Method for Pretensioned Spun High-Strength Concrete Pile Installation

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Abstract: Pile installation has an environmental impact through its various processes ranging from raw material extraction to construction. In addition, the environmental performance, productivity, and cost of pile installation depend on the construction plan. Therefore, the chain of activities must be considered when analyzing the sustainability of pile installation. A rational construction plan must carefully examine the factors that affect the productivity and sustainability of pile installations. This study presents a method for evaluating eco-economic performance by analyzing the resource utilization and processes of PHC pile installation. First, a process modeling technique, wherein details are broken down to the work task level, based on energy consumption and resource cost, is proposed. Second, a simulation method that calculates the eco-economic performance of the PHC pile process and resources (e.g., equipment) is presented. Third, a quantitative comparison of durations, costs, and emissions resulting from simulation, estimation based on the CSPR (Construction Standard Production Rate) and IUC (Itemized Unit Cost), site contract, and actual construction is presented. The results reveal that the method effectively reflects the prediction of duration, cost, and carbon emissions generated in the real world during the construction planning stage.

Keywords: PHC pile; construction process modeling; eco-economic performance; construction equipment emission; discrete event simulation

Citation: Yi, C.-Y.; Park, J.-Y.; Park, C.-Y.; Lee, J.-C.; Park, Y.-J. Eco-Economic Performance Estimation Method for Pretensioned Spun High-Strength Concrete Pile Installation. *Sustainability* **2022**, *14*, 11990. https://doi.org/10.3390/su141911990

Academic Editor: Jorge de Brito

Received: 19 July 2022
Accepted: 19 September 2022
Published: 22 September 2022

1. Introduction

1.1. Research Background

A pile foundation is a columnar structural element located in the lower part of a structure, such as a building or bridge, that transfers load from the structure to the ground [1]. It supports the structure and prevents subsidence or inclination by transmitting the load to the ground. The pile consists of cement, sand, aggregate, and chemicals, and the construction process consumes various materials. These production and construction processes generate waste and pollutants, which contaminate natural resources, such as land and water, and affect the functioning of the construction site and surrounding natural systems. This series of activities must be carefully considered to analyze the sustainability of pile installation, and it is necessary to establish a reasonable construction plan after closely examining the factors that affect the productivity of pile installation [2,3]. Reducing carbon emissions in pile construction is mainly related to minimizing fuel and material consumption and reducing waste generation during installation, which can be achieved by implementing sustainable construction practices and improving the quality of construction processes [4]. Fossil fuels used for heavy equipment in pile construction generate 2.62 kg of CO_2 emissions from 1 L of diesel and 0.537 kg of CO_2 per 1 kWh of electricity used [5]. The most carbon-emitting resource during pile construction is the construction equipment, and various studies on the carbon emission of construction equipment are being conducted because of this importance [5–7]. However, there is an absence of quantitatively predicting the amount of carbon emitted by the resources used for pile construction at a detailed level. Environmental performance, productivity, and cost depend on the construction plan. Therefore, a system that helps quantitatively evaluate these factors simultaneously and supports decision-making is essential.

This study presents a simulation modeling and analysis method for simultaneously estimating stochastic carbon emissions generated by the resources (i.e., equipment) and the amount of time and cost required for the completion of pile installation. The method evaluates productivity and environmental performance during the planning stage of the pile installation. Additionally, it helps establish a reasonable pretensioned spun high-strength concrete (PHC) pile construction plan considering the environmental and economic feasibility.

1.2. Research Aim and Scope

This study presents a method for stochastically estimating the duration, cost, and carbon emissions of the PHC pile installation process. The proposed method deals with tasks that have repetitive attributes, such as adjusting axis, drilling, removing auger and grouting, pile erection and placement, and moving to the next pile location, using discrete event simulation (DES). DES can be used to build and analyze a cyclical network model of the construction process. Additionally, analyzing the construction process in detail and improving the accuracy of estimating the duration, cost, and emissions is possible using DES [8–13]. DES is recognized as a useful tool that can effectively deal with the detailed analysis of energy consumption and carbon emissions of resources during the construction process. Therefore, in this study, after establishing a simulation model of PHC pile installation using DES, an eco-economic analysis method of the process is presented.

The detailed research procedure undertaken to achieve this research goal is detailed as follows. First, previous studies on pile construction and DES were investigated. Subsequently, processes and procedures were established to evaluate the productivity and environmental performance of the PHC pile installation process. Second, by conducting on-site surveys and expert interviews, information on the resources required for PHC pile installation (e.g., the hourly cost of resources, fuel consumption of equipment, etc.) was obtained. In addition, the task time data required for the pile installation and simulation modeling data (e.g., the relationship among tasks and the process of each resource) were collected through video recordings. Third, the PHC pile installation process was identified for simulation modeling based on the process information obtained from field surveys, expert interviews, and video recordings. Subsequently, the precedence relationship between the work tasks and the system input and output values were defined. Finally, an application for estimating the duration, cost, and carbon emissions to complete the PHC pile installation process was developed and used to create a simulation based on the collected and analyzed information. Furthermore, the validity of the model was verified by analyzing and comparing the results with an actual field case.

2. Literature Review

Sustainable construction is reflected in applying sustainable development practices in the industry, and efficient implementation of the construction process is the most critical aspect of sustainable pile construction [14,15]. According to [16], construction and design encourage achieving three goals: Economic sustainability to stimulate economic growth, environmental sustainability to minimize environmental impact, and social sustainability approach, a sustainable construction practice for social well-being. Therefore, it contributes tremendous utility to economic, environmental, and social development and ultimately creates a sustainable construction environment [17]. Optimization of the construction process and reduced uncertainty are expected to improve sustainability and component performance [18]. However, this uncertainty poses challenges for underground infrastructure, such as foundations [19,20]. Additionally, [21] found that sustainable practices of pile construction played a crucial role in gaining a competitive advantage through cost effectiveness, performance efficiency, and sustainability. [22] showed that excavated piles account for higher greenhouse gas emissions than drilled piles, and the installation process of bored piles needed optimization. [23] pointed out that high-strength prestressed concrete piles can reduce greenhouse gas emissions and economic costs by almost half compared to steel H-piles. The authors in [24] compared actual field data with alternatives (Scenarios 1 and 2) for 341 precast concrete pile construction sites. They presented a method that searches for optimal alternatives by analyzing the variability and uncertainty related to the overall pile construction (i.e., design, manufacturing, and construction) based on data obtained from interviews with precast pile manufacturing and installation experts. A foundation constructed for an eight-story reinforced concrete structure residential building in San Francisco was analyzed based on the principles of lean construction, which pursues an efficient construction production system that minimizes waste. Ref. [3] presented a method that estimates the productivity and cost of bored pile construction using a deterministic technique. Data for the analysis were collected using questionnaires, interviews, and telephone calls with construction experts. The productivity, cycle time, and cost of the five models were analyzed while taking into consideration the pile size, depth, pouring method, soil type, and construction method. Ref. [25] developed a productivity index based on factors affecting the productivity and cost of continuous flight auger (CFA) pile installation. The productivity index quantifies the subjective factors that affect the productivity of the CFA pile installation. The study analyzed the productivity, cycle time, and cost of CFA pile construction for various models using a deterministic approach. The productivity index was calculated using the analytic hierarchy process (AHP) and fuzzy theory [26]. In addition, various approaches, such as discrete event simulation [27–29], regression analysis [30,31], and neural networks [32], were applied to analyze productivity and cost according to variables, such as pile size, pile length, soil type, and auger length. In addition, [33] presented a method called the rank reversal technique and compared the simulation results of pile installation obtained from various approaches, that is, deterministic, simulation, regression, and artificial neural networks. Refs. [2,34,35] presented a quantitative analysis method for evaluating the sustainability of drilled shafts and precast concrete (PC) pile installations. The authors analyzed the environmental impact and economic feasibility of the two methods using life cycle assessment (LCA) and cost-benefit analysis (CBA). In addition, multi-criteria analysis (MCA), which evaluates the environmental impact and economic feasibility, was used to select the optimal result for supporting decision-making. Ref. [21] demonstrated that cost-effectiveness, productivity improvement, and minimization of environmental impact (attaining sustainability) are possible through a comparison of the previously implemented and alternative methods of pile foundation construction. In the case study, the author postulated that a reduction 15% in cost and 18.61% in CO_2 emissions is possible if alternative comparisons are conducted before starting pile construction.

Although numerous studies that recognize the importance of productivity and environmental performance evaluations at the construction stage have been conducted, these studies do not provide a method for the stochastic estimation of construction eco-economic performance at a detailed level. The method presented in this study provides a more accurate prediction and supports a rational decision-making process during the construction planning stage of PHC pile installation using simulation techniques.

3. Eco-Economic Performance Estimation System for PHC Pile Installation

3.1. System Structure and Components

This system consists of (1) a process simulation modeling and execution environment, (2) a graphic user interface of the simulation system, and (3) a datasheet. The graphic user interface and simulation environment of this system were built using MATLAB 2009b version. This system helps analyze the eco-economic performance using a simulation model that estimates the duration, cost, and energy consumption based on the attributes of equipment and labor deployed in the PHC pile installation process. The system consists of the following three stages.

- Simulation modeling and system setting (input variables: Resources and tasks, system and datasheets)
- Simulation execution (processing and calculation)
- Results analysis (finding probabilities under limitations)

3.2. System Process

The system process for the eco-economic performance analysis of the pile installation process is presented in this section. The system process is illustrated in Figure 1.

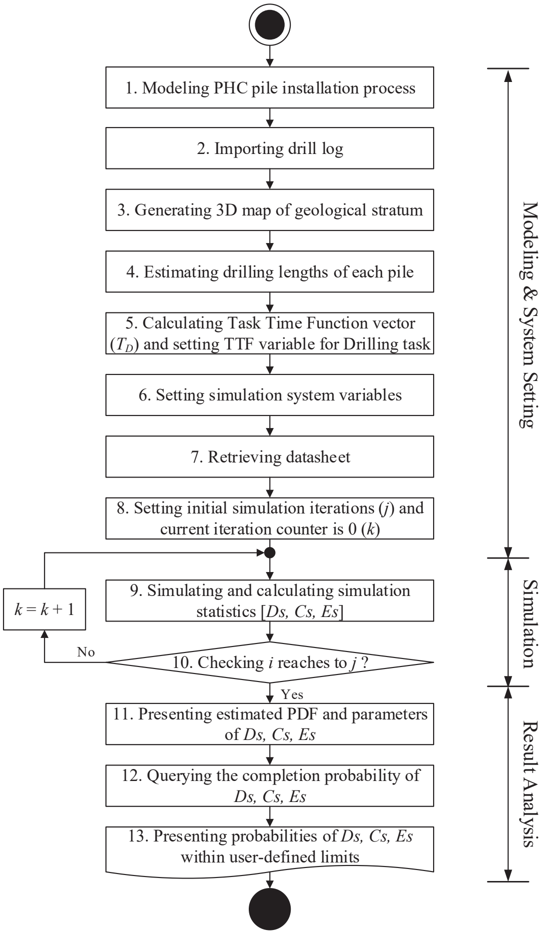


Figure 1. System flowchart.

This system performs experiments based on a DES model and the system input variables. In addition, variability data on the entity flow generated by the work task or waiting time of each modeling component are collected in a vector format, and stochastic emission, duration, and cost information of the PHC pile installation process are provided.

3.2.1. Simulation Modeling and Input Variables for Modeling Component

This section presents the model development and input/output variables for the PHC pile process. The four key components needed to build a construction process model are (1) knowledge of the construction method related to the process, (2) knowledge of the process for breaking down a construction process into a basic work task level, (3) information to identify the resources required for the process, and (4) the ability to define relationships between the resources and work tasks [36]. To analyze the eco-economic performance of the PHC pile process, a simulation model must be established, and input variables for the model must be set. This system provides a simulation model and a graphical user environment in which a simulation model is built, and the input variables of the model of the PHC pile installation process are specified. The PHC pile installation process model integrates the individual processes of all resources (Figure 2).

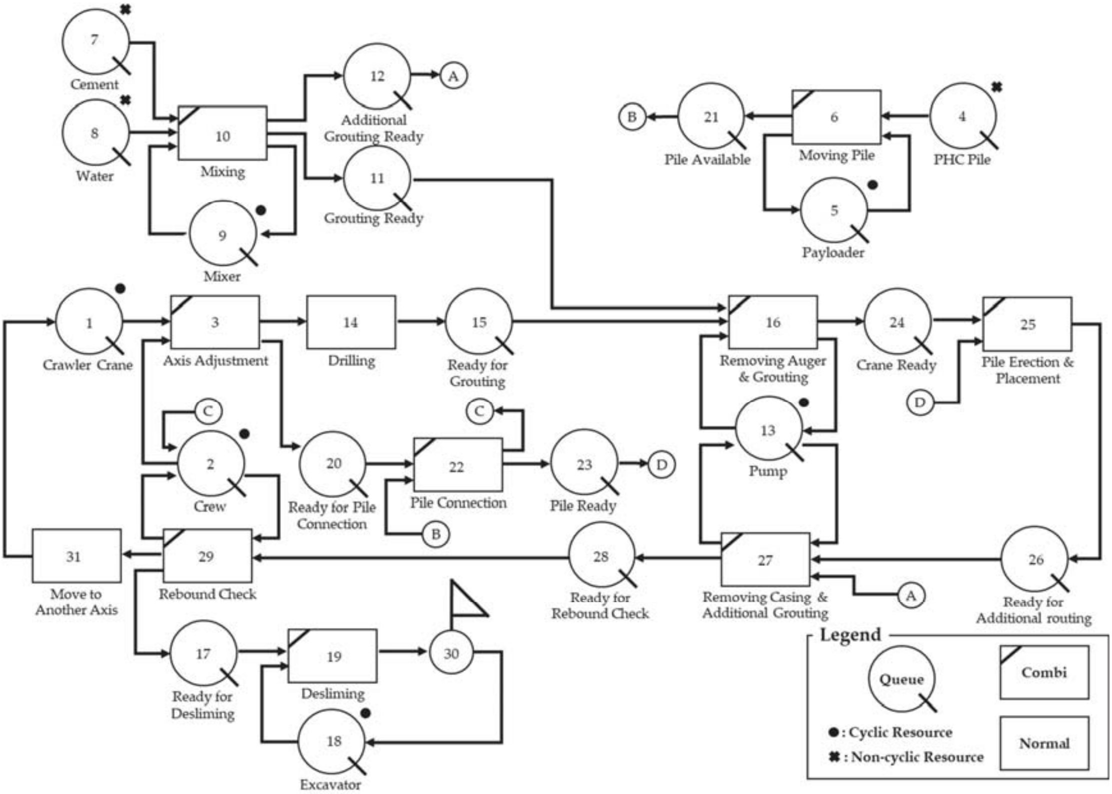


Figure 2. PHC pile installation process simulation model.

The resources involved in performing the work tasks in this study follow the process presented below.

- Cement and water mixture is used for grouting and additional grouting and is subsequently removed from the system.
- The PHC pile is moved to the work spot by the payloader, connected to the crawler crane, and installed at the location. When a rebound check is performed, it is removed from the system.
- The mixer, payloader, and excavator each perform a single task of mixing, moving piles, and removing slime, respectively. The pump injects cement paste during grouting and performs additional grouting tasks.
- The crew performs axis adjustment, pile connection, and rebound check in a cyclical manner.

- The crawler crane cyclically performs axis adjustment, drilling, removing the auger, pile connection, pile erection, removing casing, rebound check, and moving to another axis.

Combi and Normal components are used for modeling time-consuming tasks performed by the resources deployed in the process model. Queue is a component that initializes resources with a cyclic process (e.g., equipment and crew), a non-cyclic process (e.g., material), or an idle state. For example, crawler cranes, mixers, pumps, and crew are cyclic resources, whereas PHC piles, cement, and water are non-cyclic resources, as depicted in Figure 2. Resources deployed to the process model are initialized in the Queue, and the time variables (task time function (TTF)) that cause variability in the simulation are set using the Combi and Normal components. When TTFs are set for work tasks, the system runs a simulation and calculates the time taken during the simulation by each component as well as the entire system based on queuing theory. The counter component performs entity counting and stops the simulation when it receives the stopping conditions from the system.

The drilling task time is related to several conditions, such as the hole size, strata, and excavation time for each stratum. This study presents a method for estimating the drilling task time using a drill diagram. First, based on the section guide and drill logs, the system creates a 3D contour map according to the geological distribution of the site (Figure 3). By connecting each point of the drill log (e.g., BX-10, NX-9, etc.) according to the section guide and stratum level (e.g., Ground level, Soil level, Rock level, etc.), the system identifies a 3D map of the ground and stratum level of each PHC pile. The 3D geological modeling process can be found in other studies (e.g., [37–39]). Second, the system calculates the excavation time for each file (Equation (1)) by overlapping the pile location on the 3D map and saving it as a vector (T_D) for the TTF of the drilling task.

$$T_{Di} = \left(l_{Di}^{1} \times t_{Di}^{1}\right) + \left(l_{Di}^{2} \times t_{Di}^{2}\right) \cdots + \left(l_{Di}^{n} \times t_{Di}^{n}\right) \tag{1}$$

where T_{Di} is the drilling task time for i^{th} installation spot, l_{Di}^{n} is the length of each stratum for i^{th} drilling task, and T_{Di}^{n} is the drilling time for each stratum for i^{th} drilling task.

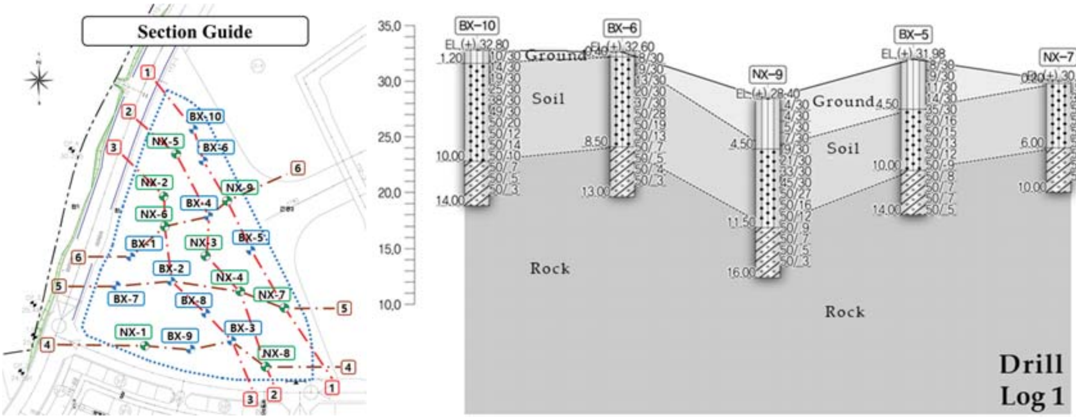


Figure 3. Section guide of the construction site and example of a drill log.

The system (1) imports the probability distribution function and parameters of the TTF except for the drilling task from the datasheet, (2) assigns it to each work task, (3) sets the time unit (i.e., second, minute, or hour), (4) initializes the maximum simulation iterations and sets the model's stoppage condition (i.e., cycles or simulation time limit), and (5) sets the current simulation iteration (k) to 0 and executes the computation till iteration (k) reaches the maximum simulation iteration (j). In addition, the system (6) imports the hourly fuel consumption and cost information of the resources from the datasheet and (7) stores it in a matrix. When the modeling and system input are completed, the simulation is executed.

3.2.2. Simulation Execution and Result Analysis

The system runs simulations using the developed model and input variables. In addition, the variability data arising from the entity flow generated by waiting or working time for each element are saved as a vector in each simulation. Using the generated data, the (1) process completion duration, (2) process completion cost, and (3) carbon emissions of equipment are calculated and saved. The system imports the matrix of the stored datasheet before the simulation is executed and uses it to calculate the carbon emissions from each component during the simulation. The hourly fuel consumption and cost of the deployed equipment used in this study and the average drilling time for each stratum were collected from expert interviews, and the other work task times were analyzed using video recordings and a time-lapse study.

The system calculates the total carbon dioxide emissions of the process by summing carbon dioxide emissions from each piece of equipment. The fuel consumption (F_i) of the individual piece of equipment is calculated by applying Equation (2) using the average service time of the work task (ST_t), where the equipment i is involved, and the average fuel consumption per hour (HF_i) of the equipment i.

$$F_i = HF_i \times \sum_{t=1}^{Count\ Task} ST_t \tag{2}$$

The system calculates the carbon dioxide emissions (E_i) using the total fuel consumption (F_i) of each individual piece of equipment and the emission calculation formula of the Intergovernmental Panel on Climate Change (IPCC) [40] (Equation (3)).

$$E_i = 0.000845 \times 0.837 \times \frac{44}{12} \times 1000 \times F_i \tag{3}$$

where 0.000845 is the ton of oil equivalent (TOE) of diesel, 0.837 is the carbon emission factor of diesel, 44/12 is the ratio of carbon dioxide molecular weight to carbon atomic weight, and the constant 1000 is used to convert tons to kg.

The total carbon dioxide emission (E) of the PHC pile installation process is calculated using the total carbon dioxide emission amount of the individual piece of equipment (E_i) and the number of pieces of equipment (N_i), using Equation (4).

$$E = \sum_{i=1}^{Count\ Equipment} E_i \times N_i \tag{4}$$

Subsequently, the total cost of the PHC pile installation process (C) is computed using the equipment's hourly costs (HC_i), number of deployed equipment (N_i), and elapsed simulation time (D, total duration of pile installation process), using Equation (5).

$$C = \sum_{i=1}^{Count\ Equipment} HC_i \times N_i \times D \tag{5}$$

The performance results are saved during each simulation, and the optimal probability distribution function and parameters of each performance indicator (i.e., duration, cost, and emission) are estimated and presented using the best-fit PDF algorithm by the construction operation and project scheduling (COPS) system [8]. Subsequently, a user can query the probability of completing the process within a specified duration, cost, and emission. This helps practitioners in decision-making.

4. Test Case

4.1. Simulation Modeling of the PHC Pile Installation Process

A total of 299 PHC piles (400 mm) were installed (Figure 4). The pile specifications (length, diameter, etc.) and quantity were designed based on ground investigation results.

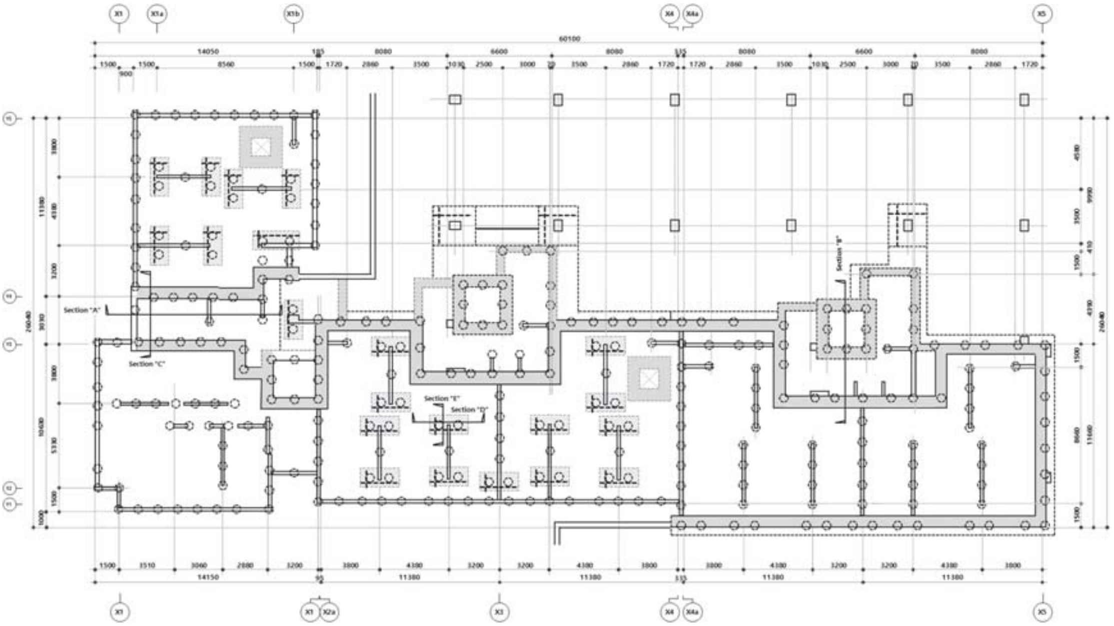


Figure 4. PHC pile location.

The work tasks performed by the deployed resources and the process of each resource were identified by site investigation and video recordings. The resources deployed in the PHC pile installation model used in the case study were material (i.e., cement paste, water, and PHC pile), labor (i.e., crew), and equipment (i.e., crawler crane, excavator, payloader, pump, and mixer). Table 1 presents the attributes of the equipment used.

Table 1. Attributes of deployed equipment.

Type	Model	Fuel (L/h)	Cost (KRW */h)
Crawler crane	Pile driver (DHP-80), auger (100 P), drop hammer (3 ton)	28	341,588
Excavator	02 (ec55c)	8	43,345
Payloader	FR 15	11	41,731
Pump	Electricity generator (350 kw) and compressor (Ingersoll-Rand 825)	10	29,133
Mixer	Plant (2000 × 4800 × 3200) and bulk silo (40 ton)	15	30,000

* South Korean Won (₩).

The attribute values of the resources used to perform the PHC installation process are listed in Tables 1 and 2. The average hourly fuel consumption and hourly cost of the equipment were obtained through expert interviews. To measure the work task time of the PHC pile process, a video recording and time-lapse study were conducted. Time measurements for each work task were performed at least 30 times to ensure sampling reliability.

Table 2. Input variables and attributes for modeling components.

Components			Predecessor	Successor	Time Delay Function * or Entity Initialization	Involved Resource(s)
ID	Name	Type				
1	Crawler crane	Cyclic resource queue	31	3	1	Crawler crane
2	Crew	Cyclic resource queue	29, 22	3, 29	1	Crew
3	Axis adjustment	Combi	1, 2	14, 20	Normal (0.88, 0.18)	Crawler crane Crew
4	PHC pile	Noncyclic resource queue	-	6	299	PHC pile
5	Payloader	Cyclic resource queue	6	6	1	Payloader
6	Moving pile	Combi	4, 5	5, 21	Normal (1.06, 0.05)	Payloader PHC pile
7	Cement	Noncyclic resource queue	-	10	299	Cement
8	Water	Noncyclic resource queue	-	10	299	Water
9	Mixer	Cyclic resource queue	10	10	1	Mixer
10	Mixing	Combi	7, 8, 9	9, 11, 12	Normal (4.18, 0.48)	Mixer Cement Water
11	Grouting ready	Idle queue	10	16	-	Grout
12	Additional grouting ready	Idle queue	10	27	-	Add. Grout
13	Pump	Cyclic resource queue	16, 27	16, 27	1	Pump
14	Drilling	Normal	3	15	According to ground Level and types	Crawler crane
15	Ready for grouting	Idle queue	14	16	-	Crawler crane
16	Removing auger and grouting	Combi	11, 13, 15	13, 24	Normal (1.11, 0.15)	Crawler crane Pump Grout
17	Ready for desliming	Idle queue	29	19	-	Soil
18	Excavator	Cyclic resource queue	30	19	1	Excavator
19	Desliming	Combi	17, 18	30	Normal (11.5, 1.23)	Excavator Soil
20	Ready for pile Connection	Idle queue	3	22	-	Crew Crawler crane PHC pile
21	Pile available	Idle queue	6	22	-	PHC pile
22	Pile connection	Combi	20, 21	2, 23	Normal (0.52, 0.01)	Crew Crawler crane PHC pile

Table 2. *Cont.*

Components			Predecessor	Successor	Time Delay Function * or Entity Initialization	Involved Resource(s)
ID	Name	Type				
23	Pile ready	Idle queue	22	25	-	Crawler crane PHC pile
24	Crane ready	Idle queue	16	25	-	Crawler crane
25	Pile erection and Placement	Combi	23, 24	26	Normal (1.04, 0.10)	Crawler crane PHC pile
26	Ready for Additional grouting	Idle queue	25	27	-	Crawler crane
27	Removing casing & Additional grouting	Combi	12, 13, 26	13, 28	Normal (1.63, 0.22)	Crawler crane Pump Add. Grout
28	Ready for Rebound check	Idle queue	27	29	-	Crawler crane
29	Rebound check	Combi	2	28	Normal (1.36, 0.12)	Crawler crane Crew
30	Counter	Counter	19	18	-	-
31	Move to another axis	Normal	29	1	Normal (3.62, 0.95)	Crawler crane

* The Time delay function in this study used Normal distribution, and the parameter values of 'mu' and 'sigma' are specified in the parenthesis.

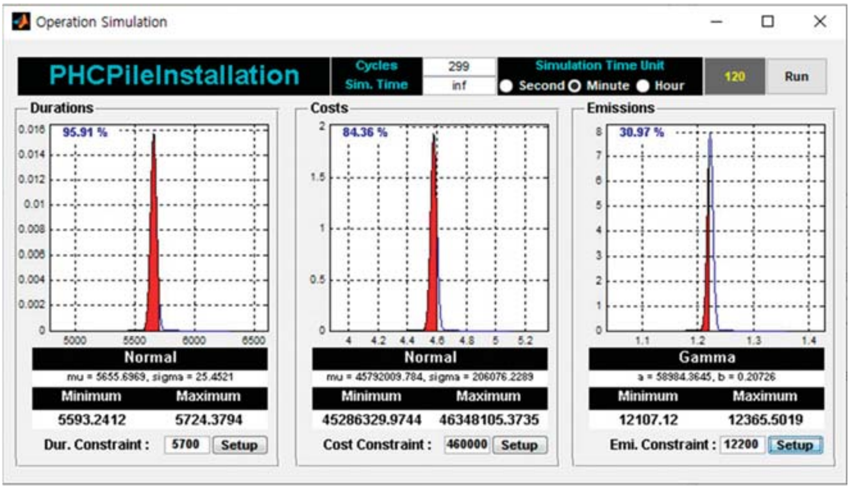
Table 3 lists the drilling task times used in this study. These task times are the result of the calculation using the location of the PHC pile (Figure 5), drill log (Figure 3), 3D contour map (Figure 4), and Equation (1).

Table 3. Drilling task time by ground attributes.

Pile Number	Ground (meter)	Soil (meter)	Drilling (meter)	Drilling Task Time (minutes)
1	0.6522	11.0952	11.7475	11.13
2	0.6559	10.9824	11.6383	11.03
3	0.6567	10.8516	11.5083	10.90
4	0.6575	10.7303	11.3877	10.79
5	0.6582	10.6080	11.2662	10.67
…	…	…	…	…
295	1.8542	8.5922	10.4464	9.62
296	1.9883	8.5647	10.5530	9.69
297	2.1272	8.5362	10.6634	9.77
298	2.2189	8.5063	10.7252	9.81
299	2.2613	8.5087	10.7700	9.84

4.2. Simulation Experiment Results and Discussion

Figure 5 shows the results of the simulation based on the information presented above. The system executes iterative simulations to calculate and present the optimal probability distribution function and parameters of the process completion duration, cost, carbon dioxide emissions, and interval values (minimum and maximum) for each performance. Additionally, the probability of delivering the process within the specified value for each simulation result was calculated and presented by querying the value specified for each output. The simulation results for each output are presented in Figure 5 and Table 4. An eco-economic construction plan for the PHC pile was established using these simulation experiments. For example, if the probabilities of performance are low, a project manager can secure a margin on deadline, budget, or carbon emissions.


Operation Simulation

PHCPileInstallation

Cycles: 299
Sim. Time: inf
Simulation Time Unit: ● Second ○ Minute ● Hour
120

Durations: 95.91 %
Normal
mu = 5655.6969, sigma = 25.4521
Minimum: 5593.2412
Maximum: 5724.3794
Dur. Constraint : 5700

Costs: 84.36 %
Normal
mu = 45792009.784, sigma = 206076.2289
Minimum: 45286329.9744
Maximum: 46348105.3735
Cost Constraint : 460000

Emissions: 30.97 %
Gamma
a = 58984.3645, b = 0.20726
Minimum: 12107.12
Maximum: 12365.5019
Emi. Constraint : 12200

Figure 5. Simulation results.

Table 4. Simulation results.

Performance	PDF & Parameters	Minimum	Maximum	Limitation	Probability
Duration (min)	Normal (mu = 5653.37 sigma = 29.26)	5593	5724	5700	95.91%
Cost (KRW)	Normal (mu = 45,792,009.78 sigma = 206,076.23)	45,286,330	46,348,105	46,000,000	84.36%
Emission ($kgCO_2$)	Gamma (a = 58,984.36 b = 0.21)	12,107	12,366	12,200	30.97%

The simulation results of this study showed that Duration and Cost are the Normal probability distribution functions, and Emission is the Gamma probability distribution function. The system presents PDF (Probability Distribution Functions) and values of parameters (e.g., 'mu' and 'sigma' of Normal distribution and 'a' and 'b' of Gamma distribution) after the simulation experiment is finished. The system calculates the minimum and maximum of Duration, Cost, and Emission as [5593:5724], [45,286,330:46,348,105], and [12,107:12,366], respectively. In this simulation results, the constraint conditions of the construction site are set as duration [5700 min], Cost [46,000,000 KRW], and Emission [12,200 $kgCO_2$], and the system calculates and presents 95.91%, 84.36%, and 30.97%, respectively (Table 4).

The simulation results, estimation based on the CSPR (Construction Standard Production Rate) and IUC (Itemized Unit Cost), site contract, and actual construction results are presented to compare and validate the presented method in this study (Table 5). The CSPR and IUC are used to estimate the duration and cost of construction projects in Korea. The estimation process using CSPR and IUC of Korea is similar to the process of using RS Means of the U.S. and Rawlinsons Construction Cost Guide of Australia. Based on the CSPR, the construction quantity and duration of tasks are calculated, and the costs of the works are calculated using the ICU. The detailed calculation process of estimating duration, cost, and carbon emission based on the CSPR and IUC is presented in Appendix A.

Table 5. Simulation result comparison.

Category	Duration (day)	Cost (KRW)	Emissions (ton)
Simulation (average)	11.8 *	45,792,009	12.23 **
CSPR and IUC	8.5	27,577,938	13.35 ***
Contract	15	46,412,076	-
Site results	17 (12)	46,412,076	-

* Working duration is calculated using the simulation result of average duration as 5655.7 min in Figure 5. The working day is calculated based on the eight working hours per day, ** Simulation result of average emission is replaced by tonnage, *** The total emission is calculated by Equation (3) using the working hour calculated by the CSPR and IUC and the equipment's average fuel consumption (L/h) shown in Table 1.

All four results of the duration appear to be different. First, the number of actual working days of the construction site was 17. However, if we substituted the six days when less than seven piles per day were erected per day, the number of average working days becomes 12. This result differs from the CSPR and contractual working days and is similar to the simulation result. Second, the cost of the on-site contract was considered the actual construction cost. As a result, the cost was significantly different from the result calculated using CSPR. On the other hand, the cost also appears to be similar to the simulation results. Lastly, the results calculated by the CSPR were higher than the simulation results. This result is because, in the case of carbon dioxide emissions calculated by simulation, the variability of the emissions is effectively reflected by capturing the work tasks in which only the equipment is operated rather than using the entire construction period. Therefore, this result shows that even though the calculated number of working days in simulation is higher, the carbon emission is lower than the CSPR result. This test case reveals that the estimation accuracy of the emissions is improved, and the method effectively reflects the prediction of duration, cost, and carbon dioxide emissions in real-world construction.

5. Conclusions

In this study, the duration, cost, and carbon dioxide emissions generated by the resources (e.g., equipment) used for PHC pile installation were estimated using a discrete event simulation. A comparison between actual construction and simulation results shows that the accuracy was 98.3% for the duration and 98.7% for the cost. On the other hand, a comparison between actual construction and CSPR shows that the accuracy was 70.8% for the duration and 59.4% for the cost. Therefore, the simulation results are more accurate in predicting the duration and cost of the PHC pile installation process. In addition, since the presented method calculates the total amount of emission by calculating only the time when the equipment is working in the simulation, it reflects reality more effectively. In addition, a stochastic analysis method was presented to estimate the eco-economic performance. This study provides the following benefits. (1) This study presented a method that simultaneously evaluates the productivity and environmental performance of pile construction, whereas, in previous studies, pile construction productivity and environmental performance evaluations were conducted individually. (2) This study presented a model for measuring the carbon dioxide emissions of the PHC pile installation at a detailed level of the construction process. This provides a basis for quantifying the productivity and environmental impact of PHC pile processes in the construction field. (3) By performing iterative simulations of the PHC pile installation, stochastic estimation of the duration, cost, and carbon dioxide emissions were enabled. This enables more accurate management of these outcomes during the planning stage of PHC pile construction.

However, this study has several limitations, described as follows. (1) The eco-economic performance of only a single method (i.e., a PHC pile) was evaluated in this study. In future studies, the modeling, simulation, analysis, and comparison of various pile methods are recommended. (2) Carbon dioxide emissions were calculated using the average fuel consumption of the equipment, assuming that all the conditions of the work tasks performed by the equipment are identical. However, all work tasks have different work intensities, and the fuel consumption of the equipment is not the same. In future studies, it is necessary to improve the accuracy of the emission estimation by classifying and calculating the fuel consumption of the resources according to the conditions of the work tasks. (3) Various factors affecting the productivity and environmental performance of pile construction, such as soil type, site weather conditions, and working conditions, need to be analyzed and applied to the simulation models.

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

Funding: This research was supported by the Kyungpook National University Development Project Research Fund 2019.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

Appendix A

The total drilling depth is 3345 m, and the total number of drilling holes is 299 in this case study. Crane (DHP-80: 50 ton), Auger (100P), Drop hammer (3 ton), Excavator (ec55c: 0.2 m^3), Payloader (FR 15), Electricity generator (350 kw), Compressor (Ingersoll-Rand 825), Plant (2000 × 4800 × 3200) and Bulk silo (40 ton) were utilized.

Appendix A.1. Duration Calculation

$$SS = 3345 \text{ m (Total drilling length)}$$

$$AL = SS \div 299 = 11.2 \text{ m (Average drilling length)}$$

$$T_E = 0.12 \times AL = 1.34 \text{ min/EA (Drilling time for one pile), where } \varnothing = 400 \text{ mm}$$

$$T_B = 1 \text{ min/EA (Hammering time for one pile)}$$

$$T_G = 2 \text{ min/EA (Grouting time for one pile)}$$

$$T_S = 10 \text{ min/EA (Preparation time for one pile)}$$

$$T_C = T_E + T_B + T_G + T_S = 14.34 \text{ min (Construction time per one pile unit)}$$

$$Q = 60 \div T_C \times AL = 46.86 \text{ m/h (Work capability)}$$

$$\text{Duration} = T_C \times 299 = 4287.7 \text{ min} \div 60 = 71.5 \text{ h} \div 8 = 8.9 \text{ day}$$

Appendix A.2. Emission Calculation

$$\text{Emission} = \text{Duration} \times 72 \text{ L/h} \times 0.000845 \times 0.837 \times \frac{44}{12} = 13.35 \text{ tonCO}_2$$

where 72 kg/h is the sum of the average hourly fuel consumption of equipment, 0.000845 is the combustion rate of diesel, 0.837 is the carbon emission coefficient of diesel, and 44/12 is the ratio of carbon dioxide molecular weight to carbon atomic weight.

Appendix A.3. Cost Calculation

Cost calculation is divided into six sub-categories (1) Drilling, (2) Inserting piles, (3) Hammering piles, (4) Transporting piles, (5) Grouting, and (6) Desliming. The standard unit price was referred to the IUC, and all cost unit is South Korean Won (₩).

1. Drilling
    - 1.1 Machine Cost
        - 1.1.1 Crane

$$Labor\ Cost = ₩\ 23{,}389 \div Q = ₩\ 499.13$$

$$Material\ Cost = ₩\ 22{,}276 \div Q = ₩\ 499.13$$

$$Expenses = ₩\ 63{,}037 \div Q = ₩\ 1345.22$$

        - 1.1.2 Auger

$$Labor\ Cost = ₩\ 0$$

$$Material\ Cost = ₩\ 0$$

$$Expenses = ₩\ 30{,}135 \div Q = ₩\ 643.09$$

        - 1.1.3 Electricity Generator

$$Labor\ Cost = ₩\ 18{,}982 \div Q = ₩\ 405.08$$

$$Material\ Cost = ₩\ 102{,}819 \div ((60 \div T_E) \times AL) = ₩\ 205.03$$

$$Expenses = ₩\ 11{,}927 \div Q = ₩\ 254.52$$

    - 1.2 Crew Cost

$$Foreman = ₩\ 105{,}826 \times 1.0 = ₩\ 105{,}826$$

$$Scaffold\ labor = ₩\ 149{,}852 \times 1.2 = ₩\ 179{,}822.4$$

$$Crew\ sub\ total = ₩\ 285{,}684.4 \div 8 \div Q = ₩\ 761.97$$

2. Inserting Piles

$$Labor\ Cost = ₩\ 23{,}389 \div (60 \div (0.3 \times T_C) \times AL) = ₩\ 149.73$$

$$Material\ Cost = ₩\ 22{,}276 \div (60 \div (0.3 \times T_C) \times AL) = ₩\ 142.61$$

$$Expenses = ₩\ 63{,}037 \div (60 \div (0.3 \times T_C) \times AL) = ₩\ 403.55$$

3. Hammering Piles

$$Labor\ Cost = ₩\ 0$$

$$Material\ Cost = ₩\ 35{,}231 \div ((60 \div T_B) \times AL) = ₩\ 52.43$$

$$Expenses = ₩\ 33{,}792 \div ((60 \div T_B) \times AL) = ₩\ 50.29$$

4. Transporting Piles

$$Labor\ Cost = ₩\ 23{,}389 \div (60 \div (0.2 \times T_C) \times AL) = ₩\ 99.82$$

$$Material\ Cost = ₩\ 12{,}080 \div (60 \div (0.2 \times T_C) \times AL) = ₩\ 51.56$$

$$Expenses = ₩\ 6262 \div (60 \div (0.2 \times T_C) \times AL) = ₩\ 26.73$$

5. Grouting

5.1 Pump

$$Labor\ Cost = ₩\ 0$$

$$Material\ Cost = ₩\ 0$$

$$Expenses = ₩\ 1554 \div Q = ₩\ 33.16$$

5.2 Mixer

$$Labor\ Cost = ₩\ 0$$

$$Material\ Cost = ₩\ 0$$

$$Expenses = ₩\ 687 \div Q = ₩\ 14.66$$

5.3 Electricity Generator

$$Labor\ Cost = ₩\ 18,982 \div Q = ₩\ 405.08$$

$$Material\ Cost = ₩\ 33,378 \div Q = ₩\ 712.29$$

$$Expenses = ₩\ 4533 \div Q = ₩\ 96.73$$

6. Desliming

$$Labor\ Cost = ₩\ 23,389 \div Q = ₩\ 499.13$$

$$Material\ Cost = ₩\ 9359 \div (60 \div (0.4 \times T_C) \times AL) = ₩\ 79.89$$

$$Expenses = ₩\ 10,597 \div Q = ₩\ 226.14$$

7. Subtotal

$$Labor\ Cost = ₩\ 3431.26/\mathrm{m}$$

$$Material\ Cost = ₩\ 1719.17/\mathrm{m}$$

$$Expenses = ₩\ 3094.09/\mathrm{m}$$

$$\mathrm{Cost} = (3431.26 + 1719.17 + 3094.09)₩/\mathrm{m} \times 3345\mathrm{m} = ₩\ 27,577,938$$

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Article

Location Optimization of Tower Cranes on High-Rise Modular Housing Projects

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Abstract: In high-rise modular housing complex projects, tower crane layout planning is the key to ensuring the efficient lifting of components during construction. To improve the lifting efficiency of the cranes and control costs, the layout plan should minimize the distance the tower cranes must move the prefabricated units. The distance between the trailer holding the components, the tower crane, and the structure under construction should be kept to a minimum. However, most current studies consider the relative positions of the tower crane and the trailer without fully considering the movement efficiency of the trailer, and when multiple trailers and multiple tower cranes are involved, the optimization scheme is more complicated. In this study, a mathematical model based on mixed integer linear programming (MILP) is built to determine the type and location of tower cranes as well as the location of trailers to solve the problem of situating multiple tower cranes in a high-rise modular housing complex project. Finally, the validity and practicality of the model are demonstrated with case studies.

Keywords: tower crane layout planning; modular building; high-rise residential complex; mixed integer linear planning

Citation: Zhou, C.; Dai, F.; Xiao, Z.; Liu, W. Location Optimization of Tower Cranes on High-Rise Modular Housing Projects. *Buildings* **2023**, *13*, 115. https://doi.org/10.3390/buildings13010115

Academic Editor: Hongping Yuan

Received: 13 September 2022
Revised: 12 December 2022
Accepted: 29 December 2022
Published: 1 January 2023

1. Introduction

Currently, assembled housing is used in large numbers in high-rise, high-density cities [1,2]. The construction of high-rise modular housing includes the prefabrication of components in factories and the assembly of components at construction sites [3,4]. As large-scale lifting equipment to assist in the assembly of the components at construction sites [5,6], tower cranes should be positioned based on exact calculations of the height and operating radius of the cranes as well as on lifting capacity [7], installation, and disassembly methods. The lifting efficiency of the tower crane largely determines the speed of construction, thus affecting the construction period and overall cost of the project [8]. Therefore, it is crucial to choose the type and location of the tower crane carefully [3].

In modular projects, tower cranes are usually used for lifting the prefabricated components from a trailer onto the structure under construction, and the weight and volume of individual components cannot be changed and adjusted. Therefore, the lifting capacity and operating radius of tower cranes need to be carefully matched to the proposed project [9]. To reduce the cost of the cranes, their carrying capacity as well as the distances they must move when lifting components onto the structure should be minimized as much as possible [10].

Due to the high cost of land and the limited space for construction in urban areas, there is often no spare space to stack a large number of prefabricated components when constructing modular housing projects [9,11]. Instead, the components are transported to the construction site on trailers and lifted directly from the trailer to the building by the tower crane [12]. In this case, the positions of the trailers vary, while the lifting capacity of the tower crane is estimated based on a combination of the distance from the crane to the trailer and the distance from the crane to the structure [7,13]. Therefore, when selecting the location and type of crane, the impact of the changing locations of the trailers must be taken into account; otherwise, there is a risk that the lifting capacity of the tower crane will be overestimated, i.e., the weight of the components will be greater than the maximum lifting capacity of the crane, thus leading to safety hazards.

However, in tower crane layout planning (TCLP) for high-rise modular building projects, although the method of lifting materials directly from the trailer to the structure is considered [14], it does not take into account multiple trailer parking locations, a major variable in the layout planning for the tower crane. For the above reasons, this study takes dynamic trailer location, tower crane type, lifting capacity of the relevant jib length, and distance between the tower cranes as the constraints for location selection and optimization. Additionally, we introduce four 0–1 variables to determine the type and location of the tower crane and the location of the trailer and describe the demand information for the components at the demand point and the supply information for the components at the supply point, with the overall goal of minimizing the cost of the tower crane. Then, a mixed integer linear programming (MILP) mathematical model for crane location optimization and trailer location selection in a high-rise modular housing complex project is developed using these conditions and solved using branch-and-bound techniques based on available engineering information. We then select the optimal crane configuration and location and most appropriate trailer parking location to ensure the lowest crane cost. To achieve these objectives, this study analyzes the important factors that should be considered in the planning of tower crane locations in high-rise modular housing projects after an extensive review of the relevant literature. Finally, the validity of the optimization model is verified with examples.

2. Related Research Studies

2.1. Layout Planning of Tower Cranes in Traditional Buildings

In traditional construction, tower cranes are mainly used to lift construction materials such as steel bars, formwork, and concrete. The location of the tower crane is usually determined first according to the location of the building, and then various material yards and material-processing sheds are arranged around the tower crane. The location optimization of the tower crane is mainly based on its running time/cost. As early as 1983, Ramos developed a mathematical model to reduce the total cost of transporting the crane and thus determine the best location for the crane on the construction site [15]. With the continuous development of computer technology, Zhang et al. developed an optimization model for a single tower crane using computer technology based on the shortest crane transport time [16]. Subsequently, to improve the optimization results of single tower crane operation, Huang et al. used the stacking location of materials as a variable as well and proposed a mixed integer linear model based on Zhang's model, which can be used to determine both the location of a single tower crane as well as the stacking location of materials [17]. Ji et al. optimized the stacking location of multiple tower cranes and materials simultaneously based on Huang and considered the collaboration capability of tower cranes within the overlapping range of tower cranes [10]. With the continuous development of Building Information Modeling (BIM) technology in the construction industry, many construction-related planning tasks are gradually shifting to BIM platforms, including the planning of tower cranes. Wang et al. developed an optimization model based on BIM + Firefly Algorithm (FA), which can automatically generate the layout of tower cranes and the location planning of materials [18]. Marzouk et al. further proposed a model framework involving the type, number, and location selection of tower cranes based on the previous work [19] and then performed a four-dimensional simulation based on an agent to prevent collisions during tower crane operation [20]. Han et al. proposed a 3D-based tower crane evaluation system, which designed, validated, and simulated a mobile tower crane. The 3D visualization of operations not only supports efficient tower crane operations but also allows for integrated consideration in tower crane planning based on safety and efficiency aspects [21]. Ji et al. proposed an architecture that integrates a 4D model with rule checking for reviewing tower crane work plans and developed a tower-crane-specific rule template based on current tower crane design standards. The automatic layout of tower cranes was implemented in a rule-checking platform using 4D models as input data, and additional tower crane alternatives could also be viewed [22]. Recently, Riga K et al. presented another mathematical model that considers the location of tower cranes and storage areas in relation to cost optimization [13].

Although there are many similarities between the tower crane layout planning of traditional buildings and the tower crane layout planning of modular buildings, the tower crane layout planning of traditional buildings cannot be directly applied to modular buildings because in the tower crane lifting process of traditional buildings, we can reduce the demand for tower crane lifting capacity by adjusting the weight of materials, thus weakening the influence of tower crane lifting capacity on tower crane layout planning. However, the weight and volume of the components in modular projects cannot be changed, so the lifting capacity of the tower crane must be considered as a key factor. In addition, although the material yards in traditional buildings can be considered as variables, the types of materials in each yard are unique, and the location of the yard is fixed. While the focus of this paper is to optimize the distance from the trailer to the demand point and the distance from the trailer to the tower crane, the trailer's location is variable, and the types of components carried by the trailer are not unique.

2.2. Tower Crane Layout Planning in Modular Buildings

The lifting in modular buildings is more complicated compared to the lifting in traditional buildings. In addition to lifting heavy and bulky components, the lifting work also requires component rotation as well as positioning and even assistance in assembling. To improve the efficiency of tower cranes in modular projects, much research has also been conducted by previous authors. Lei et al. established the lifting paths of component units through an automated system and then performed lifting path checks of mobile tower cranes to prevent collisions [23]. Han et al. proposed a visualized 3D simulation model for collision prevention checks in crane operations [24]. In all these studies, the authors considered the tower crane boom length as an important factor in preventing tower crane collisions and assumed that the trailer location was within the boom length of the tower crane. Dutta et al. performed discrete and continuous collision detection and path planning at the construction site based on the CALP (Computer-Aided Lift Planning) system. This system is based on Building Information Modeling (BIM) and uses Single-level Depth Map (SLDM) representation to reduce the huge BIM model dataset [25]. Regarding the planning layout of tower cranes, Olearczyk et al. proposed a method for the tower crane selection process and considered relevant factors such as tower crane loads and capacity checks in the paper [6]. Zhang et al. developed a virtual reality (VR) tool for selecting the optimal tower crane layout for high-rise buildings; the tool includes three functional components, a real-time feasibility check, multi-criteria evaluation, and simulated lifting, which allows project managers to visualize the whole process of tower crane lifting in the VR world [26]. More recently, Zhang et al. proposed a new decision framework for tower crane layout planning for high-rise modular buildings. The framework is divided into two parts, including feasibility assessment and performance analysis using fuzzy integration techniques [3]. Lu et al. developed an integrated CSLP (construction site layout plan) model to optimize the facility layout problem at prefabricated construction sites, combining the lifting efficiency of prefabricated components with previous CSLP considering safety risks and transportation costs [8]. Hussein et al. analyzed the literature on tower crane hoisting in modular structures by reviewing previous studies, in which he pointed out that the number of papers related to tower crane hoisting in modular construction is increasing every year and that most of the research is focused on automation. In particular, unlike mobile tower cranes, attached tower cranes need to be operated until the end of the project after the installation is completed on-site, thus again emphasizing the importance of tower crane specification and location selection [27].

Furthermore, in addition to the abovementioned studies conducted for the lifting simulation of tower cranes and the optimization of the tower crane arrangement based on setting up a member yard at the construction site, Smith et al. [12] and Thomas [14] et al. also proposed lifting the members directly from the trailer to the member demand point, and Thomas proposed three lifting options for modular buildings of steel structures in their paper, namely, using the yard for transit, disassembling the steel structure for assembly, and lifting directly from the yard, and then demonstrated the advantages of lifting the members directly from the trailer by comparison [28]. However, they do not provide the specific method used for trailer location selection in the paper. Hyun et al. proposed a genetic-algorithm-based optimization model for optimizing tower crane and trailer locations [9], but Hyun et al. only considered a single tower crane and a single trailer location.

In this study, multiple cranes are considered as variables for multiple trailer docking points simultaneously. In this case, the maximum distance used to estimate the tower crane capacity can vary depending on the trailer parking location and the tower crane location. Then, we use the optimization process to reduce the distance of the trailer from the demand point and the distance of the trailer from the tower crane, i.e., to reduce the movement distance of the tower crane, which minimizes the cost of the tower crane.

2.3. Relevant Algorithms in Tower Crane Layout Planning

The site-selection problem in tower crane layout planning can be summarized as the Quadratic Assignment Problem (QAP) in operations research [29], while the tower crane lifting problem involved in tower crane layout planning belongs to the Traveling Salesman Problem (TSP) in operations research. The main role of QAP in the tower crane location problem is to ensure the transportation of materials to meet the requirements of construction, while TSP is to improve the lifting efficiency as much as possible based on QAP and to establish the component transportation network (supply point–tower crane–demand point) in the construction site at the minimum cost.

In general, there are three types of methods for solving combinatorial problems: exact algorithms, approximate algorithms, and heuristic algorithms. The exact algorithms include branch-and-bound and dynamic programming methods. Approximate algorithms include greedy algorithms, local search algorithms, relaxation algorithms, sequence algorithms, etc. Heuristic algorithms include simulated annealing algorithms, evolutionary algorithms (genetic algorithms, differential evolutionary algorithms, etc.), ant colony optimization algorithms, particle swarm algorithms, etc.

The genetic algorithm (GA) is a popular heuristic algorithm that applies probabilistic search logic that works well in various objective functions and even nonlinear solution spaces. Genetic algorithms have also been applied in the configuration of building facilities and in optimizing the layout of facilities [30]. However, in genetic algorithms, the optimization problem is solved by applying the evolutionary principle, which requires repetitive operations and tends to converge in advance. The ant colony optimization (ACO) algorithm also applies to the tower crane location optimization problem. However, the limitations of the ACO algorithm are the large number of parameter values, the over-sensitive response to parameters, and the increased deviation of the resultant values [31]. Particle Swarm Optimization (PSO) is a wide-area optimization method that iteratively computes and simultaneously improves the candidate solutions to finally optimize the objective function, but it is difficult to obtain search results that consider both the optimal distance and constraints of the tower crane [32]. In addition, new optimization research methods such as Collision Body Optimization (CBO) and Vibration Particle Systems (VPS) are also powerful, but these methods have a problem in that it is difficult to express the lifting conditions and trailer position of the tower crane in a relatively simple and easy way [33]. Others have tried to improve the algorithm themselves. Wang et al. developed an integrated method that combines BIM and the Firefly Algorithm (FA) to automatically generate an optimal tower layout scheme. The method first uses BIM to provide input to the mathematical model and then uses FA to determine the optimal location and supply points of the tower crane [18]. Inspired by sine and cosine mathematical functions, Kaveh et al. investigated an improved sine cosine algorithm (USCA), which is based on the operator of harmonious search to simultaneously improve the search and handle variable constraints and then use the improved algorithm to optimize the location for the optimal tower crane layout [34]. Briskorn et al. proposed an optimization method covering polygons on uniform and non-uniform radius planes and then used a construction site as an application scenario with a finite set of candidates as the optimal location of the tower crane [35]. Dasovi et al. proposed an active building for optimal positioning of work facilities and tower cranes at repetitive operations construction sites using an information model approach. Additionally, the transformation method of passive BIM to active BIM is described in the paper [36].

In addition to the above algorithm, the QAP formulation can be transformed into a mixed integer linear programming formulation [17]. Usually, the linearization of QAP into MILP requires introducing a large number of variables and constraints to describe the problem [29]. In this study, however, it is necessary to consider multiple variables, such as the trailer location, supply point location, and crane-placeable location simultaneously in tower crane location selection, as well as constraints such as the supply of components, the number of supply points, the number of tower cranes, and the lifting capacity of tower cranes. Additionally, all the relational expressions in the constraints and optimization objectives of MILP are linear [13], and the relevant variables contain both 0–1 variables and continuous type variables. So for this study [37], we choose to build a mixed integer linear programming model to solve the problem and apply the branch-and-bound (BAB) technique to find the globally optimal solution.

3. Information and Mathematical Models

The model in this paper is divided into two parts: the information model and the mathematical model. The information model includes establishing the BIM model of the construction site and the discretization of the construction site with (x, y, z) coordinates. A unit of 1 m is chosen as the reference of (x, y, z) coordinates in this paper, and the boundary of the edge of the building, which is less than 1 m, is not counted in the site. The information related to the crane location (Variable 1), trailer location (Variable 2), and component installation location (Variable 3) can be identified after the site location is turned into data by coordinates. The construction of the mathematical model is described in detail in Sections 3.1–3.11.

3.1. Problem Statement and Hypothesis

The purpose of this paper is to give guidance in the selection and placement of tower cranes for a high-rise modular housing complex project during pre-construction. The objective is to determine the type of tower crane, its location, and the parking location of the trailer to transport each component so that the total cost of the tower crane is minimized.

Tower cranes can generally be divided by type into mobile and fixed tower cranes. Mobile tower cranes mainly rely on tracks or tires to move around the project cluster to achieve the work task, which is obviously unsuitable for crowded construction sites. Stationary tower cranes, on the other hand, do not move, use the rotation of the tower boom and trolley luffing to complete the work, and do not occupy a large area. Fixed tower cranes can be divided into two types: attached and internal climbing. The attached tower crane is mainly used in high-rise buildings because it can be raised according to the building and does not use too many tower standard joints and attachment rods as well as corresponding anchorages. The internal climbing tower crane is mostly used in super high-rise buildings, using the internal climbing device inside the core to raise the tower, which is not in line with the main body of this study. Therefore, this study selects the attached tower crane as the focus. The tower crane type refers to the different jib lengths and lifting capacities. A sketch of the attached tower crane structure is shown in Figure 1.

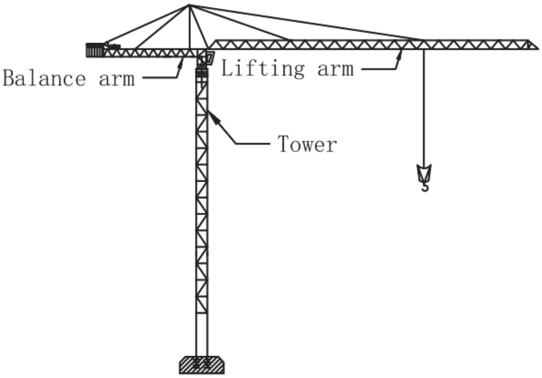


Figure 1. Structure diagram of attached tower crane (part).

To build the mathematical model, we used some information from the actual project, among which the available crane locations and crane configurations are limited and determined in advance; the height of the tower cranes is considered to meet the height requirements of the building as the number of tower sections increases; the trailer capacity is considered to meet the demand of the construction site because the trailers can continuously transport the components from the component factory to the construction site; the demand information of the components (location, component type, weight, and quantity), as well as the location of the demand points, are specific to the project itself. The operating cost of the tower crane is determined by the type of tower crane and the operating time of the tower crane. In addition to the above conditions, this paper also needs to set some assumptions:

1. For each lifting task, the tower crane operates at the same rate under full-load and no-load conditions;
2. The maximum lifting height of the tower crane meets the requirements of the building height;
3. There is no collision between tower cranes in operation;
4. The effect of component installation time on tower crane running time is excluded;
5. Multiple components can be provided for a particular trailer dock.

One workflow of the tower crane is to start from the supply point, lift the components to the demand point, and then return from the demand point to the supply point to facilitate the next operation in this cycle. That is, the tower crane runs the same two distances in a lifting task, the difference is that during the first half, the tower crane is running with a heavy load and during the second half the crane is running with no load. However, the specific running rate is not only limited by the running rate of the tower crane itself but also related to the proficiency of the tower crane operator. In the model, the operator's proficiency is adjusted by a factor, so the model defaults to the same operating rate for the tower at full and empty load, i.e., the tower spends twice as much time per hoisting task as it does one-way.

Because the model in this study is based on the jib length, lifting capacity, working rate, and the corresponding cost of the tower crane to make the selection, it does not take the height of the tower crane as the evaluation criterion, and because the selected tower crane is attached, as long as the maximum lifting height meets the requirements, the tower height can be increased by increasing the standard section of the tower. At this time, if the lifting boom length and lifting capacity also meet the requirements. the tower crane can meet the requirements. However, without Assumption 2, the maximum lifting height of some tower cranes will not meet the height requirements of the building, which may lead to the wrong answer for the model selection. Therefore Assumption 2 is necessary.

The constraint of minimum safe distance between tower cranes is set in this model, but it is not a conflict-free area between tower cranes, and there will be certain delays between tower cranes due to avoidance or coordination work, and these delays are affected by many factors and cannot be accurately evaluated in this study. So, this study assumes that there will be no collision between tower cranes; thus it is not affected by the delay time.

Unlike cast-in-place projects, tower cranes in modular projects also need to assist in the assembly of components. The difference in the difficulty of assembly between the components and the different proficiency of the staff in assembly will lead to different delay times for the tower crane to assist in assembly, which will only affect the progress of the project and will not affect the time for the tower crane to lift the components, so the impact of the assembly time of the components on the running time of the tower crane is not considered in the model.

Because the trailer consignment has the characteristic of walking and stopping, the components do not stay after lifting, and as long as the location is optimal, the next vehicle consigning the components can stop at the location where the previous vehicle stopped, which will not cause vehicle congestion, so the model considers that the trailer parking can be used many times, i.e., multiple components can be provided.

3.2. Symbol Definition

The following parameters and symbols are involved in the mathematical model established in this paper, and their specific meanings are shown below:

i: Available trailer parking spots;
I: Total number of available trailer parking spots;
j: Demand points for components;
J: Total number of component demand points;
k: Available tower crane locations;
K: Total number of available tower crane positions;
l: Component type;
L: Total number of component types;
Kc: Tower crane type;
V_r^k: Speed of the radial movement of the hook along the boom;
V_ω^k: The tangential motion speed of the boom;
R_K: Tower crane jib length.

3.3. Horizontal Motion Model of Tower Crane

The motion of the tower crane can be divided into horizontal and vertical. In the horizontal motion of the tower crane, the running trajectory can be decomposed into two parts: the tangential motion of the boom and the radial motion of the hook along the boom, as shown in Figure 2.

In the figure, $\left(Tc_k^x, Tc_k^y, Tc_k^z\right)$ are the coordinates of the tower crane at position k, $\left(S_i^x, S_i^y, S_i^z\right)$ are the coordinates of the trailer at position i, and $\left(D_j^x, D_j^y, D_j^z\right)$ are the coordinates of the demand point at position j.

Zhang et al. originally developed an equation to represent these motions for estimating the running time of a tower crane in 1999 [16]. In this study, we decided to refer to this equation to represent the distance traveled by the tower crane to determine the running time of the tower crane, and a new equation, Equation (4), was added to assist in the calculation of Equation (6).

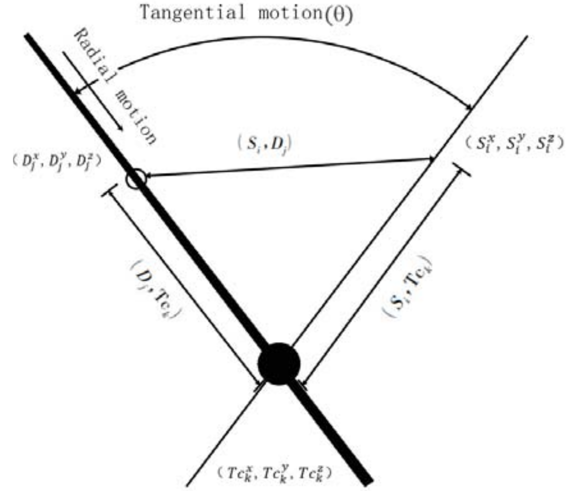


Figure 2. Horizontal motion of a tower crane.

Equations (1)–(3) show the tower crane, trailer location, and the horizontal distance between the three components' demand position:

$$\rho(S_i, Tc_k) = \sqrt{\left(S_i^x - Tc_k^x\right)^2 + \left(S_i^y - Tc_k^y\right)^2} \tag{1}$$

$$\rho(D_j, Tc_k) = \sqrt{\left(D_j^x - Tc_k^x\right)^2 + \left(D_j^y - Tc_k^y\right)^2} \tag{2}$$

$$\rho(S_i, D_j) = \sqrt{\left(S_i^x - D_j^x\right)^2 + \left(S_i^y - D_j^y\right)^2} \tag{3}$$

where the angle of the radial movement of the boom can be used to express the distance between the three; Equation (4) is:

$$\rho(S_i, D_j)^2 = \rho(S_i, Tc_k)^2 + \rho(D_j, Tc_k)^2 - 2\rho(S_i, Tc_k)\rho(D_j, Tc_k)\cos(\theta) \quad (0 \leqslant \theta \leqslant \pi) \tag{4}$$

Defining $T_{r(i,j)}^k$ as the time of radial movement of the hook along the boom and V_r^k as the speed of radial movement of the hook along the boom, then $T_{r(i,j)}^k$ is expressed in Equation (5) as:

$$T_{r(i,j)}^k = \left|\rho(S_i, Tc_k) - \rho(D_j, Tc_k)\right| / V_r^k \tag{5}$$

Defining $T_{\omega(i,j)}^k$ as the time of the tangential motion of the boom and V_ω^k as the velocity of the tangential motion of the boom, $T_{\omega(i,j)}^k$ is expressed in Equation (6) as:

$$T_{\omega(i,j)}^k = \arccos\left\{\left[\rho(S_i, Tc_k)^2 + \rho(D_j, Tc_k)^2 - \rho(S_i, D_j)^2\right] / 2\rho(S_i, Tc_k)\rho(D_j, Tc_k)\right\} / V_\omega^k \\ (0 \leqslant \arccos(\theta) \leqslant \pi) \tag{6}$$

Regardless of the horizontal motion of the tower crane or the vertical motion mentioned below, the specific operation of the tower crane is controlled by a human, and the coherence of the tangential motion and radial motion in the horizontal motion of the tower crane will be influenced by the operator's operation level, so a coefficient α is introduced to measure the degree of coherence of the tangential motion and radial motion, and its value ranges from 0.0 to 1.0 motion, and the more discrete the radial motion, the longer the horizontal running time $T^k_{l(i,j)}$. $T^k_{l(i,j)}$ is finally expressed in Equation (7) as:

$$T^k_{l(i,j)} = \max\left(T^k_{r(i,j)}, T^k_{\omega(i,j)}\right) + \alpha\min\left(T^k_{r(i,j)}, T^k_{\omega(i,j)}\right) \tag{7}$$

3.4. Model of Vertical Motion of Tower Crane

The vertical movement of the tower crane can be simplified to the vertical movement of the hook; that is, the hook lifts the member from the trailer parking point (the height at which the member is on the trailer) to D^z_j plus h, and then descends to D^z_j. Note that a loss height h is introduced here because in the lifting process, the members of the assembled building have strict installation sequence requirements to avoid the lifting of the next piece of the member in the process of lifting the previous piece installed. The height difference is defined as h (h is taken as 1.5 m in this paper), as shown in Figure 3.

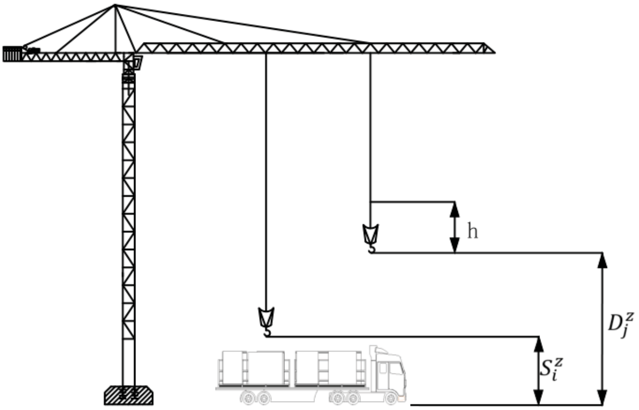


Figure 3. Vertical movement of the hook.

Defining $T^k_{v(i,j)}$ as the vertical motion time of the tower crane and V^k_v as the velocity of the hook in the vertical direction, $T^k_{v(i,j)}$ is expressed by Equation (8) as:

$$T^k_{v(i,j)} = \left(\left|D^z_j - S^z_i\right| + 2\mathrm{h}\right) / V^k_v \tag{8}$$

Additionally, considering the operation level of the tower crane operator, there is a certain degree of coherence between the horizontal and vertical movements of the tower crane, and the coefficient β is introduced to measure the degree of coherence between the horizontal and vertical movements of the tower crane, and its value range is also 0.0~1.0. When β is larger, the lower the operation level of the operator, the more discrete the horizontal and vertical movements of the tower crane, and the longer the single running time $T^k_{(i,j)}$ of the tower crane. $T^k_{(i,j)}$ is expressed in Equation (9) as:

$$T^k_{(i,j)} = \max\left(T^k_{l(i,j)}, T^k_{v(i,j)}\right) + \beta\min\left(T^k_{l(i,j)}, T^k_{v(i,j)}\right) \tag{9}$$

3.5. Decision Variables

For better optimization and solution of the model, multiple binary decision variables are introduced, where:

The binary variable $€_k$ indicates whether the candidate position of a particular tower crane at the construction site is selected or not, and the value of $€_k$ is one when the tower crane is placed at position *k*, and zero otherwise. This is expressed in Equation (10) as

$$€_k = \begin{cases} 1 & \text{Placement of tower crane at } k \\ 0 & \text{No tower crane was placed at } k \end{cases} \tag{10}$$

The binary variable $\&_{k,kc}$ denotes the type *Kc* of the tower crane at *k*. The value of $\&_{k,kc}$ is one when the type *Kc* of the tower crane at *k* is selected; otherwise, it is zero. It is expressed in Equation (11) as:

$$\&_k = \begin{cases} 1 & k \text{ at tower crane type selection } Kc \\ 0 & k \text{ at the tower crane type does not choose } Kc \end{cases} \tag{11}$$

The binary variable $X_{i,l}$ represents the relationship between the member and the trailer parking point. The value of $X_{i,l}$ is one when member *l* is consigned to the trailer parking point *i* and zero otherwise. It is expressed in Equation (12) as:

$$X_{i,l} = \begin{cases} 1 & \text{Component } l \text{ consignment to trailer parking point } i \\ 0 & \text{Component } l \text{ was not consigned to trailer parking point } i \end{cases} \tag{12}$$

The binary variable $D_{l,j}$ indicates whether there is a demand for component *l* at point *j*. When the demand exists, the value of $D_{l,j}$ is one; otherwise, it is zero. This is expressed in Equation (13) as:

$$D_{l,j} = \begin{cases} 1 & \text{The existence of a demand for } l \text{ at point } j \\ 0 & \text{There is no demand for } l \text{ at point } j \end{cases} \tag{13}$$

3.6. Demand Identification and Supply of Components

The introduction of the parameter $DN_{l,j}$ indicates the number of components of type *l* demanded at point j (it can also be interpreted as the number of times *j* needs to be lifted); in most cases, a *j* point is at most one, and the number of components demanded is one. This is because this model is more customized to the site, and the general volume of the components is larger than the reference unit of the coordinates. To prevent some smaller components needing to be lifted more than once, as well as to further improve the applicability of this model, Formula (14) is proposed, at which time the relationship between $DN_{l,j}$ and $D_{l,j}$ is expressed in Equation (14) as:

$$\sum_{l=1}^{L} DN_{l,j} \geqslant \sum_{l=1}^{L} D_{l,j}, \quad \forall j \in \{1, \ldots\ldots J\} \tag{14}$$

The auxiliary variable $\Omega_{k,kc,i,l,j}$, which represents the single supply of components, is introduced to simulate the motion flow of the tower crane, indicating that the value of $\Omega_{k,kc,i,l,j}$ is one when the tower crane is located at *k*, and type kc delivers the component *l* located at the trailer parking point *i* to the demand point *j*. The relationship between demand and supply at this point is expressed by Equation (15) as:

$$\sum_{k=1}^{K} \sum_{kc=1}^{KC} \sum_{i=1}^{I} \sum_{l=1}^{L} \Omega_{k,kc,i,l,j} = DN_{l,j}, \quad \forall l \in \{1, \ldots\ldots L\}, \forall j \in \{1, \ldots\ldots J\} \tag{15}$$

3.7. Constraints on Trailer Stopping Points

The difference between a trailer transporting components to the construction site and a conventional yard is the stop-and-go characteristic, and because of the sequential characteristic of component installation and the existence of component installation time, it is considered that a certain trailer stopping point can supply multiple components without conflict (i.e., Assumption 5). To ensure that the required components are delivered by trailers to the trailer parking point, the binary parameters $D_{l,j}$ and $X_{i,l}$ need to satisfy Equation (16):

$$\sum_{i=1}^{I} X_{i,l} \geqslant \sum_{j=1}^{J} D_{l,j}, \quad \forall l \in \{1, \ldots L\} \tag{16}$$

Then, the relationship between $DN_{l,j}$ and $D_{l,j}$ at this point again needs to satisfy Equation (17) expressed as:

$$\sum_{j=1}^{J} DN_{l,j} \geqslant \sum_{j=1}^{J} D_{l,j}, \quad \forall l \in \{1, \ldots L\} \tag{17}$$

Of course, we can also have a separate constraint on a trailer stop to limit the types of components supplied by a certain supply point, i.e., Equation (18). The constant is a custom constant (how much is defined according to the actual engineering information for human control).

$$\sum_{l=1}^{L} X_{i,l} \leqslant \text{ constant}, \quad \forall i \in \{1, \ldots I\} \tag{18}$$

3.8. Constraints on Tower Crane Position

Constrained by the candidate locations of the tower cranes and the total number of tower cranes, Equation (19) restricts the lifting of the members to occur only on one of the tower crane candidate locations:

$$\begin{aligned} &\Omega_{k,kc,i,l,j} \leqslant €_k, \quad \forall i \in \{1, \ldots . I\}, \quad \forall j \in \{1, \ldots J\}, \quad \forall k \in \{1, \ldots . K\}, \\ &\forall kc \in \{1, \ldots \ldots Kc\}, \quad \forall l \in \{1, \ldots \ldots L\} \end{aligned} \tag{19}$$

In the example of this paper, the number of tower cranes is fixed, and Equation (20) requires that the total number of selected tower cranes is equal to a constant K_{numble}. However, Equation (20) can also be an inequality constraint to accommodate situations where the number of tower cranes is uncertain. This is because, for generally assembled residential cluster projects, a single tower crane is sufficient to cover a single building. For some large residential projects where multiple tower cranes are required to cooperate, it is sufficient to change Equation (20) into an inequality, where K_{numble} indicates the maximum number of tower cranes.

$$\sum_{k=1}^{K} €_k = K_{\text{numble}} \tag{20}$$

In this study, although Assumption 3 exists, it is still necessary to ensure the minimum safety distance (msd) between tower cranes. In general, msd is taken as 2 m, which can also be adjusted according to the actual demand and site conditions but cannot be smaller than the minimum safety distance required by the codes around the world. The distance between arbitrary tower cranes is expressed by Equation (21) as:

$$\rho(Tc_k, Tc_{k'}) = \sqrt{\left(Tc_k^x - Tc_{k'}^x\right)^2 + \left(Tc_k^y - Tc_{k'}^y\right)^2} \tag{21}$$

Then, the safety distance between the tower cranes is expressed by Equation (22) as:

$$\rho(Tc_k, Tc_{k'}) - \max(R_k, R_{k'}) \geqslant \text{msd} \tag{22}$$

3.9. Constraints on the Type of Tower Crane

The model and configuration specifications of the tower crane are predetermined by the person in charge of the project. For each tower crane *k*, Equation (23) constrains all component lifting movements made at k to use the same type of tower crane *kc*,

$$\begin{aligned}&\Omega_{k,kc,i,l,j} \leqslant \&_{k,kc}, \quad \forall i \in \{1,\ldots I\}, \quad \forall j \in \{1,\ldots J\}, \quad \forall k \in \{1,\ldots K\},\\ &\forall kc \in \{1,\ldots Kc\}, \forall l \in \{1,\ldots L\}\end{aligned} \tag{23}$$

3.10. Capacity Constraints on the Selected Tower Crane Configuration

The lifting capacity of a tower crane is limited, and its performance varies with distance and structure. The specific relationships are described in the project examples. The weight of the rigging and pulleys has been considered in the calculation of the tower crane lifting capacity. To ensure that the lifting capacity of the selected tower crane meets the lifting requirements, the parameter $AM_{k,kc,i,j}$ is introduced, which indicates the maximum lifting capacity of the kc model at *k* at the relevant boom length, when it transports the component *l* at the supply point *i* to the demand point *j*. The value of parameter $AM_{k,kc,i,j}$ depends on the distance between *i* and *j* at time $\rho(S_i, Tc_k)$ and the size of $\rho\left(D_j, Tc_k\right)$ as well as the load of the relevant boom length of the tower crane. $DW_{l,j}$ indicates the weight of Type l member (single member) at *j*. Equation (24) ensures that the lifting capacity of the tower crane meets the lifting requirements.

$$\begin{aligned}&AM_{k,kc,i,j} - DW_{l,j} \geqslant 0, \quad \forall i \in \{1,\ldots I\}, \quad \forall j \in \{1,\ldots J\},\\ &\forall k \in \{1,\ldots .K\}, \quad \forall kc \in \{1,\ldots Kc\}\end{aligned} \tag{24}$$

3.11. Objective Function

The objective function defined in Equation (25) represents the total operating cost (TC) of lifting the components from the supply point to the demand point using a tower crane in a feasible configuration (i.e., $\Omega_{k,kc,i,l,j}$).

$T^k_{(i,j)}$ expresses the total time of one tower crane operation (i.e., lifting of the component from the supply point to the demand point), and due to Assumption 1, the time for the tower crane to return to the supply point to facilitate the next lifting operation is also $T^k_{(i,j)}$. C_{kc} is the operating cost of the tower crane *kc*, determined by the type of tower crane.

$$\mathrm{TC} = \sum_{k}^{K}\sum_{kc}^{KC}\sum_{i}^{I}\sum_{l}^{L}\sum_{j}^{J}\Omega_{k,kc,i,l,j}\left(2 * T^k_{(i,j)}\right)DN_{l,j}C_{kc} \tag{25}$$

4. Case Study

4.1. Project Overview

The project is located in Wuhan City, Hubei Province. The project covers an area of about 114,000 square meters, with a total construction area of about 524,000 square meters, (including 264,000 square meters of general commercial housing, 95,000 square meters of price-restricted resettlement housing, 13,100 square meters of public rental housing, 18,000 square meters of commercial buildings, and about 0.87 million square meters of supporting buildings and kindergartens). The project has 15 high-rise buildings (including 1 college student rental apartment and 3 returned houses), 3 super high-rise residential buildings, 1 sales office, and 1 supporting kindergarten.

The overall building volume of the project is too large for all of them to be substituted in the study. Therefore, in this paper, three high-rise modular residential buildings in Area 2, #6, #7, and #8, are selected as examples to substitute, as shown in Figure 4.

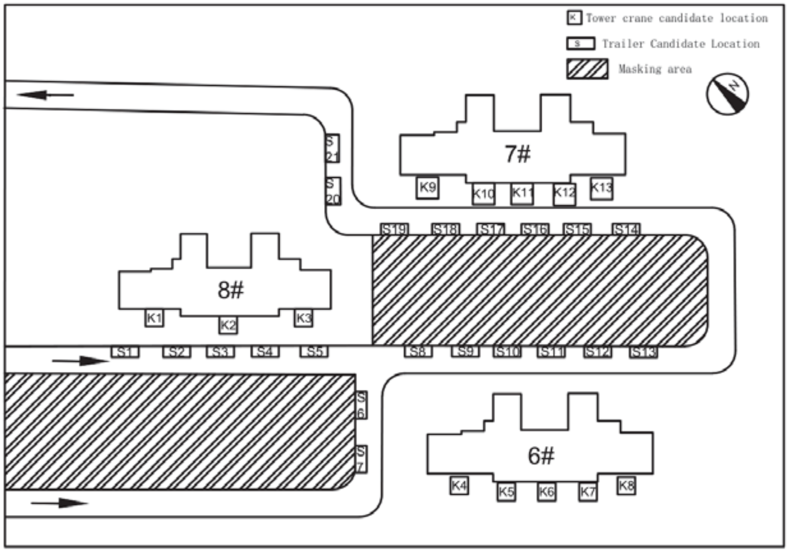


Figure 4. High-rise modular housing in Area 2.

The building height of #6 and #7 is 34 stories, and the total height of the building is 95.54 m. The building height of #8 is 22 stories, and the total height of the building is 63.75 m. The width of the building is 46.8 m, and the depth is 18.2 m. The horizontal spacing between #8, #6, and #7 is about 17 m, the vertical spacing is about 18 m and 13 m, and the vertical spacing between #6 and #7 is about 48.5 m. The main prefabricated components are prefabricated facades, prefabricated windows, and prefabricated staircases, with a total of 60 types of components. (The information on demand points below is mainly based on building #8, and the information on supply points and tower cranes will be given).

4.2. Data Information

The floor plans of buildings #6, #7, and #8 are shown in Figures 5 and 6.

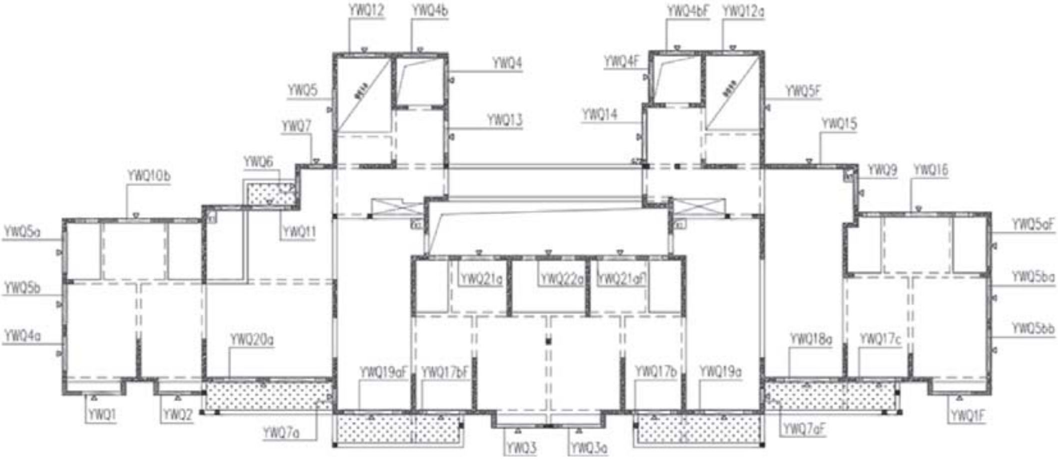


Figure 5. Plan of vertical prefabricated components of buildings #6 and #7.

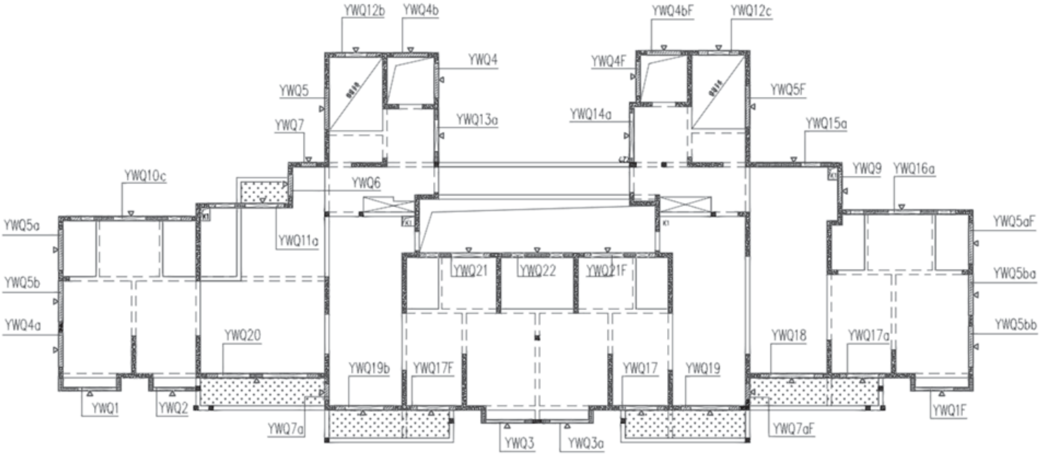


Figure 6. Plan of vertical prefabricated components of building #8.

Building #8 is an assembly floor from the 5th floor onwards. The number of requirements for each type of component and the weight of each component in building #8 are shown in Table 1.

Table 1. Information table of prefabricated components demand for building #8 (13 floors, for example).

Demand Point Serial Number	Required Component Number	Number of Components (Pcs)	Weight of Individual Components (T)	Demand Point Coordinates (x, y, z)
D81	YWQ1	1	4.348	(27.9, 53.5, 34.8)
D82	YWQ1F	1	4.348	(68.7, 53.5, 34.8)
D83	YWQ2	1	2.403	(30.9, 53.5, 34.8)
D84	YWQ3	1	2.461	(48.9, 52, 34.8)
D85	YWQ3a	1	2.461	(51.6, 52, 34.8)
D86	YWQ4	1	2.304	(45.3, 66, 34.8)
D87	YWQ4F	1	2.304	(54.3, 66, 34.8)
D88	YWQ4a	1	2.248	(27.6, 55.2, 34.8)
D89	YWQ4b	1	2.304	(43.5, 68.1, 34.8)
D90	YWQ4bF	1	2.304	(55.5, 68.1, 34.8)
D91	YWQ5	1	2.736	(39.9, 66, 34.8)
D92	YWQ5F	1	2.736	(59.7, 66, 34.8)
D93	YWQ5a	1	2.736	(27.6, 60, 34.8)
D94	YWQ5aF	1	2.736	(69.9, 60, 34.8)
D95	YWQ5b	1	2.67	(27.6, 55.8, 34.8)
D96	YWQ5ba	1	2.67	(69.9, 57, 34.8)
D97	YWQ5bb	1	2.67	(69.9, 54, 34.8)
D98	YWQ6	1	1.347	(38.1, 61.2, 34.8)
D99	YWQ7	1	0.98	(39, 63, 34.8)
D100	YWQ7a	1	0.958	(39.9, 51.6, 34.8)
D101	YWQ7aF	1	0.958	(59.7, 52.5, 34.8)
D102	YWQ9	1	2.11	(63.9, 61.8, 34.8)
D103	YWQ10c	1	4.961	(30, 60.6, 34.8)
D104	YWQ11a	1	1.82	(37.5, 61, 34.8)
D105	YWQ12b	1	2.046	(40.5, 68.1, 34.8)
D106	YWQ12c	1	2.046	(58.5, 68.1, 34.8)
D107	YWQ13a	1	2.445	(45.3, 63, 34.8)
D108	YWQ14a	1	1.71	(54, 63, 34.8)
D109	YWQ15a	1	4.257	(63, 63, 34.8)
D110	YWQ16a	1	5.254	(66.6, 60.6, 34.8)
D111	YWQ17	1	1.82	(54.9, 51.6, 34.8)
D112	YWQ17a	1	1.82	(65.4, 52.8, 34.8)
D113	YWQ17F	1	1.82	(44.7, 51.6, 34.8)
D114	YWQ18	1	1.52	(61.5, 52.8, 34.8)
D115	YWQ19	1	1.59	(58.8, 51.6, 34.8)
D116	YWQ19b	1	1.59	(41.1, 51.6, 34.8)
D117	YWQ20	1	3.61	(36, 53.1, 34.8)
D118	YWQ21	1	3.118	(45, 57.5, 34.8)
D119	YWQ21F	1	3.118	(57, 57.5, 34.8)
D120	YWQ22	1	3.83	(51, 57.5, 34.8)

The tower cranes in this project are mainly used for vertical and horizontal transportation of various PC components. After technical and economic selection, a total of 17 tower cranes are required. Among them, 3 cranes are required for buildings #6, #7, and #8. The project provides four kinds of optional tower cranes: JP6513, ZTT6513, TC6513, and TC7030 (see Table 2).

Table 2. Optional tower crane types.

Type	Model	Arm Length (m)	Lifting Weight at the End of the Jib (t)	Maximum Lifting Weight (t)	Operating Cost (Yuan/min)
KC1	JP6513	30	5.1	6	1.48
KC2	ZTT6513	40	3.21	6	1.87
KC3	TC6513	50	2.14	6	2.16
KC4	TC7030	45	6	12	2.23

There is no restriction on the number of tower cranes of a certain type that can be used. The jib length of each type of tower crane is fixed in this study, and since it is assumed that the lifting height of the tower crane satisfies the building's needs. The cost of the tower crane is only related to the model of the crane and its operating time. Based on the determined jib length in advance, information on the lifting capacity of the tower crane at the relevant distance (see Table 3) and the tower crane operating rate (see Table 4) can be obtained from the tower crane information provided by the tower crane rental company.

Table 3. Lifting capacity of optional tower cranes.

Type	Model	10 m	20 m	30 m	40 m	50 m
KC1	JP6513	6.0	6.0	5.1	—	—
KC2	ZTT6513	6.0	6.0	4.8	3.21	—
KC3	TC6513	6.0	6.0	3.77	2.86	2.14
KC4	TC7030	12.0	12.0	9.76	6.93	—

Table 4. Operating rates of optional tower cranes.

Type	Model	Hook Lifting Speed (m/min)	Rotation Speed of the Boom (r/min)	Radial Velocity of the Trolley (m/min)	Difficulty of Operation	
					α	β
KC1	JP6513	36	0.7	30	0.2	0.7
KC2	ZTT6513	45	0.7	35	0.2	0.7
KC3	TC6513	40	0.7	50	0.2	0.7
KC4	TC7030	50	0.6	60	0.2	0.7

A total of 13 candidate tower crane locations were identified in the project example, of which 5 candidate locations were identified for buildings #6 and #7, and 3 candidate locations were identified for building #8. The candidate locations of the tower cranes were input into the computer as model data in the form of coordinate points, and the specific coordinates of the candidate locations of the tower cranes are shown in Table 5.

Table 5. Coordinates of the candidate location of the tower crane.

Location	x	y	z	Location	x	y	z
K1	33	51	0	K8	138	13.5	0
K2	49.5	49.5	0	K9	93	79.5	0
K3	66	51	0	K10	105	78	0
K4	95	13.5	0	K11	114	78	0
K5	111	12	0	K12	123	78	0
K6	120	12	0	K13	132	79.5	0
K7	129	12	0				

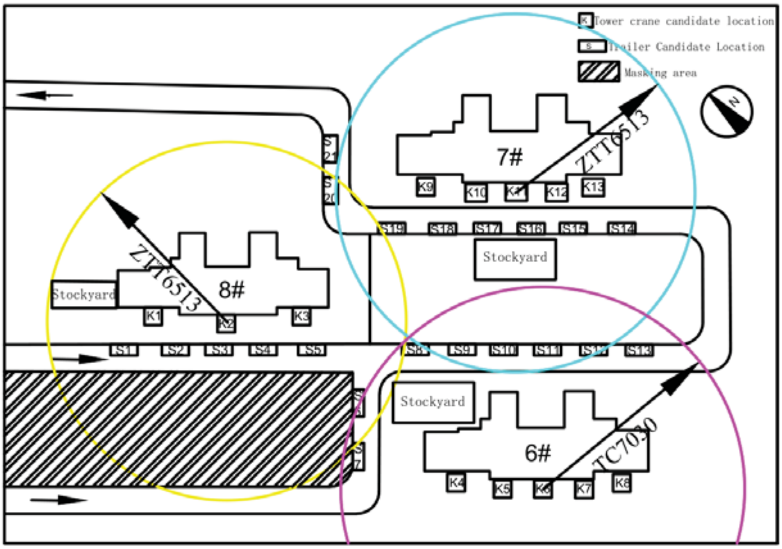
According to the project plan, there are 3 roads designed for the 3 high-rise assembly buildings #6, #7, and #8, 2 of which are used as the entrance and 1 as the exit for the trailers. All the trailer stops are along the left side of the road so that the road will not be blocked due to the trailer stops. Trailer stops are spaced to ensure sufficient space for trailers to enter and exit. To ensure enough parking points for trailers, 21 available trailer parking points were set up in the project, and the coordinates of the trailer parking points are shown in Table 6.

Table 6. Coordinates of trailer parking points.

Location	x	y	z	Location	x	y	z
S1	27	43.5	2	S12	129.9	43.5	2
S2	37.5	43.5	2	S13	141.6	43.5	2
S3	48	43.5	2	S14	138	70.5	2
S4	57.6	43.5	2	S15	126.9	70.5	2
S5	67.2	43.5	2	S16	120.6	70.5	2
S6	78.9	31.5	2	S17	111	70.5	2
S7	78.9	19.5	2	S18	102	70.5	2
S8	91.5	43.5	2	S19	91.5	70.5	2
S9	102	43.5	2	S20	72.6	78.6	2
S10	111	43.5	2	S21	72.6	87.6	2
S11	120.9	43.5	2				

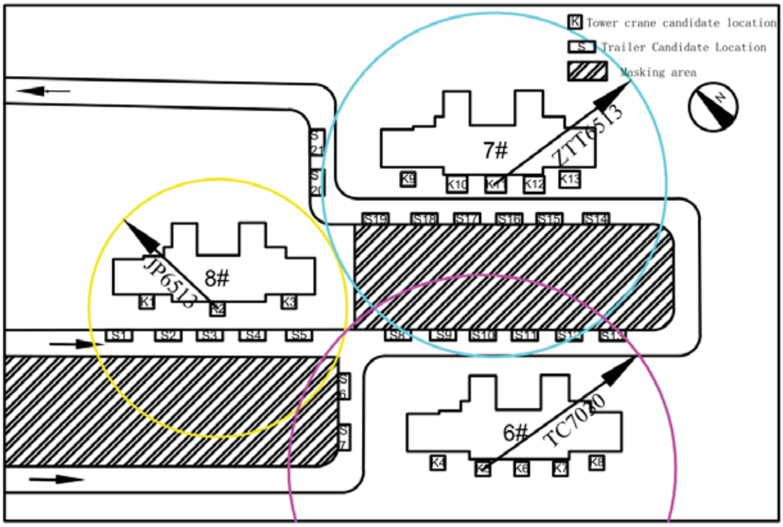
4.3. Optimization Results

As the project is completed, in this project, the construction unit chose to arrange the component yard at the construction site, and the arrangement is shown in Figure 7a.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. (**a**) Tower crane arrangement before optimization; (**b**) optimized tower crane arrangement diagram.

To meet the requirements of the three buildings, a total of three yards were arranged to stack the components, one yard for each building. Among them, the yard of building #6 is located at the top left of the building, the yard of building #7 is located in an unusable plot, and the components need to be dismantled immediately after the completion of lifting. The yard of building #8 is located at the left side of the building. To meet the construction demand, the tower crane of building #6 is located at K5, and the selected model is TC7030; the tower crane of building #7 is located at K11, and the selected model is ZTT6513; the tower crane of building #8 is located at K2, and the selected model is TC6513.

Based on the known data information, the solution is programmed based on Python to produce the solution results. The optimized tower crane arrangement is shown in Figure 7b.

The optimized crane locations, crane types, docking point locations for each type of component, and crane run times and final costs are depicted in Table 7.

Compared with the results before optimization, the tower crane of building #6 is adjusted from K6 to K5 with the same tower crane model, the tower crane location and tower crane model of building #7 are unchanged, and the tower crane location of building #8 is unchanged, but the tower crane model is adjusted to JP6513. Lifting components from trailers reduces crane work time by 8.68% and total cost by 12.47% compared to lifting from the yard and reduces the yard footprint. In some central cities where land is expensive, the cost of yard space is not negligible, and some building sites simply do not have extra space for a component yard. In addition, the overlapping area between the tower cranes in building #8 has been reduced by 28.1% due to the shortening of the tower crane jib length, and the overlapping area between the tower cranes in building #8 and building #7 has completely disappeared, which means the operation of the tower crane in building #8 will not be affected by the tower crane in building #7.

Table 7. Optimization result information.

Selected Tower Crane Location	Selected Tower Crane Model	Selected Trailer Stopping Points and Supply Components	Tower Crane Operation Time (min)	Tower Crane Operation Cost (Yuan)
KC2	JP6513	S1(YWQ1, YWQ2, YWQ4, YWQ4a YWQ4b, YWQ5, YWQ5a, YWQ5b YWQ7, YWQ10c, YWQ12b) S2(YWQ3, YWQ6, YWQ7a, YWQ11a YWQ13a, YWQ17F, YWQ19b, YWQ20 YWQ21) S4(YWQ3a, YWQ7aF, YWQ17, YWQ18 YWQ19, YWQ21F, YWQ22) S5(YWQ1F, YWQ4F, YWQ4bF, YWQ5F YWQ5aF, YWQ5ba, YWQ5bb, YWQ9 YWQ12c, YWQ14a, YWQ15a, YWQ16a YWQ17a)	1699.74	2515.68
KC6	TC7030	S7(YWQ1, YWQ2, YWQ20a, YWQ7a YWQ10b, YWQ5a, YWQ5b, YWQ4a) S10(YWQ19aF, YWQ17F, YWQ21aF, YWQ22a, YWQ13, YWQ4, YWQ4b, YWQ12, YWQ5, YWQ7, YWQ6, YWQ11) S11(YWQ3, YWQ3a, YWQ4bF, YWQ4F YWQ14, YWQ21a) S12(YWQ17, YWQ19a, YWQ7aF, YWQ18a YWQ17c, YWQ1F, YWQ5bb, YWQ5ba YWQ5aF, YWQ16, YWQ9, YWQ15 YWQ5F, YWQ12a)	2854.98	6366.6
KC11	ZTT6513	S14(YWQ17c, YWQ5bb, YWQ5ba, YWQ5aF, YWQ16, YWQ9, YWQ15, YWQ5F, YWQ12a, YWQ4bF YWQ4F, YWQ14) S15(YWQ3a, YWQ17, YWQ19a, YWQ7aF YWQ18a, YWQ1F, YWQ21a) S18(YWQ20a, YWQ7a, YWQ19aF, YWQ17F, YWQ3, YWQ21aF) S19(YWQ1, YWQ2, YWQ22a, YWQ13 YWQ4, YWQ4b, YWQ12, YWQ5 YWQ7, YWQ6, YWQ11, YWQ10b YWQ5a, YWQ5b, YWQ4a)	3129.63	5852.4

5. Discussion

For conventional buildings, the layout planning of tower cranes has been well studied, and new research is growing every year, while relatively little research has been conducted on TCLP compared to TCLP for high-rise modular buildings, especially when trailer supply components are incorporated into TCLP. Previous authors have only solved the calculation of single tower cranes and individual component supply points using genetic algorithms. Therefore, this study focuses on the selection of trailer locations, considers multiple trailer locations as variables to consider the location of the tower crane, builds a mixed integer linear programming model, and substitutes it into the project example to prove the validity of the model.

From the results of the above example, it can be observed that in the tower crane layout planning for the high-rise modular housing complex project, building a mixed integer linear programming model and solving it with Python is possible and can determine the type of tower crane, the tower crane location, and the trailer parking location based on the lowest cost objective. Based on the results of the model, we can also obtain some suggestions for this example, such as the tower crane TC7030 for building #6 in the example. In fact, the jib length of the ZTT6513 model fully meets the needs of construction, but the lifting capacity cannot meet the needs of the relevant location of the component YWQ16, and the lifting capacity of the TC7030 model is too powerful, which will also cause waste of tower crane resources at this time. Thus, we suggest that the construction unit communicates with the tower crane leasing party to provide a more suitable tower crane. In addition, even for a simple site shape and building design, the crane layout diagrams for the two cases of setting up a yard and lifting from a trailer are different. For example, for building #8, to have the tower crane cover the component yard, a TC6513 crane with a 40 m jib has to be used, but if the crane is lifted from a trailer parked on the road, a JP6513 crane with a 30 m jib is perfectly adequate.

For modular building projects with complex sites and building shapes, even though it becomes more difficult to choose the location of the cranes and trailers, it only increases the time for the computer to calculate the results and does not affect the validity of the model. However, at the same time, we also note that there are more limitations due to the presence of linear features of the algorithm. In the follow-up research plan, we are considering: feature screening in different dimensions, optimization algorithms for multiple objectives, and exploration of the applicability of machine learning in large sample low latency scenarios. In addition, we can also set other constraints in the model or add multiple objectives when we only need to change the model slightly by adding weights between multiple objectives. It is worth noting that the premise of using trailers as the variable does not take into account the delay in the supply of components from the factory or other possible delays in the supply of components, which will result in the loss of costs for the tower crane if the components are delayed and the corresponding tower crane has no components to hoist. At this point, if these lost costs are added, the comparison between lifting from the yard and lifting directly from the trailers will need to be re-examined, and a more suitable solution will be chosen for projects where there is sufficient space to stack the components.

6. Conclusions

High-rise modular houses are usually located in cities with dense or small construction sites. Construction sites often do not have enough space to store a large number of prefabricated components, and even if a demountable component yard is established at some spare sites, it will waste resources, increase the cost of storing the components on-site, and cause the double-handling of components. In addition, due to site constraints, even if a component yard is set up, it is often not in the best location, resulting in the layout of the tower crane also being affected, which further increases the workload and cost of the tower crane. Lifting the components directly from trailers to the construction site will not only save the area of the construction site but also greatly reduce the workload of the tower crane, thus reducing the cost. Based on this, this study builds a mixed integer linear programming model for pre-construction tower crane planning in high-rise residential construction, reflecting the type of tower crane, tower crane location, and trailer location with minimum cost.

In the TCLP of a high-rise modular housing complex project, the main factors affecting tower crane cost are the type of the tower crane and the running time of the tower crane. The type of tower crane mainly meets the lifting capacity of the members at the relevant jib length, and the running time of the tower crane depends on its distance from the members and the distance from the member demand point. Therefore, with the member demand point unchanged, this study constructs an optimization model for minimizing the running distance of the tower crane by taking both the location of the crane and the trailer as variables, which can give suggestions for crane location and, type and the stopping position of each trailer at the site. Then, the conclusions drawn from this study model were compared with the original proposal of a completed project, and it was found that lifting the components directly from trailers would reduce the working time of the tower crane by 8.68% and the cost by 12.47% compared with setting up a component yard on site, thus verifying the validity of the model.

This study presents a new approach to TCLP for high-rise modular housing complex projects with some academic value. The problem of optimizing multiple tower cranes and multiple docking points simultaneously is solved with the trailer docking point as the variable. In addition to the variables listed above, we can also take more variables into account when deriving optimization results and transform the single-objective problem into a multi-objective one, such as weighting the running time of the tower crane, the capacity of the tower crane, etc.

This study also has some limitations. The trailer delivery of components has very strict time requirements, is affected when the delivery of components happens to be delayed, the wrong components are sent from the factory, or there is a public channel to deliver the components, etc. These situations will lead to no component lifting at the site, thus to wasted resources and delays in construction. In addition, when planning the layout of tower cranes, the land cost in urban areas and the grid towers around the construction sites can also influence the optimal results of tower cranes. In future studies, we could consider the production shipment of the component plant, traffic conditions, limitations of the construction site for the tower crane, etc., as factors affecting tower crane layout planning.

Author Contributions: Conceptualization, C.Z. and F.D.; methodology, F.D.; software, Z.X.; validation, F.D.; formal analysis, W.L.; investigation, F.D.; resources, C.Z.; data curation, F.D.; writing—original draft preparation, F.D.; writing—review and editing, C.Z.; visualization, W.L.; supervision, C.Z.; project administration, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the 5G-based tower intelligent remote control technology research project funded by CSCEC Science and Technology Department (CSCEC-2020-Z-25).

Data Availability Statement: Data supporting the results of this study are available from the corresponding author upon reasonable request.

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

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The Effect of Fines Content on Compressional Behavior When Using Sand–Kaolinite Mixtures as Embankment Materials

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Abstract: In South Korea, Honam High-Speed Railway has a relatively large residual settlement issue and high fines content has been pointed out as one of the causes. Design guidelines regulate not to use soils containing fines content higher than 25%. However, there is no background information on the effect of fines content on settlement. Therefore, this paper aims to investigate compressional behavior according to fines content using sand and kaolinite. Oedometer test results showed that the compression index is lowest with fines content of 15% to 20% at which the mixture produced maximum density. The optimum fines content for inducing low settlement would be 15% to 20% for the sand–kaolinite mixture. Transition fines content (TFC), which shows sand-like to claylike behavior, was observed to have between 21% and 26% of fines content. Critical fines content (fcrit) where a minimum void ratio occurs was estimated as 21.67%. These behavioral changes appear when fines content is greater than the optimum fines content. SEM also shows that the kaolinite particles were overlapped, creating flat surfaces with a fines content higher than 30%, and showing clay-like behavior. Based on the analysis results, engineers can simply identify the behavior of embankment materials to ensure optimum fines content and consequently minimize long-term settlement potential.

Keywords: compaction; oedometer; intergranular void ratio; transition fines content; compression index; optimum fines content

Citation: Kaothon, P.; Lee, S.-H.; Choi, Y.-T.; Yune, C.-Y. The Effect of Fines Content on Compressional Behavior When Using Sand–Kaolinite Mixtures as Embankment Materials. *Appl. Sci.* **2022**, *12*, 6050. https://doi.org/10.3390/app12126050

Academic Editors: Albert P. C. Chan, Srinath Perera, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 2 May 2022
Accepted: 8 June 2022
Published: 14 June 2022

1. Introduction

In South Korea, Honam High-Speed Railway was constructed as a concrete slab track and opened to the public in 2015. Some sections of high embankment in the Honam High-Speed Railway have produced large residual settlement. Geotechnical engineers investigated the causes of the residual settlement and pointed out that the presence of fine materials was one of the potential causes that could induce high creep settlement [1]. Soeung et al. [2] concluded that embankment materials for railway or road constructions in Korea habitually contain silty and clayey soils which would result in residual settlement. Regarding residual settlement of embankments, Korea Rail Network Authority regulated that fines contents should not be greater than 25% as embankment materials and 12% to 25% of fines needed to be stabilized (KDS, 2021). These regulations do not have mechanical background on the amount of fine particles that should be used.

Many researchers have studied the behavior of fines content. The ratio of low-plastic fine grains in the clayey soil has a major influence on the behavior of sand–silt mixtures including both physical (index void ratio and relative density) and mechanical properties (instability, critical state, strength, and stress-dilatancy). For instance, the presence of kaolinite clay, as fine particles in sand grains, changes the engineering properties of sandy soils. The behavior of sand–silt mixtures has been investigated by researchers for low, intermediate, and high contents of fine particles [3–5]. Pitman et al. [6] carried out a laboratory study to observe the effect of fines (kaolinite, crushed silica fines, and 70–140 silica sand) and gradation on the collapse behavior of loosely compacted soil mixtures. The experimental results showed that an increase in fines content has a noticeable effect on the undrained condition at large strains, while the gradation variation of the sand seems to have a minor effect on the undrained condition. Osipov et al. [7] investigated the mechanism of liquefaction for the artificial mixture of sand with various clay contents by means of a ring shear apparatus. They could divide liquefiable and non-liquefiable clayey soils according to plasticity index. Moreover, the increase of clay content (bentonite clay) increased the liquefaction resistance. Monkul and Ozden [8] conducted oedometer tests on kaolin-sand mixtures to investigate compression behavior based on transition fines content (TFC). The results showed that when the fines content was below the TFC, the mixture behaves like sand–silt mixtures while, in the range exceeding the TFC, silt controls the compression behavior. Belkhatir et al. [9] carried out undrained monotonic triaxial tests on sand with non-plastic silt. The outcomes indicated that undrained shear strength can be linked to the fines content, intergranular void ratio, and saturated hydraulic conductivity. Phan et al. [10] studied the effects of low-plastic silt content on geotechnical properties based on the static triaxial, cyclic triaxial, and resonant column tests. Their results indicated that an increase in silt content caused an increase in cohesion and a decrease in the internal friction angle, cyclic stress ratio, and maximum shear modulus. Hsiao et al. [11] performed drained and undrained triaxial compression tests with the specimens of sands with low plastic fines content. The results showed that an increasing fines content gradually causes a high compressibility of sand–silt mixture.

Judging by the aforementioned studies, most of the research has been concerned with the overall effect of fines content on simple artificial mixtures. In South Korea, embankment materials consist of low-plastic fines. In this sense, sand and kaolinite have been selected to simulate embankment materials in a simple and systematic way. As a first step to investigate the effect of fines content on settlement behavior, sand–kaolinite mixtures were mixed according to fines content and tests were conducted under controlled conditions. This paper aims to investigate the effect of fines content on basic material properties and settlement characteristics, and thus to provide the background to fines content limitations for embankment materials in order to reduce residual settlement. Fundamental material properties were measured including compaction and oedometer tests. In addition, the effect of particle size and shape was investigated by using Scanning Electron Microscope (SEM) images. The outcomes of this study can offer useful information for investigating the behavior of embankment materials containing low-plastic fines and provide a background or a basis for proper guidelines for the selection of embankment materials.

2. Test Materials and Program

CEN standard sand and kaolinite are used to simulate embankment materials and the effect of fines content. The host material is CEN standard sand or ISO sand [12]. CEN standard sand is an artificial product consisting of several different sand fractions produced industrially by sieving. Its grain size distribution and related basic properties are provided as shown in Figure 1. The initial moisture content is less than 0.2%. The second material is kaolinite clay which is one of the most common minerals of natural clays. As an abundant mineral in soils and deposits, it has been frequently used to enhance the mechanical stability of soil structures via interaction with other soil particles [13,14]. The value of liquid limit, plastic limit, and plastic index for kaolinite are 34.98, 29.86, and 5.12, respectively. Moreover, its grain size distribution is also indicated in Figure 1 and was obtained by sieve analysis (wet sieving) and a hydrometer test with materials passing #200 sieve.

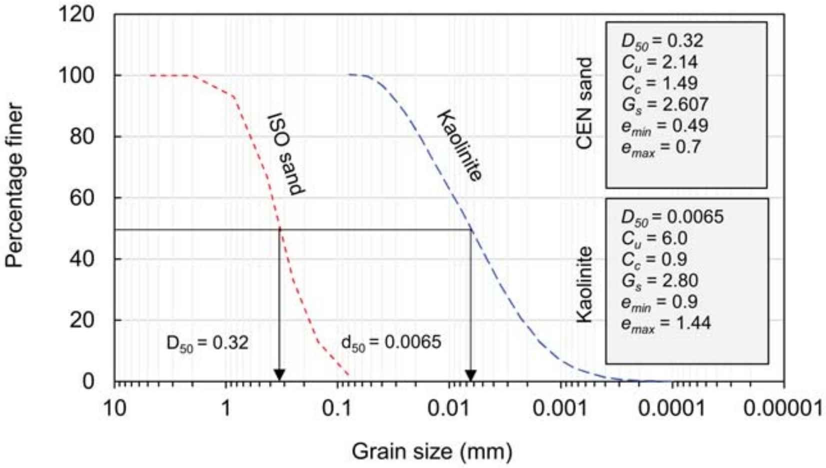

Figure 1. Grain size distribution of CEN standard sand and Kaolinite clay.

2.1. Index Properties of Mixtures

Mixtures of CEN sand and kaolinite were prepared for the tests with 8 different ratios of kaolinite (10, 15, 20, 25, 30, 40, 60, and 70% of KC (kaolinite clay) over the CEN sand weight). The mixtures were manually mixed in a container, then were put in an oven for 24 h. The dried mixtures were used to perform basic property tests such as a specific gravity test [15], sieve analysis [16], and Atterberg limit [17]. The results are summarized in Table 1. Figure 2 shows the gradation of all the mixtures.

Table 1. Index properties of kaolinite–sand mixtures.

Material	KC (%)	G_s	f_c (%)	*LL*	*PL*	*PI*
10% KC	10	2.608	10.38	11.30	0.00	11.30
15% KC	15	2.611	15.90	14.96	5.00	9.96
20% KC	20	2.615	20.41	16.60	7.20	9.40
25% KC	25	2.619	26.33	17.50	8.81	8.69
30% KC	30	2.632	31.81	18.60	9.66	8.94
40% KC	40	2.640	41.31	21.50	17.57	3.93
50% KC	60	2.655	60.49	25.70	21.48	4.22
60% KC	70	2.659	71.95	26.20	22.52	3.68

2.2. Compaction Test

As soil is compacted, bearing capacity and stability increased while permeability, erosion, subsidence, and heaving from freeze-thaw cycles were reduced. In this regard, embankment material needs to be well-compacted. In order to investigate the effect of fines on compaction, compaction tests were performed according to ASTM D-698 [18] and D-1557 [19] with method D. The optimal water content (w_{opt}) and the maximum dry unit weight ($\gamma_{d,max}$) were mainly compared.

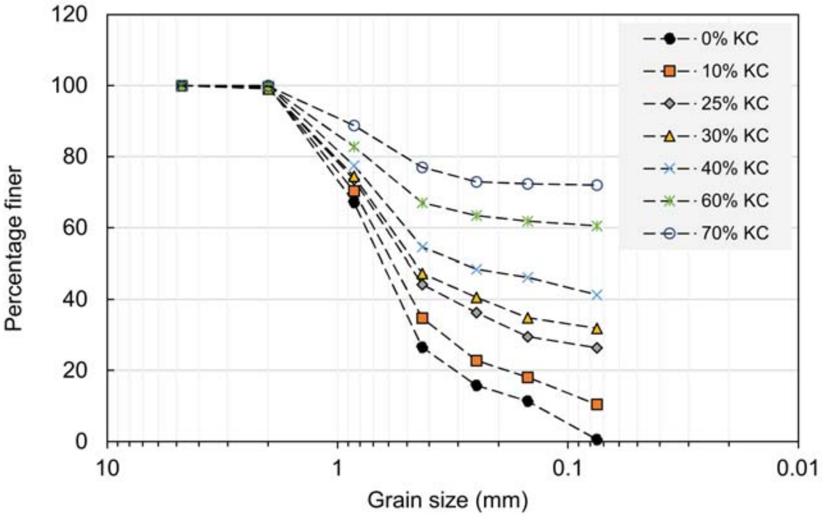

Figure 2. Gradation of sand–kaolinite mixtures according to fines content.

2.3. Oedometer Test

One-dimensional consolidation tests were carried out by the standard method of measuring compression properties [20]. Samples were fabricated using the optimum water content (W_{opt}) obtained from the compaction tests and compacted up to 90% of maximum dry unit weight ($\gamma_{d,max}$). The 90% of the degree of compaction was similar to the field condition where KDS [21] regulated the desired degree of compaction of 90% for earth embankments.

Step loading was applied from 24.5 kPa to 784 kPa with a standard load increment ratio (LIR) of unity. The applied load doubled in each loading step (e.g., 24.5, 49, 98, 196, 392, 784 kPa). The diameter and height of the specimens were 58 and 20 mm, respectively. Figure 3 presents the picture of all specimens extracted after the oedometer tests.

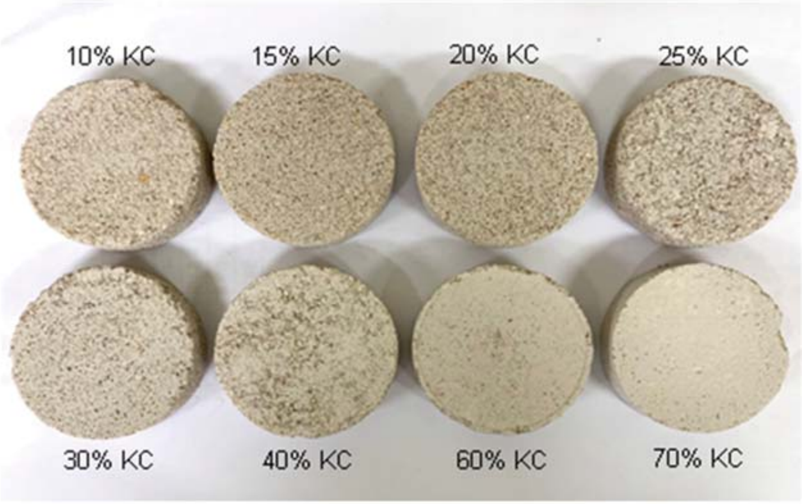

Figure 3. Top view of all specimens after the oedometer tests.

2.4. Scanning Electron Microscope Image

To observe the microstructure of the mixtures (bonding structure, physicochemical component, grain size, and shape), high resolution images with high magnifying power were examined as the representative samples. FE-SEM (Field Emission Scanning Electron Microscope, Model: LEO SUPRA 55, Carl Zeiss, Jena, Germany) which can capture a number of photos in magnifications from 12× to 2,000,000× was used. The equipment can analyze the shape, structure, and components of a substance by detecting various signals generated on the sample surface. Figure 4 shows the setup of the Scanning Electron Microscope used in this study.

Figure 4. Scanning Electron Microscope, Model: LEO SUPRA 55.

3. Test Results and Discussion

3.1. Compaction Test Results

Moisture-unit weight curves for all specimens were established using a modified Proctor compaction test [18,19]. Figure 5 represents the results of optimum water content (W_{opt}) and maximum dry unit weight ($\gamma_{d,max}$) in terms of various fines contents.

The overall trend shows that the optimum water content increased with an increase of fines content. This trend can be explained by the water absorption capacity of kaolinite clay [22,23]. It was also noticeable that the $\gamma_{d,max}$ increased and then decreased after the fines content reached 20%. Generally, the presence of low-plastic fines in the soil could make the soil soft and weak (i.e., the value of $\gamma_{d,max}$ decreases). However, the mixtures with fines contents of 15% and 20% enable the soil to achieve higher $\gamma_{d,max}$. Rearrangement of soil particles in these two mixtures could change the soil structure from a loose to dense state better than other mixtures. In other words, the fines (kaolinite) fill the void between granular particles, thus the mixtures are compacted better. However, as the fines content increases or decreases above or below 15 to 20%, the fine materials behave like obstacles to the compaction.

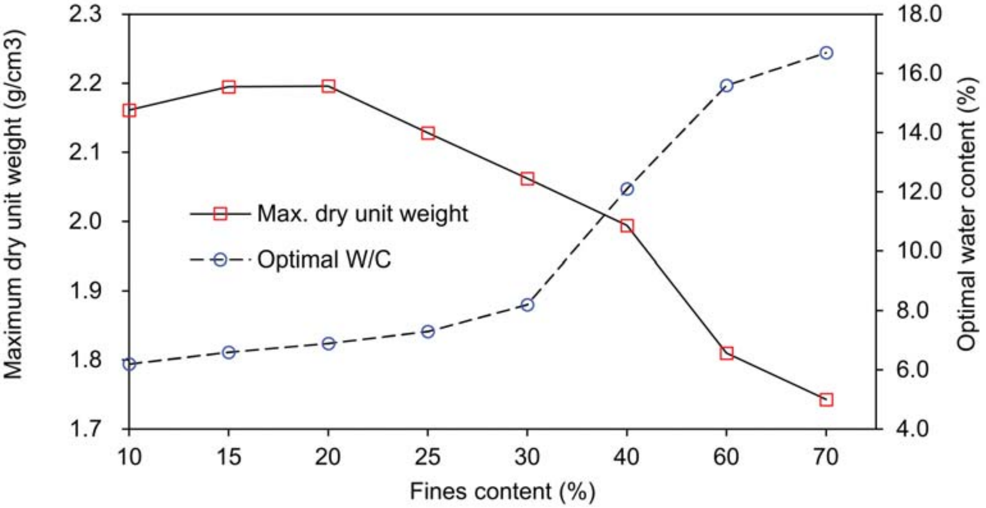

Figure 5. Maximum dry unit weight and optimal water content in various fines contents.

3.2. Void Ratio

The test results of the mixtures of CEN sand and kaolinite clay demonstrate that the characteristics of the mixtures are ascribable to the presence of the kaolinite in the samples tested in an oedometer. From the one-dimensional compression results, it was proved that the presence of kaolinite had a significant effect on the compressibility of the soil under various loading conditions. The variation of void ratio with vertical effective stress in each fines content are presented in Figures 6 and 7. As can be seen from Figure 6, the values of the initial void ratio for the mixtures are scattered in a relatively wider band ($\Delta e = 0.38$) and the differences became smaller at the end of the test ($\Delta e = 0.33$). Compared to the variation of the initial void ratio in each mixture, the change of void ratio by increasing vertical effective stress from 24.52 kPa to 784.53 kPa was very small (about 0.84 on average). This is because the initial condition was determined by the compaction with 90% of the maximum dry density. Under the higher compaction energy, the specimen showed a higher strength and lower settlement leading to lower void ratio change [24]. Regarding the percentage of fines content, the change of void ratio in low fines content was smaller than that in high fines content. This is because the fines do not participate in the resistance of shear in the case of low fines content; on the contrary, the sand grains contribute to the shearing resistance under the high fines content [5].

In Figure 7, the 3D graph clearly illustrates the overall behavior of the mixtures: as the fines content increased, the initial void ratio also increased. The vertical effective stress led to an overall decrease in the void ratio. However, exceptional change was observed; that is, even though fines content increased from 15% to 20%, the void ratio decreased regardless of vertical effective stress. This phenomenon is similar to the observation in Figure 6, where maximum dry density increased until fines content became 20%. Beyond 20% of fines content, maximum dry density decreased. Therefore, it can be concluded that a specific range of fines content would improve a mixtures' behavior. In the case of the sand–kaolinite mixture, the soil that contained 15% and 20% of fines is appropriate in embankment construction when considering minimum residual settlement.

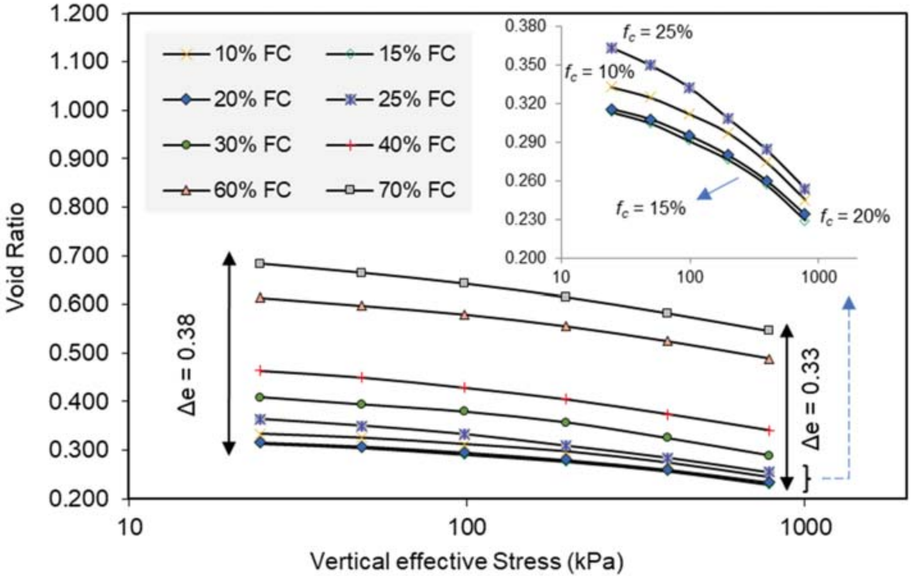

Figure 6. Variation of void ratio with vertical effective stress for each fines content.

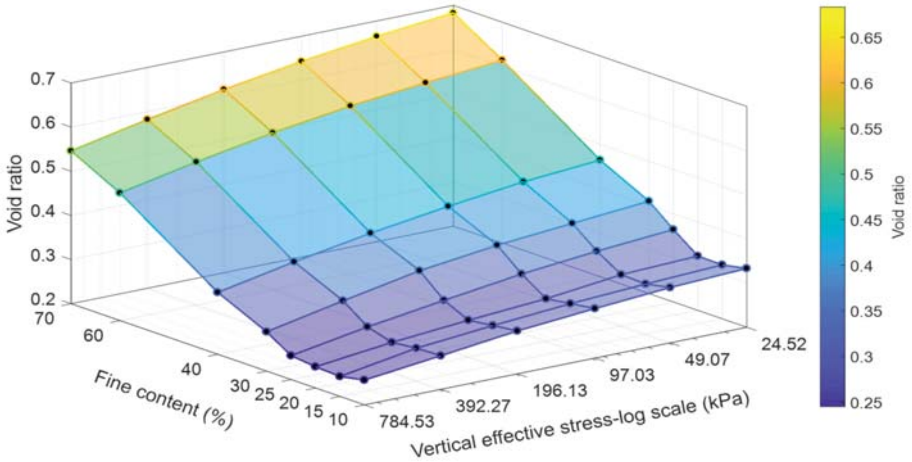

Figure 7. Variation of void ratio with fines content and vertical effective stress.

3.3. Behavioral Analysis

3.3.1. Transition Fines Content

Many researchers have reported that the intergranular void ratio has a strong correlation with various aspects of silty sand behavior [25–29]. The concept of the intergranular void ratio is referred to as the void ratio where the part of volume of voids is occupied by the fine and this can be determined by Equation (1) [30]:

$$e_s = \frac{e + \frac{G \times FC}{G_f \times 100}}{\frac{G}{G_s} \times \left(1 - \frac{FC}{100}\right)} \tag{1}$$

in which G is the specific gravity of the soil itself or the mixture, G_s is the specific gravity of the host material, G_f is the specific gravity of fines, e is the void ratio, and e_s is the intergranular void ratio.

Monkul and Ozden [31] suggested that transition fines content (TFC) could be an indicator that can classify a mixture's behavior into granular-dominant or clayey-dominant. The TFC can be signified when the value of the intergranular void ratio (e_s) is equal to the maximum void ratio of the host material (e_{max}). In this study, the CEN standard sand had an $e_{max} = 0.7$, obtained from the relative density test [32] and the values of e_s were computed by using Equation (1) with $G_s = 2.607$ and $G_f = 2.8$. The variation of intergranular void ratio with fines content in each vertical effective stress is indicated in Figure 8.

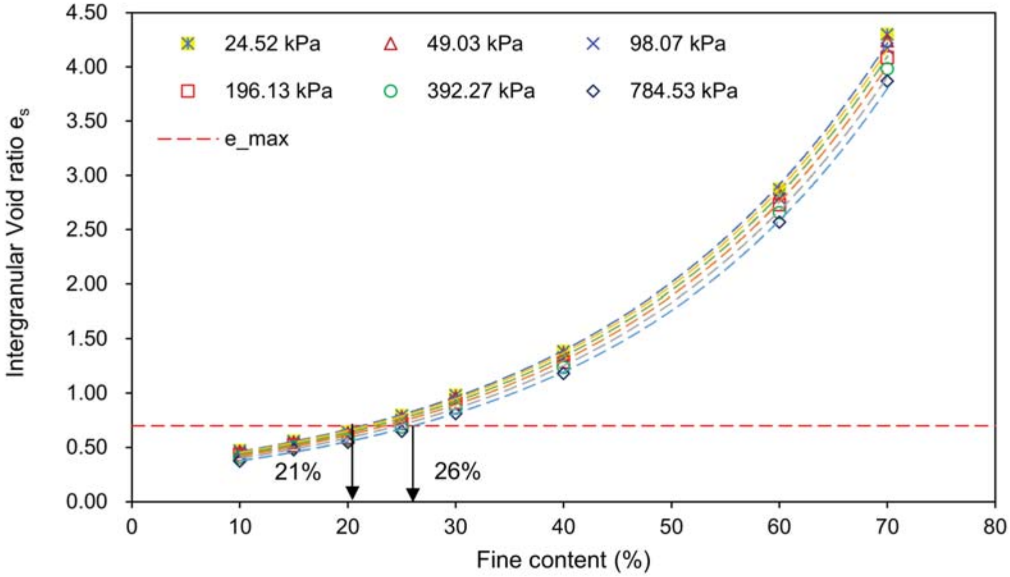

Figure 8. Variations of intergranular void ratio according to fines content.

As a general observation, the e_s was found to increase with an increase of fines content. The TFCs can be estimated by the intersection of the red dashed line (e_{max}). Therefore, the possible range of TFC was 21 to 26% for six different vertical effective stresses (24.52–784.53 kPa), respectively. The TFCs are shown in Table 2 and increase according to the vertical effective stress. This is because the higher effective stress led to more contact among granular materials, thus, higher TFCs were produced [8].

Table 2. Transition fines content under different vertical effective stress.

Effective Stress (kPa)	TFC (%)
24.52	21
49.03	22
98.07	23
196.13	24
392.27	25
784.53	26

3.3.2. Behavioral Threshold Analysis

A behavioral threshold can be defined as a threshold where a small change in mixing ratio resulted in a significant change in overall behavior or response of the soil. The behavioral thresholds exist at a critical fines content where a minimum void ratio occurs; in other words, it happens when the voids between coarse particles are fully filled by fine particles [33]. Choo and Burns [34] and Yang et al. [5] described critical fines content f_{crit} as a function of minimum void ratio and specific gravity (Equation (2)):

$$f_{crit} = \frac{e_{\min,c} G_f}{G_s(1 + e_{\min,f}) + e_{\min,c} G_f} \tag{2}$$

where $e_{min,c}$ is the minimum void ratio of the coarse particles, $e_{min,f}$ is the minimum void ratio of the fine particles, G_s is the specific gravity of the host material, and G_f is the specific gravity of fines.

To identify the behavioral threshold of sand–kaolinite mixture, the value of $e_{min,c}$ = 0.49, $e_{min,f}$ = 0.9, G_s = 2.607, and G_f = 2.80 were used. As a result, the critical fines content f_{crit} was equal to 21.67%. Therefore, this critical fines content is where the threshold was defined as the point changes in sand–kaolinite mixture ratio result in behavior changes. Moreover, this value was found within the possible range of transition fines content (21–26% KC) which was obtained from experimental observation. In other words, this value of f_{crit} could be related to the TFCs.

3.3.3. Compression Behavior

In order to better observe the compression behavior of the mixtures, the parameters of the global and granular compression indices (C_c and $C_{c\text{-}s}$) were utilized. The physical meaning of granular compression index ($C_{c\text{-}s}$) is similar to the global compression index (C_c) and can be expressed as the Equations (3) and (4) [20], respectively:

$$C_c = \frac{\Delta e}{\log\left(\frac{\sigma_2{}'}{\sigma_1{}'}\right)} \tag{3}$$

$$C_{c-s} = \frac{\Delta e_s}{\log\left(\frac{\sigma_1{}'}{\sigma_2{}'}\right)} \tag{4}$$

in which e is the void ratio, e_s is the intergranular void ratio, and $\sigma_1{}'$ and $\sigma_2{}'$ are the vertical effective stress (kPa).

Figure 9 represents the variation of maximum dry unit weight ($\gamma_{d,max}$) and the global and granular compression indices (C_c, $C_{c\text{-}s}$) according to fines contents (f_c). As can be seen from Figure 9, the trend showed an increasing trajectory for both C_c and $C_{c\text{-}s}$ and a decreasing one for $\gamma_{d,max}$. However, the value of C_c at the high fines content (i.e., 40%, 60%, and 70% of fines content) were found to gradually increase compared with $C_{c\text{-}s}$. This is because the value of C_c could define that there are sand particles which participate in the deformation control of the mixtures, while the value of $C_{c\text{-}s}$ signified that at high fines content, the deformation was controlled by fine grains. It is recommended that the parameter of $C_{c\text{-}s}$ can be used for future studies on the settlement of sand–kaolinite mixture. It was noted that the values of C_c and $C_{c\text{-}s}$ at 15% and 20% of fines content decreased while $\gamma_{d,max}$ increased. That is to say, fines content of 15% to 20% makes the mixture behave differently. A certain level of fines content would enhance compacting efficiency, which results in a low compression index (i.e., small residual settlement). For sand–kaolinite mixture, around 15% to 20% of fines content are the optimal ratio. Henceforth, one could assume that the presence of kaolinite clay at a certain amount (15% and 20%) could also provide a significant effect to reduce the creep settlement in well-compacted conditions. This certain amount can be called optimum fines content (f_{opt}), at which the minimum creep settlement would happen.

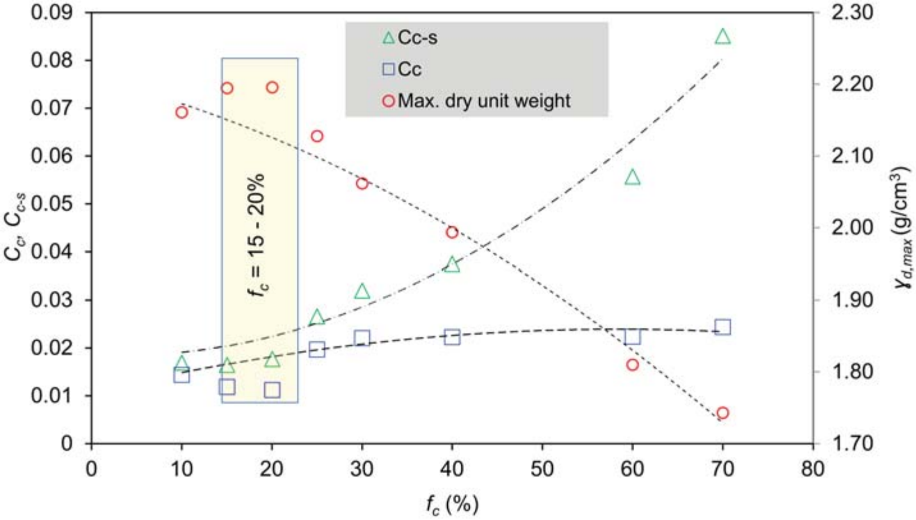

Figure 9. Relationship between the granular compression index and maximum dry unit weight.

3.3.4. Particle Shape Analysis

It is well-known that the engineering properties (shear strength, compressibility, and permeability) of soil mixtures are affected by the shape of soil particles [35]. The particle size and shape of the mixture can be estimated by crystallographic structure, surface area, and particle volume [36]. In this study, the particles of CEN sand are generally isometric and have angular shape, and the clay particles (kaolinite) have a hexagonal plate shape (Figure 10).

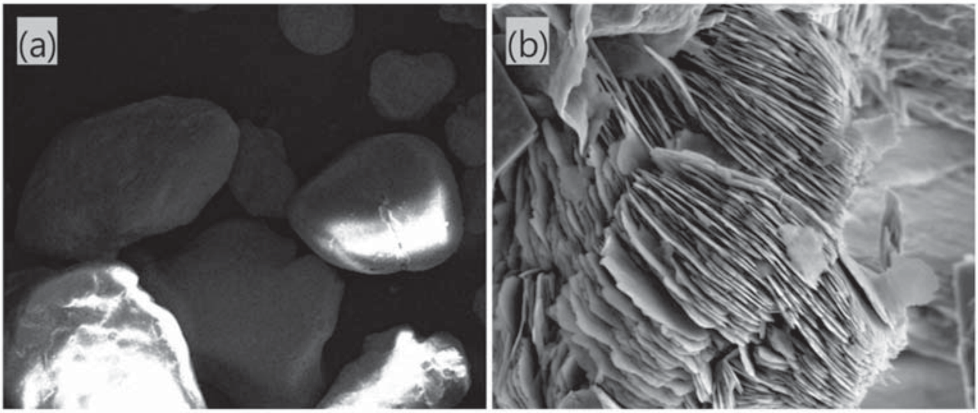

Figure 10. Particle shape: (**a**) CEN standard sand, (**b**) Kaolinite Clay.

In the mixture of 10% KC in Figure 11, we can see the smooth surface of a sand particle under kaolinite particles. However, with the mixture which has the amount of kaolinite up to 25%, the kaolinite particles were found to take over the sand grains—findings consistent with previous research [22]. In Figure 11, the particle shape in all mixtures was with 10,000× (i.e., 10,000 times magnification) and 100,000× magnification by SEM.

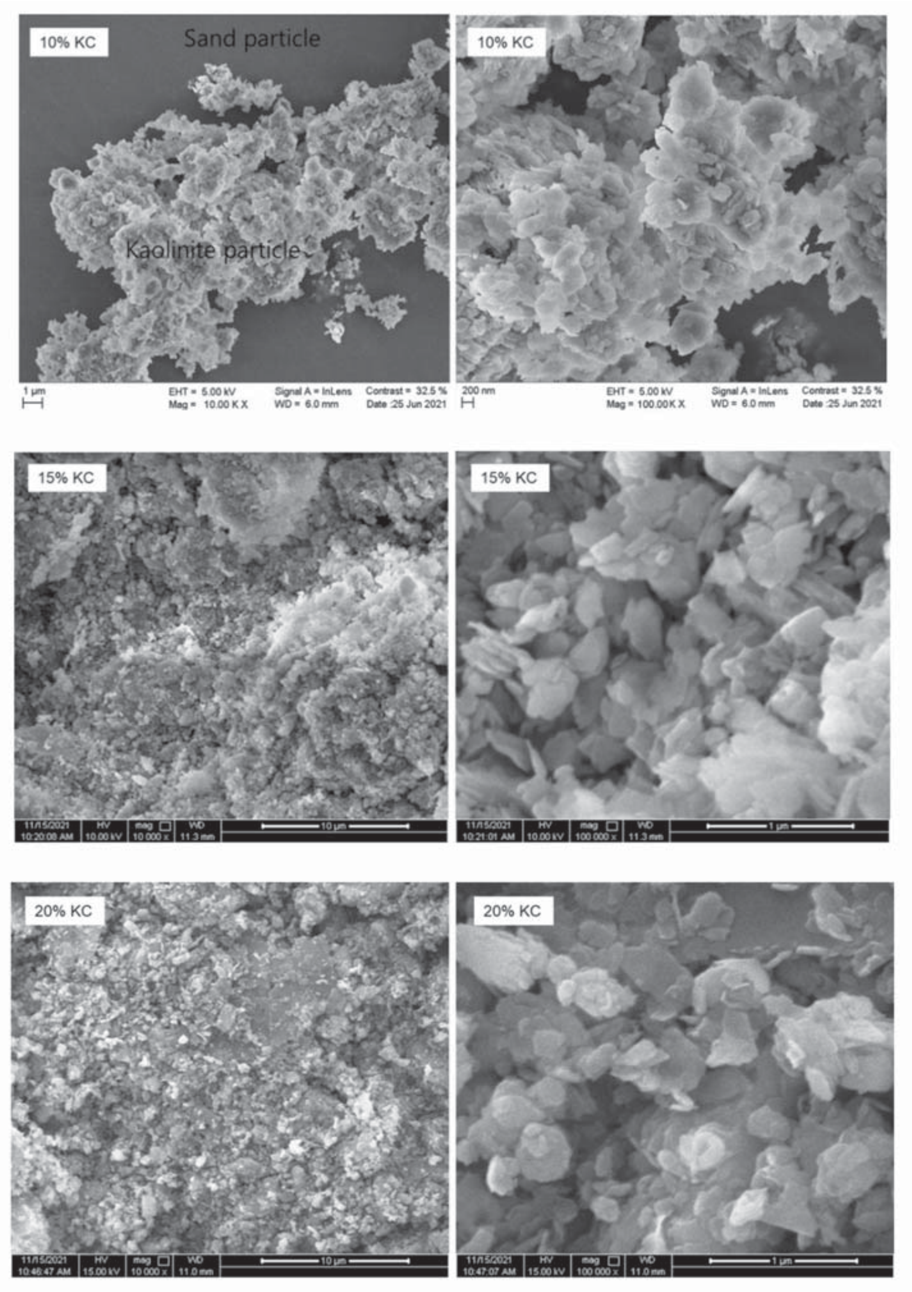

Figure 11. *Cont*.

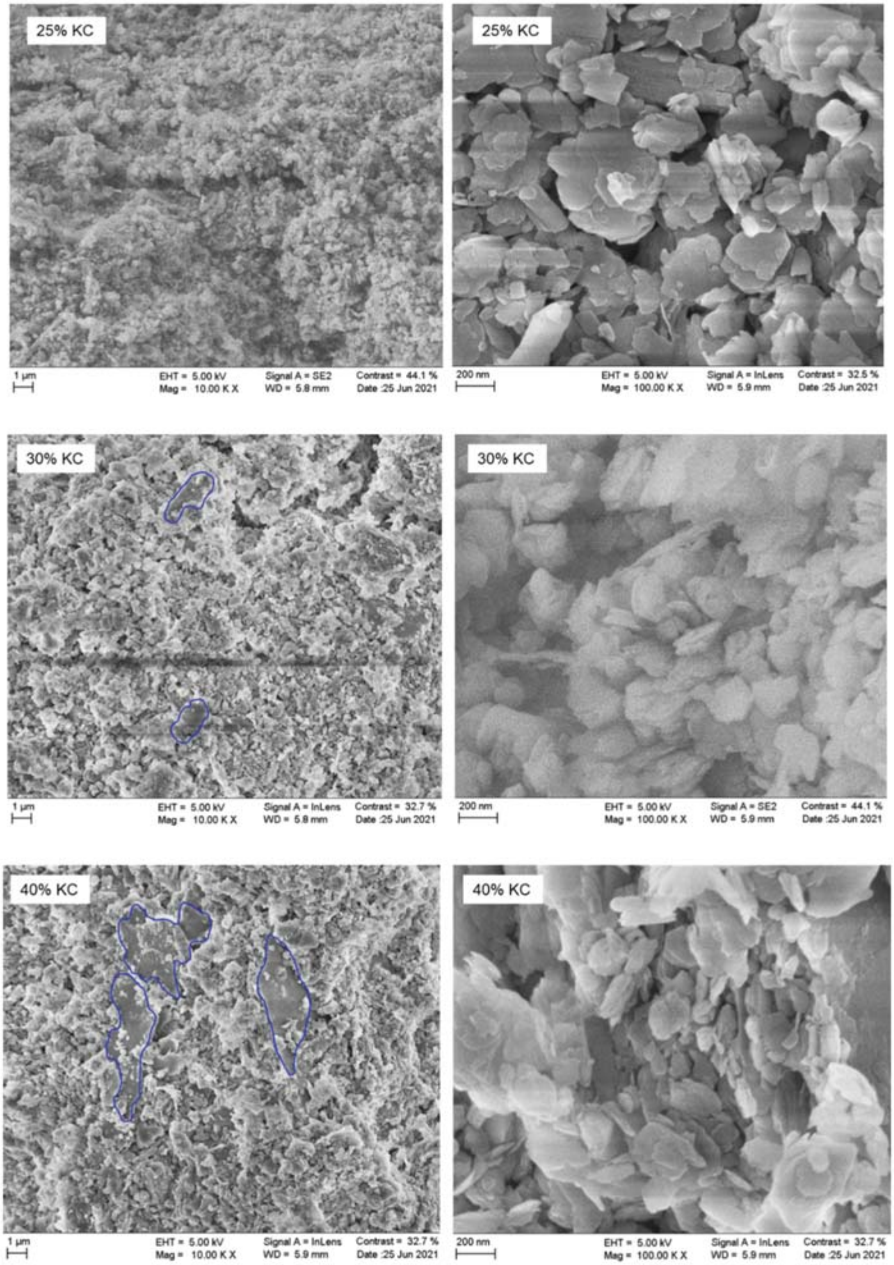

Figure 11. *Cont*.

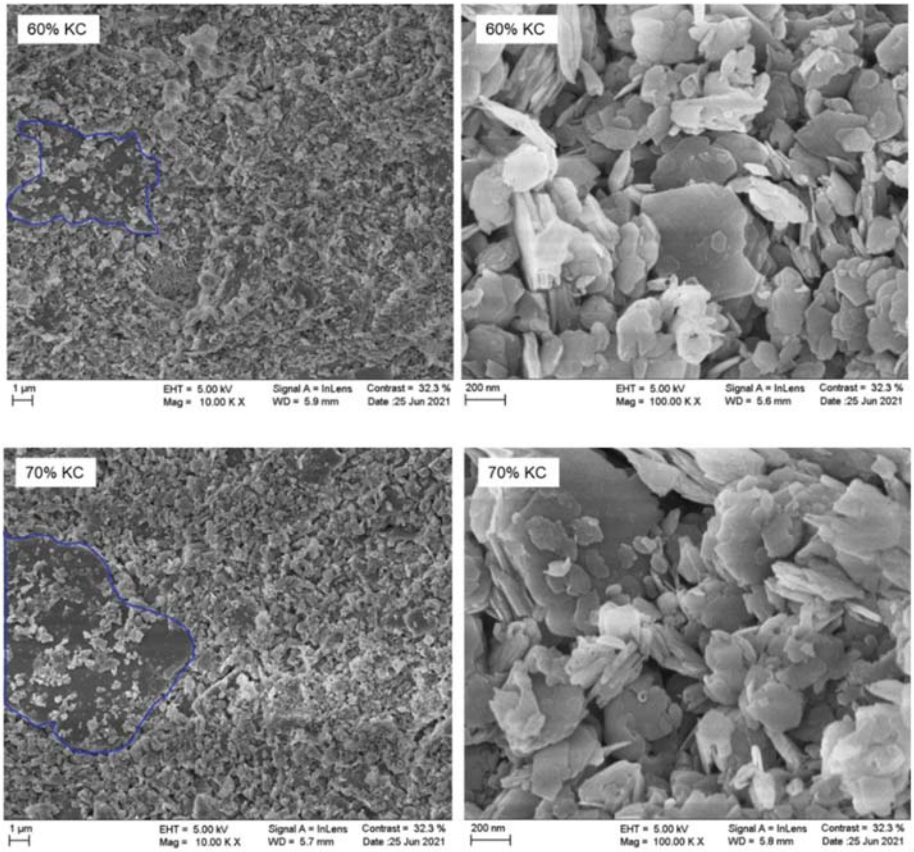

Figure 11. Particle shape in all mixtures with 10,000× and 100,000× magnification by SEM.

Additionally, also observed in SEM photos (100,000×), the present kaolinite particles were found to be large as kaolinite content increased. Moreover, with the content of kaolinite up to 30%, the kaolinite particles were contacted one to another creating flat surfaces (blue solid line) from small to large according to the percentage of kaolinite as can be seen in photos with 10,000× magnification. For this reason, the fines particles could not fully fill in the voids between sand particles which also leaves high local porosity between the kaolinite particles themselves resulting in an effect on the packing density of CEN sand. Therefore, with the high percentage of kaolinite (60% and 70% KC), the sand grains were assumed to float in the fines grain network and were regarded as void in the mixture.

3.3.5. Behavioral Variation

Based on the aforementioned analysis, we could identify the different types of behavior of the embankment materials (Figure 12) according to fines content. TFC (transition fines content) indicated a boundary of sand-like and clay-like behavior of the mixtures, and this possible range of the tested mixture was around 21% to 26%. The optimum fines content (f_{opt}), defined as the fines content that produces greatest dry density, was around 15% to 20%. The critical fines content was 21.67%.

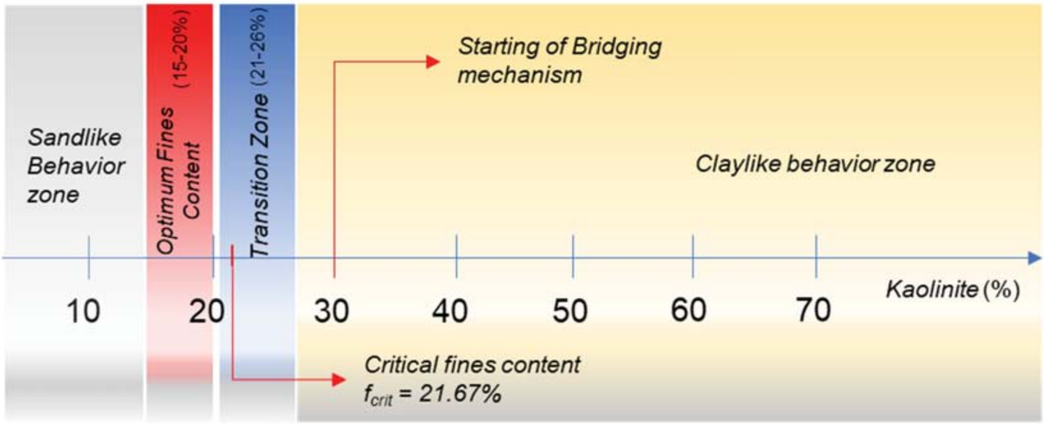

Figure 12. Overall behavioral of the mixture.

Since the clayey soil (low plasticity) has its own optimum fines content which could provide a denser state, low compression index, and low void ratio, engineers could consider using the soil with f_{opt} as an embankment material. Based on the observations in this research, there could be three simple approaches to specify the value of f_{opt}: (1) simple compaction test with method D, (2) identification of the possible transition zone, and (3) determination of the critical fines content. However, these three approaches are based only on the sand–kaolinite mixtures. For a more specific method to define optimum fines content, more laboratory tests are required.

4. Summary and Conclusions

Based on the fact that embankment materials in South Korea contain low plastic fines, kaolinite was selected as a fine material. Sand represents granular materials of the embankment to simplify the testing matrix. Sand–kaolinite mixtures were tested by changing the fines content. The basic material properties gradually vary as fines content increased. Maximum dry density tended to decrease according to fines content; however, it slightly increased at fines content of 15% and 20%. One-dimensional compression tests (i.e., oedometer tests) provided details on settlement behavior in terms of fines content. To categorize behavior of sand–kaolinite mixture, the transition fines content (TFC), defined as an intergranular void ratio in which the maximum void ratio of the host material (i.e., sand) is equal to, was adopted. SEM images were taken and analyzed to investigate the microscale grain network of the sand–kaolinite mixtures. The findings of this study can be summarized as follows:

1. An increase in fines content caused an increase in both void ratio and compression index. However, settlement-related properties such as e, C_c, and $C_{c\text{-}s}$ decreased or showed the smallest values. Maximum dry density of 15% and 20% of fines content was also the greatest.
2. Presence of fine materials at a certain amount, 15% and 20% of kaolinite in this study, played a role in helping ensure better compaction. Therefore, appropriate fines content of embankment materials resulted in less deformation.
3. With the mixture of 10% KC, the smooth surface of a sand particle under kaolinite particles can be seen in the SEM images. However, in the mixture with up to 25% kaolinite content, the kaolinite particles were found to take over the sand grains. Moreover, the kaolinite particles were overlapped, creating large flat surfaces with the fines content higher than 30%, and inducing the claylike behavior of mixtures.
4. Transition fines content of sand–kaolinite mixture was about 21% to 26%. Different types of behavior were identified: a transition zone ($21\% \leq f_c \leq 26\%$), which was

a behavioral change point of the mixture; sand-like behavior ($f_c < 15\%$), which was when the mixture behaved like sand; clay-like behavior ($f_c \geq 30\%$), which was when the mixture behaved like clay, and an optimum fines content ($15\% \leq f_c \leq 20\%$) which induced a low compression index.

Based on oedometer tests and compaction tests, 15% to 20% of fines content of sand–kaolinite mixture is the most appropriate fines content for inducing the least settlement. Transition fines content, critical fines content, optimum fines content (mentioned above) were similar to those of e, C_c, and maximum dry density. Therefore, the best fines content or transition fines content can be approximately predicted by following these approaches: (1) simple compaction test with method D, (2) TFC by laboratory testing, and (3) calculation of the critical fines content. However, this approach should be verified through more laboratory and field testing with actual embankment materials used in South Korea. Consolidation settlement and long-term settlement should also be investigated according to fines content. Based on this research, the design criteria on materials, especially fines content as embankment materials, can be suggested to control residual settlement.

Author Contributions: Conceptualization, Y.-T.C.; Data curation, Y.-T.C.; Funding acquisition, S.-H.L.; Investigation, P.K. and Y.-T.C.; Methodology, C.-Y.Y.; Project administration, S.-H.L.; Supervision, S.-H.L. and C.-Y.Y.; Validation, C.-Y.Y.; Writing—original draft, P.K.; Writing—review & editing, Y.-T.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a grant from the R&D Program of the Korea Railroad Research Institute (PK2203A3), Republic of Korea and by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R1A6A1A03044326).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

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

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buildings

Article

Time-Varying Analysis of Retaining Structures Enhanced with Soil Nails and Prestressed Anchors

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Abstract: At present, the research results for the stress response and deformation characteristics of composite support structures are mostly based on ideal or standard working conditions. External disturbances often exist in practical engineering, which makes the monitoring data deviate from the calculation results. In order to analyze the causes of deviation and correct them in practice, it is necessary to consider the time-varying effect and study the construction mechanics behaviors of composite support structures. Based on in situ test data, the effects of soil predisturbance, excessive excavation, unloading on the surface of edges, the tensioning and lagging of the anchor, and continuous rainfall on the stress-time curves of soil nails were analyzed. On the basis of verifying the effectiveness of the model, ABAQUS finite element software (v.6.10) was used to simulate practical engineering based on ideal working conditions. Comparing the in situ test data and numerical simulation results, the development of mechanical response and deformation characteristics in the process of support structure installation and soil digging and filling were analyzed. Research shows that the time-varying effect has a significant impact on construction mechanics behaviors, especially on soil nailing combined with the use of prestressed anchors, due to layered excavation and support.

Keywords: prestress; composite soil nailing; in situ test; time-varying effect; construction mechanics

Citation: Cheng, J.; Guo, L.; Wang, H.; Dun, Z. Time-Varying Analysis of Retaining Structures Enhanced with Soil Nails and Prestressed Anchors. *Buildings* **2022**, *12*, 458. https://doi.org/10.3390/buildings12040458

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 24 February 2022
Accepted: 2 April 2022
Published: 7 April 2022

1. Introduction

Soil nailing is widely used in slope support and as a bracing structure for foundation pits because of its advantages of fast construction and good economy [1–3]. For the soil-nailed slope, pullout resistance of the soil-grout interface is a critical parameter in design and analysis for geotechnical engineers. Extensive research has been conducted to investigate the pullout behavior of pressure-ground soil nails through field or laboratory tests [4–7]. In addition, numerical slope stability analyses were carried out to explore the behavior of soil nails, as reported in the literature [8–11]. However, in downtown areas where deformation of the foundation pit needs to be strictly limited [12,13], the soil-nail–prestressed-anchor-composite retaining structure is preferable as the prestressed anchors can better limit the displacement of the slope surface compared with soil nails. Specifically, results [14,15] show that the maximum displacement, bending moment, and shear force in the pit can be reduced by over 50%, 40% and 30%, respectively, by soil nailing combined with prestressed anchors compared with simple soil nailing. The differences in the two building-construction methodologies are shown in Table 1.

In such a composite retaining structure, the combined resistance of soil nail and prestressed anchor is expected to provide the required safety against rain-induced or overloaded failure [16,17]. Many experts and scholars at home and abroad have done a lot of research on reinforcement mechanisms [18], stress and deformation [19], stability analysis [20], and other factors.

Table 1. The differences in the two building-construction methodologies.

Construction Methodology	Deformation of Foundation Pit	Plastic Zone	Construction Convenience	Engineering Cost
① Simple soil nailing	larger	larger	relatively good	lower
② Soil nailing combined with prestressed anchors	smaller	smaller	relatively poor	higher

In the existing research, the interaction mechanism between soil nails and prestressed anchors is documented in the literature [21], mostly based on numerical simulations, and a number of critical issues have been fully addressed. Studies in the literature [22,23] examined the working performance and reinforcement mechanism of soil nailing based on soil stress path; Other studies [24–26], based on model tests [27] or field tests [28,29], discuss the changes in earth pressure and groundwater level caused by digging and unloading and the influence of these changes on the internal force and the deformation of the composite soil nailing structure; studies [30,31] examine the influence of design parameters on safety factors and sensitivity by establishing safety factor and sensitivity analysis models used to calculate internal stability. Studies [32–34] examine the construction mechanics behaviors of retaining structures enhanced with soil nails and prestressed anchors.

Foundation pit construction is a dynamic and asymptotic process. In the design, not only the structure itself should be considered. External disturbances, that is to say, the influences of construction steps and sequences on load conditions and mechanical responses, should also be considered. The existing research results do not consider the time-varying effect on the construction mechanics of composite support structures, which leads to a difference in the actual working conditions. In this paper, the effects of soil predisturbance, excessive excavation, unloading on the surface of edges, the tensioning and lagging of the anchor, and continuous rainfall on the stress-time history curves of soil nails under actual working conditions were analyzed. Combined with the numerical simulation results under ideal working conditions, the construction mechanics behaviors of the composite support system under prestress were analyzed. The research results provide a good theoretical and scientific basis for design and construction with the use of soil nailing combined with prestressed anchors and puts forward reasonable suggestions for the current nonstandard conditions.

2. In Situ Tests

2.1. Site Conditions

The tested foundation pit was located at the cross of Fengchan Road and Dongsan Street, Zhengzhou City. The depth was 6.53 m. A soil-nail–prestressed-anchor-composite retaining structure was used to support the north wall of the foundation pit where underground pipelines concentrate and therefore strict deformation control is required. The soil-nailed retaining structure was used to support the south wall of the foundation pit. The influence of ground water on the retaining structure could be safely ignored because of the depth between −10.9 m and −10.1 m. The layout of the foundation pit is shown in Figure 1.

There is a series of testing sites, noted as C1 through C6. C1 and C2 are soil-nail retaining structures located in the south; C3 through C6 are soil-nail–prestressed-anchor-composite retaining structure located in the north, among which there are no unbounded parts in the anchors in sites C3 and C4, whereas there are 2.5 m unbounded parts in the anchors in sites C5 and C6. In this paper, the test results of C1, C4, and C5 used for analysis.

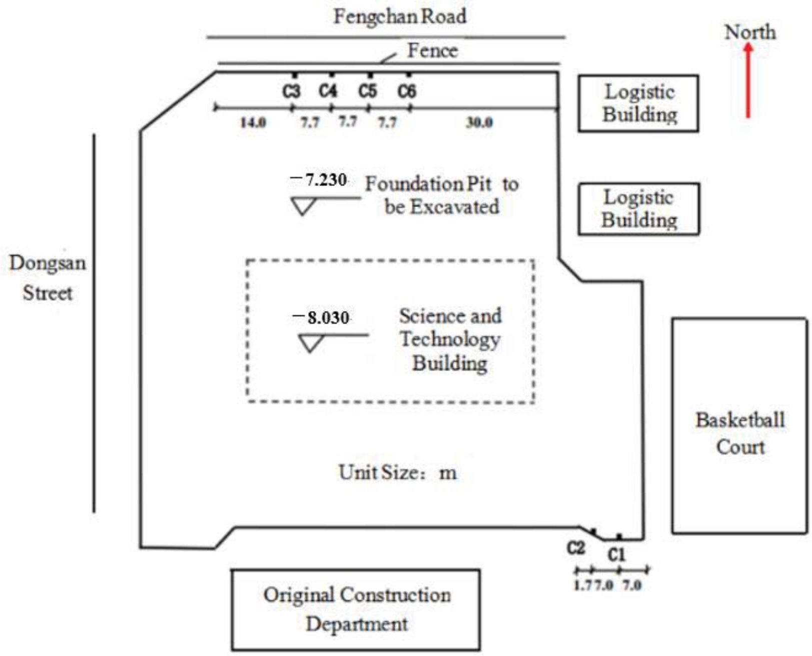


Figure 1. The plan of the foundation pit.

2.2. Soil Properties

The in situ soil layers from top to bottom were (i) silt, 2.20 m; (ii) silty clay, 2.30 m; (iii) silt, 1.10 m; and (iv) silty clay, 2.30 m, respectively. The average properties of each soil layer are listed in Table 2, in which γ is unit weight, c is cohesion, τ is the shear stress of the soil/grout interface and φ is the internal friction angle.

Table 2. The mechanical parameters of the soil.

Soil Layer	γ (kN/m^3)	c (kPa)	φ (°)	τ (kPa)
①	18.1	14.0	20.0	52.0
②	17.9	20.0	15.0	50.0
③	18.2	15.0	21.0	60.0
④	18.2	21.0	16.0	56.0

2.3. Supporting Details

Soil nails and prestressed anchors were distributed in a "square" layout with an equal vertical and horizontal spacing of 1.4 m. Boreholes with a diameter of 120 mm and an inclination of 10° were predrilled manually. After the installation of the steel reinforcement bars into the boreholes, a two-staged grouting was applied. The two-staged grouting has been used successfully in many countries and areas to reinforce cut slopes, excavations, tunnels, etc., to increase the performance of soil nails and therefore to reduce the number of required soil nails [35–37]. Each soil nail used in the experiment consisted of a ribbed steel reinforcement bar of 18/22 mm diameter, the elastic modulus of which was 200 GPa. The distribution of soil nails and anchors is shown in Figure 2.

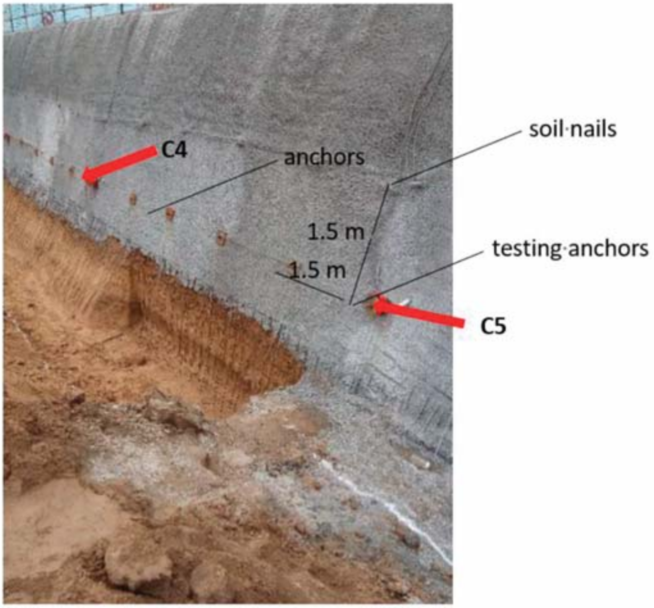


Figure 2. The distribution of soil nails and anchors.

The facing was made up of a 200 mm by 200 mm grid of thin steel mesh (6 mm in diameter). The facing was enhanced with two reinforcement bars (12 mm in diameter) in both horizontal and vertical directions. The detailed enhancement configuration of facing is shown in Figure 3.

Figure 3. The enhancement configuration of facing.

The designed value of the prestressing force of the anchor was 50 kN. The design parameters of the soil nails and prestressed anchors in different retaining structures are summarized in Tables 3 and 4.

Table 3. Design parameters of soil-nailed retaining structures.

Soil Nail	Depth (m)	Length (m)	Inclination (°)	Spacing (m)
1	1.20	9.00	10	1.50
2	2.70	9.00	10	1.50
3	4.20	9.00	10	1.50
4	5.70	7.00	10	1.50

Table 4. Design parameters of composite soil-nailed retaining structures.

Soil Nail/ Anchor	Depth (m)	Length (m)	Inclination (°)	Bonded Length (m)	Spacing (m)
1	1.20	9.00	10	-	1.50
2	2.70	12.00	10	12.0/9.5	1.50
3	4.20	9.00	10	-	1.50
4	5.70	7.00	10	-	1.50

Note: 12.0/9.5 in Table 4 indicates that there is either no unbonded part or a 2.5 m unbonded part.

2.4. Fabrication of Testing Components

In the in situ tests, the soil nails were equipped with vibrating wire strain gauges (labelled JMZX-416A), which were attached to the steel tendon of each soil nail. JMZX-416A was applied to measure the stress of stressed reinforcement in reinforced concrete structures, the measuring range and sensitivity of which are 200 MPa and 0.1 MPa, respectively. The instruments were supplied by Shandong lidaxin Instrument Equipment Co., Ltd. (Qingdao, China). Readings were obtained and stored in a data logger labelled JMZX-3001. JMZX-3001 was supplied by Beijing Heng Company Limited Company of Science and Technology (Beijing, China). Different from soil nails, each anchor (25 mm ribbed, high-yield steel bar) was equipped with a vibrating wire load cell, labelled MJ-101, at the head to monitor the anchor force, with the exception of strain gauges. MJ-101 was manufactured by Shandong Shengxin Mining Equipment Co., Ltd. (Liaocheng, China). The designation of all gauges was authorized. Figure 4 shows details of the equipped soil nails for tests. Figure 5 presents the manufactured testing anchors.

2.5. Instrumentation

As mentioned above, to investigate the mechanics behavior of composite soil nailing, a series of in situ tests was carried out under different retaining conditions. The measuring results from the testing profiles of 1, 4, and 5 were analyzed and compared such that the effects of two important characteristics, comprised of prestressing force and unbonded length, on the nail forces could be studied. Special note: the testing profiles of 1, 4, and 5 were simplified with the labels No. 1, No. 4, and No. 5 in the following analyses. For the first parameter, the influence on the deformation of the pit wall and the internal force of surrounding soil nails were examined in this paper. In particular, the construction sequence of prestressing is a research focus. For the second parameter, it can be expressed in terms of the length ratio L_u/L, where L_u = the length of the unbonded part and L = entire length of the anchor. As shown in Table 4, two different unbonded lengths for the anchors were given. No. 1 represented a simple soil-nailed retaining structure; No. 4 represented a composite soil-nailed retaining structure enhanced with a prestressed anchor without an unbonded part; and No. 5 represented a composite retaining structure with a 2.5 m unbonded length. The layout of instruments is shown in Figures 6–8.

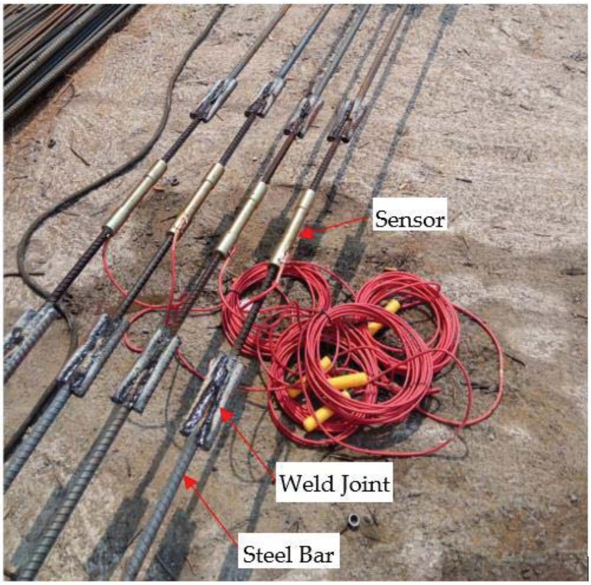


Figure 4. The manufactured testing soil nails.

Figure 5. The manufactured testing anchors.

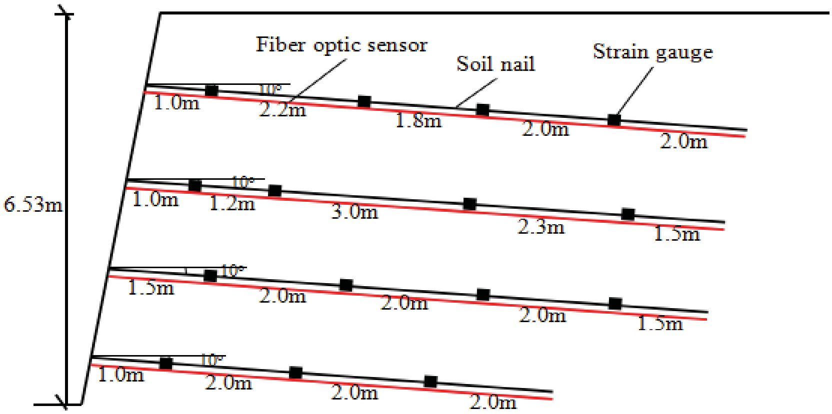


Figure 6. Location of instruments for No. 1.

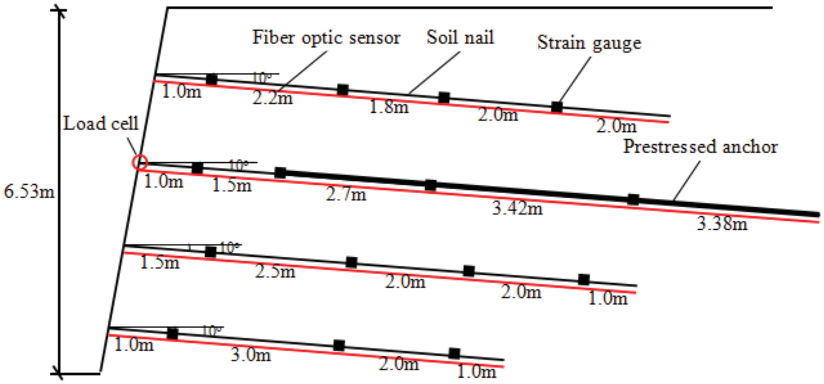


Figure 7. Location of instruments for No. 4.

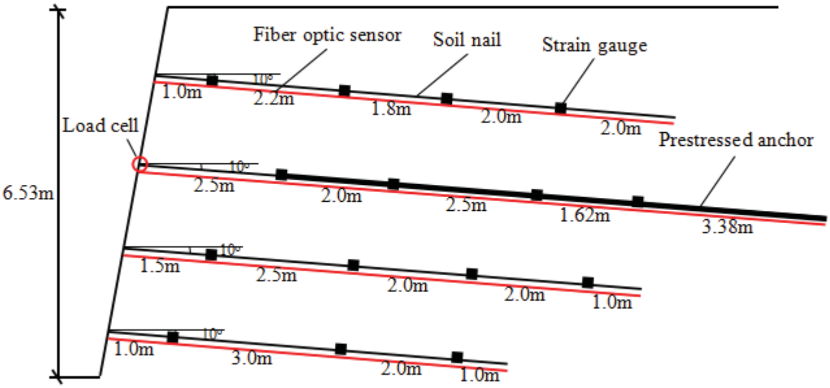


Figure 8. Location of instruments for No. 5.

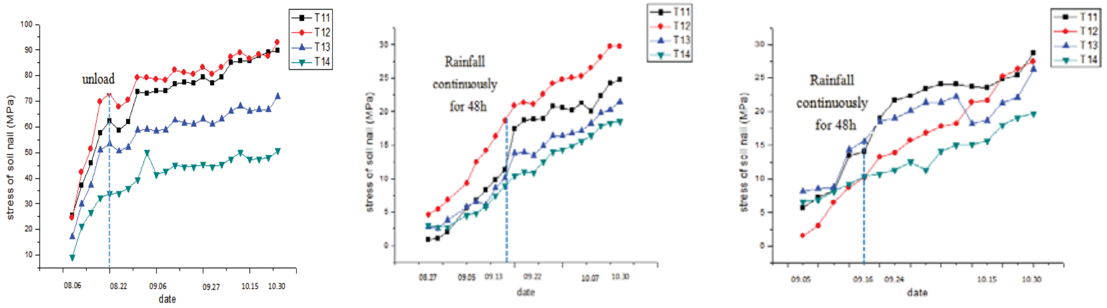
In Figures 6–8, the black lines indicate soil nails or prestressed anchors, the black squares indicate strain gauges, and the red lines indicate fiber-optic sensors arranged on soil nails or prestressed anchors.

2.6. Test Results

2.6.1. Stresses of Soil Nails

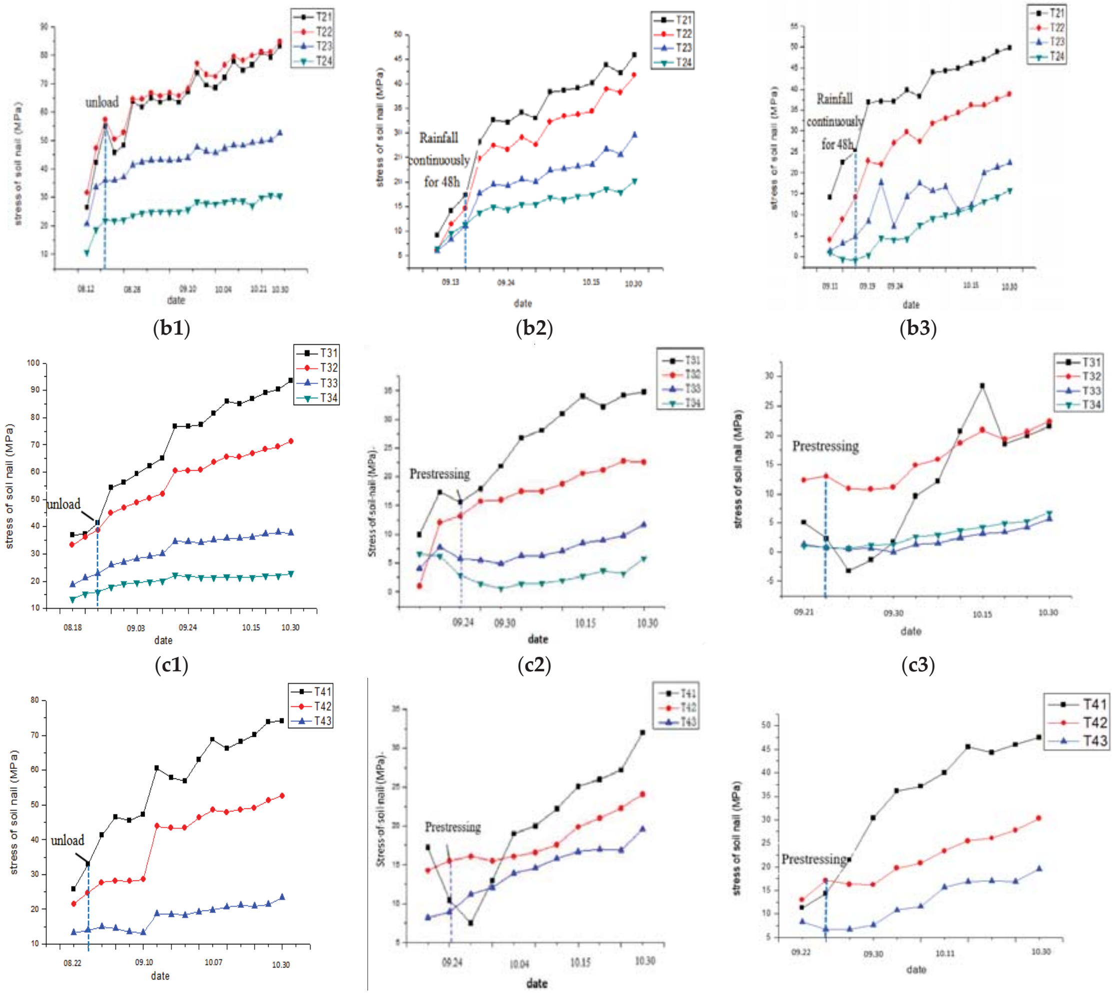
After excavation and installation of the soil nails and prestressed anchors, the data acquisition system was established, and the mechanics behavior of the soil-nail–prestressed-anchor retaining slope was monitored for about three months. Figure 9 plots the curves of stress–date relationship obtained from the in situ tests during the period of three months, in which T_{ij} presents the stress value of the j strain gauge calculated from the nail head in the i row of soil nail.

(i) As shown in Figure 9, particularly a1, b1, c1 and d1 for the No. 1 section, it is evident that there was a sudden increment in the nail force with each excavation and it gradually tended towards stability when the excavation was completed, which shows that there are effects of time and effects of excavation on the internal force of the soil nail. This is consistent with the results achieved in the literature, as reported by [28]. Compared with the No. 1 section, the effect of the excavation of the No. 4 and No. 5 sections is not so obvious; moreover, the overall stress level was relatively small, on the whole. According to stress mechanism, increments in earth pressure due to unloading are transferred to soil nails through shear stress of soil-grout interface, which drives the nail force. For this project, the foundation pit was adjacent to Fengchan Road in the north, under which a gas pipeline is buried parallel to the enclosing wall. The pipeline is 86.0 m in length and 1.0 m in depth, which was about 1.5 m away from the side of the foundation pit. Consequently, the soil at the upper part of the foundation pit for No. 4 and No. 5 sections had been disturbed before and was more loose compared to the undisturbed soil in the No. 1 section. Therefore, the friction resistance of soil/grout interface for No. 4 and No. 5 sections decreased, accordingly, and the earth pressure increment transferred to the soil nails was less. According to the above analysis, the conclusion can be drawn that the stress distribution was affected by the density of the soil, that is, it was concentrated and larger when the soil was dense, and it was uniform and smaller when the soil was loose. The obtained results are consistent with the literature, as investigated in the work of Barley [33,34];



(a1) **(a2)** **(a3)**

Figure 9. *Cont.*



(**b1**) (**b2**) (**b3**)

(**c1**) (**c2**) (**c3**)

(**d1**) (**d2**) (**d3**)

Figure 9. (**a1**) stress of 1st row of soil nail for No. 1, (**a2**) stress of 1st row of soil nail for No. 4, (**a3**) stress of 1st row of soil nail for No. 5. (**b1**) stress of 2nd row of soil nail for No. 1, (**b2**) stress of 2nd row of soil nail for No. 4, (**b3**) stress of 2nd row of soil nail for No. 5. (**c1**) stress of 3rd row of soil nail for No. 1, (**c2**) stress of 3rd row of soil nail for No. 4, (**c3**) stress of 3rd row of soil nail for No. 5. (**d1**) stress of 4th row of soil nail for No. 1 (**d2**) stress of 4th row of soil nail for No. 4, (**d3**) stress of 4th row of soil nail for No. 5. The stress-date relationship curves: (**a1–d1**) = No. 1 Section; (**a2–d2**) = No. 4 Section; (**a3–d3**) = No. 5 Section.

(ii) As can be seen from a1–a2, the stresses on soil nails decreased due to unloading, which was only manifested in that the first and second rows of soil nails close to the ground surface were affected a lot; however, the third and fourth rows were less influenced;

(iii) As can be seen from stress-history curves for No. 1 and No. 5 sections, the stresses were less affected by continuous rainfall for 48 h. This is because the infiltration rates of rain into the clay or silty clay are extremely slow, and accordingly, the depth of infiltration was relatively shallow. Furthermore, the actual locations of the first row of soil nails were moved down to keep them off the gas pipeline, and the exact location for the two test profiles was −2.0 m and −2.2 m, separately;

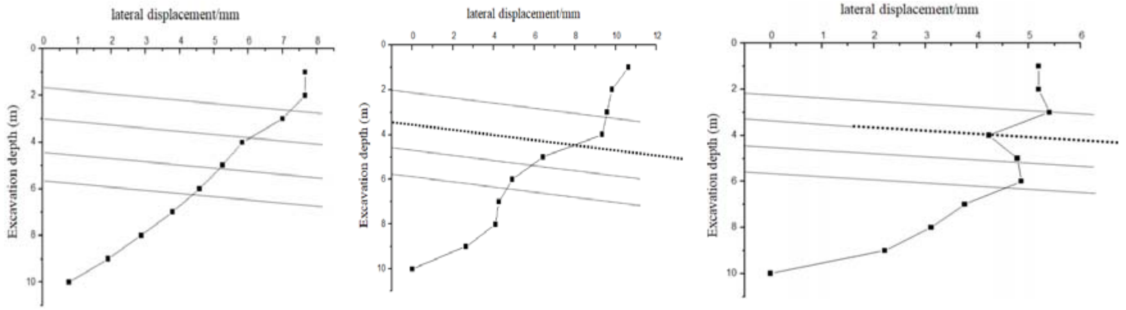
(iv) The stresses on the soil nails in the upper two rows were less affected when prestressed; in contrast, the stresses of the lower two rows decreased a lot. Based on the technical specifications, the bonded tendons can be tensioned when the strength reaches at least 15 MPa. However, in fact, the next layer was removed and followed by the second excavation as a result of arranged rapid construction, and after that, tensioning was performed. Consequently, the soil mass influenced by prestressing was the lower not upper part of the foundation pit. The conclusion can be drawn that the magnitude and distribution of the stresses on the soil nails were nearly affected by different prestressing periods: the upper rows were influenced a lot during timely tensioning; the lower rows changed greatly during lagging tensioning;

(v) The influence of prestress on the stresses of the third and fourth rows of soil nails was only manifested as a part of the nail forces changed, which was close to the slope surface. Comparatively, another part, which was away from the slope surface along the longitudinal axis of the nail, was almost not affected, which shows that the range of influence of prestress is very limited;

(vi) When comparing the measured results from the No. 4 and No. 5 profiles, the influence of unbonded length on nail forces can be investigated. As can be seen from Figure 9, the main difference lies in the distribution of nail forces on the first row. For No. 4 section, without an unbonded part, the distribution of nail forces was consistent with the documented results, which presents an inverted saddle shape, that is "small in the end and big in the middle". However, for the No. 5 test profile, with a 2.5 m unbonded length, the distribution was manifested as "double peaks", which shows there may be more than one potential slip surface in the loose fill materials. For the No. 4 section, due to grouting conducted in the overall length, there was deformation of the steel reinforcement bar when transferring the load from the anchor head to the slope, and accordingly, the anchorage effect could not function adequately. In other words, it amounted to a longer prestressed soil nail. For the other three rows of soil nails, the difference between the two sections is not so obvious. The effect of unbonded length, which is considered to be the main reason for slope stability in dense materials, is negligible in loose fill materials.

2.6.2. Foundation Pit Deformation

As can be seen from the monitoring results, two months after the excavation was finished, the lateral displacement of deep soil for all testing sets basically tended to be stable, and the distribution of lateral displacement along the excavation depth of the foundation pit is shown in Figure 10.



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

Figure 10. Distribution of lateral displacement along excavation depth. (**a**) Testing set No. 1 (**b**) Testing set No. 4 (**c**) Testing set No. 5.

According to the analysis of the lateral displacements in Figure 10, No. 5 is the smallest, No. 1 is placed in the middle, and No. 4 is the largest. Although both No. 4 and No. 5 were supported by prestressed-anchor-composite soil nailing, No. 4 represents a prestressed anchor without an unbonded part, and the transmission of prestress in loose materials was limited, which cannot limit the slope deformation well; No. 5 was provided with a free part, the length of which was 2.5 m, and the load applied to the anchor head could be better transmitted and distributed to the bonded part through the elastic deformation of the reinforcement.

The lateral displacement of the pit wall was limited by stress diffusion, and the surface displacement was reduced by about 32%. If the soil of No. 5 was the same as that of No. 1, which was relatively dense, the prestress would play better. The distribution of lateral displacement along the depth of No. 1 showed a regular "wedge", while the deformation curves of No. 4 and No. 5 were no longer smooth due to the reverse constraint from prestress, and there were sharp concave "inflection points" at the action positions of anchors, as shown in Figure 10b,c.

3. Numerical Simulation

The in situ test was performed under external disturbances, including soil predisturbance, excessive excavation, unloading on the surface of edges, tensioning and lagging of the anchor, and continuous rainfall. In order to analyze the influence of construction conditions on the stress-time history curve of the soil nails, numerical simulation was carried out based on standard conditions. ABAQUS 6.10 ® was used to conduct three-dimensional simulation of the three kinds of supporting structures with the testing sets for No. 1, No. 4, and No. 5. The numerical model is shown in Figure 11.

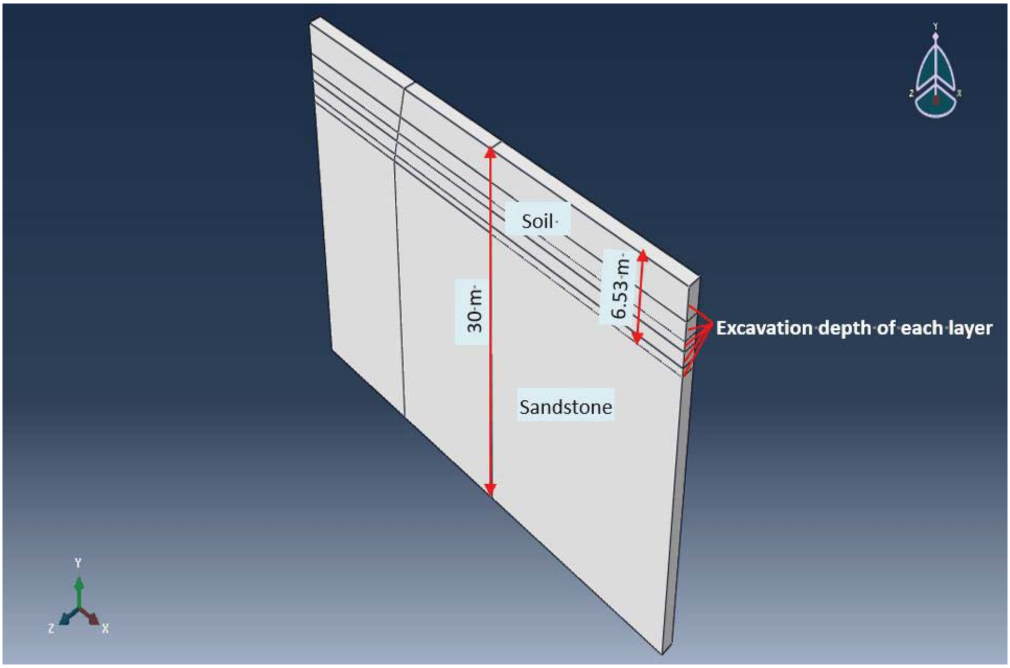


Figure 11. Numerical model.

3.1. Soil Constitutive Model

At present, in the finite element analysis of soil nailing, the soil constitutive models mainly include the Mohr–Coulomb elastic–plastic model [38], the modified Cambridge model [39], the extended D–P model [40], and others. Because the parameters required by the M-C elastic–plastic model can be accurately determined by laboratory tests, the change in yield surface, hardening or softening, can be considered by controlling the cohesion. A large number of experiments and engineering practices have confirmed that M-C strength theory can better describe the strength of geotechnical materials. Therefore, it has been widely used in the field of geotechnical engineering. In this paper, an elastic perfectly plastic model with the Mohr–Coulomb strength rule for the soil, characterized by the calculation parameters listed in Table 5, was adopted. The bonded parameters of soil nails and surface are as shown in Table 6. Gravity was not considered for the above materials.

Table 5. The calculation parameters of the soil.

Soil Layer	Thickness (m)	ρ (g/cm^3)	E (MPa)	c (kPa)	φ (º)	ν
①	2.8	1.81	27.3	14.0	20	0.25
②	1.9	1.79	11.7	20.0	15	0.30
③	2.42	1.82	30.6	15.0	21	0.25
④	22.88	1.89	90.0	3.0	27	0.23

Table 6. The bonded parameters of soil nails and surface.

Bonded Body	Diameter (mm)	ρ (g/cm^3)	E (GPa)	ν
soil nail 1	18	2.60	29.43	0.20
soil nail 2	22	2.50	31.37	0.20
surface	-	2.50	25.50	0.20

3.2. Model Parameter Selection

(i) The depth of the foundation pit was 6.53 m, and the slope of the foundation pit wall was 1:0.3; the width of the upper opening was 15 m, the width of the lower opening was 13 m, the finite element calculation area was within 35 m outward from the foundation pit wall and 23.47 m downward from the final excavation surface, and the model thickness was 1.5 m;

(ii) The origin of the coordinate system is located at the lower left corner of the model, with the *x*-axis facing right, the *y*-axis facing inward, and the *z*-axis facing up. The boundary conditions of the model were: the top was free and unconstrained; symmetrical constraints were imposed on the front and back sides, U2 = UR1 = UR3 = 0; sliding bearings were used on the left and right sides to restrict the degrees of freedom in the horizontal direction, U1 = 0; fixed hinged supports were used at the bottom to restrict the degrees of freedom in three directions, U1 = U2 = U3 = 0;

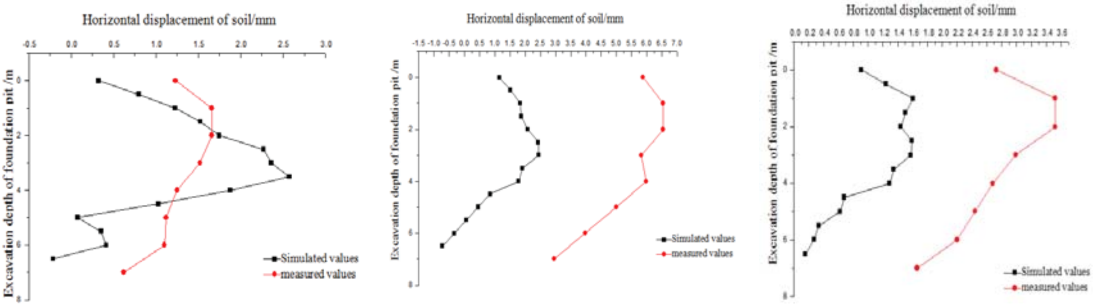
(iii) The first row, the third row and the fourth row of the retaining structure were soil nails, and the lengths of soil nails from the rows, top to bottom, was 9 m, 9 m, and 7 m, respectively. For the second row, testing sets 1, 4, and 5 corresponded to soil nails (L = 9 m), full-length bonded anchors (L = 12 m), and anchors with an unbonded section of 2.5 m (L = 12 m). Each row of soil nails and anchors was distributed in a rectangle, with horizontal spacing of 1.5 m and an inclination angle of 10°;

(iv) Combined with the actual construction conditions on site, the excavation was carried out in five steps, with excavation depths of 2.5 m, 1.4 m, 0.8 m, 1.2 m, and 0.63 m from top to bottom, respectively.

3.3. Analysis of Calculation Results

3.3.1. Comparison of the Horizontal Displacement of Soil

The simulation results of horizontal displacement of soil were compared with the monitoring data of soil nailing and soil nailing combined with prestressed anchors. The comparison results are shown in Figure 12.



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

Figure 12. Comparison between simulated and measured values of horizontal displacement of soil. (**a**) Testing set No. 1: soil nailing. (**b**) Testing set No. 4: composite soil nailing. (**c**) Testing set No. 5: composite soil nailing.

As can be seen from Figure 12, for testing set No. 1 for soil nailing, since the soil was never disturbed and was relatively dense, the simulated value of horizontal displacement of soil was therefore in good agreement with the measured value; For testing sets No. 4 and No. 5 for composite soil nailing, due to the early distribution, the soil was disturbed and relatively loose, resulting in poor consistency between the simulated value and the measured value. It can be seen from Figure 12b,c, the development trend of two curves is consistent, although the measured results are larger than the simulated values. It proves that the proposed idea is reasonable, namely, slope deformation is mainly controlled by the filling properties because of the greater looseness and compressibility compared with other media.

3.3.2. Comparison of Soil Nail Stress

Taking testing set No. 5 as an example, after the foundation pit excavation was completed, the comparison results between the simulated value and the measured value of the stress for each row of soil nails are shown in Figure 13.

As can be seen from Figure 13, for the first row of soil nails in the upper part, the field measured values are basically consistent with the numerical simulation values, but the simulation curve is relatively smooth, with a “single peak” around 1.23 m at the end of the nail; however, the measured curve has a sharp “double peak”. This is consistent with the previous analysis results, indicating that there may be 2 or more potential slip surfaces in the loose materials. For the third and fourth rows of soil nails in the lower part, the field measured value decreased greatly compared with the numerical simulation value. This is because the first row of soil nails was moved down for bypassing the previously buried natural gas pipeline (about 1.0 m deep), which brought about a small relative distance between the third and fourth rows of soil nails at the lower part. In addition, “layered excavation and layered support” were not strictly observed during construction. Instead, the third and fourth layers of soil were excavated together. In addition, during the construction of prestressed anchors, according to the specifications, the anchor was tensioned before the lower soil excavation and after the grouting materials of the anchor reached a certain strength. However, during the actual construction, due to the tight construction time period, the lower soil was excavated, then prestress was applied to the second row of anchors. Moreover, the prestress loss was large, and the design requirements could be met only after secondary supplementary tensioning. This shows that the stress of soil nails is greatly affected by the construction process, and the application of prestress has a "sequence effect": when it is delayed, the stress reduction of soil nails in the lower part is large, and the impact on soil nails in the upper part is relatively small.

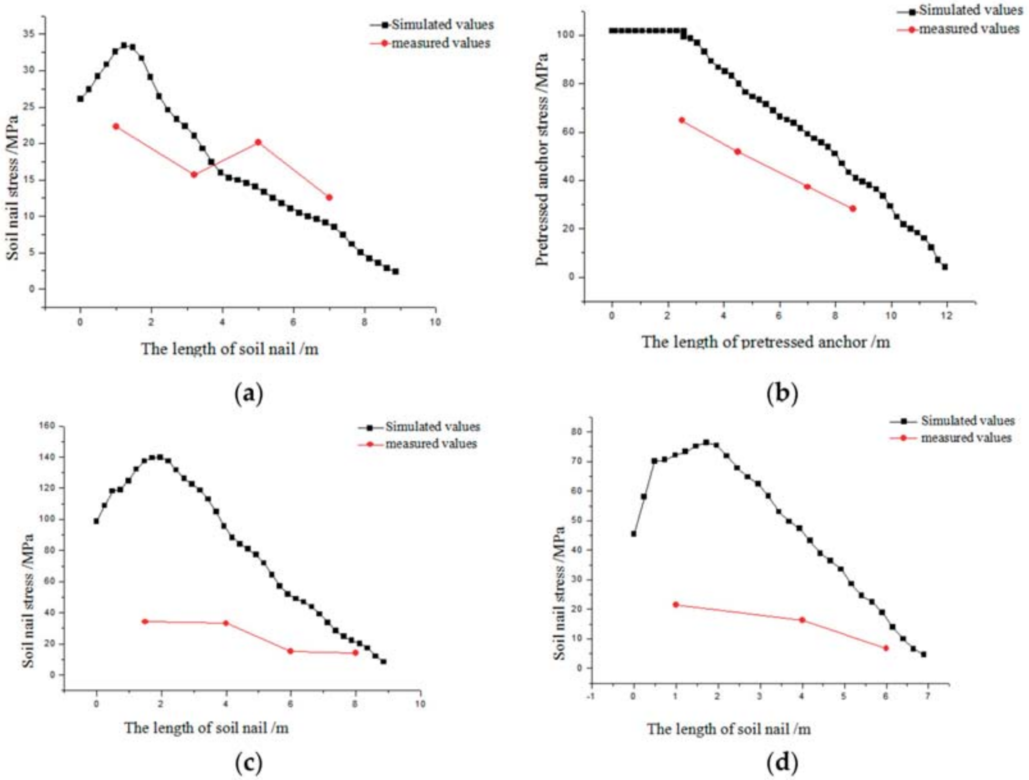
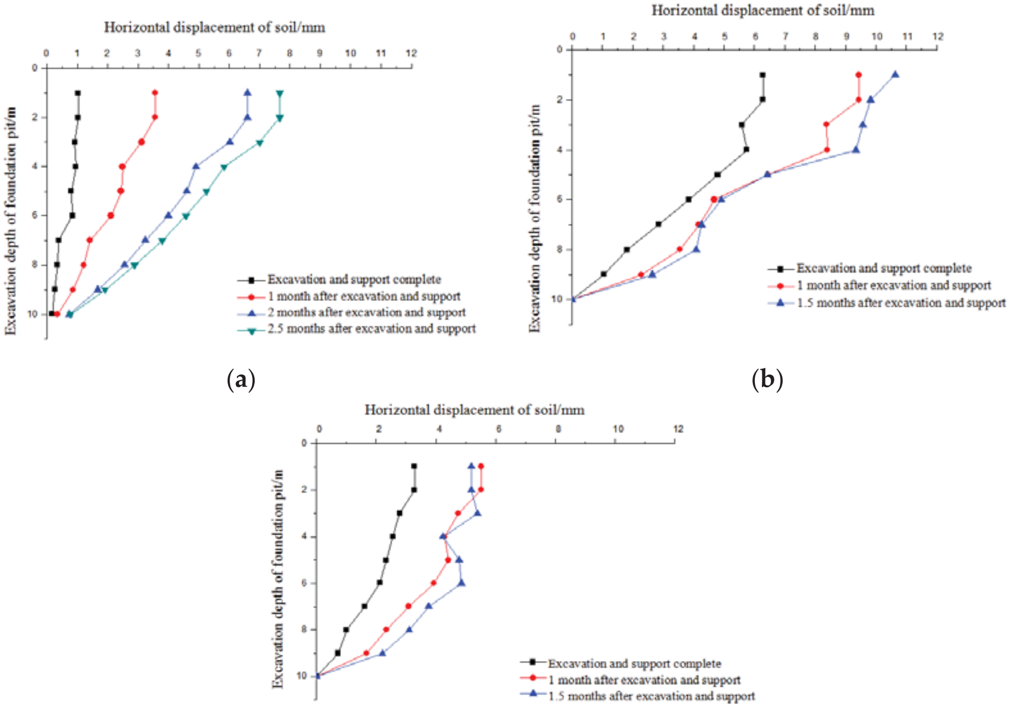


Figure 13. Comparison between simulated and measured values of soil nail stress. (**a**) Stress of the first row of soil nails, (**b**) stress of the second row of soil nails, (**c**) stress of the third row of soil nails and (**d**) stress of the fourth row of soil nails.

4. Time-Varying Analysis

According to the working mechanism of passive support structures, the stress of soil nails depends on soil deformation, and the "excavation effect" shows that the deformation of foundation pits is the most severe in the excavation period, and the stress of soil nails increases fastest; after the excavation, the bottom row of soil nails was installed. At this time, the deformation of the foundation pit tended to be stable, and the stress growth of soil nails should have been relatively slow. Time history curves for the deformation of soil for testing sets No. 1, No. 4, and No. 5 are shown in Figure 14. It can be seen that the deformation of the foundation pit increased steadily during the 3-month monitoring period. These phenomena show that the time effect of soil rheology is obvious on soil nailing and prestressed-anchor-composite soil nailing.



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

Figure 14. Time history curves for the deformation of No. 5. (**a**) Time history curve for deformation of No. 1 (**b**) Time history curve for deformation of No. 4 (**c**) Time history curve for deformation of No. 5.

During the excavation of the foundation pit, the deformation of the foundation pit mainly results from unloading. The increment in earth pressure caused by unloading destroys the original static equilibrium state of the support system, resulting in the displacement of the pit wall towards the foundation pit. The deformation of the pit wall mainly depends on two factors, one is the stiffness of the supporting structure itself, and the other is the earth pressure acting on the supporting structure. For soil nailing and prestressed-anchor-composite soil nailing, because there is no vertical advance support, only the concrete surface transmits the earth pressure, and the stiffness of the concrete surface is small. On the premise of meeting the design requirements, the earth pressure applied to the support structure is the main factor affecting the deformation of the supporting structure. During the intervals of foundation pit excavation, the properties of the foundation pit are mainly caused by soil consolidation and rheology. Accordingly, in the process of foundation pit excavation, the development of earth pressure goes through two stages. Stage I is a s follows: in the initial stage of excavation, the pit wall undergoes slight deformation under the acting earth pressure. With the passage of time, the deformation of the pit wall increases slowly, the earth pressure on the active side decreases gradually, and the bearing capacity of the soil begins gradually to play a role. When the earth pressure on active side decreases to the minimum, and the static earth pressure σ_0 converts into active earth pressure σ_a. Stage II is as follows: in the later stage of excavation, the deformation of the pit wall continues to increase, and the time effect caused by rheology is gradually highlighted, which makes the bearing capacity of the soil begin to decay, leading to a slight increase in the earth pressure on the active side, as shown in Figure 15.

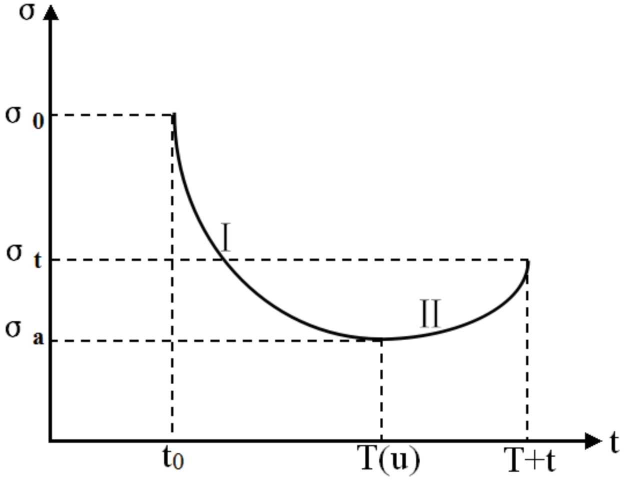


Figure 15. Time-varying characteristics of earth pressure.

5. Summary and Conclusions

In this investigation, three types of different retaining structures were investigated through an in situ test. Test results on the evaluation of mechanics behaviors were reported. The influences of external adverse disturbances on stress and deformation were analyzed. The effects of parameters such as prestress and unbonded length were discussed. The results obtained will assist practicing engineers in designing soil nails and anchors for applications in civil engineering. Through numerical simulation and comparison with ideal working conditions, the construction mechanics behaviors of composite support structures were analyzed considering the time-varying effect. In particular, it was found that:

(i) The interface stress is affected by the density and hardness of the soil around the soil nail: the interface stress is higher when soil is dense and hard, which is characterized by serious stress concentration; the interface stress is lower and uniform when soil is loose and soft, which is consistent with the theoretical hypothesis;

(ii) In all kinds of designs of bolt supports, it is generally assumed that the interfacial shear stress is evenly distributed along the length of the rod when the pull-out test is carried out on-site to determine the bonding strength between the anchor and the geotechnical medium. The average bond strength $\overline{\tau}$ is calculated by the simplified formula $P = \pi DL\overline{\tau}$ and is regarded as the ultimate bond strength τ_{ult};

(iii) The influence of prestress on the internal force of the soil nail is governed by the tensioning schedule: when the anchor is tensioned synchronously, the function of limiting deformation is obvious and the upper soil nails are affected; when the anchor is tensioned later, the lower soil nails are influenced;

(iv) Connection along all maximal nail forces along the longitudinal axis of nails is regular for soil-nailed retaining structures, which is matched with the assumed sliding surface; while for soil-nail–prestressed-anchor-composite retaining structures, prestress changes the distribution of the stress field, and there is an obvious “breakpoint” in the connection;

(v) The effect of unbonded length, which is considered to be the main reason for slope stability in dense materials, is mainly manifested as the change in stress distribution of the first row of soil nails, and the influence on the other rows can even be negligible in loose fill materials;

(vi) External adverse factors cause great disturbance to the construction process, which should be fully considered in theoretical analysis and numerical simulation, and reasonable suggestions should be put forward for design.

6. Analysis and Discussion

Construction of a foundation pit is a dynamic and gradual process, and stress and deformation are affected by construction steps and sequences. With the progress of each step, such as the installation of soil nails or anchors and the filling or digging of soil, the calculation system continues to evolve, and the load conditions and mechanical response change accordingly. From the perspective of construction mechanics, the stress analysis of the whole structural system should be formed by the successive superposition of a series of different initial strain conditions. The research shows that analysis results based on the idea of construction mechanics are very different from analysis results of one-time loading on a given complete structural system from the perspective of structural mechanics. The impacts of construction procedures and interference factors are rarely taken into account in technical specifications for retaining and protection of building foundation excavations (JGJ 120-2012) and specifications for soil nailing in foundation excavations (CECS: 96:97), which are technical specifications for foundation excavations in China and are used to guide site construction. Although these two technical specifications are not international, they have been verified by a large number of engineering practices in China and proved to be scientific and reasonable and are often used to guide engineering practice. But these impacts really exist, which results in differences between field monitoring data and theoretical analysis results. This is an urgent problem to be solved. These research results provide a theoretical basis and practical experience for the design and use of soil nailing combined with prestressed anchors for the construction of support structures and puts forward reasonable suggestions for the current situation of nonstandard construction.

Author Contributions: J.C.: writing—original draft preparation, writing—review and editing; L.G.: software; H.W.: data curation; Z.D.: investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by (1) the National Natural Science Foundation of China, grant number U1810203, and (2) the Doctoral Program Foundation of Henan Polytechnic University, grant number B2018-67.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: The writers wish to acknowledge the financial support of this research by the Comprehensive Design and Research Institute, Zhengzhou University. The kind assistance and valuable contributions of the staff of the School of Civil Engineering at Zhengzhou University, and the generosity of the Henan No. 7 Building Engineering Group who provided the site for the test, are gratefully acknowledged.

Conflicts of Interest: All authors declare that they have no conflict of interest.

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Article

Central Load-Bearing Control in the Construction Process of the Concrete Spherical Joint Nandu River Swing Bridge: A Case Study

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Abstract: The rotating mechanism is a significant procedure in swing bridges. In this paper, the Nandu River swing bridge is taken as an engineering case study to exhibit the critical technology of the monitoring process and the construction method of the swing bridge. The research focuses on the central load-bearing control system used to guarantee the security of the construction process. The mechanical problems during the construction process are discussed. Simultaneously, the cable tension and gravity center test are introduced. The non-Hertz contact theory is utilized to calculate the stress distribution of the spherical joint. Furthermore, the overturning moment is computed to monitor the stability of the rotating system based on the stress distribution calculation of the spherical joint. The monitoring process of central load-bearing control is entirely exhibited and discussed. Concurrently, the calculating result of the real-time overturning moment reflects the stability of the rotating construction process, and adjustments are made to ensure the safety of construction. The results show that, during the cable tension process, the middle position of the main arch exhibited 162.3 mm maximum vertical displacement. Meanwhile, the fraction moment was greatly larger than the unbalanced moment. Furthermore, the maximum overturning moment value was 2094.38 kN·m, which was smaller than the resistance of the overturning moment. The present research demonstrates that the non-Hertz contact theory fits the calculation of spherical joint stress distribution. Simultaneously, the middle position of the main arch should be monitored to control the vertical displacement at the cable tensioning stages. The gravity center test and stability control of the rotating construction are the key steps to reaching central load-bearing control.

Keywords: swing bridge; bridge construction; cable tension; gravity center test; non-Hertz contact theory; stability control

Citation: Liu, T.; Fan, J.; Peng, Z. Central Load-Bearing Control in the Construction Process of the Concrete Spherical Joint Nandu River Swing Bridge: A Case Study. *Buildings* **2022**, *12*, 511. https://doi.org/10.3390/buildings12050511

Academic Editors: Srinath Perera and Eva O.L. Lantsoght

Received: 28 February 2022
Accepted: 19 April 2022
Published: 20 April 2022

1. Introduction

A bridge is a structure built to span a physical obstacle (such as a body of water, valley, road, or rail) without blocking the way underneath. It is constructed for the purpose of providing passage over the obstacle, which is usually something that is otherwise difficult or impossible to cross [1,2]. The technology of rotating construction is an unusual building method caused by the surrounding topography and site of the bridge construction [3]. The rotating construction divides the bridge into two rotating systems (shown in Figure 1a) on each side of the bank or mountain. Then, the rotating system is separated from the temporary supports and rotated from the bridge axis to the butt at the proper time [4]. Several bridges have been built using rotating construction worldwide [5]. In recent decades, in order to reduce the impact on existing railway lines or municipal facilities, as well as cross valleys and other complex topographical sites, rotating construction has been widely utilized [6,7]. Consequently, the structure of the swing bridge rotating system has characteristics of large mass and ultra-long cantilevers. Therefore, to ensure the security of swing bridge construction, an investigation into central load-bearing control is needed. This procedure significantly influences the overturning moment during the rotating construction process.

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

Figure 1. (**a**) Rotating system and rotating construction process; (**b**) spherical joint.

Rotating construction is utilized in long-span swing bridges, and the superstructure of swing bridges commonly utilize long-span cantilever structures. However, they are easy to overturn and collapse during the rotating construction process [8]. During the rotating process, all the mass of the rotating system is applied to the upper rotating table, and lifting jacks push the upper rotating table to rotate the rotating system to a specific position of bridge arch closure. The rotating system and the spherical joint (Figure 1b) are hinged to the lower rotating table. Therefore, the fraction between the upper spherical joint and the lower spherical joint provides resistance to the structural overturn of the rotating system [9]. Therefore, the entire building process and the subsequent analysis of the swing bridge are important to bridging security. Simultaneously, unbalanced weight results in the gravity eccentric of the rotating system. The gravity eccentric can cause a large overturning moment, resulting in the overturn of the whole structure [10]. Alocci et al. [11] studied the lightweight swing bridge, and the main span of the bridge was 21.26 m. A feasibility study presented an asymmetric, cable-stayed, pedestrian swing bridge. However, the construction of bridges crossing valleys or rivers are of a larger scale. Therefore, the overturning moments are harder to control compared to lightweight swing bridges. At the same time, the overturning moment mainly appears at the spherical joint. The spherical joint [12] is the key component that bears the mass of all rotating systems. Generally, the steel spherical joint is utilized to undertake the gravity of the rotating system. However, the transportation and the installation of steel spherical joints are large challenges in mountainous area [13]. Therefore, ordinary reinforced concrete is often selected to be the material of the spherical joint. Meanwhile, the load capacity of reinforced concrete spherical joints is lower than that of steel spherical joints. Consequently, the distribution of contact stress on the spherical joint is a critical limit, depending on the allowable load capacity of the reinforced concrete material. Besides, the construction of other components is also important in the bridge construction process. Fuchs [4] studied the practical construction process of the El Ferdan Swing Bridge. Meanwhile, Watanabe et al. [14] characterized the whole construction process of the Yumeshima–Maishima Swing Bridge. However, the monitoring processes for the construction of these swing bridges were not presented in the studies. Furthermore, significant procedure testing details, including the determination of the gravity center of the rotating system, were not reported. Therefore, an overview of the entire construction process is necessary. The gravity center of the rotating system is the critical parameter to calculate the weight of the counterweight, and the distribution of contact stress on the surface is another important factor to ensure the central load-bearing of the special joint.

The objective of this research was to investigate central load-bearing control and the construction process of concrete spherical joint swing bridges. Concrete spherical joint contact stress is triggered by the weight of rotating system, so the non-Hertz contact theory can be applied in terms of the contact stress distribution of the concrete spherical joint. Before the rotating construction procedure, the gravity center test needs to be utilized to detect the gravity position of the rotating system after the cable tension stage. Subsequently, we propose a deducted formula based on non-Hertz contact theory to calculate the overturning moment during the rotating construction process. Meanwhile, the inclination monitoring system can be used on the back wall of the swing bridge to monitor the overturning moment in the process of the rotating construction in order to enhance the safety of the bridge construction.

2. Mechanical Problems of the Superstructure

2.1. Case Study Description

The construction of the Nandu River Swing Bridge is taken as an engineering case study (shown in 0); the bridge is the largest concrete spherical joint swing bridge in China, spans 190 m (L_0), and is located in the Enshi province. The sagitta height (F_0) is 38 m and the F_0/L_0 ratio is 1/5. Meanwhile, the arch axis coefficient (m) is 1.988. The design speed of the bridge is 40 km/h. The rotating system is formed by the rigid skeleton and the bottom of the rigid skeleton is cast by the concrete. The back wall provides a balanced weight during the process of rotating construction. The reinforced concrete spherical joint is cast by C50 concrete. Detailed information, in terms of the back wall and the spherical joint, is presented in Sections 4 and 5. Figure 2 shows the bridge layout of the Nandu River Swing Bridge.

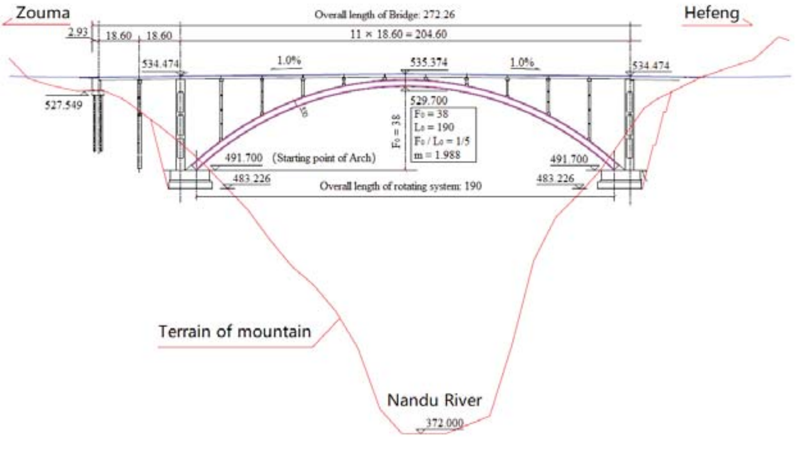


Figure 2. The layout of the Nandu River Swing Bridge (unit: m).

2.2. Construction Process of the Superstructure

Fuchs [4] expounded on the construction process of swing bridges using a case study. However, the construction of the Nandu River Swing Bridge is different: the rotating system of the bridge is an asymmetrical superstructure. The construction process of the superstructure is shown in Figure 3. Detailed information is presented below.

1. The main arch is built along the surrounding mountainous terrain (Figure 3a);
2. After the tension of the buckle cable and pulling cable, the entire rotating system is supported by the concrete spherical joint. If the gravity center of the system coincides with the axis of the concrete spherical joint, the system is only held up by the upward force of the concrete spherical joint. The overturning resistance of the entire system is

kept in a low-security state; therefore, the closure procedure needs to be implemented immediately (Figure 3b);

3. In terms of the rotating process of the swing bridge (Figure 3c), the rotating systems are derived from horizontal lifting jacks at the upper rotating table in no-wind weather;
4. Structural stiffness increases after the closure and the dismantlement of the cable, and the structure is in a stable state (Figure 3d). The entire structural weight is forced by the arch foot, forming the non-hinged arch. Under the action of self-weight and external load, the bending moment distribution in the arch is uniformly distributed along the main arch;
5. The pier founded on the main arch and the bridge deck are cast during the programmatic process, and the ancillary facilities are installed in sequence (Figure 3e).

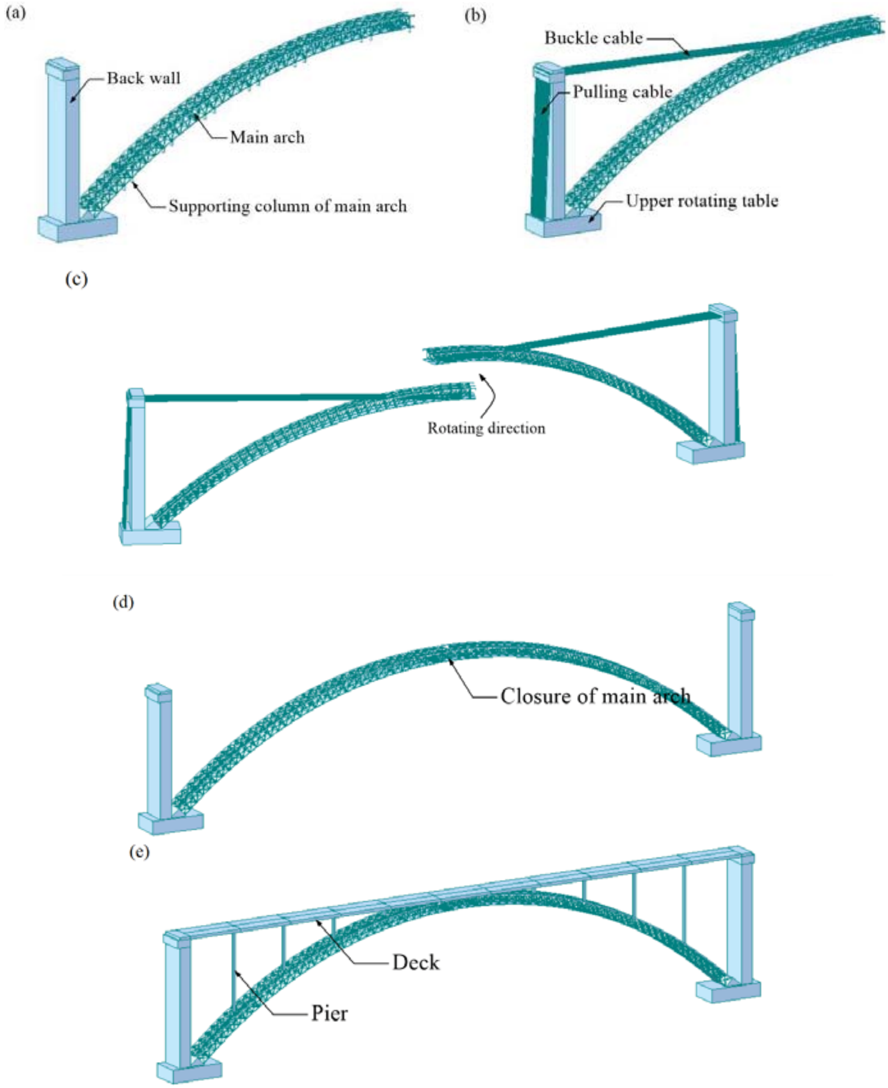


Figure 3. Construction process (**a**) main arch construction; (**b**) cable tension; (**c**) rotating process; (**d**) closure of main arch; (**e**) pier and deck construction.

2.3. Construction Process of the Concrete Spherical Joint

An ordinary reinforced concrete spherical joint consists of upper and lower spherical joints. The surface of the lower spherical joint is made by the scraper tool, which is utilized to scrape the lower spherical joint repeatedly along the busbar before the final setting of concrete. In order to decrease the friction between the upper and lower spherical joints, they grind against each other to achieve identical surface morphology after the setting of concrete. Finally, special lubricant is smeared on the contact surface to reduce rotating friction.

2.4. Non-Hertz Contact Theory of the Concrete Spherical Joint

The non-Hertz contact theory calculation model is suitable for conformal contact; therefore, the contact force of the upper and lower spherical joint can follow the law of non-Hertz contact theory [15,16]. The initial clearance of the axisymmetric structure (shown in Figure 4) is: $S = A_1x^2+A_2x^4+\ldots+A_nx^{2n}+\ldots$. Take the first two items; the other items can be ignored because they will not affect the results [17].

$$S = A_1x^2 + A_2x^4 \tag{1}$$

where S is the distance between two contact surfaces and x is the distance of the contact border to the contact circle center. In Equation (1), A_1 and A_2 are quadratic parabolic coefficients.

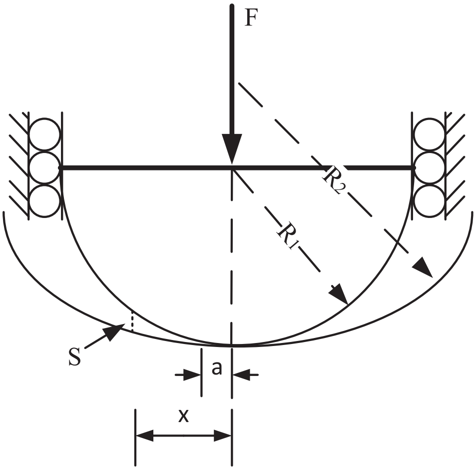


Figure 4. Sketch for analyzing the conformal contact joint with clearance.

For two-dimensional axisymmetric shapes in the form of A_nx^{2n}, the total load function and its pressure distribution curve are obtained [18]:

$$F_n = \frac{4nE^*A_na^{2n+1}}{2n+1} \cdot \frac{2 \cdot 4 \cdot \cdots \cdot 2n}{1 \cdot 3 \cdot \cdots \cdot (2n-1)} \tag{2}$$

$$p_n(x) = \frac{nE^*A_na^{2n-2}}{\pi} \cdot \left[\frac{2 \cdot 4 \cdot \cdots \cdot 2n}{1 \cdot 3 \cdot \cdots \cdot (2n-1)}\right]^2 \cdot \left\{\left(\frac{x}{a}\right)^{2n-2} + \frac{1}{2}\left(\frac{x}{a}\right)^{2n-4} + \ldots + \frac{1 \cdot 3 \cdot \cdots \cdot (2n-3)}{2 \cdot 4 \cdot \cdots \cdot (2n-2)}\right\}(a^2-x^2)^{\frac{1}{2}} \tag{3}$$

where F_n is the total load, a is the contact bandwidth, E^* is the equivalent modulus of elasticity, and A_n is the coefficient of x^{2n}.

$$\frac{1}{E^*} = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \tag{4}$$

$$A_2 = \frac{R_2^3 - R_1^3}{8R_1^3 R_2^3} \tag{5}$$

where E_1 and E_2 are the elastic modulus of two elastic bodies, respectively; μ_1 and μ_2 are the Poisson's ratio of two elastic bodies, respectively; and R_1 and R_2 are the radii of the contact surfaces, respectively.

The resultant force F and stress distribution $p(x)$ can be solved by using $n = 2$ with Equations (2) and (3).

$$F = \frac{64}{15} E^* A_2 a^5 \tag{6}$$

$$p(x) = \frac{128E^* A_2 a^2}{9\pi} \cdot \left[\left(\frac{x}{a} \right)^2 + 1 \right] \cdot (a^2 - x^2)^{\frac{1}{2}} \tag{7}$$

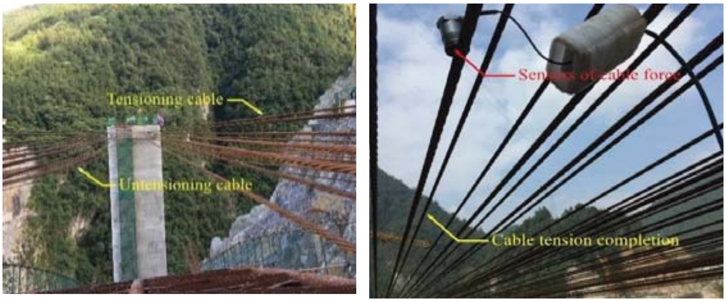
Equation (6) can be rewritten, yielding the contact bandwidth a as:

$$a = \sqrt[5]{\frac{15F}{64E^* A_2}} \tag{8}$$

3. Cable Tension

3.1. Objective of Cable Tension

After the building procedure of the upper rotating table, back wall, and main arch, the weight of the main arch structure is not transferred to the position of the upper spherical joint [6]. The buckle cable and pulling cable are anchored alternately (Figure 5a), and are able to gradually transfer the weight of each part to the spherical joint position. The stages of cable tension are from a to k, which are shown in Figure 5. At stage a, the pulling cables are anchored. Then, the buckle cables are anchored at stage b. After stage a and b, the tension of pulling cables increases at stage c. Subsequently, the tension of the buckle cable increases at stage d. To prevent the cracking of the concrete back wall caused by too much tension in the cables, the tension of the pulling cables and buckle cables are increased alternately in the following stages of cable tension until stage k. The complete rotating system (Figure 5b) is formed by the construction procedure to ensure that the back wall concrete does not exceed the affordability of the tensile and compressive stresses.



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

Figure 5. (**a**) Cable tension stage; (**b**) cable tension measurement.

3.2. Results of Cable Tension

During the cable tension process, the vertical displacement of the main arch must be monitored constantly. The vertical displacement monitoring positions are shown in Figure 6. The sensors for displacement testing were installed at every steel pipe welding position in our case study, because the joint position is the place where deformation is most likely to occur.

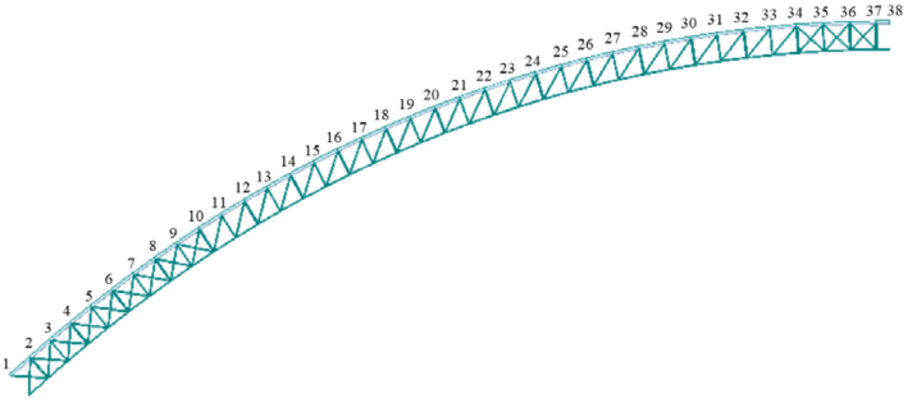


Figure 6. Vertical displacement monitoring position.

The results of the vertical displacements (No. 10, 19, 27, 36, and 38) during the cable tension stage are shown in Table 1. As can be seen, No. 19 had the largest vertical displacement during the cable tensioning process. This was due to the gravity and tensioning process bending the middle part of the arch. Special attention to the middle position of the main arch is recommended during the cable tensioning process.

Table 1. Vertical displacement of the cable tension stage.

Stage of Cable Tension	Cable Force/kN		Displacement of the Top Back Wall (Horizontal: mm)	Displacement of Main Arch (Vertical: mm)				
	Pulling Cable	Buckle Cable		10	19	27	36	38
a	11,000	0.3	−22.3	0.0	−0.9	−1.3	−1.8	0.7
b	10,600	2500	20.0	0.0	−0.4	−0.8	−1.1	0.4
c	31,500	2500	−20.1	0.0	−0.4	−0.8	−1.1	0.4
d	31,500	5000	22.2	0.0	0.0	−0.2	−0.5	0.0
e	43,500	5000	−1.3	0.0	0.0	−0.2	−0.5	0.0
f	43,500	6490	23.9	26.6	80.9	78.9	9.6	−5.2
g	49,500	6500	12.4	27.1	82.1	80.0	9.8	−5.3
h	49,500	7140	23.2	48.9	133.8	128.8	15.8	−8.4
i	52,500	7150	17.5	49.2	134.4	129.4	15.9	−8.4
j	52,500	7500	23.4	60.9	162.3	155.8	19.2	10.1
k	52,540	7580	24.8	60.2	156.9	141.3	10.1	42.2

4. Gravity Center Test

4.1. Mechanism of Gravity Center Test

4.1.1. Frictional Moment M_f Larger Than the Unbalanced Moment M_g

When $M_f > M_g$, there will be no rotation in the rotating system after the dismantlement of temporary constraint (cable system); therefore, the frictional moment of the spherical joint resists against the unbalanced moment of the rotating system, and the entire system stays in a stable state.

When the lifting force is increased on the left side, the static friction force of the rotating system becomes a dynamic friction force at a specific P_1 value. At this time, the lifting moment (P_1L_1) is equal to the sum of the friction moment (M_f) and the unbalanced moment ($M_g = Ge$), and the spherical joint rotates instantaneously and slightly. Meanwhile, the data of the vertical and horizontal displacement sensors change instantaneously and significantly. Therefore, the lifting force P_1 is increased to the maximum value. Here, the eccentric is supposed at the left side of the rotating system (Figure 7).

$$P_1 L_1 - Ge = M_f \tag{9}$$

where P_1 is the lifting force of the spherical joint rotated instantaneously on the left side of the rotating system, L_1 is the arm of the lifting force, e is eccentric, G is the weight of the rotating system, and M_f is the frictional moment.

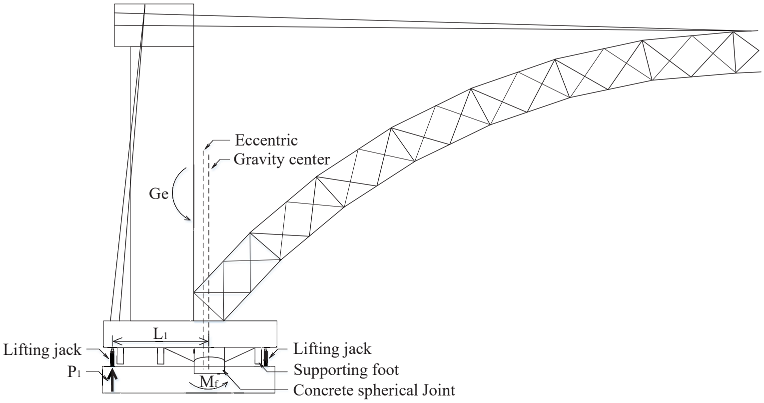


Figure 7. Lifting force on the left side of the rotating system.

When applying the lifting jack on the right side of the rotating system and increasing the lifting force, the static friction force of the rotating system becomes a dynamic friction force at a specific P_2 value. At this time, the lifting moment ($P_2 L_2$) is equal to the sum of the friction moment (M_f) and the unbalanced moment ($M_g = Ge$). The spherical joint rotates instantaneously and slightly. Just as before, the data of the vertical and horizontal displacement sensors change instantaneously and significantly. Therefore, the lifting force P_2 is increased to the maximum value (Figure 8).

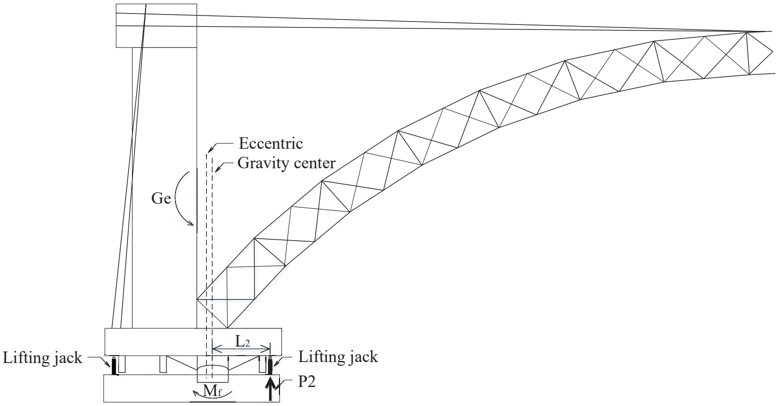


Figure 8. Lifting force on the right side of the rotating system.

$$P_2 L_2 + Ge = M_f \tag{10}$$

where P_2 is the lifting force of the spherical joint rotated instantaneously on the right side of the rotating system, and L_2 is the arm of the lifting force.

Combining Equations (9) and (10):

$$e = \frac{P_1 L_1 - P_2 L_2}{2G} \tag{11}$$

$$M_f = \frac{P_1 L_1 + P_2 L_2}{2} \tag{12}$$

$$M_g = Ge \tag{13}$$

$$\mu = \frac{M_f}{RG} \tag{14}$$

where μ is the static friction coefficient and R is the radium of the spherical joint.

The traction force of the rotating construction according to the standard [19]:

$$T = \frac{2\mu RG}{3D} \tag{15}$$

where D is the arm of the traction force.

4.1.2. Frictional Moment M_f Less Than the Unbalanced Moment M_g

When $M_f < M_g$, the frictional moment of the spherical joint is not enough to resist against the unbalanced moment of the rotating system after the dismantlement of temporary constraint; therefore, the foot falls on the slideway are supported.

When the supporting foot is on the slideway, the lifting jack is applied only on the same side of the supporting foot (Figure 9). When the lifting force is increased, the static friction force of the rotating system becomes a dynamic friction force at a specific P_1 value. At this time, the lifting moment ($P_1 L_1$) is equal to the sum of the friction moment (M_f) and the unbalanced moment (M_g). The spherical joint rotates instantaneously and slightly. Meanwhile, the data of the vertical and horizontal displacement sensors change instantaneously and significantly. Therefore, the lifting force P_1 increases to the maximum value.

$$P_1 L_1 - Ge = M_f \tag{16}$$

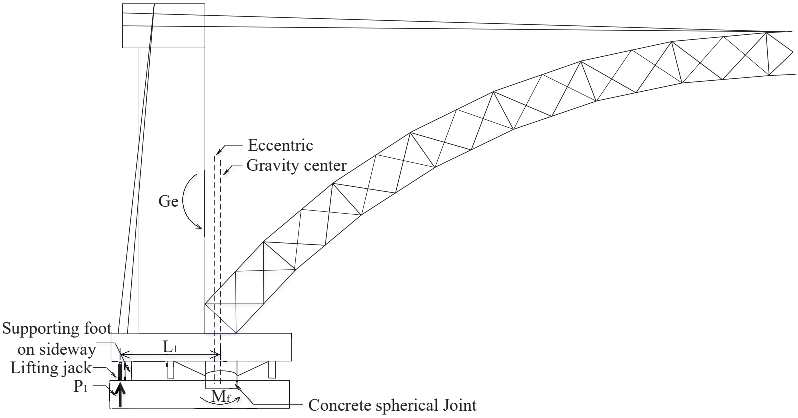


Figure 9. Lifting force on the left side of the rotating system.

Continuing the test, the lifting force on the left side starts to decrease (Figure 10). Keeping the lifting force in the declining state, the dynamic friction force of the rotating system becomes a static friction force at a specific P value. At this time, the spherical joint rotates instantaneously and slightly. Just as before, the data of the vertical and horizontal displacement sensors change instantaneously and significantly. Therefore, the lifting force P decreases to the minimum value.

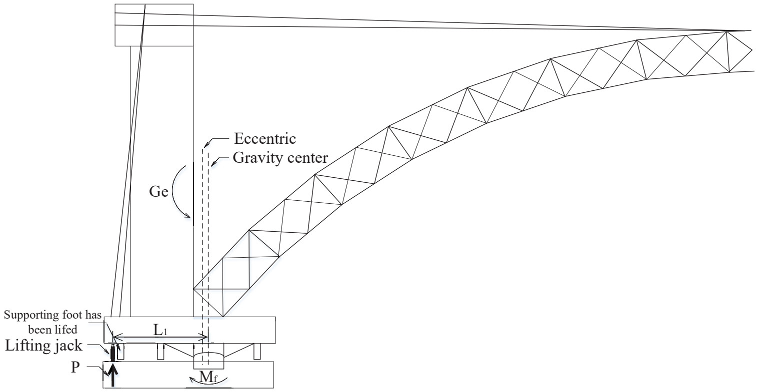


Figure 10. Lifting force on the right side of the rotating system.

$$Ge - PL_1 = M_f \tag{17}$$

where P is the declining lifting force of the spherical joint rotated instantaneously at the right side of the rotating system.

Combining Equations (16) and (17):

$$e = \frac{(P_1 - P)L_1}{2G} \tag{18}$$

$$M_f = \frac{(P_1 - P)L_1}{2} \tag{19}$$

The other parameters are the same as Equations (13)–(15).

4.2. Analysis of Engineering Results

4.2.1. Measuring Sensors

In order to ensure the accuracy of the test results, the computer synchronous control lifting equipment was used in the gravity center test. The lifting force of two pieces of lifting equipment were controlled at the same time, and the displacement measurement was carried out to guarantee the accuracy of the test. The test equipment is shown in Figure 11.

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

Figure 11. (**a**) Lifting system; (**b**) displacement sensors.

4.2.2. Position of Sensors

The layout of the gravity center test instruments is shown in Figure 12. Four lifting jacks were placed on both sides of the bridge rotating system to test the critical load during the gravity center test. The maximum load of each lifting jack was 4000 kN.

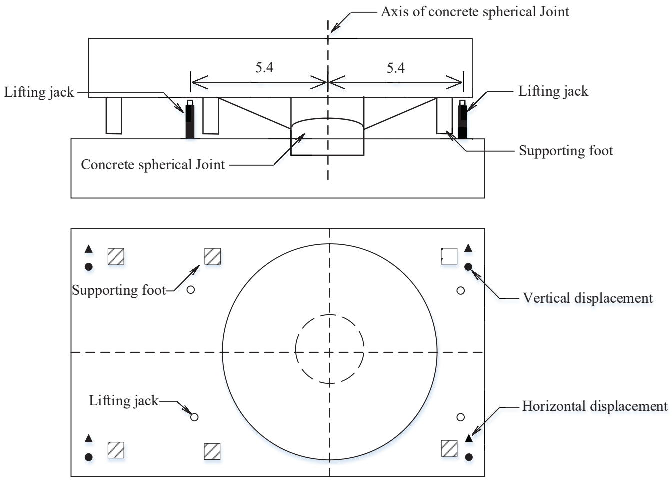
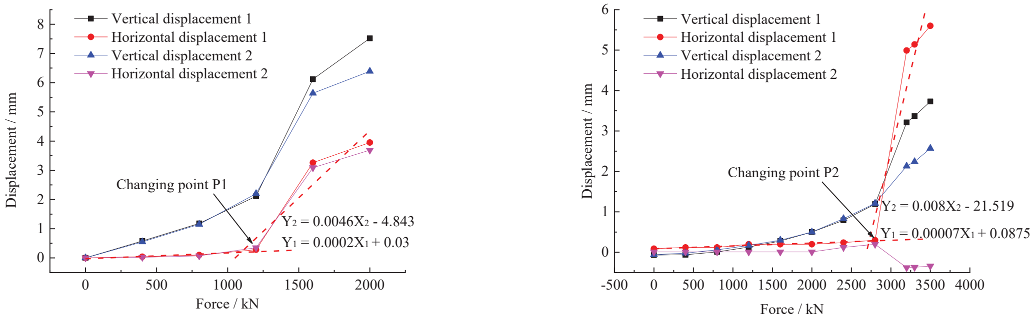


Figure 12. Position of the sensors.

4.2.3. Gravity Center Test Results

When the temporary constraints of the rotating system were lifted all the dial indicator readings remained unchanged, i.e., the rotating system did not rotate, so it was known that the system belonged to the situation of $M_f > M_g$. The test results with the lifting jacks on both sides are shown in Figure 13.



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

Figure 13. (**a**) Force–displacement curve of the main arch side; (**b**) force–displacement curve of the back wall side.

As can be seen from Figure 13a, the abrupt change point value P_1 of the main arch side during the lifting process was 1107.5 kN. As can be seen from Figure 13b, the abrupt change point value P_2 of the back wall side during the lifting process was 2695.79 kN. We used Equations (9)–(15) to calculate the related parameters (shown in Table 2).

Table 2. Calculation results of the rotating system.

Parameters	Value	Unit	Note
L	5.4	m	Lifting arm
P_2	2695.79	kN	
P_1	1107.5	kN	
G	59,600	kN	
R	8.5	m	Spherical radius
Unbalanced moment M_g	4291.2	kN·m	
Friction moment M_f	10,268.883	kN·m	
Eccentric e	0.072	m	Deflect to back wall

5. Stability Control of the Rotating Construction

5.1. Overturning Moment of Rotating Construction

The eccentricity of the rotating system produces the overturning moment of the complete rotating system when the gravity center is not at the axis of the spherical joint center. Because the rotating process is the most crucial and dangerous step of the rotating bridge's construction, the inclination of the rotating system should be monitored in real time while the rotating construction is in progress [20]. The change in obliquity angle can be used to track the rotating system's overturning moment. Figure 14 depicts the relationship between the overturning moment and the slope of the back wall:

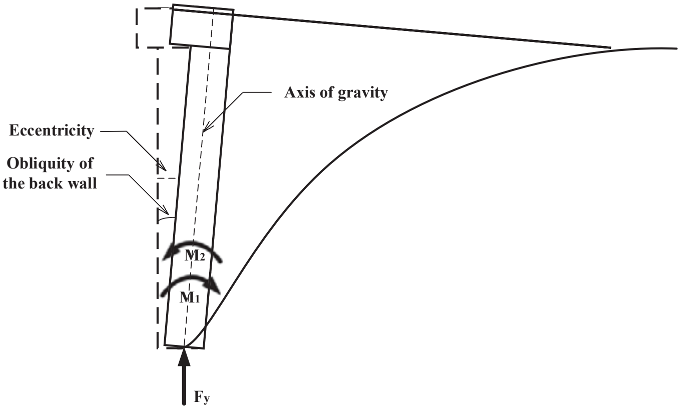


Figure 14. Overturning moment calculation.

The overturning moment and rear-wall inclination angle are calculated using the following formula:

$$M_1 = Ge \tag{20}$$

$$e = l \sin \delta \tag{21}$$

where M_1 is the overturning moment, M_2 is the resistance of the overturning moment, i.e., the frictional moment of the spherical joint, e is eccentricity, F_y is the supporting force, G is the gravity of the back wall, l is the center of gravity of the rotating system, and δ is the obliquity of the back wall.

As depicted in Figure 15, the swing bridge's overturning resistance system consists of an annular slideway, several supporting feet, and a locating pin. The overturning resistance moment is generated by the friction moment of the spherical joint when the rotating bridge's supporting foot is not in contact with the ground. When the supporting foot touches the ground, the rotating system's overturning resistance capacity reaches its apex, and the supporting foot functions as the last barrier in the overturning resistance system.

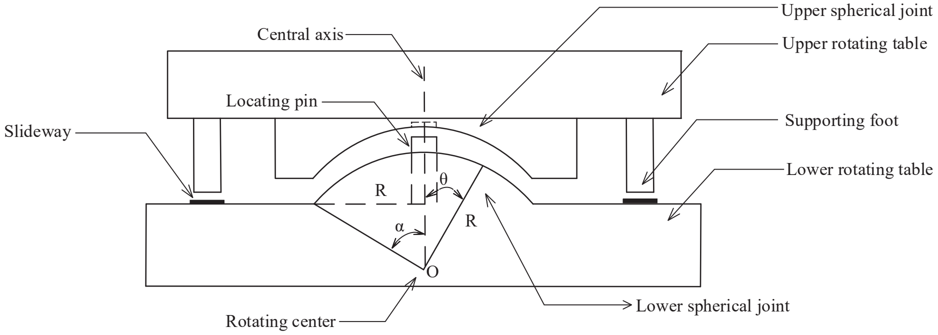
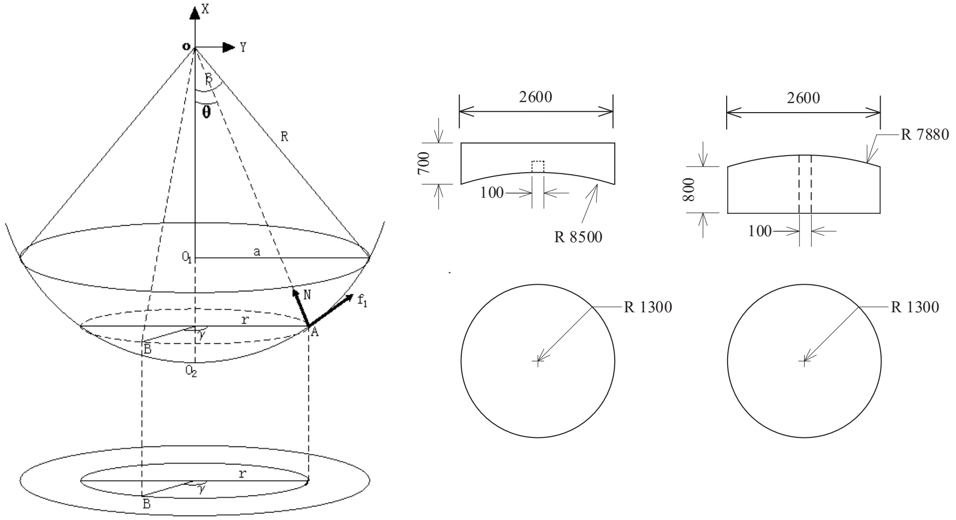


Figure 15. Resistance system of the overturning moment. R is the radius of spherical joint; R′ is the plane radius of spherical joint; α is the angle of the outer edge of the spherical joint; θ is the angle of the spherical joint.

5.2. Formula Deduction of Overturning Moment Resistance

Figure 16a depicts the spherical joint's geometry and the size of the spherical joint is presented in Figure 16b.



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

Figure 16. (**a**) The geometry of spherical joint; (**b**) upper (left) and lower (right) spherical joints (unit: mm).

There is microfrictional resistance f_1 on micro plane A, which can be estimated as follows:

$$df_1 = \mu\sigma ds \tag{22}$$

where $ds = R^2 \sin\theta d\theta d\gamma$ and μ is the friction coefficient. Therefore:

$$df_1 = \mu\sigma R^2 \sin\theta d\theta d\gamma \tag{23}$$

The overturning moment M_2 has a resistance of:

$$dM_2 = Ldf_1 = L\mu\sigma R^2 \sin\theta d\theta d\gamma \tag{24}$$

where L is the overturning arm; for each micro plane $L = \sqrt{(R\cos\theta)^2 + (R\sin\theta\sin\gamma)^2}$; and Equation (7) is:

$$\sigma = \frac{128E^*A_2a^2}{9\pi}\cdot\left(\frac{x^2+y^2}{a^2}+1\right)\cdot(a^2-x^2-y^2)^{\frac{1}{2}}$$

where $x^2 + y^2 = r^2 = (R\sin\theta)^2$. Therefore:

$$\sigma = \frac{128E^*A_2a^2}{9\pi}\cdot\left[\left(\frac{R\sin\theta}{a}\right)^2+1\right]\cdot(a^2-(R\sin\theta)^2)^{\frac{1}{2}} \tag{25}$$

The whole bridge resistance of the overturning moment is:

$$M_2 = \mu\int_\alpha^\beta\int_0^{2\pi}\frac{128E^*A_2a^2}{9\pi}\cdot\left[\left(\frac{R\sin\theta}{a}\right)^2+1\right]\cdot(a^2-(R\sin\theta)^2)^{\frac{1}{2}}\cdot\sqrt{(R\cos\theta)^2+(R\sin\theta\sin\gamma)^2}\sin\theta d\theta d\gamma \tag{26}$$

In which, α is the smallest spherical joint size (the boundary of locating pin) and β is the largest spherical joint size of the radius of the spherical joint for contact bandwidth.

5.3. Inclination Analysis of Rotating Construction

The inclination tracking system is arranged on the rotating system of the Nandu River Swing Bridge to track the changes in the inclination angle of the back wall during the rotating process and to judge the changes in the overturning moment of the rotating system in real time. When the inclination angle of the rotating system is too large, the inclination angle of the rotating system can be corrected in real time to ensure the safety, stability, and smoothness of the rotating system. The lifting jacks are placed at the lower rotating table to lift and correct the inclination of the rotating system. The parameters of the rotating system are shown in Table 3.

Table 3. Factors of the rotating system.

Factors	Frictional Coefficient μ	The Height of Gravity	Gravitation of the Rotating System
	0.1	17.802 m	59,600 kN

The upper and lower limits of θ are α = Arcsin(50/8500) and β = Arcsin(1300/8500), respectively. The spherical joint R = 8500 mm, and the contact bandwidth a = 1300 mm. Changing all of the parameters in Equation (26), the resistance of the overturning moment M_2 = 4499.79 kNm is calculated using the Mathematica program.

The back wall's inclination angles X (along the bridge) and Y (across the bridge) are determined. Equations (20) and (21) are used to compute the back wall's overturning moment in the X and Y directions. Figure 17 depicts the results:

The largest inclination angle appears in 0 during 480 min of the rotating construction. The maximum overturning moment is calculated using Equations (20) and (21), and the maximum value of our case study was 2094.38 kNm, which was less than the resistance of the overturning moment. As a result, the rotating system stayed safe during the rotating construction process.

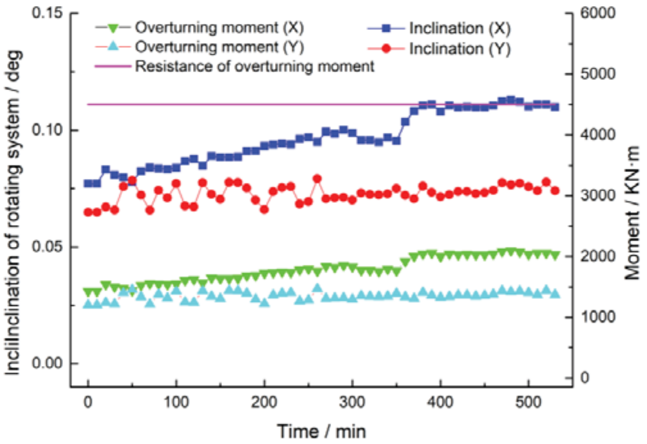


Figure 17. The rotating system's inclination and overturning moment.

6. Recommendations for Practice

The present study exhibits the whole process of rotating construction. The following recommendations are proposed for practical construction:

1. The arch rib can be entirely removed from the frame after the cable tension stages. However, the deformation of the main arch, especially vertical deformation, is obvious during the cable tension period. Therefore, the linear changes to the main arch throughout the tensioning process must be continuously monitored. This guarantees the linear shape of the main arch after cable tension, achieving the aim of structural safety;
2. During the gravity center test, the displacement of the upper rotating table has to be monitored continuously in real time. The lifting process by the lifting jack should stop immediately once the changing point appears. This prevents the overload of the lifting jack resulting in the overturn of the rotating system;
3. The inclination of the rotating system should be tracked in real time during the rotating construction of the main arch. The stability of the rotating system entirely depends on the fractional moment of the spherical joint. Thus, the central load-bearing state of the rotating system is significant to decrease the overturning moment.

7. Discussion and Conclusions

The rotating construction of swing bridges has traditionally faced the problem of achieving a central load-bearing state. The monitoring process of rotating construction is critical, as it is related to the safety of the bridge construction. With increasing amounts of bridge construction in mountainous areas, research into swing bridges needs to be thoroughly explored. The entire process of the rotating construction of swing bridges has never been fully reported. Moreover, it is important to offer an example of rotating construction for clarity, in order to ensure the safety of swivel construction.

In this study, the complete construction process of the swing bridge is presented to give an insightful overview of its key problems. All of the involved processes aim to bring the bridge construction to a central load-bearing state. During the cable tension stage, the middle of the main arch can reach 162.3 mm in vertical displacement. This might trigger structural buckling. This can be controlled by monitoring the cable tension. Furthermore, there is the risk of the fractional moment being smaller than the unbalanced moment shown by the gravity center test results. Ideally, the overturning moment reaches its maximum value at 2094.38 kNm during the rotating process, as this is smaller than the overturning resistance (fractional moment). The whole monitoring process of the swivel construction has been presented. The central load-bearing state is emphasized to safely control swivel construction.

The greatest advantage of this study is that it predicts the possible risks that could occur during swivel construction. By utilizing the following solutions, the safety of swivel construction can be ensured and a central load-bearing state can be achieved. As noted above, the following conclusions can be drawn.

1. The non-Hertz contact theory can be properly utilized to calculate the spherical joint stress distribution. It can be used to reach central load-bearing control when calculating the surface contact stress distribution of the spherical joint;
2. Special attention to the middle position of the main arch is recommended during the cable tensioning process, since this is the most dangerous position during the procedure;
3. The key problem of the gravity center test is to determine the changing point during the lifting process, as this is the most important process before the rotating construction. It enables the balance of the rotating system to be established, guaranteeing load-bearing control;
4. Overturning moments are monitored by the inclination tracking system and calculated by the deduced formula based on the non-Hertz contact theory. This guarantees the safety of the rotating construction.

Author Contributions: Conceptualization, T.L. and J.F.; formal analysis, T.L.; funding acquisition, J.F.; methodology, T.L.; project administration, J.F.; writing—original draft, T.L.; writing—review and editing, J.F. and Z.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available from the first author upon reasonable request.

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

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sustainability

Article

A Hybrid Multi-Criteria Decision Support System for Selecting the Most Sustainable Structural Material for a Multistory Building Construction

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Abstract: In recent years, the performance of the construction industry has highlighted the increased need for better resource efficiency, improved productivity, less waste, and increased value through sustainable construction practices. The core concept of sustainable construction is to maximize value and minimize harm by achieving a balance between social, economic, technical, and environmental aspects, commonly known as the pillars of sustainability. The decision regarding which structural material to select for any construction project is traditionally made based on technical and economic considerations with little or no attention paid to social and environmental aspects. Furthermore, the majority of the available literature on the subject considered three sustainability pillars (i.e., environmental, social, and economic), ignoring the influence of technical aspects for overall sustainability assessment. Industry experts have also noted an unfulfilled need for a multi-criteria decision-making (MCDM) technique that can integrate all stakeholders' (project owner, designer, and constructor) opinions into the selection process. Hence, this research developed a decision support system (DSS) involving MCDM techniques to aid in selecting the most sustainable structural material, considering the four pillars of sustainability in the integrated project delivery (IPD) framework. A hybrid MCDM method combining AHP, TOPSIS, and VIKOR in a fuzzy environment was used to develop the DSS. A hypothetical eight-story building was considered for a case study to validate the developed DSS. The result shows that user preferences highly govern the final ranking of the alternative options of structural materials. Timber was chosen as the most sustainable option once the stakeholders assigned balanced importance to all factors of sustainable construction practices. The developed DSS was designed to be generic, can be used by any group of industry practitioners, and is expected to enhance objectivity and consistency of the decision-making process as a step towards achieving sustainable construction.

Keywords: sustainability; sustainable construction; multi-criteria decision-making; decision support system; building construction

Citation: Alam Bhuiyan, M.M.; Hammad, A. A Hybrid Multi-Criteria Decision Support System for Selecting the Most Sustainable Structural Material for a Multistory Building Construction. *Sustainability* **2023**, *15*, 3128. https://doi.org/10.3390/su15043128

Academic Editors: Antonio Caggiano and Asterios Bakolas

Received: 10 November 2022
Revised: 17 January 2023
Accepted: 6 February 2023
Published: 8 February 2023

1. Introduction

Over time, the construction industry's development has been constantly questioned due to issues such as low productivity, high energy consumption, the generation of waste, and greenhouse gas emission. Buildings and their associated construction industries account for 36% of global energy use and 37% of energy-related carbon dioxide (CO_2) and greenhouse gas emissions [1]. The Construction User's Roundtable (2022) reported that the productivity of construction works has significantly reduced in the last 50 years compared to other sectors [2]. Another report showed that construction-related spending accounted for 13% of the world's GDP, but its annual productivity growth increased by 1% over the past 20 years. It also presented that $1.6 trillion of additional value could be created through higher productivity, meeting half the world's infrastructure needs [2]. During the 'UN Climate Change Conference', UK, 2021, all 26 of the participating nations of the COP (conference of the parties) collectively agreed to work to reduce greenhouse gas emissions to limit the rise of the global average temperature to 1.5 degrees Celsius [3]. Therefore, the construction industry desperately needs better resource efficiency, improved productivity, less waste, and increased value.

Sustainable construction aims to achieve 'maximum value with minimum harm,' ensuring the balance between economic, social, and environmental factors in a project, commonly known as the pillars of sustainability [4–6]. These pillars of sustainability were introduced by the World Summit on Social Development of the United Nations held in 2005 [7]. Sustainable construction is a holistic process that promotes harmony between nature, humanity, and the built environment by creating settlements that suit humans and support economic equality [8]. It applies sustainable development principles to a building life cycle from planning the construction and mining and preparing the raw materials to production, creating construction materials, usage, the destruction of construction, and the management of waste [8].

Structural elements of a building generally consist of beams, columns, tension members, and their connections [9]. The selection of the structural material in the case of building construction plays a vital role as it acts as the backbone of the structure and demands vast resources. In general, concrete, timber, steel, masonry, composite (timber–steel, timber–concrete, steel–concrete), etc., are used to construct multistory buildings. Reinforced concrete (RC) is the most commonly used structural material for building construction. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to the ecosystem and environment [10]. Structural steel (SS) may be used to replace concrete due to its numerous advantages, including strength and flexibility. Nevertheless, it requires a significant amount of energy during manufacturing and may be expensive in some situations [11]. Masonry is a time-tested alternative to concrete construction. However, burned bricks may emit significant levels of carbon during the manufacturing process, and masonry construction requires a substantial amount of cement [12]. As a building material, timber has a better energy-saving and carbon-reduction performance than other traditional materials. However, a lack of design standards and fire-resistance issues are commonly highlighted as impediments, inhibiting timber use as a structural material for multistory buildings, unlike masonry, concrete, or steel [13]. This phenomenon has led to a rethink regarding alternative building construction materials to achieve sustainability.

Making a sustainable decision is always critical as it combines several technical, social, economic, and environmental factors. From the literature review, it was identified that several studies have been carried out on the selection of building materials, sustainability indicators of materials, etc. The findings showed that construction industries select structural materials by considering the technical and economic aspects, and there was a lack of any sustainable decision-making system. Most of the previous research in this area either focused on technical or economic aspects only or considered three pillars of sustainable construction. From interviews with several industry experts, it was also identified that the decision regarding the selection of structural materials commonly considers technical and economic factors. There is no structured tool to integrate all stakeholders' opinions or assess the overall aspects of sustainable construction in the selection process.

In particular, the objective of this research was to develop a decision support system that would integrate all stakeholders' preferences into an IPD framework for selecting the most sustainable structural material from technical, economic, social, and environmental sustainability points of view. The activities associated with the fulfilment of the research objectives include the identification of structural materials used for multistory building construction through the literature review, industry practices, and expert opinion; sustainability analysis (technical, economic, social, and environmental aspects) of the structural materials in use with the help of the tools available (LCC, LCCA, etc.) and expert opinion; review of the selection process for structural materials from the perspective of sustainable construction practices; several interview sessions with industry experts, project owners, design teams, and constructors, conducted in addition to the literature review, to determine the details of existing practices; the development of sub-criteria for all of the pillars of sustainable construction, primarily through the literature review, and then validating and finalizing them with feedback from industry and academic experts; and development of the DSS using MCDM techniques to aid the selection of the most sustainable structural material for multistory building construction.

The remarkable contributions of this research comprise the integration of technical aspects with the commonly used three pillars (economic, social, and environmental) for sustainability assessment, including a case study; the application of two different MCDM methods (Fuzzy TOPSIS and Fuzzy VIKOR) to rank alternatives with Shannon's entropy to handle qualitative and quantitative data, and trapezoidal membership functions to obtain more realistic results; and the development of a DSS application that shall assist decision makers in choosing evaluation criteria and assigning relative importance to those criteria in the combination of qualitative and quantitative methods in an IPD framework, not only to select the most sustainable structural material but also to solve a wide range of construction-related problems.

The rest of the paper is organized as follows: Section 2 provides a comprehensive picture of past research. Section 3 explains the data collection and analysis process used in this study. Section 4 presents a case study to validate the theoretical model. Section 5 discusses the details of the DSS desktop application software. Section 6 explains the sensitivity analysis to verify the appropriateness of model output. Sections 7 and 8 present the discussions and conclusions to describe the usefulness and benefits of the study.

2. Related Literature and Past Research

A literature review of the proposed methodologies (structural materials commonly used for multistory building construction, multi-criteria decision-making, life cycle assessment and life cycle cost analysis, integrated project delivery, application of MCDM in construction, and the methods chosen for this research) have been discussed in this section to highlight their relevance in the construction literature. A brief discussion on the research gap was included to present the contributions of this research.

2.1. Structural Materials Commonly Used for Multistory Building Construction

The commonly used structural materials in building construction practices are steel, concrete, masonry, and timber [14]. Globally, concrete is the most utilized substance after water [15]. In terms of volume, twice as much concrete is used worldwide in construction as all other building materials combined, including timber, steel, aluminum, and plastic [14]. Approximately three tons of concrete are used per capita each year, globally, making it the most widely used material in construction [16]. Concrete manufacturing emits 2.8 billion tons of CO_2 (carbon dioxide), accounting for 4–8% of global greenhouse gas emissions [10]. The construction of buildings accounts for over one-quarter of steel production each year. Approximately 1500 million tons of steel are produced annually, accounting for 9% of the world's CO_2 emissions from energy and processes [17]. Steel demand is expected to quadruple in the next 37 years [17]. Masonry is one of the preferred construction materials for low-to-medium-rise buildings due to its availability, cost-effectiveness, durability, and excellent weather resistance [18]. It also provides excellent thermal and sound insulation for the structures compared to other construction materials [19]. However, masonry has a low tensile strength and ductility (compared with concrete). Alternative construction systems such as reinforced masonry (RM), confined masonry (CM), post-tensioned masonry, and thin-layer mortared masonry have been introduced in the past to overcome these limitations [20]. Timber is considered one of the most eco-friendly building materials available and has been used as a basic construction material for millennia [21]. It is a renewable natural substance that will sequester carbon throughout its life if managed appropriately. Trees release oxygen and absorb CO_2 (carbon dioxide) from the atmosphere, resulting in biomass and a reduction in CO_2 levels. It is estimated that the average tree absorbs approximately 55 kg of CO_2 and gives off 40 kg of oxygen when growing 2 kg of wood [22]. Therefore, during its growth period, a tree positively impacts the environment by reducing GHG [23]. The comparison of selected environmental parameters showed that wooden buildings consume 54% less embodied energy and generate 35% less SO_2 (sulfur dioxide)-equivalent emissions (acidification potential). Additionally, the production of CO_2 emissions (global warming potential) reaches a negative value; hence, emissions are reduced for wooden constructions versus emissions being increased by 156% in masonry constructions [24]. Timber construction systems have several advantages over steel, masonry, and concrete [25]. Timber has a higher ratio of load-carrying capacity to weight, and its lower weight reduces the soil load by 30 to 50%. However, knowledge regarding timber construction is still lacking, which can create skepticism and preconceptions about the features and costs of timber construction [25].

2.2. Multi-Criteria Decision-Making (MCDM)

Multi-criteria decision-making (MCDM) is fundamentally a systematic approach to solving problems of varying degrees of structure [26]. This strategy has emerged as a vital tool for addressing real-time solutions for problems of uncertainty, particularly for sustainable construction engineering and environmental sustainability [27]. It provides decision makers with an informed recommendation from a finite list of alternatives (also known as actions, objects, solutions, or candidates), while being evaluated from multiple viewpoints, called criteria (also known as attributes, features, or objectives) [28]. The MCDM technique generates alternative scenarios, establishes criteria, assesses alternatives, weighs the criteria, and ranks the alternatives [29]. Subjective (qualitative) methods and objective (quantitative) methods are the two types of weighing techniques. The subjective methods determine weights according to the preference or judgments of decision makers. On the other hand, objective techniques, such as the entropy method, multiple objective programming, etc., determine weights by solving mathematical models without considering the decision maker's preferences [30]. MCDM methods range from a single approach (such as the analytic hierarchy process and fuzzy sets) to a combination of the methods, also known as the hybrid approach [31].

2.3. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA)

The term 'life cycle assessment' (LCA) refers to a broad technique for quantitatively evaluating a product's material, energy inputs and outputs, and environmental impacts over its entire life cycle [32]. It considers all building stages' and cradle-to-grave and life cycle contributions from manufacturing, construction, operation, maintenance, disposal, and end-of-life [33–36]. In the case of building construction, these different stages include the raw material extraction for the various assembly components of the building (i.e., limestone mining and calcination for cement), the manufacturing, transport to site, construction and installation, the building's operational life, maintenance, and retrofitting, and at the end of its life, its demolition [37].

Life cycle cost analysis (LCCA) is a tool that helps the owner and stakeholders determine the most cost-effective solution [38]. Life cycle costing has been used in many studies to assist decision-making in building construction [39]. LCCA considers all costs associated with the life cycle building stages, including initial costs, operating costs, maintenance costs, and end-of-life costs, as well as any residual value (removal, resale, and salvage value) throughout the life period [39,40]. It performs economic assessments by comparing the relative cost-effectiveness of various building construction methods. The aim of LCCA on buildings is to estimate costs throughout their whole life cycle, which may then be utilized as input into a decision-making or evaluation process [41].

2.4. Integrated Project Delivery (IPD)

Integrated project delivery (IPD) is a relatively new project delivery method. IPD aims to improve efficiency and reduce risks and waste through the early involvement of stakeholders and a collaborative construction process [42]. In this method, all project stakeholders are involved from the beginning to align their goals and incentives through shared risk and rewards, which ultimately leads to the increased efficiency of this PDM. In IPD, all parties, including the owner, the designer, and the contractor, are bound together through a joint agreement [42]. Compared to other traditional project delivery methods, IPD contributes more towards sustainability by integrating all stakeholders from the initial stage of the project [43]. In the case of conventional PDMs, contractors and manufacturers are involved in the project after the project's design phase. Thereby, traditional construction processes tend to incur more costs from rework resulting from miscoordination, quality issues, the inefficiency of project delivery times, poor performance, and client dissatisfaction with the product delivered [44].

2.5. Application of MCDM in Construction

Zhu et al. (2021) studied a total of 530 civil engineering construction articles published from 2000 to 2019 and analyzed the application of MCDM in construction [45]. They reported the use of 29 single methods and 94 hybrid methods. Among the single methods, the AHP (analytic hierarchy process), fuzzy theory, generic algorithm, data envelopment analysis, and analytical neural process were the top five. At the same time, fuzzy AHP, fuzzy TOPSIS (technique for order performance by similarity to an ideal solution), AHP–fuzzy TOPSIS, fuzzy ANP (analytic network process), ANP–DEMATEL (decision-making trial and evaluation laboratory), and fuzzy DEMATEL were the top hybrid methods used in construction. The two largest hybrid categories were hybrid methods that included fuzzy logic (used in 159 articles; 30.00 percent) and hybrid methods that included AHP (used in 104 papers; 19.62 percent) [45]. The search result in the 'Scopus' database with the keywords 'mcdm' and 'construction' for 2020–2022 showed that an additional 174 journal articles were published that comprised the use of both single and hybrid methods of MCDM. The fuzzy theory was used in 43 papers, out of which 9 papers utilized a single method and the other 34 used fuzzy theory in combination with TOPSIS, ANP, AHP, PROMETHEE (preference ranking organization method for enrichment evaluation), VIKOR (visekriterijumska optimizacija I kompromisno resenje), etc. AHP alone was used in five papers, and in combination with other methods, it was used in a further four articles. TOPSIS was also used in nine articles: Twice as a single method and in the remaining seven cases as a hybrid.

After a systematic literature review, Marcher et al. (2020) concluded an increasing interest of stakeholders toward the adoption of DSS for solving decision problems in the field of sustainable management and automation in construction [46]. Minhas and Potdar (2020) reported the increasing trend in the fusion of the MCDM in the construction industry and mentioned that AHP and fuzzy and quantitative decision models made up the major combinations [47]. Hashemi et al. (2021) utilized economic, social, and environmental pillars to select sustainability indicators for conducting sustainability assessments for highway construction projects. They used a novel triangular intuitionistic fuzzy decision-making approach for scoring and ranking the indicators [48]. Bektur (2021) used a hybrid fuzzy MCDM approach for a sustainable project portfolio selection problem. In addition to the economic factors, the author integrated social and environmental factors into the decision process. The evaluation criteria were primarily selected by the literature review and then finalized by the decision-making team's opinion [49]. Marovic et al. (2021) applied AHP and PROMETHEE to selecting the optimal contractor. They chose selection criteria through an extensive literature review and used two groups of experts in collective decision-making [50]. Zhang et al. (2022) used DEMATAL–ANP to identify and analyze risk factors in green product certification. They used ANP for calculating the weight and DEMATAL to analyze causal relationships among the risk factors [51]. Lu and Wudhikarn (2022) used the MCDM method to develop an integrated model to identify intellectual capital performance indicators. In that study, the intangible key performance indicators were primarily selected by using the literature review and survey, and they were further validated using in-depth interviews with expert respondents [52]. Zoghi et al. (2022) applied fuzzy AHP and TOPSIS to select building materials in their study. In addition to economic and environmental criteria, they included deconstruction-related factors of materials to ensure environmentally friendly demolition of the buildings [53].

From the literature review, it was identified that numerous studies have been carried out on the selection of building materials, sustainability indicators of materials, sustainability analysis of green buildings, etc. However, none of these studies integrated the inputs of all stakeholders, i.e., owner, design team, and constructors, in the IPD framework from the project's inception, in order to decide on the most preferred sustainable option. However, although several researchers argued that the technical pillar is an essential analytic element of sustainability assessment for civil infrastructure, there were hardly any studies that systematically integrated the technical pillar with economic, social, and environmental pillars to analyze the overall sustainability aspects. This research developed an MCDM model that will integrate all stakeholders' preferences into an IPD framework to select the most sustainable structural material from technical, economic, social, and environmental sustainability points of view. Academia shall benefit from integrating technical aspects with the commonly used three pillars in a methodical approach. The industry shall benefit from the MCDM model, which will help to select the most sustainable alternative.

3. Material and Method

3.1. Sustainability Evaluation Criteria

There can be a variety of sustainability evaluation criteria (i.e., sub-criteria under four main criteria) for assessing the technical, economic, social, and environmental pillars of sustainable construction. From the literature review, it was observed that researchers have used different sets of evaluation criteria based on the type and nature of the construction projects. The selection of sub-criteria was also dependent on the user's preferences. Therefore, to finalize the list of sub-criteria in selecting the most sustainable structural material, we sought the opinion of several industry experts and academic researchers. A summary of sub-criteria based on overall findings is shown in Table 1. However, this list is not applicable to all cases, and users can modify it according to the location and nature of the projects and the preferences of the stakeholders.

Table 1. Summary of sustainability evaluation criteria (pertinent to this study).

Main Criteria	Sub-Criteria/Evaluation Criteria	Type	Reference(s)
Technical	Durability (life expectancy)	Qualitative	[54–60]
	Constructability (ease of construction)	Qualitative	[54,58,60–63]
	Maintainability (ease of maintenance)	Qualitative	[54,58–60,62]
	Resistance to water and weather	Qualitative	[60,64]
Economic	Material cost	Quantitative	[54–56,62,65,66]
	Construction cost	Quantitative	[56,58,61,67,68]
	Maintenance cost	Qualitative	[54,56,58,60,61,64,67,69,70]
	End of life cost	Quantitative	[56,58]
Social	Job opportunity creation	Qualitative	[63,67–69]
	Fire resistance and safety	Qualitative	[54,58,60,62,64,71]
	Skilled labor availability	Qualitative	[54,58,62]
	Compatibility with local heritage	Qualitative	[55,56,60]

Table 1. *Cont.*

Main Criteria	Sub-Criteria/Evaluation Criteria	Type	Reference(s)
Environmental	Greenhouse gas emission	Quantitative	[23,55,56,62,64,70,72]
	Impact during manufacturing	Qualitative	[58,64]
	Impact during construction	Qualitative	[54,58,60,62,64,68,70]
	Recycle and reuse potential	Qualitative	[54,58,59,64,70]

3.2. MCDM Methods Chosen for This Research

As discussed, AHP and TOPSIS are currently the most widely used MCDM techniques in construction. With the exception of a few cases, these methods were combined with fuzzy theory to eliminate crisp values and introduce vagueness to handle uncertainties, imprecision, or a lack of information. Fuzzy AHP (FAHP) is one of the most powerful and extensively used tools to assign weightage to criteria in MCDM. Therefore, it was used in this research to assign weightage to the sixteen chosen criteria. Though the triangular membership function is most widely used in FAHP for its simplicity, the trapezoidal function is considered to handle uncertainties, imprecision, or a lack of information in a better way. Therefore, the trapezoidal membership function was used in this research. Fuzzy TOPSIS was chosen to rank the alternatives as it is a widely used, familiar, and easy tool for decision-making that has acceptance in both industry and academia. However, a relatively new and less familiar tool, fuzzy VIKOR, was used in parallel to rank the alternatives. Fuzzy VIKOR was used to compare the results with a different technique and validate its reliability. It is expected that a comparison of results through fuzzy TOPSIS and fuzzy VIKOR was likely to enhance the acceptance of fuzzy VIKOR in construction. This study generated a TOPSIS extension that integrated subjective and objective weights. In addition to the subjective weights determined by decision makers, this study derived subjective weights from objective values using Shannon's entropy as a basis [73,74].

3.3. Research Framework and Hierarchy of the Decision Problem

This study considered four alternative options of structural materials (RC, SS, RM, and timber) and sixteen evaluation criteria, taking four from each pillar of sustainable construction, as mentioned in Table 1. The weightage of criteria was calculated using fuzzy AHP with a trapezoidal membership function. Fuzzy TOPSIS and fuzzy VIKOR were used to rank the alternatives using the weightage obtained through fuzzy AHP. Fuzzy TOPSIS was used to develop the DSS software out of two ranking methods. The details of the research framework are shown in Figure 1 and the hierarchy of the decision problem is shown in Figure 2.

The first phase of this research identified the structural materials in use for multistory building construction and reviewed the selection process, followed by the industries from the perspective of sustainable construction practices. An extensive literature review was conducted in the initial stage, and later, a series of interviews and discussion sessions were conducted with industry and academic experts to learn about the selection process, preferences of structural materials, sustainability options considered, etc. In phases two and three, the most appropriate decision-making techniques for solving this problem were selected by studying different research papers. The data for quantitative sub-criteria were obtained through structural analysis, market survey, and the use of the Athena Impact Estimator for the Buildings software. The information for the qualitative sub-criteria was collected from industry and academic experts. They were also requested to assign weightage for each sub-criteria. Next, fuzzy AHP was used to calculate the weightage of all sub-criteria, and fuzzy TOPSIS and fuzzy VIKOR were used to rank the alternatives. The fourth phase of this research developed a decision support computer application to help determine the most sustainable option from several viable alternatives. Finally, the model was validated through a case study and expert opinion.

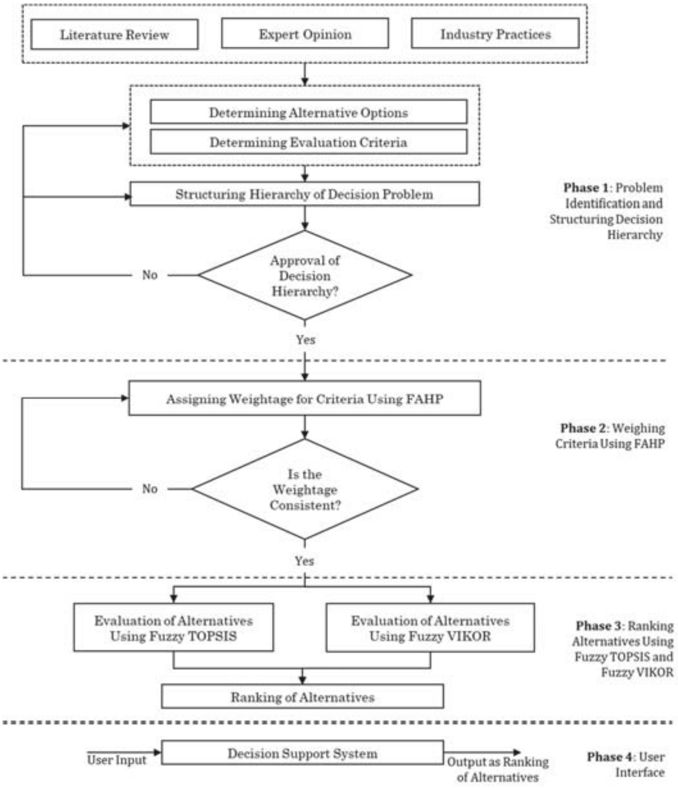


Figure 1. Research framework.

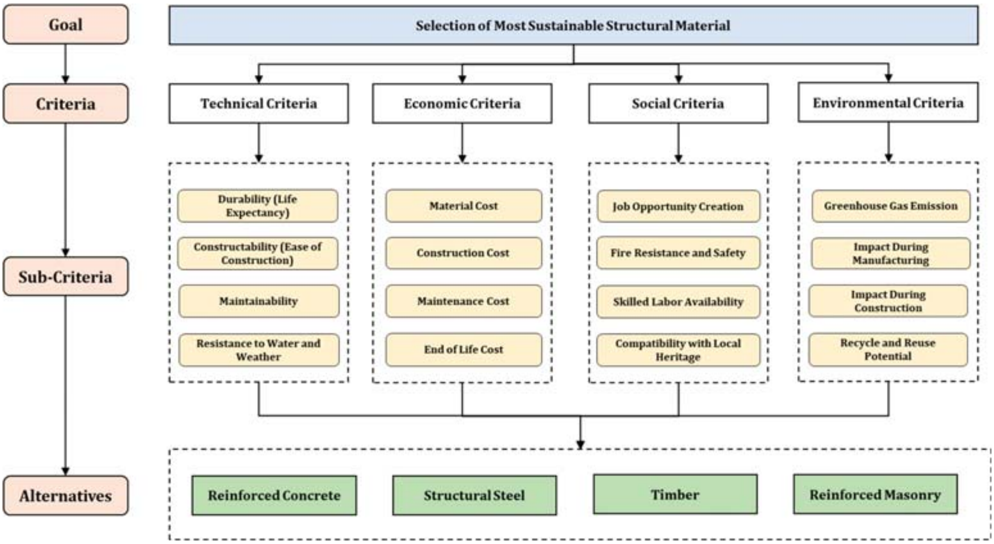


Figure 2. Hierarchy of decision problem.

3.4. LCA and LCCA Calculations

For the life cycle effect evaluation, this study used the Athena Impact Estimator for Buildings, version 5.4. While other LCA tools are available for different parts of the world, the Athena Impact Estimator for Buildings is the only North American tool for whole-building life-cycle assessment based on the globally recognized LCA methodology [75,76]. This application offers a cradle-to-grave LCA of structures, which includes resource extraction, manufacture, construction, related transportation, maintenance, replacement impacts, building operation destruction, and disposal [75]. The LCA technique employed in these investigations was based on ISO 14044 [77].

3.5. Normalizing Objective Values into Subjective Inputs

In addition to the subjective weights determined by the decision makers, this study derived subjective weights from objective values using Shannon's entropy as a basis [73,74].

Step 1: To determine objective weights using the entropy measure, the decision matrix needs to be normalized for each criterion (C_j, $j = 1, 2 \ldots n$; n = is the criteria number), to obtain the projection value P_{ij} of each:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{1}$$

where m = number of alternatives.

Step 2: After normalizing the decision matrix, we can calculate the Shannon diversity index as

$$H = -\sum_{i=1}^{m} p_{ij}\ \ln p_{ij} \tag{2}$$

Step 3: Now, the following equation is used to find out the Shannon Equitability Index or the entropy to measure the evenness of the values in particular criteria. The entropy value is denoted as e_j:

$$e_j = H/\ln(m) \tag{3}$$

where m = the total number of alternatives considered in the decision-making process.

Step 4: Now, the degree of divergence can be calculated as $d_j = 1 - e_j$. The higher the value of d_j, the higher the degree of divergence. Within the matrix, the criteria values containing a higher degree of divergence are considered for the range distribution of subjective values.

3.6. Fuzzy AHP

The AHP is one of the most widely used MCDM tools that can be used to analyze, measure, and synthesize decision problems [67]. There have been numerous applications of the AHP, including selecting among competing alternatives in multi-objective environments, allocating scarce resources, and forecasting [78]. For determining the relative priorities of different selection criteria and sub-categories, Fuzzy AHP uses fuzzy numbers as a pairwise comparison scale. This approach can adequately handle the inherent uncertainty and imprecision of human decision-making processes and offer an appropriate level of flexibility and robustness so that a decision maker can comprehend and understand a decision problem [54]. The steps of the calculations are explained as follows [79,80]:

Step 1: Generate a Comparison Matrix.

Details of pairwise comparison criteria are given in Table 2 and the equation that defines pairwise comparisons is given below:

$$a_{i-j} = \frac{w_i}{w_j}, \tag{4}$$

where $i, j = 1, 2, 3, \ldots\ n$.

Table 2. Pairwise comparison of criteria.

Importance Index	Definition of Importance Index
1	Equally Important Preferred
	Equally to Moderately Important Preferred
3	Moderately Important Preferred
	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

Here, n denotes the number of criteria compared, w_i is the weight for criterion i, and a_{ij} is the ratio of the weights of criteria i and j.

Step 2: Normalizing the Matrix.

After determining the comparison of its criteria in Table 2, the next thing is to normalize the matrix. This is carried out by dividing each cell by the summation of that column value. Here,

$$x_{ij} = \frac{a_{ij}}{\sum a_{ij}} \tag{5}$$

Step 3: Developing Criteria Weightage.

Criteria weightage is the average weightage of each row:

$$\tilde{a}_{ij} = \frac{1}{n}\sum x_{ij} \tag{6}$$

Step 4: Checking for Consistency.

Saaty listed the values in a set to compare the consistency index (CI) with a random generator (RI) value [81]. This value is variable with the matrix order n. The following equation is used to calculate the eigenvector:

$$w_{cri-i}= \frac{1}{n}\sum \tilde{a}_{ij},\ \forall_i \tag{7}$$

Here, w_{cri-i} is the eigenvector. Now we have to find out the λ (lambda) value:

$$\lambda_{maks} = \frac{1}{n}[\frac{1}{w_{cri-i}}\sum w_{cri-i} \times w_i] \tag{8}$$

After obtaining the maximum lambda value, the value of the consistency index (CI) can be determined.

$$\text{CI} = \frac{\lambda_{maks} - n}{n-1} \tag{9}$$

Here, CI is the consistency index and λ_{maks} is the largest eigenvalue of the n-order matrix. It is acceptable to tolerate the inconsistency of each opinion if the CR of a matrix is smaller than 10% (0.1).

Step 5: Fuzzification.

The given weights need to be fuzzified based on Table 3 given below.

Table 3. Importance index and fuzzy numbers.

Importance Index	Crisp Number	Fuzzy Number (*l*, *m*, *n*, *p*)
Extremely more important	9	7, 8, 9, 10
Very strongly more important	7	5, 6, 7, 8
Strongly more important	5	3, 4, 5, 6
Moderately more important	3	1, 2, 3, 4
Equal Importance	1	1, 1, 1, 1
Moderately less important	1/3	1/4, 1/3, 1/2, 1
Strongly less important	1/5	1/6, 1/5, 1/4, 1/3
Very strongly less important	1/7	1/8, 1/7, 1/6, 1/5
Extremely less important	1/9	1/10, 1/9, 1/8, 1/7

Step 6: Fuzzified Normalized Weight and Global Ranking.

Finally, the normalized fuzzy weight is calculated as

$$w_{fn-i} = \left(l_j, m_j, n_j, p_j\right)/4;\ i,j = 1,\ 2,\ 3\ldots\ m\ (\text{number of criteria}), \tag{10}$$

Here,

$$l_i = \left(l_{i1} x l_{i2} x l_{i3} x \ldots\ldots l_{in}\right)^{1/n},$$
$$m_i = \left(m_{i1} x m_{i2} x m_{i3} x \ldots\ldots m_{in}\right)^{1/n},$$
$$n_i = \left(n_{i1} x n_{i2} x n_{i3} x \ldots\ldots n_{in}\right)^{1/n},$$
$$p_i = \left(p_{i1} x p_{i2} x p_{i3} x \ldots\ldots p_{in}\right)^{1/n};$$
$$l_j = l_i x \sum(p_i),\ m_j = m_i x \sum(n_i),\ n_j = n_i x \sum(m_i),\ p_j = p_i x \sum(l_i)$$

3.7. Ranking of Alternatives with Fuzzy TOPSIS

TOPSIS is widely used for solving ranking problems in real situations [79]. The fundamental concept of TOPSIS is that the chosen alternative should be closest to the positive ideal solution (PIS) and the furthest away from the negative ideal solution (NIS) [82]. TOPSIS defines an index called similarity (or relative closeness) to the PIS and the remoteness from the NIS. Then, the method chooses an alternative that has maximum similarity to the PIS [83]. The classical TOPSIS method uses a precise weighting of the criteria and crisp values for rating the alternatives. Even though it is popular and simple in concept, the classical technique has often been criticized for its inability to adequately deal with the inherent uncertainty and imprecision involved in mapping the decision maker's perception into crisp values [79]. In order to address the shortcoming of traditional TOPSIS, several fuzzy TOPSIS methods and applications have been developed in recent years that utilize linguistic variables expressed by fuzzy numbers to determine how to evaluate criteria and alternatives [82,84,85].

In this study, we presented a TOPSIS modification that considers both subjective and objective weights. The advantage of the developed approach is that it uses decision makers' experience and tangible (numerical input) information from end users throughout the decision-making process. The steps of the calculations are explained below [80,86,87].

Step 1: Input Parameter (Preferences) from the Users.

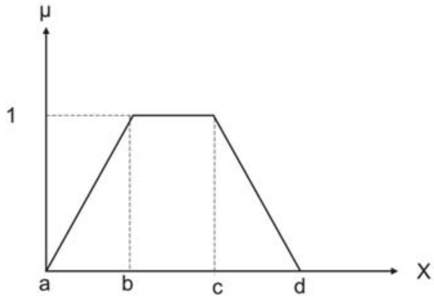
In this step, a matrix is formed comprising the preferences given by the users (Table 4).

Table 4. User preferences matrix.

Criteria	Alternative 1	Alternative 2	. . .	Alternative n
Criteria 1	High	High	. . .	Medium
Criteria 2	Low	Very Low	. . .	Low
Criteria 3	Medium	Medium	. . .	Medium
:	. . .	. . .		. . .
Criteria n	Very High	High	. . .	Very Low

Step 2: Set up Trapezoidal Fuzzy Number (TrFN) and Transform the User Input into the Fuzzy Decision Matrix.

In the FAHP scale, the trapezoidal fuzzy number (TrFN) has four boundary values *a*, *b*, *c*, and *d*: The degree of membership increases between *a* and *b*, flattens between *b* and *c* with a degree of 1 (i.e., values between *c* and *d* fully belong to the category), and then decreases between *c* and *d* (Figure 3). Each fuzzy set representing the categories described in Table 5 was represented by trapezoidal membership functions (Table 3 and Figure 4).



$$\mu_{trapezoidal}(x{:}\, a,b,c,d) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \dfrac{d-x}{d-c} & c \le x \le d \\ 0 & d \le x \end{cases}$$

Figure 3. Four parameters describing the trapezoidal membership function.

Table 5. Trapezoidal membership functions.

Number	Linguistic Variable	Trapezoidal Fuzzy Number			
		a,	**b,**	**c,**	**d**
1	Very Low	1,	1,	1,	1
3	Low	1,	2,	3,	4
5	Medium	3,	4,	5,	6
7	High	5,	6,	7,	8
9	Very High	7,	8,	9,	10

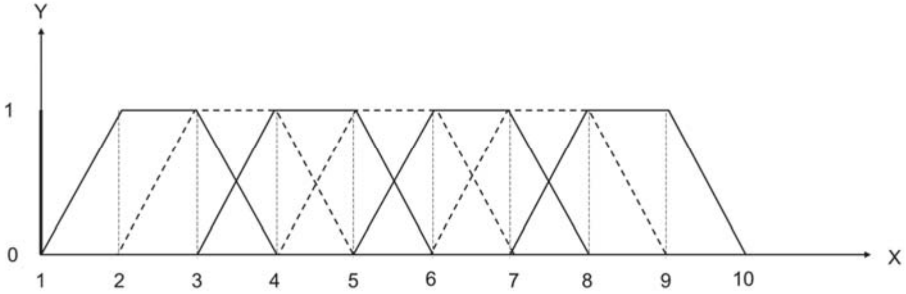


Figure 4. Trapezoidal membership functions.

Step 3: Calculation of the Combined Fuzzy Decision Matrix.

After the AHP comparison value is transformed into the FAHP scale value, a combined decision matrix is formed. The process of obtaining a fuzzy combined decision matrix value is shown using the equation of the following formula:

$$\widetilde{x}_{ij} = \left(a_{ij},\ b_{ij},\ c_{ij},\ d_{ij}\right) \tag{11}$$

where $a_{ij} = \min_k\left\{a^k{}_{ij}\right\}$, $b_{ij} = \frac{1}{K}\sum_{k=1}^{k} b^k{}_{ij}$, $c_{ij} = \frac{1}{K}\sum_{k=1}^{k} c^k{}_{ij}$, and $d_{ij} = \max_k\left\{d^k{}_{ij}\right\}$,

Step 4: Calculation of the Normalized Fuzzy Decision Matrix Based on Beneficial (Positive) and Cost (Negative) Criteria.

Now we need to identify the benefit (positive) and cost (negative) criteria and compute the fuzzy decision matrix:

$$\widetilde{r}_{ij} = \left(\frac{a_{ij}}{d^*{}_j}\frac{b_{ij}}{d^*{}_j}\frac{c_{ij}}{d^*{}_j}\frac{d_{ij}}{d^*{}_j}\right); c^*{}_j = \max_i\left\{d_{ij}\right\},\ \text{for benefit criteria} \tag{12}$$

$$\widetilde{r}_{ij} = \left(\frac{a^-{}_j}{a_{ij}}\frac{a^-{}_j}{b_{ij}}\frac{a^-{}_j}{c_{ij}}\frac{a^-{}_j}{d_{ij}}\right);\ a^-{}_j = \min_i\left\{a_{ij}\right\},\ \text{for cost criteria} \tag{13}$$

Then, the decision matrix is normalized using the following equation:

$$\widetilde{v}_{ij}= \widetilde{r}_{ij}\ \times\ w_j;\ w_j = \mathit{fuzzy\ wightage}. \tag{14}$$

Step 5: Normalized Fuzzy Decision Matrix Based on a Single User's Input.

Then, the matrix value is multiplied by the fuzzy normalized weight of each criterion obtained from the fuzzy AHP.

$$\widetilde{u}_{ij}= \widetilde{v}_{ij} \times w_{fn-i} \tag{15}$$

Step 6: Deriving Fuzzy Ideal Solution, Fuzzy Positive Ideal Solution (FPIS), and Fuzzy Negative Ideal Solution (FNIS).

Now, from the matrix, fuzzy ideal solutions are obtained by the following:

Fuzzy Positive Ideal Solution (FPIS):

$$A^* = \left(\widetilde{u}^*{}_1, \widetilde{u}^*{}_2, \widetilde{u}^*{}_3, \ldots\ldots \widetilde{u}^*{}_n\right), \tag{16}$$

where $\widetilde{u}^*{}_j = \max_i\left\{u_{ij(4)}\right\}$

Fuzzy Negative Ideal Solution (FNIS):

$$A^- = \left(\widetilde{u}^-{}_1, \widetilde{u}^-{}_2, \widetilde{u}^-{}_3, \ldots\ldots \widetilde{u}^-{}_n\right), \tag{17}$$

where $\widetilde{u}^*{}_j = \min_i\left\{u_{ij(1)}\right\}$.

Step 7: Distance from FPIS and FNIS.

Now, the distance from each alternative is calculated using the following formula:

$$d(\widetilde{x}, \widetilde{y}) = \sqrt{\frac{1}{4}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2\right]} \tag{18}$$

where $a_{1,}\ b_1, c_1, d_1 = \widetilde{u}_{ij};\ a_2,\ b_2,\ c_2,\ d_2 = A^*$ *for* the *positive distance and* A^- *for* the *negative distance*.

Step 8: Calculation of Closeness Coefficient.

Now the closeness coefficient (CC_i) of each alternative are calculated as

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}; d_i^* = \sum\nolimits_{j=1}^{n} d(\widetilde{u}_{ij},\ \widetilde{u}^*{}_j)\ \text{and}\ d_i^- = \sum\nolimits_{j=1}^{n} d(\widetilde{u}_{ij},\ \widetilde{u}^-{}_j) \tag{19}$$

The higher value of CC_i gets a higher ranking order.

Step 9: Ranking and Selection of Decisions.

For the number of members (N) in a team, the combined decision is calculated as

$$CC_{team\ i} = \frac{1}{n}\sum CC_{N\ i}\ x\ N_{importance} \tag{20}$$

where $N_{importance}$ = the *importance of* the *Nth member in* the *team* and N = the *total number of members*.

3.8. Ranking of Alternatives with Fuzzy VIKOR

Opricovic developed the VIKOR method in 1998 for the multi-criteria optimization of complex systems [88]. VIKOR focuses on ranking and sorting a set of alternatives against various or possibly conflicting and non-commensurable decision criteria [89]. Similar to other MCDM methods such as TOPSIS, VIKOR uses an aggregating function to express closeness to the ideal. However, unlike TOPSIS, where the ranking introduces an index considering closeness to the ideal solution, this technique employs linear normalization to eliminate units of criteria functions [90]. In many instances, an extension of VIKOR, such as fuzzy VIKOR, is utilized to generate a fuzzy compromise solution for MCDM cases [91]. The steps of the calculations are explained as follows [89,90,92]:

Step 1: The input parameters are assessed and weighted beneficial (positive) and cost (negative) criteria are chosen.

Step 2: Linguistic terms are converted into the fuzzy Scale, as shown in Table 5 previously.

Step 3: The importance of the decision makers' judgement is determined, and their weights for each criterion are computed (Table 6).

Table 6. Importance of decision makers' judgement matrix.

	Importance Factor	Criteria 1	Criteria 2	…	Criteria m
DM 1	X_1	S1	T1	…	Z1
DM 2	X_2	S2	T2	…	Z2
:		…	…		…
DM n	X_n	Sn	Tn	…	Zn

Step 4: Generation of combined decision matrix of the team.

The process of obtaining a fuzzy combined decision matrix value is shown using the equation of the following formula:

$$\tilde{x}_{ij} = (a_{ij}, b_{ij},\ c_{ij},\ d_{ij}) \tag{21}$$

where

$$a_{ij} = \min_k\left\{a^k{}_{ij} \times importance\ factor^k\right\}$$

$$b_{ij} = \frac{1}{K}\sum\nolimits_{k=1}^{k} b^k{}_{ij} \times importance\ factor^k$$

$$c_{ij} = \frac{1}{K}\sum_{k=1}^{k} c^k{}_{ij} \times importance\ factor^k,$$

$$d_{ij} = \max_k\left\{d^k{}_{ij} \times importance\ factor^k\right\},$$

Step 5: Now, both the benefit (positive) and cost (negative) criteria are identified, and the normalized fuzzy decision matrix is computed as

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c^*{}_j}, \frac{b_{ij}}{c^*{}_j}, \frac{c_{ij}}{c^*{}_j}, \frac{d_{ij}}{c^*{}_j}\right);\ c^*{}_j = \max_i\{c_{ij}\},\ \text{benefit criteria} \tag{22}$$

$$\tilde{r}_{ij}= \left(\frac{a^-{}_j}{a_{ij}}, \frac{a^-{}_j}{b_{ij}}, \frac{a^-{}_j}{c_{ij}}, \frac{a^-{}_j}{d_{ij}}\right);\ a^-{}_j= \min_i\{a_{ij}\},\ \text{cost criteria} \tag{23}$$

Step 6: Defuzzification: The normalized fuzzy decision matrix is normalized as

$$\tilde{x}_{ij}= \frac{1}{n}\sum \tilde{r}_{ij}. \tag{24}$$

Step 7: The best element of criteria (X_i^*) and worst element of criteria (X_i^-) are calculated as follows:

For beneficial criteria, $(x_{ij})_{\max}$ and for non-beneficial criteria $(x_{ij})_{\min}$

$$X_i^* = \max[(x_{ij})|i = 1,\ 2,\ 3\ldots m] \tag{25}$$

$$X_i^- = \min[(x_{ij})|i = 1,\ 2,\ 3\ldots m] \tag{26}$$

Step 8: The value of utility measure (S_i), regret measure (R_i), and VIKOR index (Q_i) are calculated as

$$S_i= \sum\nolimits_{i=1}^{n} w_i \frac{x_i^* - x_{ij}}{x_i^* - x_i^-} \tag{27}$$

$$R_i= \max[w_i(\frac{x_i^* - x_{ij}}{x_i^- - x_{ij}})] \tag{28}$$

where S_i and R_i denote the utility measure and regret measure for the alternatives x_i, and W_i is the weight of each criterion. Now, we compute the values of $S^* = \min(S_i)$, $S^- = \max(S_i)$, $i = 1, 2, 3 \ldots m$.

$$R^*= \min(R_i),\ R^- = \max(R),i = 1,\ 2,\ 3\ldots\ m \tag{29}$$

We determine the values of Q_i *for* $j = 1, 2, 3 \ldots m$ and rank the alternatives by values of Q_j:

$$Q_i = v\left(\frac{S_i - S^*}{S^- - S^*}\right) + (1 - v)\left(\frac{R_i - R^*}{R^- - R^*}\right) \tag{30}$$

where v is the weight for the strategy of maximum group utility and $1 - v$ is the weight of the individual regret. Usually, v is 0.5, and when $v > 0.5$, the index of Q_j will tend toward majority agreement, and clearly, when $v < 0.5$, the index of Q_i will indicate a majority of negative attitudes. With the smallest number being the best option, the three values, S_i, R_i and Q_i are ranked from biggest to smallest in ascending order.

4. Case Study

This research used a case study on an eight-story building to validate the theoretical model. A practical example with numerical computation of user, project, and structural data was essential to derive the model's output in terms of ranking alternatives. The case study also assisted in creating several scenarios to verify the developed system's consistency and sensitivity. Details of the case study are discussed in the subsequent paragraphs.

4.1. Description of the Case Study

The primary reason for selecting an eight-story building is that all chosen options of structural materials (RC, SS, RM, and timber) remain acceptable alternatives for this height. The Athena Impact Estimator for Buildings has an inbuilt database for Calgary, Canada; therefore, the structure's location was chosen for ease of LCA and LCCA calculations. Eighty years of building life expectancy were considered according to the guidelines of Infrastructure Canada for five-story or more apartment buildings [93]. Other details of the building are given in Table 7. The architectural view of the building and structural layout with different material options are shown in Figures 5–9.

Table 7. Study parameters as input in the 'Athena Impact Estimator for Buildings'.

Parameters	Details
Project location	Calgary, Alberta
Building type	Residential
Building life expectancy	80 years
Building height	26.1 metre (m)
Number of floors	8
Gross floor area	798.66 m^2
Structural components considered	Columns Beams
Options of structural materials	Reinforced concrete Structural steel Reinforced masonry Timber

Figure 5. Architectural view of the eight-story building.

Figure 6. Building structure using RC.

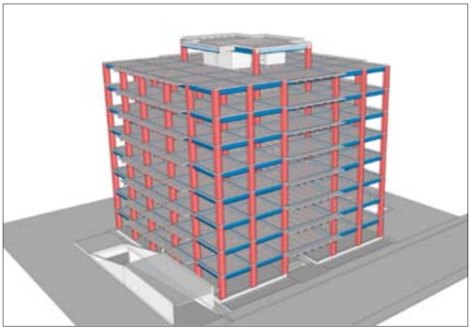


Figure 7. Building structure using SS.

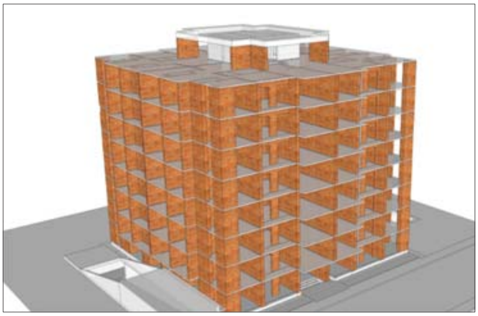


Figure 8. Building structure using RM.

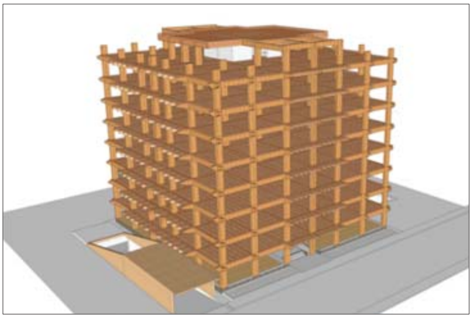


Figure 9. Building structure using timber.

The data from three teams comprising nine members were used in this case study. Each team had a representative from the owner, constructor, and design teams who were experts in their relevant fields. The members of the study teams were the project owners, prime consultants, chief structural engineers, principal architects, project coordinators, project managers, and academic researchers from some leading Canadian construction companies, such as Clark Builders, Stantec, GEC Architecture, RJC Engineers, Alberta Masonry Council, Chandos Construction, Wood Works, and the University of Alberta. It is important to note that the members of Team 1 and Team 2 were from several leading construction industries, whereas Team 3 was formed from academic researchers and people who were already practicing sustainable construction. Details of the team members are given in Table 8.

Table 8. Details of the respondents who took part in the case study.

Team	Role in the Case Study	Profession/Position	Company/Institution	Work Experience (Years)
Team 1	Owner	Chief engineer	RJC Engineers	25–30
	Design team	Principal architect	Stantec	25–30
	Constructor	Project manager	Clark Builders	20–25
Team 2	Owner	Project coordinator	University of Alberta	20–25
	Design team	Chief structural engineer	GEC Architecture	30–35
	Constructor	Principal architect	Clark Builders	30–35
Team 3	Owner	Academic researcher	University of Alberta	30–35
	Design team	Prime consultant	Chandos Construction	25–30
	Constructor	Project coordinator	Alberta Masonry Council, Wood Works	20–25

4.2. Calculation of LCA and LCCA

The Athena Impact Estimator for Buildings application was used to determine the quantity of construction materials required to build the model building. The cost criteria were then computed using the Alberta, Canada market rate, and the emission rate was calculated using the environmental analysis module of the same application. Results are tabulated in Table 9.

Table 9. The calculated cost of materials and emission rate.

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 Equivalent/sqm)
Reinforced Concrete	550	152	50	115
Structural Steel	480	115	95	110
Timber	300	85	80	25
Reinforced Masonry	380	180	65	95

4.3. Normalizing of the Quantitative User Input to Qualitative Value

Step 1: The inputs of Table 9 were normalized by dividing each cell value by the sum value of each column (total criteria values for all alternatives). The obtained normalized decision matrix is shown in Table 10.

Table 10. Converted to a Normalized Matrix.

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 Equivalent/sqm)
Reinforced Concrete	0.3216	0.2857	0.1724	0.3333
Structural Steel	0.2807	0.2161	0.3275	0.3188
Timber	0.1754	0.1597	0.2758	0.0724
Reinforced Masonry	0.2222	0.3383	0.2241	0.2753

Step 2: The Shannon diversity index measures the diversity of range values for any criterion among the alternatives. The results are shown in Table 11, with the lowest greenhouse gas emission value (kg CO_2 equivalent/sqm) factoring in at 1.28.

Table 11. Shannon Diversity and Equitability Index.

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 Equivalent/sqm)
Shannon diversity index	1.36	1.35	1.36	1.28
Shannon's equitability index	0.98	0.97	0.98	0.92

Step 3: Shannon's equitability index (Table 11) represented the value of Shannon's diversity index divided by the logarithm value of the total number of alternatives considered in the decision-making process. It is also called the entropy value.

Step 4: The degree of divergence was calculated by subtracting the Shannon equitability index from the unit value, as shown in Table 12. These range values were considered to transform all other criteria values of the matrix from objective to subjective values.

Table 12. Determination of range.

Linguistic Term	Conversion Scale in the Normalized Matrix
Very High	>0.2811
High	0.2289 to 0.2811
Medium	0.1768 to 0.2289
Low	0.1246 to 0.1768
Very Low	<0.1246

Step 5: Finally, the normalized values for Table 9 inputs were tabulated in Table 13, equalizing with the ranges shown in Table 12.

Table 13. Output subjective result.

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 Equivalent/sqm)
Reinforced Concrete	Very High	Very High	Low	Very High
Structural Steel	High	Medium	Very High	Very High
Timber	Low	Low	High	Very Low
Reinforced Masonry	Medium	Very High	Medium	High

4.4. Calculation of Weightage for Each Criteria Using the Fuzzy AHP

4.4.1. Criteria and Codes

The names of the evaluation criteria and codes for them are listed in Table 14. The subsequent results were generated based on the input of one stakeholder (owner of Team 3) using the formula and procedure described in Section 3.

4.4.2. Calculation of Weightage for Each Criterion

Steps 1 and 2: A pairwise comparison matrix was developed for each user to compute the relative priorities of criteria from the user's point of view. Each criterion was evaluated with the others on a nine-point scale, as described. Each cell was then divided by the column sum to obtain the normalized value.

Steps 3 and 4: Typically, obtaining an acceptable consistency value was complicated once there were many criteria to be evaluated with each other. The users performed a few trials and errors to achieve consistent values. The sample calculation of the consistency check of one of the users (designer, Team 3) is shown below:

$$\text{Value of } \lambda_{maks} = \frac{1}{16}\left[\frac{1}{0.08}\sum(0.08x1 + 0.05x3 + \cdots) + \frac{1}{0.05}\left(\frac{0.08x1}{3} + 0.05x1 + \cdots\right) + \cdots\ldots\right] = 17.95,$$

Here, n = 16. CI = $\frac{17.95-16}{16-1}$ = 0.1306.

RI for n = 16 was 1.59.

So, CR = 0.1306/1.59 = 8.25% < 10%, which was an acceptable result.

Steps 5 and 6: The crisp values were fuzzified using the fuzzification table. Fuzzy normalized weights were obtained and ranked in ascending order. Depending on the input in the pairwise comparison matrix, the result of the fuzzified normalized weightage of the criterion varied from user to user. Table 15 shows the fuzzified normalized weight of the criteria used by all the stakeholders in this study.

Table 14. Evaluation Criteria and Codes.

Sustainability Pillars	Evaluation Criteria	Code	Influence	Reference(s)
Technical	Durability	TEC1	Beneficial criteria	[54–60]
	Constructability	TEC2	Beneficial criteria	[54,58,60–62]
	Maintainability	TEC3	Beneficial criteria	[54,58–60,62]
	Resistance to Water and Weather	TEC4	Beneficial criteria	[60,64]
Economical	Material Cost	ECO1	Cost criteria	[54–56,62,65,66]
	Construction Cost	ECO2	Cost criteria	[56,58,61,67,68]
	Maintenance Cost	ECO3	Cost criteria	[54,56,58,60,61,64,67,69,70]
	End of Life Cost	ECO4	Beneficial criteria	[56,58]
Social	Job Opportunity Creation	SOC1	Beneficial criteria	[67–69]
	Fire Resistance and Safety	SOC2	Beneficial criteria	[54,58,60,62,64,71]
	Skilled Labor Availability	SOC3	Beneficial criteria	[54,58,62]
	Compatibility with Heritage	SOC4	Beneficial criteria	[55,56,60]
Environmental	Greenhouse Gas Emission	ENV1	Cost criteria	[23,55,56,62,64,70,72]
	Impact During Manufacturing	ENV2	Cost criteria	[58,64]
	Impact During Construction	ENV3	Cost criteria	[54,58,60,62,64,68,70]
	Recycle and Reuse Potential	ENV4	Beneficial criteria	[54,58,59,64,70]

4.5. Ranking of Alternatives with Fuzzy TOPSIS

Step 1: Five options were available to the user: "Very High, High, Medium, Low, and Very Low" for twelve subjective criteria. Additionally, a total of four criteria were fixed for a specific location and time and had an objective value. These values were transformed from objective to subjective using the Shannon entropy method, which is shown in Table 13. Finally, normalized user inputs for all evaluation criteria are shown in Table 16.

Steps 2 and 3: The user input table was then transformed into a fuzzy decision matrix using the trapezoidal membership function described in Section 3. The combined decision matrix was the combination of three stakeholders' fuzzy input values of the same team.

Steps 4 and 5: The normalized fuzzy decision matrix was calculated based on the criterion category, whether it was a beneficial or a cost criterion. For beneficial criteria, the membership function was divided by the maximum value of the sets; for the cost criteria, it was reciprocal of the values divided by the minimum values of the set. The weighted normalized fuzzy decision matrix was based on the owner's input and criteria weight derived from the fuzzy AHP.

Steps 6 and 7: Deriving the fuzzy ideal solution; The fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) were derived from the weighted normalized fuzzy decision matrix. The Euclidian distance of each criterion of any alternative was measured in this step. Distance from the FPIS is shown in Table 17 and distance from FNIS is shown in Table 18.

Table 15. Summary of the fuzzified normalized criteria weightage of all stakeholders.

	Owner 1	**Owner 2**	**Owner 3**	**Constructor 1**	**Constructor 2**	**Constructor 3**	**Designer 1**	**Designer 2**	**Designer 3**
Durability	0.06	0.06	0.07	0.09	0.12	0.05	0.07	0.05	0.09
Constructability	0.04	0.07	0.05	0.11	0.02	0.06	0.08	0.11	0.07
Maintainability	0.05	0.06	0.06	0.07	0.10	0.05	0.05	0.05	0.04
Resistance to Water and Weather	0.06	0.09	0.03	0.06	0.03	0.03	0.07	0.06	0.04
Material Cost	0.13	0.04	0.11	0.12	0.01	0.06	0.11	0.14	0.08
Construction Cost	0.18	0.07	0.06	0.14	0.01	0.05	0.12	0.14	0.08
Maintenance Cost	0.06	0.09	0.04	0.06	0.10	0.04	0.06	0.07	0.06
End of Life Cost	0.05	0.05	0.03	0.03	0.11	0.03	0.04	0.02	0.03
Job Opportunity Creation	0.04	0.06	0.04	0.02	0.04	0.04	0.04	0.02	0.03
Fire Resistance and Safety	0.10	0.09	0.04	0.06	0.07	0.03	0.08	0.09	0.03
Skilled Labor Availability	0.04	0.08	0.04	0.09	0.01	0.03	0.04	0.10	0.03
Compatibility with Heritage	0.03	0.07	0.03	0.02	0.09	0.02	0.03	0.04	0.02
Greenhouse Gas Emission	0.05	0.05	0.17	0.03	0.09	0.12	0.07	0.03	0.18
Impact During Manufacturing	0.04	0.04	0.10	0.03	0.08	0.12	0.05	0.03	0.07
Impact During Construction	0.04	0.05	0.08	0.04	0.04	0.14	0.05	0.03	0.07
Recycle and Reuse Potential	0.04	0.05	0.06	0.04	0.08	0.13	0.03	0.02	0.07

Table 16. User input after converting objective values into subjective inputs.

Alternatives **Criteria**	**RC**	**SS**	**Timber**	**RM**
Technical				
Durability	Very High	High	High	Very High
Constructability	Medium	High	Very High	Medium
Maintainability	Very High	Medium	High	High
Resistance to Water and Weather	High	High	High	High
Economic				
Material Cost	Very High	High	Low	Medium
Construction Cost	Very High	Medium	Low	Very High
Maintenance Cost	Very Low	Medium	Medium	Very Low
End of Life Cost	Low	Very High	High	Medium
Social				
Job Opportunity Creation	High	High	Very High	High
Fire Resistance and Safety	Very High	Medium	Medium	Very High
Skilled Labor Availability	Medium	Medium	High	Medium
Compatibility with Heritage	Low	Low	High	Very High
Environmental				
Greenhouse Gas Emission	Very High	Very High	Very Low	High
Impact During Manufacturing	High	High	Very Low	Medium
Impact During Construction	High	Medium	Low	High
Recycle and Reuse Potential	Very Low	High	Very High	Medium

Step 8: The alternative was ranked based on the value of CC_i in descending order as shown in Table 19.

Table 17. Distance from the FPIS.

Alternative	**Criteria**	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**	**SOC1**	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**	**SUM (di*)**
Reinforced Concrete		0.00	0.30	0.00	0.00	0.14	0.09	0.03	0.19	0.11	0.00	0.10	0.15	0.02	0.06	0.18	0.41	1.76
Structural Steel		0.18	0.17	0.22	0.04	0.13	0.07	0.00	0.00	0.13	0.19	0.07	0.14	0.02	0.00	0.00	0.17	1.52
Timber		0.23	0.00	0.13	0.03	0.00	0.00	0.00	0.08	0.00	0.18	0.00	0.04	0.06	0.10	0.08	0.00	0.94
Reinforced Masonry		0.10	0.32	0.14	0.02	0.11	0.09	0.03	0.15	0.10	0.00	0.10	0.00	0.00	0.04	0.13	0.29	1.62

Table 18. Distance from FNIS.

Alternative	**Criteria**	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**	**SOC1**	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**	**SUM (di^-)**
Reinforced Concrete		0.23	0.02	0.22	0.04	0.14	0.09	0.00	0.00	0.02	0.19	0.00	0.00	0.02	0.05	0.10	0.00	1.11
Structural Steel		0.08	0.15	0.00	0.00	0.13	0.07	0.03	0.19	0.00	0.00	0.03	0.01	0.02	0.10	0.08	0.24	1.12
Timber		0.00	0.32	0.11	0.01	0.00	0.00	0.03	0.10	0.13	0.01	0.10	0.11	0.06	0.00	0.00	0.41	1.39
Reinforced Masonry		0.16	0.00	0.08	0.02	0.11	0.09	0.00	0.04	0.05	0.19	0.00	0.15	0.00	0.06	0.06	0.12	1.12

Table 19. Ranking of one stakeholder (Owner of Team 3).

Alternatives	**di***	**di^-**	**CC**	**Rank**
Reinforced Concrete	1.76	1.11	0.38629	4
Structural Steel	1.52	1.12	0.425182	2
Timber	0.94	1.39	0.59663	1
Reinforced Masonry	1.62	1.12	0.408299	3

Step 9: The final combined result (Table 20) of Team 3′s stakeholders was calculated using the weights assigned to each person multiplied by the corresponding CC_i. The owner′s viewpoint was given greater priority in this case, with a weighting of 40%, while the opinions of the other two team members received a weighting of 30%.

Table 20. The combined result of one team (Team 3).

	CC (Owner)	**CC (Constructor)**	**CC (Designer)**	**Weighted CC**	**Rank**
Importance of Opinion	0.4	0.3	0.3		
Alternatives					
Reinforced Concrete	0.3863	0.3888	0.3139	0.3653	4
Structural Steel	0.4252	0.4873	0.4756	0.4590	2
Timber	0.5966	0.6365	0.7026	0.6404	1
Reinforced Masonry	0.4083	0.3966	0.3209	0.3786	3

Step 10: The ranking of alternatives was determined similarly for Teams 1 and 2. The overall results of all groups involving fuzzy TOPSIS are displayed in Table 21.

Table 21. The overall result of all teams (using fuzzy TOPSIS).

	Team 1		Team 2		Team 3	
Alternatives	**Weighted CC**	**Rank**	**Weighted CC**	**Rank**	**Weighted CC**	**Rank**
Reinforced Concrete	0.5753	1	0.7572	1	0.3653	4
Structural Steel	0.5502	2	0.5441	2	0.4590	2
Timber	0.3915	4	0.1892	4	0.6404	1
Reinforced Masonry	0.4327	3	0.3884	3	0.3786	3

4.6. Ranking of Alternatives with Fuzzy VIKOR

Steps 1 and 2: Here, the input parameters of stakeholders were similar to those used in fuzzy TOPSIS.

Steps 3 to 6: The importance and weightage of the stakeholders' criterion (taken from FAHP) were listed here. The owner's opinion was given a higher weightage of 40%, while the rest of the team received 30%. Later, the combined decision matrix, normalized fuzzy decision matrix, and de-fuzzified matrix were generated.

Step 7: The best element of criteria $\left(X_i^*\right)$ and worst element of criteria $\left(X_i^-\right)$ were calculated from the de-fuzzified matrix. X_i^* was the highest value among all alternatives for a criterion and X_i^- was the lowest value among all alternatives for the same criterion. The calculated result is shown in Table 22.

Table 22. Best element and worst element criteria value.

Criteria	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**	**SOC1**	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**
X_i^*	0.67	0.74	0.53	0.75	0.09	0.11	0.18	0.74	0.69	0.60	0.65	0.59	0.13	0.11	0.09	0.70
X_i^-	0.54	0.37	0.37	0.49	0.40	0.43	0.44	0.23	0.42	0.29	0.45	0.21	0.47	0.56	0.48	0.22

Step 8: Finally, using the formula, the utility measure (S_i), regret measure (R_i), and VIKOR index (Q_i) values were obtained as shown in Table 23. The alternatives were ranked based on the value of the VIKOR index (Q_i). The lower the value of Q_i, the closer the solution was to the ideal solution, and the higher the ranking of the alternative.

Table 23. Utility measure (S_i), regret measure (R_i), and VIKOR index (Q_i) value.

Criteria	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**	**SOC1**	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**	**Si**	**Ri**	**Qi**	**Rank**
Reinforced Concrete	0.0000	0.0363	0.0000	0.0000	0.1054	0.0642	0.0000	0.0278	0.0196	0.0000	0.0356	0.0256	0.1681	0.1000	0.0806	0.0589	0.7222	0.1681	1.0000	4
Structural Steel	0.0696	0.0000	0.0631	0.0000	0.0703	0.0214	0.0203	0.0000	0.0392	0.0000	0.0356	0.0256	0.1681	0.1000	0.0403	0.0147	0.6681	0.1681	0.9485	3
Timber	0.0696	0.0000	0.0315	0.0000	0.0000	0.0000	0.0405	0.0093	0.0000	0.0382	0.0000	0.0085	0.0000	0.0000	0.0000	0.0000	0.1976	0.0696	0.0000	1
Reinforced Masonry	0.0000	0.0545	0.0315	0.0000	0.0351	0.0642	0.0000	0.0185	0.0196	0.0000	0.0356	0.0000	0.1261	0.0667	0.0806	0.0295	0.5619	0.1261	0.6340	2

Step 9: Similarly, Steps 1 to 8 were repeated for the constructor and designer of the team. The combined result of the stakeholders of Team 3 was thus obtained and is shown in Table 24.

Table 24. Ranking of alternatives for one team (Team 3).

	Qi (Owner)	Qi (Constructor)	Qi (Designer)	Weighted Qi	Rank
Importance of Opinion Alternatives	0.4	0.3	0.3		
Reinforced Concrete	1.000	1.000	1.000	1.000	4
Structural Steel	0.948	0.699	0.854	0.845	3
Timber	0.000	0.000	0.000	0.000	1
Reinforced Masonry	0.634	0.663	0.796	0.692	2

Step 10: Similar analysis was carried out on the user inputs from Teams 1 and 2 to rank the alternatives. All the results are compiled in Table 25.

Table 25. The overall result of fuzzy VIKOR for different teams.

	Team 1		Team 2		Team 3	
Alternatives	**Weighted Q_i**	**Rank**	**Weighted Q_i**	**Rank**	**Weighted Q_i**	**Rank**
Reinforced Concrete	0.027	1	0.306	2	1.000	4
Structural Steel	0.342	2	0.199	1	0.845	3
Timber	0.997	4	0.850	4	0.000	1
Reinforced Masonry	0.946	3	0.580	3	0.692	2

4.7. Results

Initially, the fuzzified normalized weightage of criteria was calculated using the AHP for the nine responses. A graphical representation of the weightage summary of teams is given in Figure 10. Team 1 assigned a higher weightage for the technical criteria and a lower weightage for the environmental criteria. Criteria weightage of the technical, economic, and social criteria of Team 2 was within a close range; however, they assigned relatively minor importance to the environmental criteria. Team 3, on the other hand, closely distributed the weightage for all, giving the highest emphasis to the environmental criteria. The weightage obtained through these calculations was used in subsequent phases for ranking the alternatives. The result's acceptance in this method was determined by checking the consistency ratio, which was less than 10% in all cases.

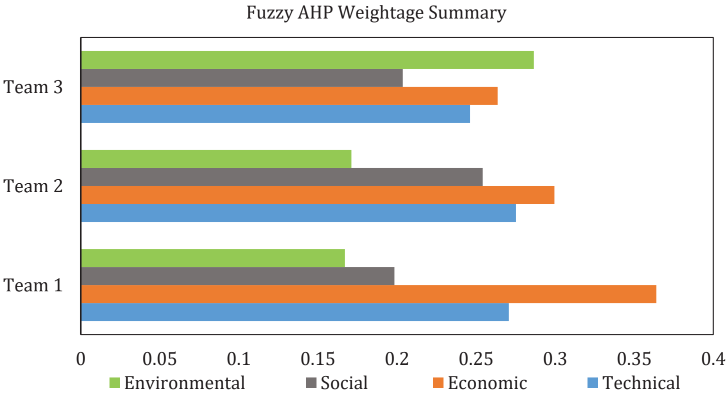


Figure 10. Summary of the fuzzified normalized weightage of all teams.

The next step of the calculation was ranking alternatives with fuzzy TOPSIS using the criteria weightage calculated by the fuzzy AHP. The result of this method was interpreted from the CC (closeness coefficient): The greater the CC, the higher the ranking. Any team's weighted CC was calculated considering the importance of the opinion of the owner, constructor, and designer as 40%, 30%, and 30%, respectively, in the group decision-making process. For Team 1, the final weighted CCs for RC, SS, Timber, and RM were 0.5753, 0.5502, 0.3915, and 0.44327, respectively. The ranking of alternatives for that group was as follows: First priority was RC; second priority was SS; third priority was RM; and last priority was timber. The weighted CCs of Team 2 for RC, SS, Timber, and RM were 0.7572, 0.5441, 0.1892, and 0.3884, respectively. RC also became the first choice according to their preferences, followed by SS, RM, and timber. In the case of Team 3, the weighted CCs were 0.3653, 0.4590, 0.6404, and 0.3786 for RC, SS, timber, and RM, respectively. Timber became the first preference for this group, and then the SS, RM, and RC, sequentially. As a whole, RC was the first and timber was the last preference of Teams 1 and 2. In contrast, timber was the first and RC was the last choice in the case of Team 3.

The same sets of data were then calculated using the fuzzy VIKOR method. Criteria weightage obtained through the fuzzy AHP was applied here while ranking the alternatives. As discussed, its ranking was based on closeness to the ideal solution and expressed with the term VIKOR index (Qi). In the case of Team 1, the Qi values for RC, SS, timber, and RM were 0.027, 0.342, 0.997, and 0.946, respectively; therefore, RC was this group's most preferred option. The Qi values for Team 2 were 0.306, 0.199, 0.850, and 0.580 for RC, SS, timber, and RM, respectively. The priority of options of this group was SS, RC, RM, and Timber, respectively. Finally, the Qi values for Team 3 were 1.000, 0.845, 0.000, and 0.692 for RC, SS, timber, and RM, and timber was the most preferred alternative among all options. In brief, Team 1 preferred RC, Team 2 preferred SS, and Team 3 preferred timber as the best option. In contrast, timber was the least preferred option for Teams 1 and 2; RC was the least preferred for Team 3.

One of the expected contributions of this research was to develop a DSS that should assist the decision makers in choosing evaluation criteria and assigning relative importance to those in the combination of qualitative and quantitative methods in an IPD framework for selecting the most sustainable structural material. Details of the multi-criteria DSS have been explained in the next section of this paper.

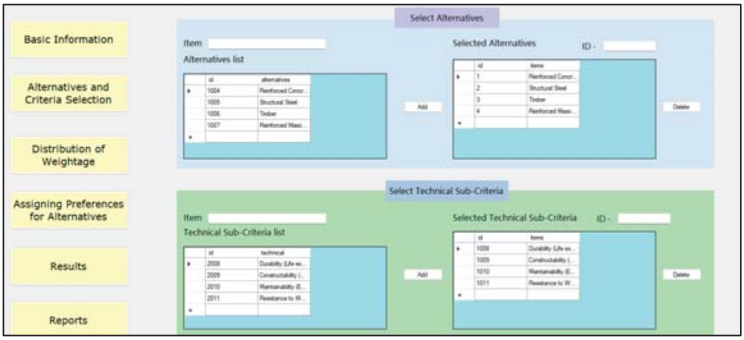
5. Details of DSS Desktop Application Software

This desktop application has been developed using the 'Microsoft dot-net framework' and is intended to operate on the Windows platform. C sharp was used in the 'Windows form application' for coding this software, and its algorithm was based on the fuzzy TOPSIS technique for ranking the alternatives. A graphical user interface was also developed using the 'Windows form application.' Microsoft Management Studio used 'MySQL' and the 'Windows database server' for database management. After logging in, users were required to create a new project (or retrieve the data of a previously saved project), and three entities were needed to give their inputs in the same interface. Users could edit or change the evaluation criteria during the initial inputs. Later, they needed to assign percentages of weightage for evaluation criteria (using text fields) and preferences for different alternatives (using dropdown menu options). Subsequently, they were required to assign a percentage for each entity (using text fields), stating the importance of stakeholders' opinions in group decision-making. This application took the qualitative inputs as the users' preferences and quantitative inputs as computed numerical values. Finally, it presented the ranking of alternatives as the output.

5.1. User Input to the System

5.1.1. Alternatives and Criteria Selection

The following input of the application concerned the selection of the alternatives (e.g., RC, SS, timber, and RM in this study). Users could include new alternatives here or retrieve information from the created database. Next was the selection of evaluation criteria for all pillars of sustainable construction, and users had the flexibility here to select criteria pertinent to any project (Figure 11).



id	alternatives
1004	Reinforced Concr...
1005	Structural Steel
1006	Timber
1007	Reinforced Maso...

id	items
1	Reinforced Concr...
2	Structural Steel
3	Timber
4	Reinforced Maso...

id	technical
2008	Durability (Life ex...
2009	Constructability (...
2010	Maintainability (E...
2011	Resistance to W...

id	items
1008	Durability (Life ex...
1009	Constructability (...
1010	Maintainability (E...
1011	Resistance to W...

Figure 11. Alternative and evaluation criteria selection.

5.1.2. Weightage Distribution

In this input stage, all stakeholders of the decision-making team needed to assign weightage for four main criteria and a group of sub-criteria under each criterion (Figure 12).

Figure 12. Distribution of weightage.

5.1.3. Assigning Preferences for Different Alternatives

The final user's input concerned assigning preference for different alternatives. Here, all stakeholders needed to assign their importance for qualitative evaluation criteria chosen at the initial stage. The inputs were 'very high,' 'high,' etc., for all the evaluation criteria that needed to be assigned, comparing all alternatives considered for the decision-making problem (Figure 13).

Figure 13. Assigning preferences for different alternatives.

5.2. System Output

In the end, this application generated several outputs for the users. A screenshot of the output is shown in Figure 14. The weightage distribution graph displays a summary of the weightage assigned by different stakeholders. It represents the different importance stakeholders gave to technical, economic, social, and environmental aspects. The results for the priority of alternatives for different stakeholders were also displayed in three tables. Finally, the stakeholders had the opportunity to assign importance to their opinion to obtain the overall ranking of the alternatives.

Owner Team

Alternatives	di*	di-	CC	Rank
Reinforced Concrete	1.69	1.39	0.452728629	3
Structural Steel	1.28	1.66	0.564077171	1
Timber	1.34	1.40	0.509726313	2
Reinforced Masonry	1.76	1.26	0.417621004	4

Designer Team

Alternatives	di*	di-	CC	Rank
Reinforced Concrete	1.94	1.73	0.471214335	3
Structural Steel	1.33	2.05	0.606284223	2
Timber	1.33	2.06	0.608214479	1
Reinforced Masonry	2.38	1.23	0.341268889	4

Construction Team

Alternatives	di*	di-	CC	Rank
Reinforced Concrete	1.61	1.39	0.464224392	3
Structural Steel	1.47	1.42	0.491643593	2
Timber	1.19	1.88	0.61218819	1
Reinforced Masonry	1.97	0.98	0.331564621	4

Importance of Opinion	Percentage
Owner Team	40
Design Team	30
Construction Team	30

Final Ranking

Alternatives	CC	Rank
Reinforced Concrete	0.4617230697	3
Structural Steel	0.5550092132	2
Timber	0.5700113259	1
Reinforced Masonry	0.3688984546	4

Figure 14. Graphical output for weightage distribution and ranking of alternatives.

6. Sensitivity Analysis

Saltelli et al. defined sensitivity analysis as "the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" [94]. It is a verification process to check that the system fulfils the intended purpose by analyzing the output results with the variations of input parameters [95]. Researchers used different techniques such as the Monte Carlo Simulations [39], the creation of different scenarios [80,96], and combinations of case studies [95], etc., for model verification. In this research, a sensitivity analysis was carried out by running the model under various scenarios to ensure that it was responsive to changes in its input and that the output produced meaningful results [80,96].

6.1. Criteria Weightage Sensitivity

The sensitivity of the user input and criteria weight was analyzed, creating four different scenarios. Four sets of weights for criteria were used to represent four instances, as shown in Table 23. Those scenarios were then tested to observe their influences on CC_i values of the developed DSS, expressing the ranking of alternatives. Here, one pillar's criterion weights were assigned larger weights than the others' for each scenario, as shown in Table 26. In Table 27, the input value findings are displayed, and in Figure 15, the results demonstrate that altering the weights of the criterion significantly affected the CC_i values of the alternatives. If the criteria weightage for any sustainability pillar increased, giving it more priority, the CC_i value also increased significantly and had a substantial impact on ranking.

Table 26. Scenarios based on the sustainability pillar's focus.

Sustainability Pillars	**Criteria**	**Code**	**Criteria Weight**			
			Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Technical	Durability (life expectancy)	TEC1	0.10	0.05	0.05	0.05
	Constructability	TEC2	0.10	0.05	0.05	0.05
	Maintainability	TEC3	0.10	0.05	0.05	0.05
	Resistance to Water and Weather	TEC4	0.10	0.05	0.05	0.05
Economical	Material Cost	ECO1	0.05	0.10	0.05	0.05
	Construction Cost	ECO2	0.05	0.10	0.05	0.05
	Maintenance Cost	ECO3	0.05	0.10	0.05	0.05
	End of Life Cost	ECO4	0.05	0.10	0.05	0.05
Social	Job Opportunity Creation	SOC1	0.05	0.05	0.10	0.05
	Fire Resistance and Safety	SOC2	0.05	0.05	0.10	0.05
	Skilled Labor Availability	SOC3	0.05	0.05	0.10	0.05
	Compatibility with Heritage	SOC4	0.05	0.05	0.10	0.05
Environmental	Green House Gas Emission	ENV1	0.05	0.05	0.05	0.10
	Impact During Manufacturing	ENV2	0.05	0.05	0.05	0.10
	Impact During Construction	ENV3	0.05	0.05	0.05	0.10
	Recycle and Reuse Potential	ENV4	0.05	0.05	0.05	0.10

In Table 26, for each scenario, four criteria of one sustainability pillar were weighted with a higher value of 0.10 each, and the other 12 criteria were weighted with 0.05. Users' input for preferences for different alternatives was kept constant to observe the impact on the decision-making process. The option with a greater input in favor of positive criteria would be ranked higher; conversely, negative or cost factors would have the opposite effect. For validation, criteria weightage from this table was then used in the same sample's fuzzy TOPSIS calculation that was explained in Section 4 to rank the alternatives. Each scenario derived one set of ranking results for the alternatives, while the criteria weightage was only altered, and user preferences were kept constant. The output results for different scenarios are shown in Table 27.

Table 27. CC_i values for four scenarios.

CC_i	Scenario 1					Scenario 2				
	Owner	**Constructor**	**Designer**	**Overall**	**Rank**	**Owner**	**Constructor**	**Designer**	**Overall**	**Rank**
CC_{rc}	0.367	0.493	0.358	0.402	2	0.287	0.393	0.337	0.334	4
CC_{ss}	0.352	0.394	0.438	0.390	3	0.451	0.471	0.478	0.465	2
CC_t	0.621	0.533	0.685	0.614	1	0.625	0.534	0.616	0.595	1
CC_{rm}	0.395	0.394	0.333	0.376	4	0.409	0.441	0.394	0.414	3
Criteria	**Scenario 3**					**Scenario 4**				
	Owner	**Constructor**	**Designer**	**Overall**	**Rank**	**Owner**	**Constructor**	**Designer**	**Overall**	**Rank**
CC_{rc}	0.308	0.398	0.339	0.345	4	0.269	0.432	0.318	0.332	4
CC_{ss}	0.308	0.357	0.390	0.347	3	0.404	0.418	0.425	0.415	2
CC_t	0.638	0.610	0.678	0.642	1	0.676	0.553	0.655	0.633	1
CC_{rm}	0.479	0.477	0.434	0.465	2	0.390	0.416	0.333	0.381	3

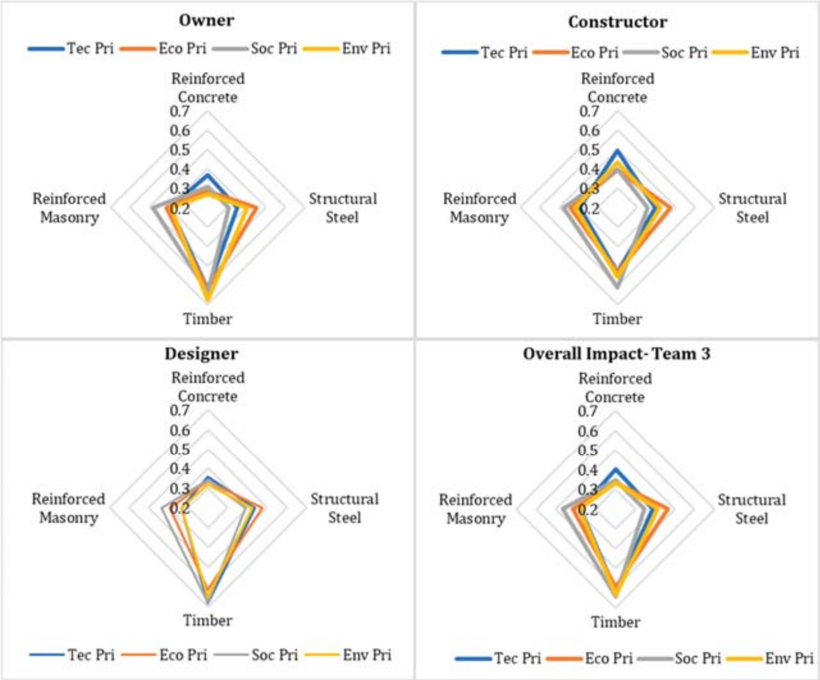


Figure 15. Radar chart showing the sensitivity of the model for criteria weightage.

In Scenario 1, it was observed that providing the technical pillars with greater criteria weightage affected the ranking of RC for Team 3, which was ranked here as the second priority. Figure 15 displays all other impacts graphically once technical, economic, social, and environmental factors were prioritized more. When the overall impact of Team 3 was considered, giving more technical priority resulted in reinforced concrete having a higher

CC_i value, whereas higher social and environmental priorities resulted in a better CC_i for timber. SS was given higher consideration when ranking according to economic priorities. Similar explanations were applicable to other scenarios too.

6.2. Sensitivity Analysis of User Preferences for Alternatives

The user's input determined how the alternatives were ranked. Four scenarios are depicted here to investigate the variability of the CC_i value caused by various user inputs regarding preferences for alternatives. Here, all the criteria were given equal weights to verify the model's sensitivity to visualize the user preference input vividly. The graphical output of the analysis is shown in Figure 16.

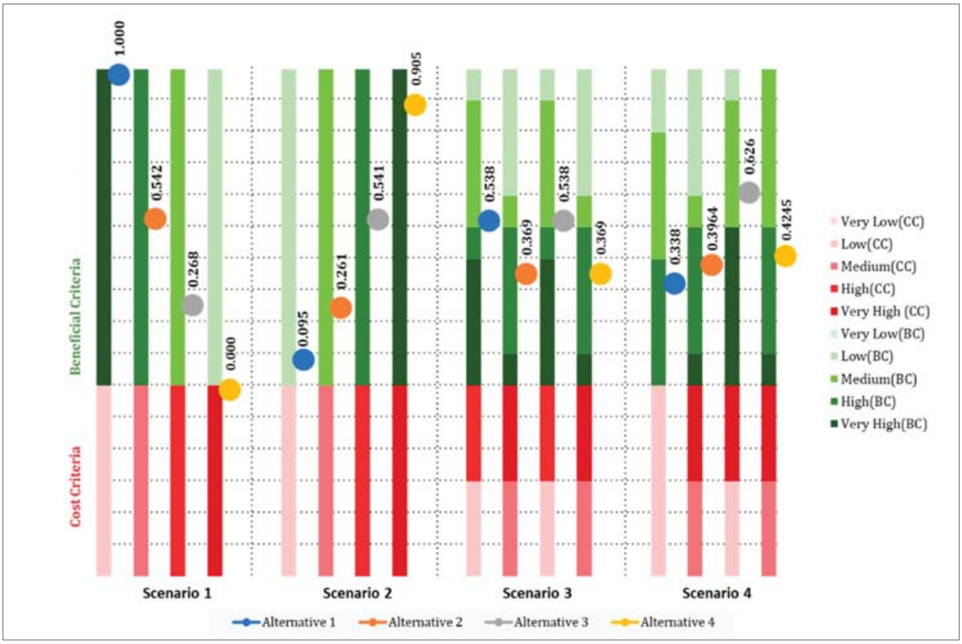


Figure 16. Chart showing the sensitivity of the model for user preferences.

For Scenario 1, the best possible condition was created for Alternative 1. It was given the highest preferences (very high) for beneficial criteria and lower preferences (low) for cost criteria. At the same time, the weightage for all criteria and stakeholders' importance was kept constant and equal. As a result, Alternative 1 obtained the highest CC_i value, which was expected to determine the model's sensitivity. Similarly, priorities for Alternatives 2, 3, and 4 were gradually altered in the case of user input, and the expected reflection of that was observed in the system's output.

In the case of Scenario 2, for both beneficial and cost criteria, the highest preferences (Very High) were given. However, higher preferences would increase the ranking when it came to beneficial criteria, but they had the opposite effect when it came to cost criteria. From the ranking result of Scenario 2, it was derived that a higher input value of cost criteria resulted in a lower CC_i value from Scenario 1. Alternative 4 added some value to the CC_i due to its lower preference input terms of the cost criteria. Similarly, priorities for Alternatives 2, 3, and 4 were gradually altered in the case of user input, and the expected reflection of that was observed in the system's output.

For Scenario 3, it was noticeable that even though each alternative had the identical nature of user preferences assigned to it ("Very High" for four criteria, "High" for four criteria, "Medium" for four criteria, and "Low" for four criteria), the outcome varied. This is due to the existence of beneficial and cost criteria. The CC_i values for Alternatives 2 and 4 were negatively impacted by higher cost criterion values. This demonstrates that the developed model was sensitive to the input given on its core cost–benefit criteria.

In the case of Scenario 4, the output result demonstrates that Alternative 3 achieved a better ranking with a higher CC_i value since it was randomly allocated with a greater number of higher-value inputs. Regarding Alternative 3, it received very high preferences across a higher number (five) of beneficial criteria, which raised its CC_i value and drove it to the top of the ranking.

7. Discussion

Both fuzzy TOPSIS and fuzzy VIKOR are based on the principle of an aggregating function representing closeness to the ideal solution [90]. However, these methods use different types of normalization, where TOPSIS uses vector normalization and VIKOR uses linear normalization. The aggregate function used in VIKOR represents a distance (Q_i) from the ideal solution, whereas TOPSIS uses a ranking index (CC) that calculates the distance between positive and negative ideal solutions. Therefore, the highest-ranked alternative by TOPSIS is the highest-ranked index and is not always necessarily the closest to the ideal solution, which is the case for VIKOR [90]. In this study, rankings of alternatives were carried out employing both of these methods using the criteria weightage from the fuzzy AHP. A comparison of the results obtained is shown in Figure 17. We obtained twenty-four ranking results in this study, involving twelve from fuzzy TOPSIS and fuzzy VIKOR. Except for four cases, all other results were similar in both techniques. These four occurred once there were conflicting situations between the distance measured from the ideal solution by these techniques.

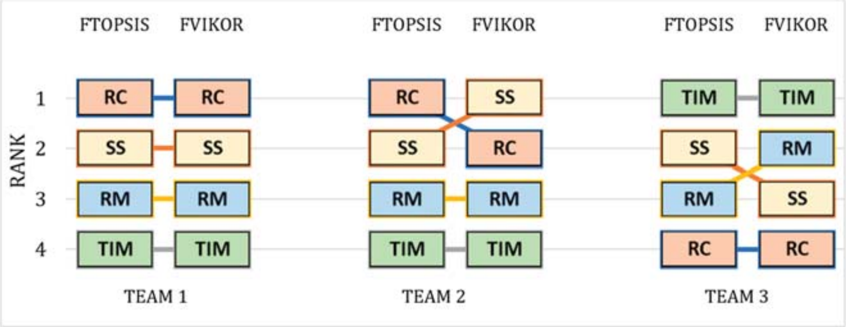


Figure 17. Comparison of final ranking results by fuzzy TOPSIS and fuzzy VIKOR.

The data analysis and results deduced that a decision from this model is entirely dependent on the user inputs. This system calculates based on the users' information: Weightage of the criteria and preferences for different alternatives. Therefore, it can be decided that a sustainable selection is only possible if the stakeholders change their traditional thinking process based on short-term economic gain and seek a sustainable solution. In this study, out of the three teams, two were from traditional construction industries, and the third team comprised members who were either researching or implementing sustainable construction. The results reflected their organizational behavior and showed that the selection of Teams 1 and 2 was more inclined toward technical and economic aspects. Their priority for social and environmental aspects was relatively lower; therefore, reinforced concrete or structural steel was the top-ranked alternative resulting from inputs on criteria weightage and preferences. In contrast, the preferences of Team 3 were more balanced, giving due importance to social and environmental aspects; therefore, timber was the most preferred selection as the structural material for this eight-story residential building.

The findings of this current approach were compared with several previous studies that used fuzzy AHP, TOPSIS, and VIKOR to solve decision-making problems in construction. Authors used the fuzzy AHP to assign weightage and prioritize the importance of criteria and TOPSIS and VIKOR to rank the alternatives [70,79,80,89,97]. They used the preferences and opinions of the stakeholders as the input of the system to determine the output as the ranking of the options. This study also followed a similar approach and integrated the opinion of all project stakeholders to make the most sustainable decision. Therefore, this confirms the reliability of this approach.

As the outcome of the study, it can be concluded that the construction industry's overall performance has raised extreme concern regarding reducing its negative impacts and improving global sustainability. The appropriate selection of materials can achieve sustainability in building construction. Each material has its own sustainability characteristics; therefore, one may be cost-effective but more environmentally harmful or aesthetically incompatible with the environment. Multi-criteria decision-making is essential for selecting the most sustainable material from several alternatives [48,52]. This research argued that sustainable selection is only possible once the stakeholders move away from the traditional short-term cost–benefit analysis and choose to balance all factors of sustainable construction to maximize value and minimize harm. Therefore, the onus is on the users to make conscious decisions to improve the balance between development and sustainability to pave the way for a harmonious society for future generations.

8. Conclusions

This study followed a hybrid approach to develop a decision support system using the fuzzy AHP, fuzzy TOPSIS, and fuzzy VIKOR multi-criteria decision-making techniques. The evaluation criteria for assessing the technical, economic, social, and environmental pillars of sustainable construction vary based on the type and nature of the construction projects and stakeholders' preferences. The opinions of several industry experts and academic researchers were obtained to finalize the list of evaluation criteria appropriate for this research. However, this list was used as the basis for the calculation and development of the algorithms of the DSS. Users would always have the opportunity to change the evaluation criteria depending on the type of project, its location, and stakeholders' preferences. Still, the methodology would work in a similar way for sustainable decision-making.

For the calculation, development, and verification of the DSS, a hypothetical eight-story building was considered in this study. The collected data were analyzed and calculated in several steps. The result showed there were notable differences in the final ranking of the alternatives of different teams. Moreover, it was deduced that there were no ideal solutions to these kinds of problems; instead, optimum solutions can be obtained considering all factors of sustainable construction practices. If users give more importance to economic gain and ignore the environmental aspects, the output result would reflect that. In contrast, if the stakeholders make a balanced choice combining all factors of sustainable construction and considering the entire life cycle of the project, their preferred option will comply with sustainable construction, as displayed by the selection of Team 3 in this study.

The DSS has been developed to assist decision makers in making a sustainable selection in an IPD framework. A few notable advantages of the developed DSS software are as follows: It is a joint application, where all stakeholders can give their input in the IPD framework for a decision, users can edit/modify the alternatives and evaluation criteria according to their needs, and users have the option to set the importance of criteria; this application can handle both qualitative and quantitative data—it can take the qualitative inputs as the users' preferences (i.e., 'very high', 'high', etc.) and quantitative inputs as computed numerical values; the stakeholder can set the importance of their opinions in group decision-making; and most importantly, it is a generic model that can be used for multiple sustainable group decision-making purposes. This convenient, adaptable, and simple DSS is expected to increase objectivity, improve transparency and consistency in sustainable construction, and systemize the process.

In this study, RC, SS, timber, and RM were included as alternatives to the structural elements, discarding any other composites. The developed DSS was tested with a hypothetical case study on an eight-story building in Calgary, Alberta, considering the opinions of nine academic and industry experts. In addition to TOPSIS and VIKOR, further researchers can use other techniques such as PROMETHEE, DEMATEL, CBA, and ANP to verify the applications developed in this research.

This study was conducted on selecting structural elements only, and there is further scope to evaluate the entire building for sustainability using the developed DSS. We identified some variations in ranking results obtained through TOPSIS and VIKOR, and there can be a more detailed study to investigate and comment on those variations in the future. The desktop application has a database to store information related to life cycle analysis, cost, location, etc., which users can enrich and update according to their needs.

Author Contributions: Conceptualization, M.M.A.B. and A.H.; methodology, M.M.A.B.; software, M.M.A.B.; validation, M.M.A.B. and A.H.; formal analysis, M.M.A.B.; investigation, M.M.A.B.; data curation, M.M.A.B.; writing—original draft preparation, M.M.A.B.; writing—review and editing, A.H.; visualization, M.M.A.B.; supervision, A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

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

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Article

Reducing Construction Dust Pollution by Planning Construction Site Layout

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Abstract: Many construction activities generate fine particles and severely threaten the physical health of construction workers. Although many dust control measures are implemented in the industry, the occupational health risks still exist. In order to improve the occupational health level, this study proposes a new method of reducing the construction dust pollution through a reasonable site layout plan. This method is based on the field measurement and dust diffusion law. The dust diffusion law can be fitted based on the field monitoring data. With diffusion law, the average dust concentration exposed to workers of different site layouts can be simulated. In addition, the cost of the dust control method is a concern for site managers. Therefore, the total transportation cost reduction is another optimization objective. Finally, the multi-objective particle swarm optimization (MOPSO) algorithm is used to search for an optimized site layout that can reduce dust pollution and transportation cost simultaneously. The result shows that average dust concentration exposed to workers and total transportation cost are significantly reduced by 60.62% and 44.3%, respectively. This paper quantifies the construction dust pollution and provides site managers with a practical solution to reduce the construction dust pollution at low cost.

Keywords: construction dust; construction site layout planning (CSLP); occupational health; MOPSO; BIM

Citation: Tao, G.; Feng, J.; Feng, H.; Feng, H.; Zhang, K. Reducing Construction Dust Pollution by Planning Construction Site Layout. *Buildings* **2022**, *12*, 531. https://doi.org/10.3390/buildings12050531

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 14 March 2022
Accepted: 19 April 2022
Published: 22 April 2022

1. Introduction

With rapid economic and industry development, air pollution has become a serious environment problem worldwide, especially in urban areas [1]. Air pollution causes critical respiratory illness to human beings. Inhalation of particulate matter (PM) suspended in the air can cause various long-term respiratory diseases and premature deaths [2]. Therefore, people are gradually raising attention to air pollution in these years. The construction industry is one of the primary air pollution sources in most counties [3]. Additionally, the construction industry is a labor-intensive industry and many workers have to work very close to various dust sources. Many construction activities, such as cement mixing and template cutting, can produce much dust during construction phases [3,4]. These dust pollutes the surrounding environment [5] and also threatens the physical health of construction workers [6,7]. Many researchers have found that this kind of working environment can lead to an increase in the number of diseases related to cardiovascular, respiratory and the skin [8–10]. Therefore, construction dust's negative effect on workers has attracted the attention of whole construction industry and academia. It is necessary to take some measures to protect construction workers.

Many researchers have conducted research about the health impact of the PM exposure on workers [3,11–14]. There are three main research directions: health impact assessment, dust monitoring, and dust control and prevention. The first one is the health impact assessment. Some researchers collected related medical data for years to confirm that the construction dust has a negative impact on construction workers. Bergdahl et al. [11] followed 317,629 construction male construction workers for 28 years and tried to find out the association between mortality from chronic obstructive pulmonary disease (COPD) and occupational exposure to construction dust. The final results show that there is increased mortality from COPD among those exposed to the construction dust, especially among never-smokers. Borup et al. [12] also analyzed the records and validated the high association of COPD among construction workers. Those with pre-existing cardiopulmonary problems and elderly workers are more sensitive to the PM [15]. PM2.5 decreased the average life span by 8.6 months in EU countries [16]. In general, construction dust threatens the physical health of workers severely.

Based on the common understanding of health risks caused by construction dust, in recent years, many researchers have tried to quantificationally evaluate the dust impact from construction sites. Tong et al. [4] applied Monte Carlo simulation and the United States Environmental Protection Agency (USEPA) risk assessment model to explore the health effects of construction dust on practitioners in the construction industry. They also divided the construction site into different functional zones, such as steel zone and floor zone, and evaluated the health impact of workers in different zones separately. The disability-adjusted life year (DALY) parameter, which was developed by Murry at Harvard University and World Health Organization (WHO) [17], was widely used in the health risk assessment study. Researchers applied DALY to quantitatively measure the burden of disease and perform a quantitative assessment of health damage [4]. Based on the DALY parameter, some researchers have tried to translate the health risks into the economic significance through willingness to pay (WTP) [13,14]. These studies analyzed the impacts of the construction dust on people and identified the main influencing factors, such as exposure time, exposure methods, dust concentration, etc. With these research foundations, researchers built the relationship between construction dust and occupational health risk. In most studies, the concentration of dust that workers are exposed to is a very important factor. It is highly positively correlated with occupational health risk. Therefore, we improve the worker's occupational health by reducing the dust concentration that workers are exposed to in this study.

Another main research direction in this research field is dust monitoring. How to monitor the dust concentration accurately is always a complex issue. Many researchers have promoted the dust monitoring research from multiple aspects [5,18,19]. In order to obtain accurate monitoring results, the up–down wind direction method was used to eliminate the interference due to environment background and reveal the absolute value of incremental dust concentration from construction sites [5,18,20]. In the process of dust monitoring, some researchers found that some of the environmental factors, such as wind speed [21], humidity [22] and temperature [23] affect the accuracy of dust sensor. In addition, researchers found that construction activities also affect the dust concentration [3–5,18]. Li et al. [3] found that the top three respirable exposures are from cement mixing, concrete breaking and manual demolition. Yan et al. [5] analyzed the field monitoring data and found that the construction vehicles were one of main influencing factors of construction dust. Tong et al. [4] compared the dust concentration in different construction zones and the results indicated that the template zone is the most polluted area. Except the research above, during the dust monitoring process, some researchers also analyzed the chemical composition of the dust [19,24] and diffusion law of dust from construction sites [18,20].

As for the dust monitoring equipment, many modern-day devices, such as sensors and the wireless sensor network (WSN) have been applied into practice nowadays with the advancement of technology. In the past, air quality monitoring stations were often built to collect dust concentration data. However, these stations have many limitations, such as the large size, high cost and power requirement [25]. To overcome these barriers, some researchers compared different sensors and applied these low-cost sensors and WSN to monitor the dust concentration on construction sites. Budde et al. [26] suggested that air quality monitors could be replaced with low-cost sensors due to their ease of use. Cheriyan and Choi [27] used low-cost sensors, Alphasense and Sharp sensors to monitor PM, and the results shows that these sensors have good performance during the monitoring process.

The final main research direction is dust control and prevention. The research above confirmed that the dust generated from construction pollutes the air and threatens the physical health of workers. The PM10 and smaller dust particles can reach the respiratory tract and lung, which can result in an irreversible respiratory disease called pneumoconiosis [3,15]. Therefore, many researchers and practitioners have put lots of effort into dust control and prevention research. Some studies used technical measures to control the construction dust. Li et al. [3] analyzed 783 samples in Hongkong and summarized that there are three commonly used dust control measures: local exhaust ventilation (LEV), blower fans and wet methods. Respirators and wet methods are the most widely used protective measures in the Hong Kong construction industry. Chen et al. [13] evaluated the isolation effect of dust masks and the results showed that the health risk could be reduced by 26% under the actual effect. Tjoe Nij et al. [28] proposed that only the combined use of more than one control measure can reduce the construction dust's negative effect to acceptable levels. In addition to technical measures, reasonable managerial instruments or measures are vital as well. Wu et al. [29] proposed that the formulation of targeted regulation and establishment of an appropriate charging scheme could increase contractors' willingness in mitigating construction dust. They also found that it is essential to give construction workers specific dissemination and training to increase their environmental awareness. In addition, a corresponding monitoring system could guarantee the effectiveness of the regulation and charging scheme.

It can be seen that researchers and practitioners have made many efforts in dust pollution control, and many dust control measures have already been taken in the construction industry. However, the current air condition on the construction sites is still not fully satisfactory [29]. These control measures have some obvious shortcomings. The wet methods, such as the spraying system and manual watering, need to continuously spray clean water mist into the air during the construction period. Considering that most of the construction projects have a long period, it would consume much of the water resources. This may lead to a local water shortage, especially in relatively arid areas. In addition, in order to ensure the safety of the use of electrical equipment, it is required to keep a safe distance from the spraying system or to install additional waterproof covers. The dust masks can significantly reduce the health risk of workers, but the uneven quality and the inappropriate usage of masks would reduce their isolation effect. The actual isolation effect of dust mask is only 26% in the construction industry [13]. Other measures, such as LEV and blower fans, would require much electricity to operate during construction. Therefore, there is an urgent need for an economical, convenient and practical dust control solution in the construction industry.

This study proposes a new method that uses a reasonable site layout plan to reduce the average dust concentration exposed to workers. This method allocates the facilities on sites according to the dust diffusion law and number of workers on each working zones. By increasing the distance between dust pollution sources and workers, this method can reduce the average dust concentration exposed to workers. Thus, the negative effect of construction dust could be reduced. However, the longer distance between facilities would increase the transportation cost on the site. Therefore, the multi-objective particle swarm optimization (MOPSO) algorithm is applied in this study to balance the construction dust negative effect and total transportation cost. In addition, the BIM model, due to its rich sources of building information, is also used in this study to automatically provide basic construction information [30], which can help site managers save much time and effort in designing the site layout plan in the pre-construction stage.

2. Methodology

In order to properly design the site layout to reduce the negative dust impact while maintaining the minimum on-site transportation cost, the following framework is proposed, shown in Figure 1.

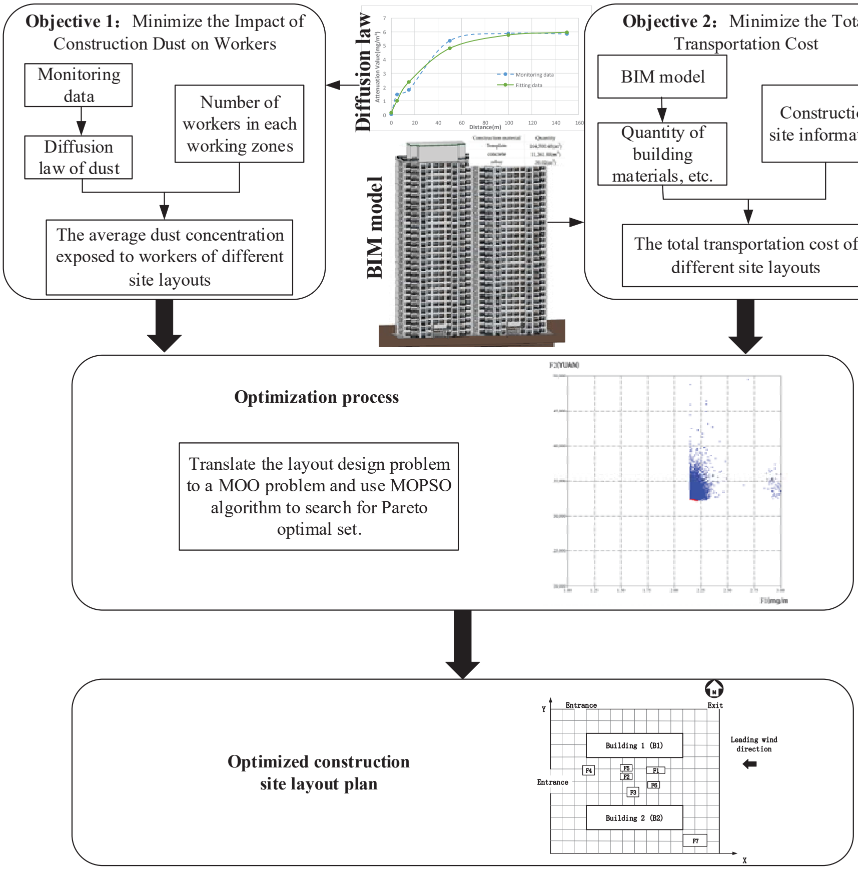

Figure 1. The framework for reducing construction dust effect by CSLP.

2.1. Determine the Scope of Study

In this study, reducing the impact of construction dust on workers and the on-site transportation cost of building materials are the two objectives. As for reducing the impact of construction dust, this study only focuses on the impact of dust generated by construction activities on the construction site. Dust from outside the construction site is not considered in this study. The construction site condition (e.g., the phase of construction and wind condition of the construction site) and number of workers in each facility are also considered in this study. In addition, the proposed model only considers the direct impact of construction dust on workers. The indirect impact caused by physicochemical effects is not considered in this study [18]. As for the total on-site transportation cost, only the horizontal transportation of building materials within the boundary of the construction site is considered in this study. The total transportation cost consists of the horizontal and vertical transportation costs. The horizontal transportation cost generally accounts for a large proportion of the total transportation cost. The vertical transportation of building materials generally relies on tower cranes, which cost much less than the horizontal one [31].

Therefore, only the horizontal transportation cost is applied when optimizing the site layout. Generally, workers would engage their corresponding types of construction activities during the construction period, and they spend much time at their workplace. Therefore, the movement of workers is ignored in this study.

2.2. Modeling of Multi-Objective Construction Site Layout Problems

The purpose of the study is to reduce the impact of construction dust on workers and total on-site transportation cost by planning the construction site layout. In this section, a multi-objective optimization (MOO) model is built to balance the construction dust impact and total transportation cost.

2.2.1. Minimize the Impact of Construction Dust on Workers

The construction dust can lead to construction workers suffering from respiratory diseases, such as cardiovascular disease, cerebrovascular disease, etc. [32]. In a previous study, researchers often took the inhalation health risk assessment model [33], which is recommended by the United States Environmental Protection Agency (USEPA), to evaluate the health damage of workers. According to the USEPA model, the degree of health damage is highly positively correlated with the dust concentration. In other words, the prevalence will increase with an increasing construction dust concentration. Therefore, the concentration of dust is selected as the indicator to measure the impact of construction dust on workers. In this study, the total suspended particulate matter (TSP) concentration in the air is chosen as the indicator to represent the dust concentration on the construction sites. The TSP denotes the total suspended particulates with aerodynamic diameters of less than 100 μm, which could cause a threat to workers' health [4]. To eliminate the interference due to environment background dust and accurately reflect the impact of construction dust on workers, the up–down wind direction method is adopted in this study to monitor the dust concentration [5,18,20]. The leading winds, which are the prevailing winds in the meteorology, blow constantly in a given direction [34]. Therefore, the leading wind direction is applied as the up–down wind direction in this study [5,18].

Generally, the pollutant is subjected to diffusion in all directions in the presence of advection and settling due to gravity [35]. Therefore, under the action of wind, the attenuation value of dust concentration shows a certain relationship with the distance from the pollution source. The construction dust attenuation relationship between construction dust concentration and distance in the wind direction can be statistically fitted depending on the monitoring data and exponential law model [18,36] (see Figure 2). For the construction dust concentration at the workers' workplaces i ($i = 1, 2, \ldots, m$) that originates from the dust source j ($j = 1, 2, \ldots, n$), the construction dust concentration is the sum of each dust source, which can be denoted by Equations (1)–(3):

$$CDC_i = \sum\nolimits_{j=1}^{n} C_{ij} + C_b, \tag{1}$$

$$C_{ij} = \begin{cases} SC_j - Y, \left|SC_j \geq Y\right. \\ 0, \left|SC_j < Y\right. \end{cases}, \tag{2}$$

$$Y = 6.02 - 5.882e^{-\frac{wd_{ij}}{31.59}}. \tag{3}$$

In Equation (1), CDC is the construction dust concentration at workers' workplace i, where $i = 1, 2, \ldots m$; C_{ij} represents the construction dust concentration at workers' workplace originating from the dust source j, which can be derived from Equation (2); C_b is the background construction dust concentration. Due to the up–down wind direction method [20], the upwind point concentration is taken as C_b.

In Equation (2), SC_j is the concentration of the dust source j; Y is the construction dust concentration attenuation value. If the concentration of dust source SC_j is greater than the attenuation value Y, then C_{ij} is equal to the concentration of dust source SC_j minus attenuation value Y. If the concentration of dust source SC_j is less than the attenuation value Y, then the C_{ij} is equal to 0, i.e., in this situation, the dust source j has no negative impact on the workplace i. In Equation (3), wd_{ij} is the distance between workplace i and dust source j in the leading wind direction. This equation is derived by fitting the monitoring data (Figure 2).

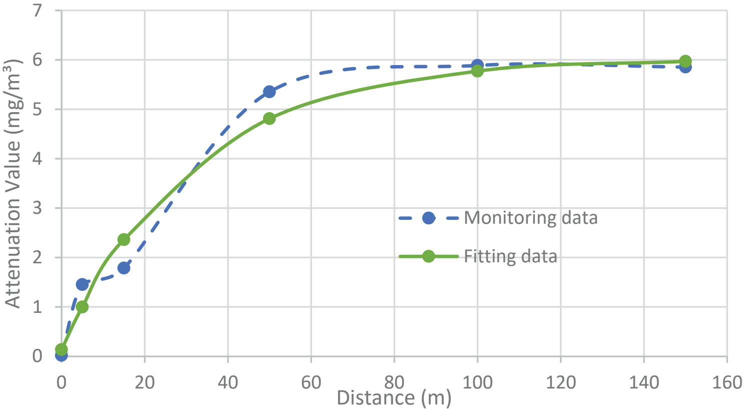

Figure 2. The construction dust concentration attenuation relationship.

In order to reduce the impact of construction dust on workers, the construction dust reduction objective function F_1 should fulfill the following requirement in Equation (4):

$$F_1 = \min \frac{1}{W} \sum_{i=1}^{m} CDC_i \times W_i. \tag{4}$$

F_1 is the objective function that minimizes the average construction dust concentration exposed to workers. W is the number of workers on the construction site and W_i is the number of workers at the workplace i. The number of workers on the construction site is equal to the sum of number of workers at all workplaces, i.e., $W = \sum_{i=1}^{m} W_i$. In order to reduce the impact of construction dust, the main dust sources should be assigned as far as possible at the downwind points.

2.2.2. Minimize the Total Transportation Cost

A good construction site layout plan could help site managers reduce the impact of construction dust within the cost budget [37]. On the construction sites, the transportation of building materials incurs a certain cost. The total transportation cost is an important part of the cost budget. Therefore, the second optimization objective, F_2, is to minimize the total transportation cost, as shown in Equation (5).

$$F_2 = \min \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} d_{ij} C_{ij} f_{ij}. \tag{5}$$

In Equation (5), d_{ij}, C_{ij} and f_{ij} denote the Euclidean distance, the transportation cost per unit length and the frequency of transportation between facilities i and j. Different site layouts would profoundly affect the transportation distance d_{ij} between facilities. C_{ij} depends on the mode of transportation. f_{ij} is determined by the quantity of building materials to be transported and transportation mode.

2.3. Constraints of the Construction Site Layout Problem

When optimizing the construction site layout planning, the proposed model should comply with the corresponding constraints to make the optimization results more realistic. For the convenience of representation and calculation, the construction site layout should be put in the coordinate system.

2.3.1. Construction Site Boundary Constraint

All the facilities should be assigned within the boundary of the construction site. To prevent facilities positioned outside the borders of the available locations, Equations (6)–(9) are formulated:

$$x_i \geq \frac{b_i}{2}, \tag{6}$$

$$x_{bd} - x_i \geq \frac{b_i}{2}, \tag{7}$$

$$y_i \geq \frac{l_i}{2}, \tag{8}$$

$$y_{bd} - y_i \geq \frac{l_i}{2}. \tag{9}$$

where (x_i,y_i) denotes the Cartesian coordinates of the centroid of facility i; b_i and l_i represent the horizontal and vertical lengths of facility i, respectively; and x_{bd} and y_{bd} mean the horizontal and vertical boundaries of the available locations. The four equations above ensure that the boundaries of each facility are all within the borders of the construction site.

2.3.2. Overlapping and Safety Constraint

When two or more facilities are assigned on the construction site in the same phase, facilities cannot overlap each other or overlap with buildings. In addition, the minimum distance between the facilities is set in this model to avoid mutual interference and ensure the construction safety. The constraint is applied using Equation (10):

$$\min\left\{0.5\left(b_i + b_j\right) + h_{ij} - \left|x_i - x_j\right|, 0.5\left(l_i + l_j\right) + v_{ij} - \left|y_i - y_j\right|\right\} \leq 0. \tag{10}$$

where h_{ij} and v_{ij} denote the minimum horizontal and vertical safe distances between facilities i and j, respectively. These two parameters can ensure the safety of construction activities in the corresponding facility and basic transportation of building materials on the sites. The specific values of the minimum safety distance can be determined according to the requirements of construction projects.

2.4. Optimization Using MOPSO Algorithm

The proposed model above reflects how the construction site layout affects the two objectives: impact of construction dust and total transportation cost. From the computation point of view, the CSLP is an NP-hard question [38]. In addition, the proposed model in this study is also a multi-objective optimization (MOO) problem [37]. According to several research studies [37,39,40], heuristics algorithms are often used to solve CSLP. MOPSO, due to its ease of implementation and ability to handle multi objectives [41], is applied in this study to solve the site layout problem. The essence of MOPSO is that the local and global optimal values guide the particles and generate the brand-new position and speed of the particle. This can make the result of the proposed model converge toward the global optimal position. Due to these characteristics of the MOPSO algorithm, the construction dust pollution and total transportation costs can be reduced simultaneously. The details of the algorithm are as follows.

Procedure of MOPSO Algorithm

In this algorithm, the coordinates (x_i, y_i) of the centroids of facility i are regarded as a decision variable. A set of coordinates, which represent all available positions in the construction site, is regarded as the input of the algorithm. The detailed procedure of the MOPSO is the following.

Step 1. Initialize the particles. Randomly generate initial position $POP_i(0)$ and velocity $V_i(0)$ for each particle. In the construction site layout planning, a possible position of the particle represents a possible assignment for all site facilities.

Step 2. Initialize the external archive and find the initial previous best position of particle *i* ($pbest_i$) and the global best position of particles (*gbest*). The fitness function of each particle is calculated in terms of the objective function. Compare the fitness function value of each particle and store the nondominated particles in the external archive. The global best position (*gbest*) is a value taken from the external archive. Since the particles in the archive are all nondominated, the global best position should be selected according to certain rules. The details are as follows.

(a) Divide the objective function space into grids. The objective function space is a coordinate system and particles can be located in this system according to the values of the particle's objective functions, F_1 and F_2.

(b) Choose a grid by using Roulette-Wheel Selection. The grid which contains more than one particle is assigned a fitness equal to the result of dividing any number $x > 1$ by the number of particles that the grid contains. This kind of fitness assignment can ensure that the grid which has fewer particles has more probability to be selected. Then Roulette-Wheel Selection is applied to choose a grid. This selection method can avoid the particles from quickly converging to the local optimum position.

(c) Randomly select a particle within the grid chosen above as the global best position $gbest$. The initial previous best particle *i* is the initial position itself (see Equation (11)).

$$pbest_i = POP_i. \tag{11}$$

Step 3. Update the velocity and position of particles. The velocity $V_i(t)$ is updated according to Equation (12):

$$V_i(t+1) = w \times V_i(t) + c_1 r_1 \times (pbest_i(t) - POP_i(t)) + c_2 r_2 \times (gbest_i(t) - POP_i(t)). \tag{12}$$

In Equation (12), w is the inertia factor; c_1 and c_2 are the local and global acceleration coefficients, respectively; r_1 and r_2 are random numbers uniformly distributed within [0,1]; and t represents the tth iteration of the algorithm. It can be seen from Equation (12) that the velocity is guided by the previous best position and global best position simultaneously.

The position of particles POP_i is updated as follows:

$$POP_i(t+1) = POP_i(t) + V_i(t+1). \tag{13}$$

The updated position is equal to the position of particle in the last iteration plus the updated velocity.

In order to avoid the particles from searching beyond the available search space, all the particles need to be checked. If the particle goes beyond the boundary, the position of the particle takes the value of the corresponding boundary, and the velocity is multiplied by -1 so that the particles can search in the opposite direction.

Step 4. Update the fitness function value of the particles and external archive. Calculate the fitness value according to the position of the particles in the $(t+1)$ iteration. Then add the nondominated particles into the external archive and eliminate the dominated particles from the archive. Due to the limited size of the archive, particles which are located in more populated area of objective function space are more likely to be eliminated when the external archive is full.

Step 5. Update the previous best position and global best position of particles. When the current position of particle is better than previous best position $pbest_i$ in the last iteration, update the $pbest_i$ with the current position.

$$pbest_i = POP_i \tag{14}$$

If the current position is worse, then the value of $pbest_i$ is kept in its current iteration. If neither of them is dominated by the other, one of them is selected randomly. As for the $gbest$, it is updated in the same way as that in step 2.

Step 6. Repeat steps 3 to 5 until the number of iterations reaches the set value. In the external archive, the position of particles represents the location of the facilities on the construction site. The objective functions of particles in the archive represent the impact of construction dust on workers and the total transportation cost.

3. Case Study

In order to validate the effectiveness and practicability of the proposed methodology above, a residence construction project is adopted. In this section, an analysis for the construction project and a comparison with the original site layout plan are conducted to highlight the approach.

3.1. Case Study Description

The residence construction project is located in Nanjing, China. Usually, the dimensions of the temporary facilities are determined according to the scale of the construction projects and the amount of building materials. In this case, the dimensions of facilities, which are all predefined by site managers, are presented in Table 1. The facilities on the site could be divided into three categories: (1) storage facilities, (2) processing facilities and (3) residence facilities. Building materials are delivered to the construction site and then stored temporarily in storage facilities. When needed, building materials are first transported to the processing facilities for processing and then transported to the floor zone for construction. As for the residence facility, it provides a comfortable office and rest environment for site managers and workers. This residence construction project uses BIM to design and construct. Therefore, the quantity of different building materials could be extracted from the BIM model (see Figure 3). Additionally, trunks and forklifts are used to transport building materials horizontally in this construction project.

Table 1. The required facilities and their dimensions.

Symbol	Facility	Type	Width in x Direction (m)	Length in y Direction (m)
F1	Template storage yard	Storage	15	5
F2	Rebar storage yard	Storage	10	5
F3	Concrete warehouse	Storage	10	8
F4	Template processing yard	Processing	10	8
F5	Rebar processing yard	Processing	10	5
F6	Concrete mixing station	Processing	10	5
F7	Site office	Residence	20	10

According to the climate data, the leading wind direction of the construction site is east. That means that the construction dust sources located in the east side will affect the workers on the west side of construction site. Due to the long construction period, many workers and many kinds of construction activities required, the superstructure construction stage was selected in this case study. The number of workers at different workplaces in this residence construction project can be seen in Table 2.

Table 2. Number of workers at the corresponding workplaces.

Symbol	Workspace	Number of Workers Required
F4	Template processing yard	5
F5	Rebar processing yard	10
F6	Concrete mixing station	5
F7	Site office	10
B1/B2	Floor zone	20 [1]

[1] Each floor zone needs 20 workers.

Construction material	Quantity
Template	164,500.48(m^2)
concrete	11,261.88(m^3)
rebar	38.02(m^3)

Figure 3. BIM model of the project and corresponding quantity of building materials.

On the construction site, some construction activities, such as template processing, rebar processing, cement mixing, etc., generate lots of construction dust [3,4]. In this construction project, the TSP monitoring tool, dust sampler, was applied to collect dust concentration data of major construction dust sources. In order to measure the dust concentration more accurately, the dust sampler was mounted on a tripod and sampling points were close to the operator without affecting the operator. In addition, the wind speed of the construction site is around 1.0 m/s, which is a light wind, during the monitoring period. The detailed concentration of dust sources is seen in Table 3.

Table 3. Mean concentration of dust sources.

Symbol	Dust Source	Corresponding Construction Activity	Dust Concentration (mg/m^3)
F4	Template processing yard	Template processing	5.65
F5	Rebar processing yard	Rebar cutting and bending	1.50
F6	Concrete mixing station	Concrete mixing	2.24
B1/B2	Floor zone	Concrete pouring, template dismantling, etc.	1.20

3.2. Results of the Case Study

The optimized construction site layout plans could be generated by applying the proposed multi-objective construction site layout model and the MOPSO algorithm. Python was used to code the model and algorithm. After a few rounds of searching, the Pareto front and Pareto optimal set, which represents potential construction site layout plans, was generated. In Figure 4, the red dots represent the non-dominated solutions and the blue dots represent the non-optimal solutions. One characteristic of the non-dominated solution is that a gain in an objective from one solution to the other is only obtained by sacrificing at least one other objective [42]. Due to this characteristic, the site managers need to choose the most suitable solution according to the practical situation of the construction project. In this case, the site managers pay lots of attention to the health of construction workers. Therefore, the red dots on the left are more likely to be selected by managers. However, the total transportation cost of the leftmost red dot is particularly high, compared with other dots in Pareto front. Finally, the dot enclosed by the red box is selected as the final optimization solution. The optimized construction site layout plan is shown in Figure 5.

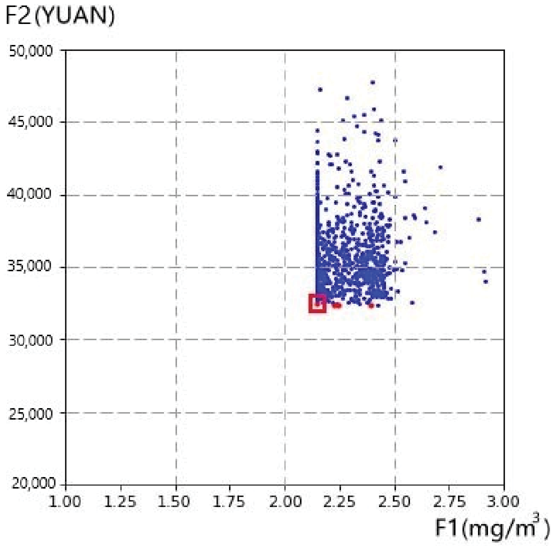

Figure 4. Pareto front for the proposed two objective functions.

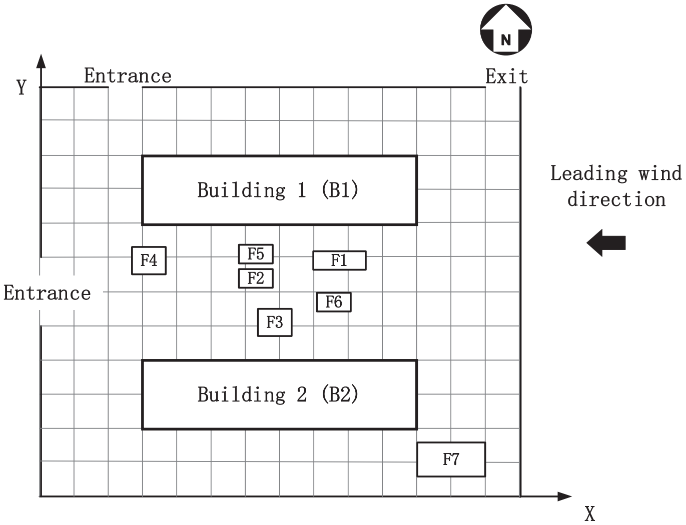

Figure 5. The optimized construction site layout plan.

In order to demonstrate the benefit of the proposed method more intuitively, the original construction site layout plan (see Figure 6), made by site managers, was also considered in this study. Traditionally, the site layout plans are often made based on site managers' experience. Table 4 compares the impact of construction dust and total transportation cost corresponding to the two cases. From Table 4, we can see that optimized CSLP plan has better performance in both construction dust control and transportation cost.

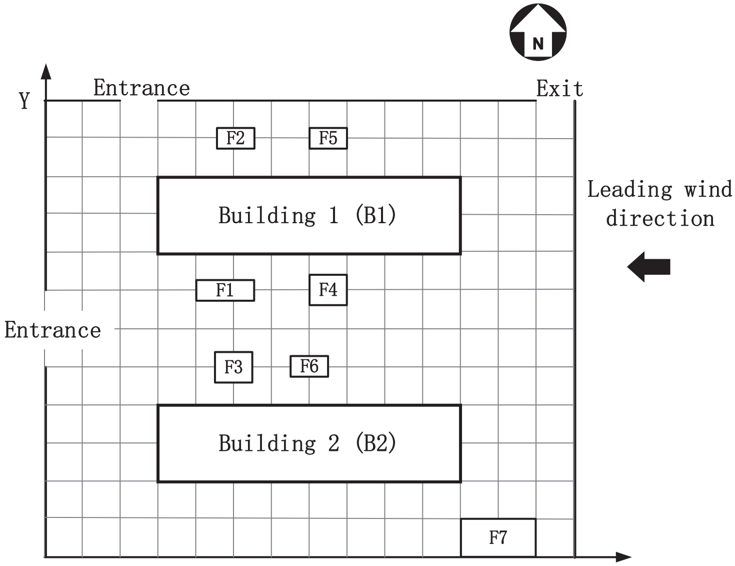

Figure 6. Original construction site layout plan.

Table 4. Comparison of the construction dust impact and total transportation cost.

Construction Site Layout Plan	Objective Functions	
	F1 (mg/m^3)	**F2 (yuan)**
Original CSLP	5.46	57,129.62
Optimized CSLP	2.15	31,819.56

3.3. Result Analysis

It can be seen that the optimized CSLP (see Figure 5) has less construction dust impact and less transportation cost simultaneously compared with the original one. In Figure 5, the temporary facilities are relatively concentrated between two buildings and close to each other. This kind of construction layout could greatly shorten the transportation distance and reduce the total transportation cost. For the templates required on the site, workers need to take them out from storage yard F1, and then transport them to the processing yard F4. After the cutting and other processing processes, templates are finally transported to the floor zone B1 & B2. Since F4 has produced the most serious construction dust pollution among all facilities, it is assigned to the westernmost part of the construction site, close to the site entrance. No other facilities are assigned on the west side of F4. This layout could significantly reduce the construction dust impact of F4 on workers at the downwind area. However, the transportation distance of templates is relatively long. For the rebars, they need to be transported from F2 to F5 for cutting and bending, and then be delivered to two floor zones. F2 and F5 are adjacent to each other and F5 is also close to the two buildings. Therefore, the total transportation distance of rebars is very short. F5 is just adjacent to the east side of the facility. However, the construction concentration of F5 is relatively low and it would slightly affect the workers' work in F4, B1 and B2.

As for the concrete, the transportation route is from F3 to F6, then to B1 and B2 separately. Among all the building materials, the quantity of concrete that needs to be transported is the largest. Therefore, the layout of F3 and F6 would have a relatively large impact on the total transportation cost. In the optimized plan, F3 and F6 are both located on the middle part of two buildings. The distance between F3 and F6 is also short. This kind of layout could greatly reduce the transportation cost of concrete. Although the dust concentration of concrete mixing station F6 is relatively high, F4 is relatively far away from F6. In other word, F6 does not have much negative impact on workers in F4. However, the workers in F5, B1 and B2 may suffer a certain degree of construction dust. As for the site office F7, it is allocated on the easternmost side of the construction site. Therefore, the construction site staff in F7 would not be affected by construction dust. The optimized CSLP balances the construction dust effect and total transportation cost. The average dust concentration to which workers are exposed is 2.15 mg/m^3 and the total transportation cost is CNY 31,819.56.

The original plan (see Figure 6) was designed by site managers, who considered the convenience of transportation and construction on the site. The assignment of facilities in original plan is more widely dispersed than that in optimized CSLP. Due to the sufficient operation space around the facilities, workers can load and unload building materials more conveniently. The sufficient distance between facilities can also ensure the safety and convenience of transportation. However, this layout has some disadvantages. First, the transportation distance of building materials on the site is increased due to this dispersed layout. The total transportation cost is correspondingly increased. According to the results in Table 4, the total transportation cost is increased by 44.3% compared with the optimized plan. Another disadvantage is that site managers did not consider the negative impact of construction dust on workers when planning the site layout. In original plan, storage facilities are all assigned on the western part of the construction site, and the processing facilities are assigned on the eastern part. The storage facilities (F1, F2, F3) are close to the entrances, which is convenient for trunks to unload building materials. However, dust pollution sources (F4, F5, F6) are assigned upwind, and this layout exposes workers downwind to more dust pollution. According to the results, the average construction dust concentration to which workers are exposed is increased by 60.62% compared with the optimized CSLP. In summary, the optimized site layout plan is a more appropriate and reasonable choice for site managers.

4. Discussion

4.1. Theoretical Implications

This study enriches the dust suppression approaches in the construction industry by incorporating the CSLP method. There are some theoretical implications as follows.

Firstly, this study enriches the research about the construction dust suppression. In previous studies, many researchers have performed many studies about the health impact of PM exposure on workers [3,18]. Based on the research about the health impact assessment, dust monitoring [4,5], this study proposes a new dust suppression method that utilizes the CSLP method to reduce the average dust concentration exposed to workers. Compared with other common dust suppression methods in the construction and other industries, such as local exhaust ventilation (LEV), blower fans, wet methods, and dust masks [3,13,43,44], this method has many advantages. This method does not require any other special equipment and electricity power, which saves much cost and improves the sustainability of construction projects. Additionally, the CSLP method also has a good dust suppression effect. This method reduces construction dust pollution in a more economical, practical and convenient way. In addition, it also enriches the CSLP research and expands the application of the CSLP research.

Secondly, this study develops the relationship between construction dust impact and facilities layout quantitatively. The construction dust-induced occupational health risk is positively correlated with the dust concentration [4]. Therefore, the dust concentration is used as the indicator to assess the occupational health risk. The up–down wind direction method [5,18] was applied to monitor the dust concentration data on the site. With the exponential law model [36], which is suitable for describing the spatial diffusion of construction dust, the quantitative relationship between the construction dust impact and facilities layout could be derived. The quantitative relationship can reveal the effect of the site layout on construction dust pollution exposed to workers and it aids future researchers in searching for more sustainable site layouts.

Thirdly, the proposed model could reduce the construction dust impact and total transportation simultaneously. There is a conflict between these two optimization objectives. In order to reduce the negative impact of construction dust on workers' health, the facilities that generate dust need to be placed on the most downwind position of the construction site [20]. Other facilities should be assigned as far away from them as possible to avoid the potential negative effect. However, this decentralized site layout plan will greatly increase the transportation distance on the site. Therefore, how to balance these two conflicting optimization objectives is a key problem for site managers when planning the site layout. This study quantifies the relationship between the impact of construction dust, transportation cost and site layout, respectively. The MOPSO algorithm is also used to trade off the two objectives and generates a balanced and reasonable construction site layout plan. Therefore, the proposed CSLP method could solve the construction dust pollution problem in a more comprehensive approach.

4.2. Practical Implications

In this study, the proposed CSLP method provides a practical, convenient and economical tool for site managers to reduce construction dust pollution and total transportation cost. The practical implications are as follows.

Firstly, those facilities with many workers and little dust, such as the site office, should be assigned to the upwind positions or keep a safe distance from the dust pollution sources. Generally, those facilities with high dust pollution level would pollute the air quality of downwind locations [18]. Therefore, the facilities with many workers should be assigned at upwind locations. If the construction sites cannot be assigned according to the above suggestions, the facilities with many workers should keep a safe distance from dust pollution sources.

Secondly, this method could help site managers to judge the dust pollution level in the pre-construction stage. The dust pollution level of the site layout could be calculated by using the dust diffusion law. For some very small construction sites, the site layouts are difficult to optimize due to the area restriction, and the proposed method cannot be applied directly to these construction sites. Site managers could judge whether to take some other dust suppression methods according to the simulated dust pollution level.

Thirdly, facilities with high interactive flows should be placed close to each other. This kind of site layout could significantly reduce the distance between facilities, and then the total transportation cost can be reduced as well. However, the distance between facilities has a negative impact on dust pollution exposed to workers. In addition, very close distance between facilities would also increase the risk of accidents of workers. Therefore, the site managers could use the proposed method to balance these factors when planning the site layout.

4.3. Limitations and Future Directions

One limitation in our research is that the simulation results of dust concentration are influenced by many external factors that are hard to measure. The dust diffusion is a complicated issue [45]. The external factors can affect dust concentration on the site, such as wind speed, relative humidity, and other meteorological factors. Some construction activities, such as the movement of vehicles, are also positively correlated with the construction dust [46]. However, these influencing factors are irregular. Therefore, it is difficult to monitor and simulate the dust concentration caused by these factors. To mitigate these irregular factors, we suggest that future research should study the relationship between these factors and construction dust in a targeted manner. With these relationships, the generated site layout could be more reasonable.

The other limitation in our research is that the proposed model does not give enough consideration to the convenience of transportation and construction. The move of vehicles and construction activities on site both need enough operation space. In the future, researchers could study the relationship between site layout and construction convenience. Each operation space of construction activity should be determined. The reasonable trunk route should also be planned in the model. With these research, the optimized site layout could be more practical.

5. Conclusions

This study presents a BIM-based model to design an optimized site layout plan, which can fulfill the requirements of construction dust negative effect reduction and transportation cost saving, simultaneously. The relationship between construction dust impact and facilities layout can be obtained based on the dust diffusion law and monitoring data of dust concentration on site. The total transportation cost of different layouts can also be simulated according to the BIM model and transportation mode. Finally, the MOPSO algorithm is implemented to search for the optimal site layout plan that can balance the cost and dust pollution effect. The result of the case study indicates that the construction dust pollution effect and transportation cost can be reduced by optimizing the site layout. As the construction dust pollution can bring negative impacts on workers' health, the optimal site layout can provide environmentally friendly site environments for workers by means of dust reduction. Compared with previous research about dust suppression, this study proposes a new method that uses CSLP to reduce dust pollution in a more economical, practical and convenient way. The proposed method can be widely applied in the construction industry. Even for some very small construction sites, it can also help site managers plan the site layouts and improve the occupational health level. With this study, the sustainable and economical objectives can be realized on the construction sites.

Author Contributions: Conceptualization, G.T.; methodology, G.T.; software, G.T.; validation, H.F. (Haibo Feng), H.F. (Hui Feng) and K.Z.; formal analysis, H.F. (Haibo Feng); investigation, G.T.; resources, J.F.; data curation, H.F. (Hui Feng); writing—original draft preparation, G.T.; writing—review and editing, H.F. (Haibo Feng) and K.Z.; visualization, G.T.; supervision, J.F. and K.Z.; project administration, J.F.; funding acquisition, J.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Social Science Fund of China, grant number 17BGL156; Science and technology project plan of the Ministry of Housing and Urban-Rural Development of the P.R.C., grant number 2018-K8-23.

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

Data Availability Statement: Not applicable.

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

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Response Strategies of UK Construction Contractors to COVID-19 in the Consideration of New Projects

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Abstract: COVID-19 presented a catastrophic event, creating a unique environment and resulting in lasting repercussions globally. The construction industry has been one of the worst affected sectors relating to the public health pandemic. Challenges such as workplace closures and site cessations led to untold uncertainty, developing into contractual grievances and supply-chain disruption, amongst others. The focus of this study is to determine the response strategies of UK construction companies in the face of the COVID-19 global pandemic and the subsequent recession the UK fell into as a direct result. A literature review of previous recession responses was examined and four areas for further consideration were identified, which included contracting, risk management, cost control and finance. The study compared the previous response strategies to identify whether lessons had been learned from prior experience, or if new strategies had emerged due to the different economic and political circumstances. A qualitative methodology was adopted to provide the required depth of analysis for the research. Thirty-two participants from different size construction organisations were interviewed, which provided evidence of strategies across the four categories analysed. The results indicated that in the early stages, uncertainty around all aspects of the pandemic caused organisations to anticipate the worst financial consequences, as the scale or scope of government intervention was initially unknown. As a result, companies reacted by downsizing, halting expansion, introducing competitive pricing to ensure there were projects in the pipeline and diversification to ensure stability and survival of the company. Organisations used the pandemic as an opportunity to restructure and invested in new technology to remain competitive. Client relationships and supply-chain partnerships were deemed to be of upmost importance in resolving contracting challenges that the pandemic brought about.

Keywords: construction management; UK construction supply; construction business assessment and COVID-19

Citation: Rhodes, O.; Rostami, A.; Khodadadyan, A.; Dunne, S. Response Strategies of UK Construction Contractors to COVID-19 in the Consideration of New Projects. *Buildings* **2022**, *12*, 946. https://doi.org/10.3390/buildings12070946

Received: 10 May 2022
Accepted: 23 June 2022
Published: 3 July 2022

1. Introduction

The construction industry has been one of the worst affected industries directly relating to the COVID-19 pandemic [1]. Total workplace closures and site cessations were among the early signs of uncertainty and problems the industry would face, bringing untold uncertainty for an indefinite period [2]. As the pandemic materialised, initial closures developed into contractual grievances, supply-chain disruptions and other major issues hindering the sector with immeasurable costs and burden [3].

Workplace closures, a persistent factor of global pandemics, have decreased productivity. Infections resulting in the reduced supply of labour and lockdowns shutting nonessential businesses, in addition to heightened uncertainty have meant that economic decline has been unavoidable, with a large proportion of the economy coming to a halt [4]. In terms of the construction sector, private and some public sector projects ceasing to operate, project backlogs were experienced. This led to numerous other issues including termination or suspension of current contracts, and future tenders being put on hold [5]. The resultant slowdown, with delays and disruption rife within the sector, has rendered some projects impossible to complete, leading to losses and strain on organisations within the industry [6].

In addition, the global macroenvironment changed as a result of COVID-19 in terms of aggregate demand and total supply, labour income and financial market trade [4]. Disruption to supply and demand manifest in three principal areas as a result of COVID-19: direct effects on global production, supply-chain and market disruption, and financial impact on organisations and markets [7]. The dramatic contraction caused by global lockdowns and the halting of production created uncertain timeframes and caused knock-on effects across the global economy [8]. The full impact of COVID-19 on the UK economy will not be ascertained for some time, although short term indicators can provide some evidence of the effects [9]. The initial impact was on the supply side, as factory closures in China then moved to the West, causing contractions in the macroeconomic supply. In turn, reduced output resulted in shortages and increasing global prices, a phenomenon known as 'stagflation' [10]. Demand-side responded by a reduction in interest rates, but due to an inability to find alternate supply in the short term, global shortages and inflation were observed as a result [10]. This has proven to be a vulnerability in organisation supply chains [7]. Owing to the sector's heavy reliance on overseas supply, the cessation of travel and trade ceased with the closing of borders. This has been further exacerbated by lockdowns and restrictions that halted the supply of materials for the primary, secondary and tertiary sectors. In the context of construction, companies have not been able to obtain materials to complete projects because of trade restrictions and the heavy reliance on eastern exports; additionally, as organisations have also adopted lean production methods and other efficiency gains, inventory levels are nonexistent, causing the inevitable suspension or termination of contracts unless cost-effective alternatives could be sourced [11]. Further impacts followed as closures occurred, with consumers cutting back on spending, which reduced the demand side, causing GDP to contract and causing unemployment [10].

Fiscal and monetary policies have been used on numerous occasions in an attempt to stabilise construction cycles [12], which result from the disproportionate share of corporate insolvency and individual bankruptcy in relation to the wider economy in the UK [13]. In addition, the construction industry is among the greatest contributors to GDP in the UK, attributing to the purpose of prioritisation regarding policy [14]. Adaptability and reaction to change is essential for survival and to avoid insolvency. Natural systemic fragmentation increases industry sensitivity to economic cycles and increases the rate of business failure [15], posing the question whether a high proportion of insolvencies could be prevented through the correct government policy. The construction industry is relatively labour intensive, with previous estimates valuing labour at 35–50% of total costs [16]. Therefore, as wages increase, the cost of construction inflates. In previous recessions, as monetary policy has ensured high interest rates, investment has fallen, resulting in a worsening of market conditions [16]. In recent history, recessions and high inflation have occurred together, usually combined with a high interest policy [16]. The cost of capital increases with high interest rates. As the industry has a high requirement for capital, demand decreases concomitantly [17], and as inflation increases labour costs increase, causing a fundamental problem for the industry [16]. Although the low interest rate environment that characterised the COVID-19 pandemic may have stimulated investment and growth, liquidity problems run rife, as finance is limited. Together with restive flows through the economy, there is little financial incentive for lenders to lend, thus restricting capital flows further [18]. Furthermore, construction organisations are affected by the level of external debt, demonstrating a direct relationship with the wider economy and the requirement for lending in these periods. This is a deterrent for investment and creates a vicious cycle, which causes further contraction of the economy [19].

Preventing recession is a top priority of governments and can be extremely challenging, the most important factor being economic policy [20]. Through manipulation, this attempts to force the behaviour of individuals and organisations to either save or spend, depending on interest rates and the policy introduced, essentially restarting the economy and increasing capital flows [20,21]. The stimulus package, including a variety of measures aimed at employees and businesses, totalled 330 billion GBP over a 20-month period [22]. The stimulus package provided by the UK government to ameliorate the impact of shutdowns on organisations and employees included loans, debt purchasing and the furlough scheme. In the short term, these measures support the economy, providing jobs and keeping businesses afloat. However, issues surrounding the liabilities will continue as cost obligations will need to be paid. National debt will increase, creating the conditions for hyperinflation due to the injection of liquidity into the economy, money the government has had to borrow [22], indicating the importance of internal company response strategies for organisations to survive or thrive in economic disparity.

Cyclical fluctuations, which characterise economic growth, have an intrinsic relationship with the level of construction activity in that stage of the cycle [23]. As the nature of the business environment changes constantly, the effects on businesses also change [24]. Therefore, organisations need to adapt and respond to change, as business failures are disproportionally concentrated in these periods with little diagnosis or prescription [25]. Tansey et al. [26] suggest that in volatile market conditions, it is difficult to obtain a consistent flow of contracts and therefore companies must be dynamic and be able to react to change quickly, or risk failing. Similarly, much of the existing literature suggests the importance of knowledge banks and lessons learned from previous times of economic hardship. Yet, the shock of COVID-19 causing the downturn, the unique economic and legislative restrictions applied, having a versatile and dynamic supply chain, along with sufficient capital or work in the pipeline, has emerged as more important when defining response strategies [26,27].

This study aims to examine the most effective corporate response strategies of UK construction companies to mitigate the economic effects of a pandemic. The objectives are to understand the effects of recession on UK construction organisations and what strategies have been previously employed in this regard, which are then used to compare with the response strategies immediately following the COVID-19 pandemic. Analysis of these strategies is used to recommend future considerations to prevent issues arising from downturns in the business cycle.

Recessionary periods are inevitable and are indiscriminate toward their victims. With many of the 'larger' construction firms appearing to remain unscathed during these periods, it seems appropriate to investigate the challenges of different sized UK construction firms. To understand the full extent that a recessionary period has on construction, the appropriability of research design is of the essence. Research can be challenging due to the construction industry's dynamic nature [28]. Therefore, correct research design of paramount importance.

The scope of the research was formulated off the basis presented from past research focus and the current organisational landscape that construction companies are presented with. Table 1 presents the focus of historical research on response strategies of construction companies, which has provided a foundation to narrow the field of view for the current research. From this research, the categorisation of response strategies was often found with blurred lines throughout the process, with overlap and variation occurring among published research reports. To combat this, popular and generic categories were selected, which may incorporate other categories from various literature. The categories selected are as follows: contracting, risk management, cost control and financial. Conjointly, categories selected are associated with KPI's during construction operations, and are therefore directly correlated to response strategies in adverse environmental conditions.

A qualitative methodology was selected to provide the required depth of analysis of the research. An inductive approach was undertaken to allow the researcher to explore the topic at a satisfactory depth and to capture the participants' perceptions of the threats faced by their firms. Organisations of different sizes across several sectors were chosen so that the results would be superior to a larger analytic nomological sample. The open-ended nature of the questions, attention to attitudes and the incorporation of human experience justify this methodology [38]. Furthermore, the qualitative nature encourages reliability and validity as all participants were anonymous, while the environment allowed the researcher to obtain the actual experience and responses of the organisations they employed within this period. Other studies, such as Danforth et al. [35], conducted their research through interviews, for the reasons stated above, which has assisted in building the research area due to its strengths, such as flexibility and exploration value, which some quantitative methods do not provide [35].

Table 1. Response strategies.

Author	**Response Strategies**							
	Contracting	**Financial**	**Risk Management**	**Cost Control**	**HR**	**Investment**	**Strategic**	**Operations**
Lansey [24]			X				X	X
Hillebrandt et al. [27]		X		X			X	
Pearce and Michael [25]		X	X	X			X	
Ocal et al. [29]	X		X				X	X
Lim et al. [30]	X	X		X				
De Waal and Mollema [31]		X		X				X
Li and Ling [32]				X		X		
Honek et al. [33]	X			X				
Jung et al. [34]	X						X	
Tansey et al. [26]				X	X			
Ruddock et al. [23]		X			X			X
Danforth et al. [35]	X	X	X	X	X	X		
Frick [36]		X		X		X		
Raoufi and Fayek [37]	X	X	X		X			

2. Methodology

This research is designed based on a qualitative method to identify the key response strategies of UK construction contractors to COVID-19. The findings related are currently being reviewed and extended for the purposes of developing a framework that might be deployed in the future by construction practitioners. Based on the extant pertinent literature (see Table 1), response strategies were considered to identify the key factors faced by contractors in new construction projects. This exercise provided the opportunity to refine and augment the content of the literature review and, moreover, to probe some of the key issues faced by practitioners on the ground. The exercise also added breadth to the research and formed the basis for the content of semi structured interviews. Qualitative semi structured interviews were conducted during the data collection phase of study. All the participants were current professionals working within the UK construction industry. To ensure the quality of the information collected, participants were provided with an outline of topics to be discussed in advance. Each participant performed one of the following professional roles: senior project manager, project director or project coordinator.

Interviews were conducted one-to-one over Zoom and Teams video conferences due to the restrictions in place from the COVID-19 pandemic, and were recorded to allow detailed analysis, to ensure reliability and accuracy. Recording also helped in the transcribing process and allowed the interviewer to give the participants full attention. Participants were recruited through email and professional social networks, ensuring the participants had the attributes relevant to the study. Stratified sampling was used in the recruitment process. Through population subgroups (strata), this ensured that appropriate participants could be selected based on their attributes/group membership [39]. In this case, the requirements were employment in the UK construction industry and having at least 5 years work experience. This ensured that respondents understood the effects that COVID-19 has had on their company and the wider industry, including the difference between the pre- and post-COVID-19 periods. All participants remained anonymous in the study, preventing any liability or subsequent issues arising by divulging information. Furthermore, questions were tailored to avoid participants providing sensitive or company-specific information, which may inhibit themselves or the organisation. The interview questions and related responses were split into four principal sections, derived from the principal literature research, as follows: contracting, risk management, cost control and financial. The full list of questions is detailed in Appendix A.

3. Results

Pope et al. [40] indicate the importance of examination and analysis of raw data, allowing any patterns and themes evident in the data to define the relationships between multiple factors or cohorts. As the method of enquiry was by interview, the qualitative data gathered and analysed is presented in this section. Table 2 displays the total responses by category from the whole sample, with the overall total being a frequency of 177. The majority of responses involved cost control, with 33.3% (n = 59) of the total number. These were divided into three subcategories: (1) cost reduction, (2) efficiency, and (3) human resources. There were 27 different strategies representing the cost control responses, with the frequency representing the number of samples utilising the strategy. Contracting-related responses represented the second most popular response category, generating 23 different responses and comprising 24.3% (n = 43) of the total responses. The strategies employed were divided into six different categories as follows: (1) diversification, (2) client relationships, (3) enterprise tactics, (4) bidding, (5) subcontractor relationships, and (6) marketing. Following on, risk management strategies were the third most popular category comprising 21.5% (n = 38) of the total responses with 18 different individual strategies. The responses were classified into five different subcategories, as follows: (1) risk identification/mitigation, (2) unfamiliar risk, (3) recovery risk, (4) project risk, and (5) enterprise risk. Lastly, financially related responses comprised 22 different strategies, representing 20.9% (n = 37) of the total strategies employed by the sample, and, therefore, a minority of the total results. The responses were allocated into three subcategories as follows: (1) profit and cashflow, (2) investment, and (3) payment terms.

Table 2. Total responses by category.

Response	Frequency	Percentage
Cost control	59	33.3
Contracting	43	24.3
Risk management	38	21.5
Financial	37	20.9
Total	177	100

4. Discussion

The concept of organisational and behavioural changes dependent upon the position within the economic cycle has been investigated and accepted by many authors previously [23,26,27,30,35]. The rarity of a global pandemic that changes everyday life means that its effects have not been explored in the way that other recessions have. The last event similar to the period in question was the global Spanish flu epidemic of 1918, but there were considerable differences with government regulation, the research of the pandemic and the availability of the data. Therefore, there is a lack of knowledge regarding the response of construction companies in this environment, indicating that research is required.

Previously conducted studies found that responses were split into subsections, although they were categorised slightly differently. Sections included contracting, financial, risk management, strategy, investment, human resources and cost control, which were among the subsections presented by previous authors [27,30,31,35]. These have been analysed, and based on the answers of participants, were classified into four response categories in the present study: cost control, contracting, risk management, and financial. Furthermore, to expand the knowledge base, such as in Danforth et al. [35] each area was further categorised into the subsections presented in the results section. Not only was the intention to expand the body of knowledge, but it also allowed patterns and comparisons in behaviour with previous recessions to be recorded. This should aid the practical application of the research and provide construction companies with clear guidance, if an event with similar characteristics or magnitude were to occur again.

5. Main Findings

The study produced 91 unique strategies in the four categories studied. These categories were also highlighted by Lim et al. [30] and Danforth et al. [35]. The subcategories were categorised based on the participant responses and were refined accordingly. The number of unique responses indicates a situation in which UK construction companies had to react to remain competitive. The individual responses from the organisations are mainly from a reactionary view, the majority occurring after the event. This indicates the spontaneous nature of the response to the pandemic and the uncertainty around it, with limited knowledge and time to prepare. As legal restrictions were implemented across the UK, one of the main findings was the organisational changes companies had to endure to continue operations whilst adhering to the restrictions. The results demonstrated that 100% of the samples experienced an increase in virtual presence, as working from home was the main change. Not only did this occur during the restrictions, but many companies also opted to continue remote working in some form, benefitting from the cost saving it provided. This was a key difference from previous studies where organisational changes stemmed from the hardship imposed by recessions, rather than legislation imposed by government [30,34].

The restrictions also caused a complete closure of sites and 'nonessential' businesses, a period of three months during which many projects were paused. This resulted in responses in all four categories, although the financial strains caused by other recessions due to increased competition and reduction in demand were not observed [23,36]. As government schemes, such as furlough and loans were rolled out, companies were able to cover liabilities and pay employees, reducing the strain placed on their organisations. Although respondents also indicated that projects were paused, contractors were not receiving payments and subcontractors were not paid, causing a ripple effect all the way through the supply chain. Furthermore, a significant finding was uncovered, caused by the expected lag of the real effects of the recession. As all work was paused, backlogs of projects have occurred, pushing back future projects which could affect corporate viability; as government schemes end, costs are likely to increase in each organisation, adding to the potential termination of future projects and the possibility of reduced demand in the future [37]. Although the effects of previous recessions have been endured, several participants voiced concerns about the future.

Cost control was the most frequently stated response, representing a third of the total responses. This reveals the uncertainty of the situation, with companies opting to reduce costs as there was no timescale for the pandemic and no indication of how long restrictions may last. This also indicates the importance of cashflow and the need for companies to stay afloat in an adverse economic climate [13,41]. The least popular response was financially related. This could be attributed to the pausing of the industry and the economic support given by the government. As restrictions were lifted and sites reopened, many projects have continued, leading to the resumption of payments, therefore reducing the number of financial actions and responses.

5.1. Cost-Related Responses

A cost control strategy involves reducing both fixed and variable costs of a business through a variety of means. In the context of the current research, this ensures financial stability, with cashflow remaining positive in uncertain times. The strategies have developed since first being recognised by Hillebrandt [27], who recommended cost control with a strategy of reducing permanent employee wage growth due to the impact of lower workload and a smaller number of required staff. As confirmed by the results of the present study, organisations have incorporated a much wider view of different factors in relation to cost control from previous studies, suggesting that there is growing competition in the business environment. The cost control responses represented a third of the total results (33.3%), creating 27 unique strategies, a clear majority. The strategies were divided into three subsections, consisting of: (1) cost reduction, (2) efficiency, and (3) human resources (HR) (Table 3).

Table 3. Cost-related responses.

Subcategory	**Response**
Cost reduction	Use of government furlough scheme to pay employees
	Continue with remote work to reduce costs
	Reducing number or moving premises
	Reduce overheads
	Expansion put on hold
	Policy and mitigation charged to client
	Reduced number of contractors used
	Debt reduction strategies employed
	Outsourcing admin overseas
	Closing sister company
	Stop dividend payments
Efficiency	Diversification of employee skills (cross training)
	Decreased efficiency resulting from decreased workload
	Employment of new technology
	Increased capacity utilization
	Increased workload post-period
	Use of cash reserve
	Use of resources from larger subcontractor
	Increasing audit
	Introduction of referral bonus for recommending new employees
	Grouping organizational sectors together
Human resources	Stop pay reviews
	Freeze recruitment
	Employee redundancies
	Working overtime
	Increased employee training
	Bonuses stopped or reduced

The use of the government furlough scheme to pay employees was the most popular response, with 100% of the sample indicating that their organisation took advantage of it. This comes as no surprise, considering that restrictions were applied for 20 months, which ensured stability and survival. According to Lim et al. [30], proper financial management is a key to the survival of construction firms. As periods of lockdown resulted in zero income, companies had less capital to cover overheads, demonstrating the importance of this response strategy. In these periods, raising profit is challenging, therefore by exploiting cost reduction, firms can utilise it as a measure to prevent losses [23], rather than as a strategy to increase profits. Although government policy aided in mitigating costs, as there was no ability to estimate the loss in opportunity cost, the respondents indicated that the company needed to be in the best financial position because of uncertainties surrounding the pandemic. The results of Lim et al. [30] mirrored these responses, as the eight-year recession described in their study had similar uncertainty variables.

Similar responses included the halting of pay reviews (100%), the freezing of recruitment (80%), and conducting employee redundancies (60%), responses consistent with previous studies. Lim et al. [30] observed scores of 91% for the same metrics when Asian contractors were faced with a prolonged recession. These responses are key components of Hillebrandt's definition of cost control retorts [27], essential for reducing overheads resulting from disruption caused by recessions. Moving or reducing the size of premises and preventing expansion were common within the respondents to prevent adverse financial conditions, as some organisations were not eligible for mortgage or lease holidays. Many experienced this as a progressive strategy rather than a reactionary measure, executing the strategy before it was required to protect cashflow. Remote work was a prominent response, with 80% of respondents utilising this policy. This was a compulsory part of the initial lockdown restrictions, yet many organisations chose to continue because of the cost reduction, with little impact on efficiency. Many respondents believe this will become part of the working norm going forward, because of the cost benefits and the lack of impact on quality or efficiency of operations.

In the second subsection, represented by efficiency-based responses, diversification of employee skills was the most prominent response with 80% of respondents indicating its implementation. Lansey [24] expressed the importance of creating systems that develop and enhance the diversification of skills in an environment characterised by competitive change. According to the participants, this was to assist in retaining efficiency when moving to remote working, but also to counteract any redundancies and employees' sickness due to the virus. Organisations considered this period as a window to restructure and change the working environment, with 60% of respondents indicating that the organisation invested in new technology or operating systems. This also was due to changes in the working environment and the need to remain competitive in these uncertain times. This is consistent with the observations of Lim et al. [30], who indicated that in prolonged recessions, companies used the opportunity to restructure and invest, exploring other business avenues to remain competitive. Despite this, some respondents indicated that the investment was minimal, as cash and liquidity was essential for contingency, acting as a buffer should the company face tough times, generally following the mantra that cash is king.

Efficiency from workload was another theme emerging from this subsection. In total, 60% indicated that efficiency decreased due to the decrease in workload, a natural consequence of there being zero output due to lockdown restrictions, with efficiency naturally decreasing. Following from that, 40% of respondents indicated that an increase in workload post-lockdown was observed due to the backlog of projects, with organisations increasing workload to regain some of the lost efficiency. It is more than likely that the same participants also indicated that overtime was worked because of this, as reflected in the HR section of the cost control responses. Capacity utilisation (CU) and increased audit were two other strategies companies used to target efficiency, at a rate of 40% and 20%, respectively. Using CU, costs are more efficiently allocated, reducing the cost per unit, as overall cost is usually reduced with companies moving premises and cross-training employees. Such auditing will reduce wastage, among other factors, and in addition to ensuring efficient spending, employee performance will refine cost data and improve overall company performance.

The final subsection is the HR category, which had the least number of unique responses. The most popular response was the cessation of pay reviews (100%); this reduces any unnecessary increase in costs over the period, increasing the likelihood that the organisation will maintain financial stability. Freezing recruitment (80%), making redundancies (60%) and stopping bonuses (20%), combined with the pay review action, also reduces the fixed and variable expenses of the organisation. This is consistent with Tansey et al. [26], who indicated that a combination of a freeze of salaries and making redundancies were the most popular responses, as cost leadership was a popular strategy adopted from the Porter's 5 Forces model for contractors facing a recession. These strategies were apparent in the research of Danforth et al. [35], although the proportion of companies in the present study utilizing the strategy was higher, suggesting their need was greater. This could be attributed to the uncertainty and spontaneous nature of the event compared with previous recessions [35], where organisations had no legal restrictions preventing operations in combination with the experience of past recessions in which there was more certainty about which strategies were successful. Therefore, by preparing for the worst, organisations have been able to thrive if the conditions were in fact not as bad as they had initially appeared, or after improvements, for example, following the lifting of restrictions post-lockdown. Li and Ling [32] observed that management practices such as cost reductions in operations combined with administrative activities are not significantly correlated with profitability. Therefore, organisations should exploit other types of strategies to increase their profitability.

5.2. Contracting-Related Responses

Contracting-related responses are actions undertaken to obtain or continue work and maintain a company's financial position [27]. Obtaining work was less apparent than in previous recessions due to the backlog of projects accumulated because of government restrictions; therefore, in this section the study concentrated on how organisations implemented competitive strategies throughout and following the period. Despite this, large organisations always plan ahead and therefore bid for future projects to place in the pipeline. One therefore may argue that Hillebrandts' definition [27] is accurate for the present study. This response was popular among the participants, splitting into six subcategories based on the participant responses, creating 24 unique strategies, and representing 24.3% of all responses in the study. The section was divided into the following subcategories: (1) diversification, (2) client relationships, (3) enterprise tactics, (4) bidding, (5) subcontractor relationships, and (6) marketing (Table 4).

Table 4. Contracting-related responses.

Subcategory	Response
Diversification	Increased virtual presence
	Diversification of markets during period
	Diversification of geographic location
	Diversification of markets post-period
	Vertical diversification
	Pursue new project sizes
Client relationships	Use of repeat/familiar clients
	Importance of client relationships
	Working for new clients
	Clients more demanding
	Reduced communication with clients during period
	Stop working private contracts
Enterprise tactics	Demand reduced during period
	Increased competitiveness to increase demand
	Maintain business plan despite economic climate
Bidding	Increased competition
	Not bidding for low value projects
Subcontractor relationships	Importance of relationships
	Use of new subcontractors
	Use of new suppliers
Marketing	New marketing campaigns
	Increased social media presence
	Marketing on motor vehicles

Diversification and client relationships were the most popular response categories, with 17 individual responses each. According to Jung et al. [34], diversification is a strategy that increases profitability through rapid movement into different markets and products. This was the most popular strategy reported by Danforth et al. [35] and Tansey et al. [26], indicating that it was effective in past recessions, as it was used in the face of the current recession. Increased virtual presence as mentioned in the last section was the most popular, with 100% of the respondents indicating its utilisation, which is likely to change general working life. Diversification of markets during the period and diversification of geographic location both represented 40% of responses. Companies were able to shift resources to these markets and other locations, indicating flexibility within the corporate structure. As some of the large organisations have decentralised organisational structures with adequate resources and capability, this has allowed them to diversify whilst increasing profitability.

This is in line with results from Danforth's [35] and Lim's [30] research. Jung et al. [34] also found that geographic diversification was effective in the award of new contracts, with 40% of respondents in the present study indicating that their company was involved in the strategy.

Client relationships were another popular category, with six strategies employed. The importance of client relationships and the use of repeat/familiar clients were the two most popular responses, with a 60% utilisation rate. Wong and Logcher [12] suggested that reputation and relationship quality play significant roles in allowing companies to survive or thrive in a recession, especially applicable in the private sector [12]. Lansey [24] contradicted the statement, expressing the need to develop new relationships in troubled times. The present study indicates that both were utilized; working with new clients was utilized by 40% of the respondents. Whether the relationships are established or fresh, firms with better relationships weather downturns better and are more likely to thrive, according to Hillebrandt [27]. The participants representing smaller firms indicated their gratitude to some of their clients, as their relationship may have been crucial to survival after the pandemic period, after the government incentives ended. There was little indication of the strains on relationships as noted in Danforth et al. [35], as hardships experienced during the period were not as prominent due to government aid. However, one participant indicated that clients were more demanding over this period. This could be attributed to strains that such clients were experiencing themselves, providing contractors less flexibility within the constraints of the contract. Finally, due to the backlog of projects in the pipeline and the number of public sector contracts awarded to them, one respondent indicated they had halted working on private contracts. There tends to be greater availability of government contracts during recessions to stimulate the economy. These are attractive to construction firms because of the reduced construction costs associated with them [35].

The previously published literature relating to construction demand in a recession suggests that a slump in demand is experienced within downturn periods [24,27,30,32,35]. Sixty percent of participants agreed with this, although their experience differed slightly. As companies now work so far ahead organising contracts for the future, pausing projects caused significant disruption and uncertainty. As the projects were delayed, resources from companies were reallocated to execute the current contracts. As some organisations were not actively searching for new contracts during the months of lockdown, due to company closures, few or no new projects were available, with demand levels recovering after the lifting of most restrictions. This resulted in increased competitiveness after the pandemic period according to 40% of the participants, as organisations moved from being in a passive state to actively pursuing new projects, as many predicted future struggles after the period. This was further represented in the bidding section with 60% indicating an increase in competition. As public sector contracts become more available, the number of organisations tendering for projects increased because of the cost and profit benefits associated with them. This process reduced the profit potential, with one participant indicating their reluctance to bid for low-value contracts. This could be the reason for the high subscription to diversification strategies and new technology, to identify new and diverse ways to lower project costs, winning contracts and retaining or increasing margins. Two respondents indicated that there had been no change to the business plan during this time, a result of booming demand with many projects lined up. This action is supported by Danforth et al. [35], as diverse business plans prepare organisations for success, regardless of the economic conditions in which they operate.

The subcontractor relationships subcategory was represented by only three unique strategies, yet participants discussed their importance and implications. Firstly, the importance of relationships was essential for many of participants. As the cashflow of several organisations fluctuated, such relationships allowed increased payment terms and ensured retention of good rates. This was essential for both contractors and subcontractors who both felt the effects of the recession during this period. Respondents indicated the engagement of new subcontractors. As competitiveness increased across multiple industries, the domino effect from construction companies trying to apply better rates to win contracts influenced subcontractors. Therefore, new relationships and agreements were formed with subcontractors offering better rates, ultimately reducing construction costs for contractors. Furthermore, as the insolvency of subcontractors occurred, new subcontractors had to be recruited to enable the completion of contracts, as evidenced by the participants of the study. This has been noted in previous studies, such as Lim et al. [30] and Li and Ling [32]. For similar competitive reasons, new suppliers were also used, with 45% of the interviewees indicating this. Furthermore, as supply chains were so heavily disrupted, imports, especially from China and India, were not readily available. Therefore, diversification of suppliers had to be conducted in order to complete contracts.

The final subsection relates to marketing, which was represented by only three unique strategies, each having eight responses, which were the least utilised responses. Roberts [42] has indicated that marketing should be intensified during a recession to exploit the competitive advantages of the organisation. Increased social media presence, marketing the company on motor vehicles, and creation of new marketing campaigns were the responses initiated during the period. The lack of marketing campaigns resulted from the backlog of projects and a focus on other functional areas of the organisation according to some participants, whilst others indicated that the capital from less critical budgets (including marketing) were cut and used in other functional areas of the business to ensure liquidity in cash-stricken periods. Hillebrandt [27] has indicated that marketing strategies should be altered in these periods, but should not be decreased, in fact, the opposite.

5.3. Risk-Management-Related Responses

The third section relates to risk-management responses, capturing the risks that organisations have faced, and the strategies employed to mitigate such risks. In previous studies, there has been clear neglect of this aspect when discussing the strategies employed by organisations. Only research studies by Pearce and Michael [25], Ruddock et al. [23] and Danforth et al. [35] describe in detail the strategies undertaken in this section and the importance of this category in the face of a recession. Within this section, five subcategories were identified based on answers from the participants, as follows: (1) risk identification/mitigation, (2) unfamiliar risks, (3) recovery risks, (4) project risks, and (5) enterprise risk (Table 5).

Risk identification/mitigation was the first subcategory identified, of which there were five unique strategies, which were used to protect the companies against risks either created or present during the period. All respondents indicated that COVID-19 clauses had been included in contracts. For example, the extension of time, maximum site presence and other issues that could arise were also considered and inserted. Participants indicated that prior to resuming any work after lockdowns, meetings with all parties were conducted to consider such events, as it was in the interests of all parties to work together and cooperate to complete each project. This contrasts with previous studies which indicated that contracts can be terminated as a result of excessive delay. During the problems created by COVID-19, there was little indication from the participants that this had occurred [37]. However, one participant indicated that force majeure had been utilised, as the project pre-COVID-19 was in an unsatisfactory state. Because of the disruption caused by the pandemic, the parties saw no way of completing the project. Participants identified the ways that their organisations had mitigated risks, representing 20% of the responses. COVID-19 risk was passed onto clients in one circumstance, which had been agreed when revising the contract post-lockdown, putting the organisation in a more favourable financial position. This is rarely observed in contractual negotiations and not recorded in previous research but can be agreed by mutual consent, so that a contract can be completed in usual times. Specialisation in certain sectors, rather than diversification was used by one participant. By providing overwhelming resource in a particular sector, the organisation was able to gain a competitive advantage through refining their core competence and by their relationship with clients. This can reduce opportunity during boom periods as competencies in other areas may become obsolete due to the narrow view.

Table 5. Risk-management-related responses.

Subcategory	Response
Risk identification/mitigation	Insertion of COVID-19 clauses into contracts COVID-19 regulation from governing body COVID-19 risk passed onto clients Specialisation to reduce risk Use of force majeure
Unfamiliar risk	COVID-19-related risk Increased contingency planning Diversification of new market risks
Recovery risk	Specialisation limits options post-period
Project risk	Changes in policy affecting site operation Reduction in site presence Riskier project undertaken during this period Project documents contain more unknowns Competitors bidding too low Lump sum risk in new contracts
Enterprise risk	New technology risk Rapid growth post-lockdown and closures New regulations more challenging

The unknown risk was the next subsection. COVID-19-related risks were unfamiliar and changed the operation in many aspects comprehensively, affecting 100% of participants of the study. As legislation changed throughout the pandemic, organisations had to adapt and be flexible, adhering to new regulations whilst trying to remain competitive and profitable. According to Pearce and Michael [25], firms should invest to bolster their position in uncertain and adverse economic times. This was observed to a lesser extent, but through legal advice, diversification and exploration of new options, organisations were able to identify cost effective ways to mitigate unknown risks. Extensive contingency planning was undertaken by 78% of participants, likely to be representing the same companies already invested in diversification and other investment or expansion strategies. As organisations undertake such strategies, new risks emerge. Therefore, comprehensive contingencies are essential for any business plan to prevent losing a competitive position and putting the future of the organisation in question. Seven participants indicated the risk of diversification separately. These participants had contrasting views of the financial and competitive position of the organisation. One indicated that the move was rushed due to the unforeseen circumstances, because their competitive position had not been damaged. Conversely, the other respondents indicated that the move was premeditated and occurred at the right time, as the combined organisation already was making the move prior to the pandemic and any uncertain times that may follow.

Project risk was the most popular subcategory, representing six responses. Of the participants, 60% indicated that policy changes had been introduced that affected site operation, attributed to legislative changes brought about by COVID-19 to ensure site safety and that social distance measures were being used. Participants explained that due to the additional restrictions, work typically slowed because of manpower shortages due to sickness, isolation and restrictions in labour-intensive workplaces. Raoufi and Fayek [37] presented the additional bureaucratic stages that ensured the safety and well-being of employees, also indicated by respondents, slowing projects, and altering site operation. Concerning site presence, 45% percent specified that there was a reduction. The reduction was not 100% in these latter two strategies because of the line of work of some participants, as some operate on the consulting side of the industry, therefore having little or no presence on site. Despite this, all participants expressed how the pandemic altered normal operations.

Riskier projects were undertaken during this period according to 40% of the participants, attributable to uncertainty during the period. Organisations wanted to ensure there was work in the future, as there was no certainty about the duration or severity of the recession, especially after the government stimulus schemes ended. These organisations took the view that riskier work was better than no work. These projects represented additional unknowns according to the study, attributable to riskiness. This increased the difficulty in the identification and mitigation process, with contingencies hard to formulate as a result, consistent with the results from Danforth et al. [35]. Competitors that bid too low and the lump-sum risk of new contracts were identified by 20% of the sample. These are typical behaviours observed in past research, as firms wanted to ensure that cash was moving through the company, even where margins were little or nonexistent. However, as previously expressed, several organisations had projects in the pipeline and backlogs, so new projects were not required. As a result, organisations saw no need to enter projects with little profit as they viewed them as a waste of time and resources, able to be spent better elsewhere (opportunity cost).

Enterprise risk was also considered, with three individual strategies that were employed. The risk of new technology was most mentioned, with a 60% response rate, with the same three participants whose companies invested in that technology. The risks related to the cost benefit analysis of such investment, because in troubled times there is a risk that any investment may not pay off, causing an organisation to be placed in a financially adverse position and the whole organisation at risk. Respondents indicated that new regulations were more challenging, with a 40% response rate. This is due to the unfamiliarity of it, increasing the time and cost as working practices become less efficient. Quality assurance was also employed to ensure that work was 'right first time', according to the participants. This further increased the time and cost of operations. This contrasts with the study by Danforth et al. [35] in this respect, as they indicated that manpower shortages and reduced budgets increased the difficulty in contracting new work, related to new regulations as quality controls were employed. In the present study, quality assurance was employed as organisations had no time or spare budget for work to be completed incorrectly, according to participants. Rapid growth post-lockdown occurred according to 40% of participants. This is typical following a recessionary period, especially considering that the downturn resulted from closures rather than an economic shock. With the aid of stimulus packages, a restart of the economy was experienced, allowing organisations to make up for lost time. Jung et al. [34] indicated that firms should balance between extending business opportunity and securing financial risk, depending on market conditions. Too great an expansion can cause resources to be too widely spread, while if liabilities are due before an organisation has collected its payments, the organisation can be placed in an adverse financial position.

5.4. Financially Related Responses

The final section related to financially related responses which, according to Hillebrandt [27] have a greater effect on the balance sheet and financial stability. Danforth et al. [35] went further, suggesting that companies could perform actions to improve their financial position in preparation for and during a recession. The list of responses compared with past studies is more extensive. This could be attributed to the drastic changes in regulation, legislation and the economic environment, which is unique. The responses were divided into three subcategories, as follows: (1) profit and cashflow, (2) investment, and (3) payment terms (Table 6). These generated 22 individual responses, 20.9% of the total responses collected in the study. The reason is that there was sparser distribution of responses in this category, due to a comparatively higher number of individual responses than in other categories, thus representing a higher proportion of the overall study. This indicates that organisations have followed different strategies regarding financial responses during the period analysed.

Table 6. Financially related responses.

Subcategory	Response
Profit and cashflow	Careful monitoring of cashflow
	Large fluctuations in cashflow
	Perform little or no profitable work
	Profit margins retained
	Profit margins decreased
	Profit margins increased resulting from increased workload
	Rigorous budgeting
	Increased rates
	Specialisation limits options post-period
	Noncontract work completed
	Implementing minimum margins
Investment	Investment in diversification
	Cost of new technology
	Investing in rebranding
	Preventing employees purchasing shares
Payment terms	COVID-19-related payment events
	Increased retention
	Longer payment terms
	Fees retained
	Fees diminished
	Payment time decreased
	Governing body sped up payment terms

The first subcategory was related to profit and cash flow, providing an understanding of how the strategies used by different firms ensured competitiveness, maintaining a positive balance sheet. Careful monitoring of cashflow was the most popular response in this subcategory, with 80% of the respondents agreeing. This is not a surprise, because in turbulent times this would be a natural response, to ensure that the company is able to pay any liabilities and remain afloat. There were indicators or triggers within the internal processes of firms to identify if cashflow went below a certain threshold, with management meetings and other processes occurring to ensure company survival. Large fluctuations in cashflow were observed (60%), with one participant indicating that they had come close to the threshold during the beginning of the period, just before the announcement of the government stimulus package, whilst organisations still paid overheads and liabilities. A key strategy described in previous studies was the performance of work with little or no profit (40%) [30]. This can be attributed to increased competition and the reduction in fees as a result. As demand falls, particularly in an uncertain economic climate, some firms (usually smaller ones) enter such contracts to ensure cash is running through the business, allowing them to pay any liabilities with such capital. The participants who indicated the use of this strategy expressed that their use was minimal and only in smaller projects, and that the organisations were likely to attempt to recuperate costs through variations and other contractual clauses.

The results show clear differences in margins, with one participant in each stating that margins were increased, maintained or decreased. Some respondents were not included due to their lack of knowledge on their company's margins, and so declined to answer to prevent false reporting. These margins are systematically linked to the other responses in the study, for example, one respondent indicating a decrease in margins resulted from an increase in competition for projects, linked to a diversification strategy, as they felt they needed to offer lower margins in new sectors to win projects, ultimately leading to increased workload, increasing revenues and profits as a result. On the other hand, where margins had been maintained, the reasons given were due to company policy and a minimum margin threshold. That particular organisation also used the same business plan prior to the period with little or no general changes in the organisation. The other strategies in the subcategory are typical and have been implemented as a strategy to meet organisational objectives in the period. The only other strategy of significance was the performance of noncontractual work. This resulted in smaller jobs, providing the business with a fast influx of cash relative to contractual work, improving cashflow and their competitive position as a result. According to Tansey et al. [26], such a strategy increases their position in terms of competition, allowing an organisation to be more flexible in contract particulars, increasing the likelihood of winning new contracts in the future.

Investment in technology and diversification were the two most popular investment strategies over the period analysed, with a 54% response rate. Organisations regarded these two as having the lowest risk for increasing their competitive advantage, with organisational competency to increase profitability. According to Jung et al. [34], differentiation strategies providing innovative products and services with high quality inputs are directly related to profitability, hence the importance of the investment. One participant stated that their organisation prevented employees from buying shares. They did not provide reasoning, but is likely to stem from preventing a reduction in control in these uncertain times, which could lead to backlash from corporate decisions or increases in dividend payments causing an increase in costs.

The COVID-19 payments were the most common response, with an 80% response rate. This is unsurprising as contractors will have recuperated costs for which they were not liable, related to COVID-19. Contract particulars will have been negotiated and discussed at the restart following lockdown. Longer payment terms were also negotiated as a result, according to 40% of participants, easing the requirement for capital in such times, ensuring that the contract could be completed correctly and through cooperation, favouring both parties. Two of the final strategies in this category relate to fees. One participant indicated that fees were retained while one stated that they had diminished. The other participants did not comment on this aspect. A reduction in fees was not surprising in this period, but the participant indicated that they bounced back quickly, contrasting with Danforth et al. [35], who indicated that the recovery in fees was slow. The retained fees are consistent with other results in the present study, as one company did not change its margins, fees or business plan, indicating that the recession caused by the pandemic had little or no effect on the organisation.

6. Conclusions

This research explored the response strategies of UK construction companies in the face of a global pandemic and, importantly, the response of organisations facing the greatest reduction in GDP in recent history and the subsequent recession. The research compared the response with strategies previously employed during past recessions to explore the principal differences, identifying whether lessons had been learned from prior experience, or if new strategies had emerged due to the different economic and political circumstances.

The study found that in the early stages, uncertainty around all aspects of the pandemic caused organisations to anticipate the worst financial consequences, as the scale or scope of government intervention was initially unknown. As a result, companies reacted by downsizing, halting expansion, introducing competitive pricing to ensure there were projects in the pipeline and diversification to ensure stability and survival of the company. Following the introduction of government stimulus packages and reopening after the lockdowns, participants acknowledged that the implications for their companies were less severe than had been initially feared, although changes to operations had to be implemented to comply with restrictions such as social distancing. Almost universally, for example, remote working was implemented. Thus, the research investigated how construction companies react in the face of a global pandemic in comparison with past recessions and economic shocks. The findings of the study provide an understanding of: (1) the scale and scope of the economic shock caused by the pandemic and the subsequent recovery phase, (2) the effectiveness of the response of construction companies, (3) the real effects of the pandemic following the end of various government schemes, and, finally, (4) the breakdown of response strategies implemented due to the pandemic.

The results of this study suggest several avenues for development in future research. Firstly, documentation of the full impact of the pandemic on different companies in the sector and contrasting it with previous recessions would allow organisations to make sound corporate choices during future economic shocks and downturns. Secondly, additional investigation could explore the effects on different sizes of firms, how their actions differed and the results of such actions. Finally, a mixed methods approach including quantitative methods with respondents from more diverse organisations, would allow holistic analysis of the effects of the pandemic and identification of the successful actions employed by companies.

Author Contributions: Literature review, O.R. and A.K.; data collection, O.R. and A.K.; methodology, O.R., A.R. and A.K.; writing—original draft preparation, O.R.; writing—review and editing, A.R. and S.D.; formal data analysis, A.K.; supervision, A.R.; proof reading, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

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

Data Availability Statement: The data supporting reported results can be found at the LJMU Research Data Repository on an Open Access basis. https://opendata.ljmu.ac.uk/ (accessed on 9 May 2022).

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

Appendix A

Interview questions

1. Since the start of COVID-19, the lockdowns and the economic downturn resulting, have you noticed any threats which have arisen to the company in any aspect?

Contracting-related responses

1. Has there been any change to demand/the number of projects undertaken? Furthermore, has there been any change in diversity of new projects undertaken post, or in this time frame?
2. Has there been any change in relationships from any aspect in this time period?
3. Any other contracting responses which have not been covered?

Risk management responses

1. Has there been any change to risk identification/mitigation policy or legislative/regulatory changes regarding risk?
2. Have you witnessed any differences to the risks associated with projects now which were not present before the period?
3. Any other risk management responses which have not been which you have witnessed?

Cost control responses

1. Has the company conducted any cost reduction strategies to your knowledge, if so, what strategies have they employed?
2. Have efficacies in any respect changed during this period? (i.e., technological, supply chain, staff, process)
3. Any other cost control responses which have not been covered?

Financial-related responses

1. Have projects been undertaken with little or no profit?
2. Have there been any diversification/alternate revenue streams exploited during this period?
3. Any other financial-related responses which have not been covered?

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The Emergence Process of Construction Project Resilience: A Social Network Analysis Approach

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Abstract: For construction projects, resilience is the process of resisting and recovering from adversity. With the global economic and social environment constantly changing, improving the resilience of construction projects has become a research hotspot in the field of project management. On the basis of social capital theory, this study constructs a construction project organization resilience evaluation system from two dimensions of bonding and bridging social capitals. Then, a new theoretical framework is proposed: the network dynamic evaluation model of project resilience based on the resource conservation strategy. Using survey data of 247 construction engineering practitioners, this study considers the emergence of organization resilience in the three phases of adversity. The results reveal that when the construction project is hit by adversity, the investment capital will increase but decrease in the recovery phase. Protective capital demonstrates the opposite. However, both types of capital finally reach a higher level than before the adversity, thus forming an emergence curve of project resilience. This study helps to understand the emergence process of the construction project resilience, provides a feasible method to calculate the resilience and social capital of construction projects in different phases of disasters, and improves the risk response ability of construction projects.

Keywords: project resilience; construction project; social capital; organization behavior; social network

Citation: Wang, D.; Wang, P.; Liu, Y. The Emergence Process of Construction Project Resilience: A Social Network Analysis Approach. *Buildings* **2022**, *12*, 822. https://doi.org/10.3390/buildings12060822

Academic Editor: Audrius Banaitis

Received: 14 May 2022
Accepted: 8 June 2022
Published: 14 June 2022

1. Introduction

Affected by adverse events that are difficult to predict or prepare for in advance, such as the outbreak of COVID-19 and the consequent global political and economic turbulence, organizations often suffer disruptive shocks such as business process disruption and loss of performance [1,2]. These outcomes have quickly led to efforts to understand the trend that organizations are more effective at responding to and recovering from adversity, that is, showing resilience [3,4]. At a time of increasing uncertainty, understanding the resilience of project-based organizations in complex and changing internal and external environments has become a core issue in project management [5]. The present study focuses on the organization resilience of temporary projects represented by construction projects, which are highly likely to be affected by external events and are of great importance to socio-economic development [6–8].

In the field of management, research on resilience is generally divided into three levels: individual resilience, team resilience, and organizational resilience [9–11]. In more regular and stable environments, resilience at different levels has been observed to help improve one's own performance, promote collaboration, enhance cohesion, and achieve performance recovery and maintenance [12]. However, we know little about how it operates in a project-based environment and what mechanisms might contribute to such a valuable project state. This is because the construction project could not be simply regarded as a work team or organization; it often involves the collaboration of multiple participants, and is a temporary system composed of multiple teams or organizations for specific construction tasks, with the characteristics of heterogeneity and loose coupling [13,14]. Despite this, the study of resilience in construction projects needs to be further expanded. To fully consider the characteristics of the project system itself, it is necessary to consider both the integrity of the project system and the coordination of all participating units within the project. Therefore, one of the tasks of this study is to explore how resilience changes when project systems encounter a crisis within a comprehensive theoretical framework.

Social capital theory makes it possible to study resilience in the context of construction projects [15]. Social capital refers to the value of an individual's or social unit's position in an organizational structure [16]. It refers to the accumulation of behaviors and norms that make members of a group support each other. In projects, social capital exists in the interpersonal structure of the project life cycle [17]. It brings additional benefits to the project through constant, positive interaction between members [18]. Therefore, understanding project system social capital helps us to better define and discuss resilience. Of course, social capital such as cohesion and trust are not exactly the same as resilience, but they are certainly some manifestations of resilience. As described in the study of [19], resilience is largely a social process that is fundamentally shaped by the relationships between the components of an organization. Therefore, according to the social capital theory, we propose that the resilience of construction projects is based on the process of resisting adverse impact and realizing recovery reflected by the accumulation of project social capital, which can be described through the measurement of social capital. Under this concept, project resilience is broken down into the different effects of social capital. Therefore, in this study, we hope to explain the mechanism of project resilience by investigating several key social capitals and establish a project resilience measurement system under the theoretical framework of social capital.

To solve the above problems, we use social network analysis (SNA), because SNA provides a tool for measuring social capital that results from connections between subjects embedded in social networks [20,21]. In this model, we refer to the research of Cui [22] and take the network topology index as a reflection of the social capital of construction projects. We establish a network model of construction project participants at different phases of a disaster's impact to investigate the changes in social capital at different phases. Finally, through the normalization of social capital, the resilience process of the project is summarized.

Our paper contributes to the project management literature in at least three respects. First, we provide a definition of project resilience based on social capital theory, in which resilience can arise in project-based social capital. Secondly, our paper focuses on the evolution of project networks before and after disasters, providing a methodological basis for understanding the evolutionary process of project resilience, and complements the process perspective that has dominated research on resilience in the project management literature [23]. Third, we explore a social capital indicator system that can be used to describe project resilience quantitatively, reducing the difficult-to-measure resilience to an observable social capital framework. On the basis of these theoretical insights, we discuss how to improve project management practices.

In the next section, we provide a literature review, followed by the research design and methods. Then, on the basis of the construction projects that were in progress during COVID-19, the data are analyzed from two levels of bonding and bridging social capital in three phases: preparation, coping, and post-disaster recovery. The emergence of project resilience is identified, and the theoretical and practical significance of the development of resilience in construction project governance is discussed. Finally, the conclusions and limitations are given.

2. Literature Review

2.1. Construction Project Resilience

As COVID-19 brings about the sustained development of global economic, political, and social instability, studies on the resilience of various social systems are gaining popularity and attention [24]. Existing conceptualization studies suggest that resilience can be defined by adopting a process or capacity perspective [25,26], focusing on resilience-related coordination activities or states and resources that resilient organizations can develop, respectively. Similarly, scholars have distinguished different manifestations of resilience, including predicting adverse events, reducing the perturbation of adverse events, or recovering from failure [27,28]. Therefore, a comprehensive understanding of resilience should include the processes and capacity that enable organizations to anticipate and manage adversity, which can be combined into four complementary dimensions: crisis prediction, crisis management, rebound recovery, and reverse improvement [29].

At present, a systematic research system on resilience has been formed, which can be divided into individual resilience, team resilience, and organizational resilience at the research level. The research objects include the antecedents, processes, and results of resilience [30]. However, project resilience is still a relatively new concept, and although publications on it are increasing, there is still conceptual debate as to whether project resilience should be considered as a capacity or a process [31].

From the perspective of capacity, Turner and Kutsch [32] proposed an interpretation of project resilience, defining it as the art of detecting changes in the project environment, understanding these changes, planning answers, minimizing damage when changes occur, and adapting to new realities. Giezen [33] put forward the concepts of prevention, response, and adaptation in their definition of project resilience, and also mentioned two types of project resilience: Passive resilience and active resilience. In all of these studies, project resilience takes a capacity perspective.

The process perspective sees project resilience as a long-term strategy to deal with complexity and risk. Williams et al. [26] believed that resilience is a process in which individuals or groups avoid the tendency to react negatively to challenging situations and maintain positive adjustment or coping. Similarly, Crosby [34] points out that resilience is the process of managing risk, crisis, or contingencies. Another group of studies, starting with project teams, views resilience as a collective construct, including "an interactive, coordinated, and collaborative team interaction process that describes the actual behavior of teams in coping with adversity" [35,36].

Due to different research objects and focuses, and different research methods [37], empirical studies rarely integrate the process perspective and capacity perspective into the same research. Researchers select one of the perspectives according to the research purpose and the theoretical contribution they are trying to make [38]. In this study, we use a process perspective (i.e., project resilience as the whole process of recovery from disaster) to construct meaningful theories and conduct reasonable in-depth research. As Kahn's research shows, resilience stems from the relationships between the components of a system and is a social process. Therefore, we define project resilience as the whole process in which the positive interaction between component units enables the project collective to withstand shocks, cope with challenges, and recover.

2.2. Social Capital: A Theoretical Framework

Consistent with previous studies based on organizational relationships and structure [39], we propose the use of social capital theory to study the resilience of building projects. Social capital has been studied in different areas of social, economic, and political science, creating a wealth of definitions and characterizations of its characteristics [40]. Different researchers distinguish social capital by the context, form, possible use, and group of interactions. Bourdieu [41] proposed the most widely accepted and applied concept of social capital, believing that social capital is the total amount of actual or potential resources obtained through the relationship network, that is, social network is social capital. Coleman [42] defined social capital as a kind of social structural resource from a macroperspective, which is the relationship of responsibility, expectation, trust, and power between individuals or groups. He believed that various exchanges based on the interests of different actors in the social network form a continuous social relationship, which is social resource and social capital. Portes [43] also proposed that social capital is a special connection attached to social relations and an expression of ability. Burt [44] believes that structural hole is social capital and the ultimate competitive advantage of enterprises and other economic activity subjects. Finally, Lin's [45] discussion on social capital represents the general consensus of theoretical research on social capital. In his view, social capital is the investment of rewarding resources embedded in social networks.

In addition, there are many research angles on social capital theory. In sociology, Carrillo et al. [46] argue that social capital is the most important indicator of family health. In terms of enterprise management, Harris et al. [47] tested the effect of coordination between human capital and social capital on enterprise performance. In the field of policy research, Muringani et al. [48] found that different types of social capital have different incentive effects on European economic development, thus adjusting economic policies.

Of course, there are contradictions between different schools of study on social capital theory. One of the principal contradictions is that between the individual and the collective. Burt and Lin regard social capital as individual capital, which is acquired based on people's action network. However, in Bourdieu and Coleman's study, social capital can be acquired in groups. The two views are not completely opposite fundamentally. The individual is embedded in the collective, and the collective is embedded in the larger social network. Therefore, this study is based on Bourdieu's view to identify collective social capital at the project level but also combines Burt's network-based analysis method. Based on the view that resilience emerges due to the interaction of each unit of the system, we believe that the process of project resilience can be represented by the change in social capital, and try to summarize the process of project resilience by measuring the change in social capital in each phase of the project network under adversity.

2.3. Social Network Analysis: A Computing System

Social network analysis (SNA) is a quantitative analysis method based on graph theory and mathematical symbols [49]. In SNA, a social network is a collection of social actors as nodes and relationships between nodes as edges [50]. Its essence provides a mathematical method to evaluate the impact of the embeddedness of nodes and related actors in the social network on their behavior and decision-making results [51,52].

The social capital available to actors of a group is integrated into their social networks [53]. In other words, social capital lies in actors' social relationships and network positions. Therefore, using SNA to research social capital is a feasible method. One dominant view is that the connections made between network actors form the basis of social capital [54]. This view is strongly influenced by network theory.

Some progress has been made in the measurement of social capital based on SNA [53]. On the one hand, some researchers have constructed social network capital measurement scales and considered the measurement results as social capital [55]. These scales have been used in a large number of surveys, using surveys or questionnaires as data collection tools. On the other hand, some researchers use SNA to measure social capital, which is measured by the description of network genus [22]. These studies provide us with the possibility to review the resilience capital of construction projects.

For a long time, construction projects have been considered as temporary organizations involving multiple participants [56]. One theoretical bridge to using SNA in construction is to view a construction project as a set of networks [57]. By taking the key actors in the construction project as nodes and the relationship between actors as connections, we can quantitatively analyze the cooperation ability of the project organization and implement effective project network management [58–60].

3. Method

To construct a social capital system to assess the resilience of construction projects and measure the resilience process within a system framework, this study designed a construction project resilience measurement method based on SNA and social capital theory, including the following four steps: (1) Establish a social network model for construction projects; (2) through a systematic literature review (SLR) and keyword frequency statistics, identify the key social capital of construction projects, and establish the project resilience evaluation framework based on social capital theory; (3) use the SNA method to calculate the different types of social capital of construction projects to establish the evaluation model of project resilience; and (4) use the data from the construction industry in China, which had experienced the impact of COVID-19, to analyze the changes in construction projects' resilience in the preparation, coping, and post-disaster recovery stages (hereinafter, the three stages are represented by 1, 2, and 3, respectively), which provides a benchmark for engineering projects to withstand impact.

3.1. Establishing a Network of Construction Projects

The identification of network nodes was the first step of SNA. In the research on construction projects from the perspective of the network, the network construction method regards all stakeholders of construction projects as network nodes. This method can be used to analyze the impact of the relationship structure between participants in the project from a macroperspective, but it cannot accurately and in detail describe the specific structure of the project. Another method is to focus on a specific construction project case and regard each project actor as a node to build a complete network of the project [61]. This method can accurately and in detail describe the structural characteristics and relationship composition of the project. However, it is also limited to only conclusions within. In addition, the method is difficult to extend for applications to a larger field. Therefore, in this study, we abstracted the actors with the same function in the project into one node, so that the construction project network not only fully describes the project relationship structure but also has higher universality and is not limited to a single project. The network constructed in this way allows the conclusions of this study to characterize the commonness of different construction projects to a certain extent.

Through reading and combing of the relevant literature, including papers, laws, and regulations from China, combined with the actual situation of most construction projects in China, we determined the main composition of construction projects in China [62]. In-depth interviews were conducted with 18 project practitioners, experts, and scholars in the construction field. The respondents were asked to prepare a list of the main project participation roles in their own unit as the basis for constructing network nodes. We also asked respondents to briefly describe the functions and main contacts of the participating roles they provided, and to identify the final node list through mutual screening. As shown in Table 1, although not all construction projects had the same personnel composition, the participating roles provided in the list cover almost all the functions required for the operation of construction projects and could represent the network structure of construction projects to a certain extent.

The second step was to establish connections between nodes. All respondents were asked to rate their own relationships with others. The 5-point scoring system was adopted, that is, {very high, high, medium, low, very low} = {5, 4, 3, 2, 1}. On the basis of the assignment undirected network model, the relationship matrix was transformed into a 0–1 binary matrix. The edge with score {0, 1, 2} was set to 0, and the edge with score {3, 4, 5} was set to 1. More detailed questionnaires are described in the data collection section. Thirdly, UCINET software was used to draw the social network diagram and calculate the social network indicators of the social capital of construction projects.

Table 1. List of relationship network nodes.

Project Actors	Agents (Network Nodes)	Node Codes
Owner unit	Project construction management personnel Business operation management personnel Quality inspection and safety management personnel	S1 S2 S3
Design unit	Unit leader	S4
Construction unit	Construction director Business director Safety director Material director	S5 S6 S7 S8
Construction control unit	Chief supervisory engineer Professional supervisory engineer Safety supervisory engineer	S9 S10 S11
Subcontractor	Professional subcontracting director Labor subcontracting director	S12 S13
Material supplier	Supply manager	S14
Government sector	Personnel of urban and rural construction department Audit department personnel	S15 S16
Consulting unit	Consulting engineer	S17
Financial institution	Accounting personnel	S18

3.2. Selecting the Key Social Capitals Using SLR

In this study, a systematic literature review (SLR) was used to select the most appropriate social capital indicators for project resilience. The SLR was used to conduct a quantitative analysis of the literature and reduce subjective factors and errors in literature selection and evaluation [63]. Two electronic databases were selected to collect the literature, including Science Direct and Web of Science. In the subject category covering the title, abstract, and keywords, two keywords, including resilience and social capital, were set as search protocols. In addition, the article type was set as review papers, and the publication time was set between 2000 and 2021. Then, the obtained results were filtered to remove irrelevant articles, including the following steps: duplication, attribute filtering, title and summary filtering, and full-text relevance filtering [64]. Finally, 110 articles on the project resilience or the social capital of construction projects were determined. Instead of filtering articles based on the field of construction project, we selected keywords from all articles on social capital research to avoid artificial disciplinary boundaries.

The most concerned social capital index in the study of resilience was screened by antconc3.5.9 software. Referring to the screening characterization proposed by Zhang et al. [65], only the indicators that appeared in more than three pieces of literature and whose relevance was in the forefront were selected. Then, the author discussed and analyzed these indicators from the theoretical perspective of the type of social network connection. In this process, seven kinds of social capital (Ci, $i = 1, 2, 3, \ldots, 7$) were selected, including cohesion (C1), trust and reciprocity (C2), information sharing (C3), information superiority (C4), social identity (C5), social influence (C6), and interpersonal relationship (C7) [66,67].

Finally, we referred to Putnam's classification of social capital and divided social capital into two types: bonding and bridging social capital. Bonding social capital originates from the interactions of actors within the system and emphasizes cohesiveness. On the other hand, bridging social capital originates from external network relationships, emphasizing the role of brokerage. A construction project is a unified whole, which needs the maintenance of bonding social capital. However, there are many heterogeneous actors from different teams inside the project, which needs the development of bridging social capital. Therefore, on the basis of the types of social capital, we discussed the identified social capital and built an evaluation system for the emergence process of project resilience, as shown in Table 2.

Table 2. Calculation system of Resilience Social Capital for construction projects based on SNA.

Level	Social Capital	SNA Indicators	Parameter
Bonding	Cohesion	Cohesion	Density
	Trust and reciprocity		Subgroup
	Information sharing		Average distance
Bridging	Information superiority	Structural hole	Efficiency
	Social identity	Cohesion	Clustering
	Social influence	Centrality	Degree centrality
	Interpersonal relationship		Betweenness centrality

3.3. Calculating the Social Capitals Using SNA

In terms of the calculation of social capital, this study used [68]'s calculation system for reference and established a resilience social capital calculation system for construction projects based on network indicators, as shown in Table 2.

3.3.1. Bonding Social Capital Computing

Cohesion refers to the ability to keep actors of a social network together by sharing common standards, values, ideas, and beliefs. According to Sanchez's research [69], the concept of group cohesion can be measured by the network density. In SNA, network density refers to the ratio of actual connections to potential connections. The more connections between each group actor and other group actors, the greater the density of the network. At the project level, the project network density corresponds to the average number of contacts per actor. From the perspective of social network analysis, network density is equivalent to group cohesion, which as a tightly connected network is considered to be more cohesive.

Trust and reciprocity represent one of the first indicators of social capital research. According to Sun et al. [70], trust and reciprocity are informal norms that promote cooperation between multiple individuals. The SNA subgroup refers to the closeness of the association among actors of a social network, who have a reciprocal relationship with each other and combine to form a substantial subgroup. Therefore, we used subgroup analysis in the social networks to measure the levels of trust and reciprocity.

Information sharing is defined as revealing the existence of relevant information and knowledge without the need for overall dissemination. If the construction project is regarded as a network, the information sharing ability of the project is closely related to the communication distance between network actors [71]. Therefore, we used the average network distance of SNA to measure the information sharing level of projects.

3.3.2. Bridging Social Capital Computing

Information superiority refers to the ability of actors to obtain non-redundant information, which is of high quality and conducive to decision making. In SNA, structural holes are used to analyze non-redundant links between any two nodes. From this point of view, we used the structural hole efficiency to measure actors' information superiority ability, that is, to what extent they possessed and used the structural hole superiority ability.

Social identity is the definition of one's own attributes and those shared with others when identifying oneself and comparing oneself with the group to which one belongs. Therefore, we used cluster analysis to measure the level of social identity. A higher clustering coefficient means that the node had a more united relationship with its neighbors, that is, a high sense of identity to its network membership.

Social influence is used to measure the ability of actors to directly or indirectly influence the emotions and actions of others. High social influence means that actors are able to interact with more other actors or with a higher frequency. Therefore, we used degree centrality to describe social influence, measuring the degree to which one node in a network is related to other nodes.

Interpersonal relationships represent the process by which actors connect indirectly or directly, establish connections, and allow the access and exchange of resources. Strong interpersonal skills mean that they are at the hub of network communication and could contact other actors directly or indirectly through this actor. Thus, betweenness centrality was used to measure interpersonal competence.

3.4. Establishing the Construction Project Resilience Evaluation Model

After the establishment of the social capital measurement system, social capital needs to be normalized to form a measure of project resilience. This study established an evaluation model of project resilience. The model referred to the RL model in the resilience evaluation of large-scale systems and estimated the resilience as the ratio of recovery to loss (Shen et al. 2020). The model is shown in Formula (1), where t = 1, 2, and 3 represent different phases of disaster impact, including pre-disaster, during the disaster, and post-disaster. $R(t)$ represents community resilience in phase t; i = 1, 2, . . . , 9 represent different types of social capital in the construction project organization; and Ci is the value of social capital in phase t. The specific value was obtained in the case study according to the method described in the method section:

$$R(t) = \sum_{i=1}^{n} \frac{C_i(t) - C_i(t_{min})}{C_i(t_{max}) - C_i(t_{min})} \tag{1}$$

3.5. Data Collection

To clearly express the changes in the construction project network before and after the disaster, this study selected the organization leaders, managers, and experienced employees and scholars of each participating subject of 9 construction projects in Hubei Province of China as the main sample sources. Because Hubei province was the first province in China to be affected by COVID-19, respondents from Hubei province clearly felt the impact of the disaster. The principles for selecting these respondents adhered to the following rules: (1) The selected respondents covered all 18 categories of construction project actors mentioned in the network node identification section; and (2) the working years of the respondents had to be greater than 5 years (to ensure that the respondents not only have a certain understanding of their work but also have experienced the impact of epidemic disasters). In other words, the selected respondents can include all participating organizations of construction projects in terms of categories and have a rich theoretical basis and practical experience in terms of individuals.

The researchers conducted a questionnaire survey based on the network actors identified above to measure their relationship network. Before the questionnaire, respondents were asked to review the impact of the epidemic on the project before answering. Thereafter, respondents were asked to evaluate how their relationship with others changed during different stages of a disaster from three dimensions: trust, communication frequency, and communication quality, as shown in Table 3. This table was adapted from the SNA questionnaire proposed by Wang et al. [72] to infer structural changes in the construction project relationship network.

The following measures were taken to ensure the return rate and validity of the questionnaire. First, during the questionnaire distribution process, we assured respondents that their information would be kept strictly confidential and that the results would be used for scientific purposes only. Second, we used a dual incentive mechanism in which respondents were not only rewarded for their participation but also for recruiting a reliable new respondent. A total of 391 questionnaires were distributed through online surveys, and construction site interviews. Then, 247 valid questionnaires were recovered, with an effective response rate of 63.2%, as shown in Table 4. After that, we interviewed 18 project managers with 5 years of project management experience, who were asked to validate the authenticity and validity of the networks constructed in different phases of our study and supplemented the data with specific interviews with specific project actors. Finally, the valid scores of the respondents were averaged as the result of the final relationship strength matrix.

Table 3. Data Collection Form.

1. Please briefly describe your position and work in the project. 2. Please list the other members of the project with whom you work or exchange information frequently. 3. The position of the member in the project and the main work content.
Please provide your evaluation on the following questions about the quality of your relationship (The evaluation is based on a 5-point scale, 1 = very low, 2 = low, 3 = medium, 4 = very high, 5 = high).
4. Please evaluate your level of trust in the pre-disaster phase. 5. Please evaluate your level of trust during the disaster phase. 6. Please evaluate your level of trust in the post-disaster phase.
7. Please evaluate the frequency of your communication in the pre-disaster phase. 8. Please evaluate the frequency of your communication during the disaster phase. 9. Please evaluate the frequency of your communication in the post-disaster phase.
10. Please evaluate the quality of your communication in the pre-disaster phase. 11. Please evaluate the quality of your communication during the disaster phase. 12. Please evaluate the quality of your communication in the post-disaster phase.
13. Would you like to help us contact the member to receive the questionnaire?

Table 4. Descriptive statistical analysis of the respondents.

Classifications		Actors	Percentage
Sex	Male	139	56
	Female	108	44
Working years	5–10	145	59
	11–15	65	26
	>15	37	15
Stakeholder party	Project construction management personnel	22	9
	Business operation management personnel	17	7
	Quality inspection and safety management personnel	23	9
	Unit leader	19	8
	Construction director	20	8
	Business director	19	8
	Safety director	15	6
	Material engineer	13	5
	Chief supervision engineer	11	4
	Professional supervision engineer	8	3
	Safety supervision engineer	14	6
	Professional subcontractor	11	4
	Labor subcontractor	12	5
	Supply manager	10	4
	Personnel of urban and rural construction department	9	4
	Audit department personnel	8	3
	Consulting engineer	9	4
	Accounting personnel	7	3

4. Result and Analysis

4.1. Social Network Description

UCINET 6.0 software was used to draw a social network diagram showing the stakeholder relations in three different phases, as shown in Figure 1. Obviously, S1 and S9 were the most connected nodes in the whole social network in phase 1 (the pre-disaster period). Intuitively, at the beginning of the disaster, the number of edges between the network nodes of the project organization, especially S1, decreased significantly, which meant that the relationship and interconnection among project actors loosened due to the impact of the disaster. After the disaster, the social network became type 3, which was closer than when the disaster occurred, and even stronger than before the disaster to a certain extent. Some possible reasons might have included the following: First, in phase 2, the connection between the project actors was weakened by the impact of the disaster.

However, the connections that enabled the project to exhibit resilience were retained, so the project system could resist or even survive the impact of a disaster. Second, by drawing lessons from disasters, the project organization accumulated more experience in dealing with disasters. An organizational network with more redundant connections was formed to enhance the resilience of the project.

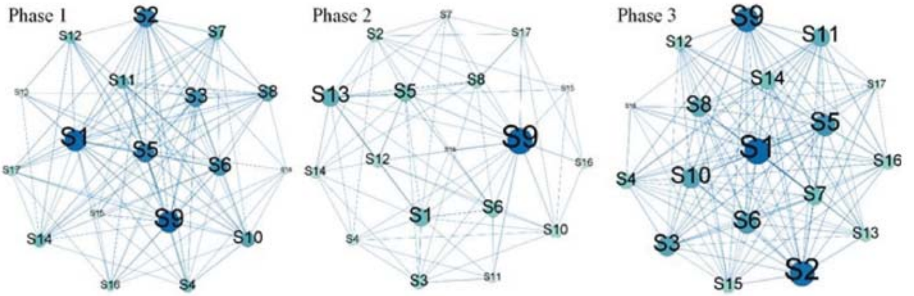

Figure 1. Social network graphs of the construction project before, during, and after the disaster.

4.2. Bonding Social Capital of the Whole Project

The bonding social capital of the project in the three phases of the epidemic is shown in Figure 2. In general, compared with phase 1, the social capital index basically showed a downward trend first and then an upward trend (the rise in the distance indicators represents a decline of the level of information sharing).

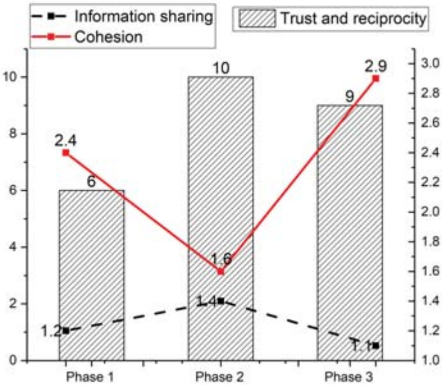

Figure 2. Bonding social capital during different phases of the disaster.

Based on the changes in the network indicators, when the disaster occurred, the project network became sparse and loose. Project actors were uncertain whether the project could successfully deal with the crisis, and the cohesion of the project was weakened. The communication bridge between project actors that could be directly contacted in the past was broken, and the communication distance between different nodes to achieve cooperation was lengthened, which compromised the ability to share information within the project. However, the number of small groups increased from 6 to 10, and the trust and reciprocity between the actors of the common group were improved, thereby increasing the level of trust throughout the project. When the project successfully overcame difficulties, the cohesion of the project was restored to a higher level than phase 1. The number of factions decreased from 10 to 9. Part of the temporary small groups that formed to deal with the impact of disasters was retained, the resources of reciprocity and trust were developed, and a higher level of information sharing was formed.

Table 5 describes the major subgroups and their major actors that existed at each phase of the disaster impact. As the social network diagram shows, actors of a small group were connected to each other without structural holes. As a result, information could be transferred directly between them, point-to-point, without mediation. This meant that the trust levels within these four subgroups were high, were less affected by the impact of the disaster, and played an important role in maintaining the normal function of the project. It is worth noting that node S13 did not appear in any subgroup at any phase, which meant that its relationship with other nodes should be improved. Other subgroups were flexibly combined based on the different needs of the disaster response. For example, the subgroups with S1, S4, and S9 as actors appeared in stage 2 but disappeared in stage 3, indicating that the project management personnel of the construction unit, the leader of the design unit, and the chief supervisory engineer played the role of a temporary emergency response team in the case of the impact on the project.

Table 5. Construction project subgroup analysis.

Subgroup	T1	T2	T3	T4
Actor	S1 S2 S3 S4 S5 S6	S7 S8 S9 S10	S11 S12 S14	S15 S16 S17

4.3. Bridging Social Capital of Actors

In the previous section, the project was regarded as a cohesive whole, and the bonding social capital of the project was calculated through the network's overall indicator. However, the normal operation of a construction project involves the cooperation of multiple actors, and bridging social capital also plays an important role for each actor. Therefore, this section calculated the node indicators of the network to obtain the changes in the four bridging social capitals: information superiority, social identity, social influence, and interpersonal relationship, of the actors in the three periods, as shown in Figure 3. It is part of the project resilience assessment framework.

In Figure 3, in the bridging social capital of the project actors, information superiority and interpersonal ability showed a similar trend: rising in phase 2 and then declining in phase 3 but higher than phase 1. This suggests that information superiority and interpersonal relationships were even more important to keeping projects running during a disaster impact. However, the interpersonal relationship of S4, S11, and S15 declined in phase 2, indicating that the quality of their relationship with other actors needs to be further improved.

The social capital of project actors, social identity and social influence, showed a downward trend in phase 2 but recovered to a higher level in phase 3. This meant that for construction projects, actors' social identity and social influence were the bridging social capital that was most vulnerable to damage when experiencing the disaster's impact. To ensure the project survives the crisis, it is necessary to take measures to protect actors' social identity and social influence ability.

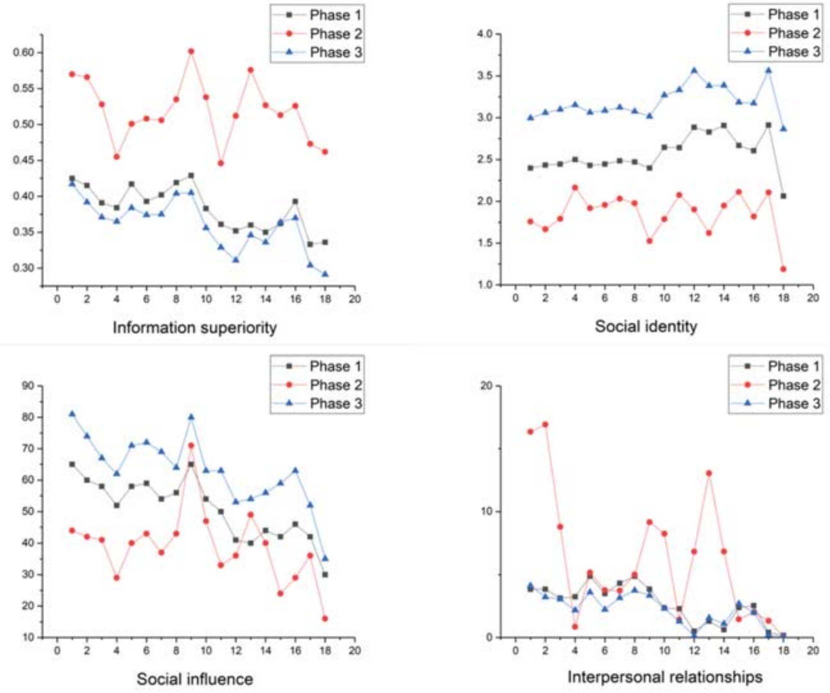

Figure 3. Bridging social capitals during different phases of the disaster.

4.4. Resilience of Construction Project

The above research demonstrates that in the social capital system, to evaluate the resilience of construction projects, the trust and reciprocity in bonding social capital and the information superiority and interpersonal relationships in bridging social capital were required, which was manifested when encountering adversity, as the project needed to protect the existing capital constantly from loss through resource investment, and ensure faster recovery from lost resources. Meanwhile, the cohesion and information sharing in bonding social capital, the social identity and social influence in bridging social capital, showed the characteristics of protective capital. In case of adversity, the project would take a series of protective measures to reduce the loss of protective capital and wait for rescue and turnaround to over difficulties. Therefore, project resilience evaluation system could be characterized from two dimensions: social capital attribute and resource conservation strategy, as shown in Table 6.

Table 6. Project resilience measurement system.

	Bonding Social Capital	**Bridging Social Capital**
Investment	Trust and reciprocity	Information superiority Interpersonal relationships
Protect	Cohesion Information sharing	Social identity Social influence

According to Formula (1), nine social capital indicators of the construction project in three phases of adversity were normalized and summarized by type to reflect the emergence of the project resilience, as shown in Figure 4. From the perspective of investment resources, the project resilience scores before, during and after the disaster were 0.89, 1.99, and 1.25

respectively. From the perspective of protective resources, project resilience was 2.79, 0.98 and 3.4 respectively. As can be seen from Figure 4, the project resilience as the result of the interaction between the construction project system and the environment had the characteristics of dynamic and repeated iteration: (1) the construction project had a certain level of investment and protective social capital in phase 1, and paid attention to the preparation and readiness capability, i.e., early warning capability, at the level of strategy, structure and resources. (2) The project paid attention to the ability of adjustment and skillful creation in phase 2, and increased the investment in investment capital when the protective capital was seriously damaged, so that the construction project could survive the emergency. (3) In phase 3, the project paid attention to recovery, learning and improvement transcendence. Although the investment capital decreased, it was still higher than the level before the adversity. The protective capital recovered after a major blow and surpassed the original level, so that the project would have more sufficient social capital when the next adversity came, thus completing the emergence of project resilience.

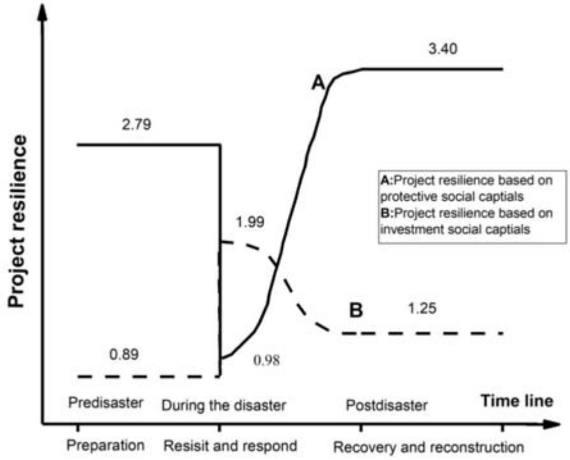

Figure 4. Construction project resilience in the three phases of the disaster.

5. Discussion

This research is based on the investigation and study of China's construction projects, which were hit by COVID-19 in 2020. Moreover, this study analyzed the relationship network and the evolution of social capital among project actors. The data demonstrates how the macrostructure of the network changes in the different phases of impact, thus allowing the present research to discuss the evolution of network social capital further, and establish a dynamic measurement system of project resilience based on the categories of social capital. The findings of this study provide insights into how construction project actors can improve the resilience and performance of complex cross-organization project teams through a structural review and intervention of relationship networks in adversity.

Previous studies have shown that complex organizational systems can actively adapt to environmental changes, dynamically coordinate different subjects, and promote project organizations to overcome adversity and achieve success, that is, show resilience; however, a detailed description of the emergence process of project resilience in the field of construction project management involving multi-department participation is lacking [73,74]. To fill this gap, this study developed a dynamic research method based on the data of three time points. The results reveal that construction projects in the three phases (e.g., before, during, and after the adversity) will adjust the network structure and the development and transfer of social capital to make the project resilient and rebound during adversity. From the changes in the network indicators, when a disaster occurs, given the uncertainty of whether the project can successfully deal with the crisis, the psychological security level within the project is reduced and the cohesion of the project is weakened. The communication bridge between project actors that can be directly contacted in the past is broken, and the communication distance to achieve cooperation between different nodes is lengthened, and the information sharing within the project becomes more difficult.

However, the number of subgroups increased from 6 to 10. The project actors of the same subgroups have the same goals and strive to reduce the impact of the disaster on the operation of construction projects. As a result, their trust and mutual benefit are improved. When the organization successfully overcomes the adversity, the broken communication bridge can be restored. At the same time, given the impact of the disaster, the organization may pay extra attention to the investment in the early warning, recovery, and reconstruction of disasters, thus resulting in a new communication bridge, shortening the communication distance, and restoring the cohesion and information sharing of the project to a higher level than before the disaster. The number of factions was reduced from 10 to 9, and the clustering coefficient increased to a higher level than before the disaster. Given that the project as a whole has overcome the difficulties together, the temporary subgroups formed to deal with the impact of the disaster have been retained, and the resources of reciprocity and trust have been developed, with a higher level of psychological security. Therefore, managers should fully consider the relationship dynamics among multiple subjects. On the one hand, they should pay attention to the network areas that are hardest hit by adversity, and to the organizations, teams, or individuals with the most serious decline in social capital indicators, which are often the focus of post-disaster recovery and prevention. On the other hand, they should pay attention to the new relationship connections established in adversity. These connections show a tighter network structure and higher network efficiency, which means that the growth of project investment social capital is closely related to the emergency response ability and resistance ability of the construction project.

Considering the increasing complexity of construction projects, to further identify the resilience development process of a construction project, this study established an evaluation system of seven social capital resilience factors of construction projects from the perspective of bridging and bonding social capital, and explored the emergence process of organizational resilience based on two resource strategies: investment and protection.

Based on bonding social capital, we note that the observed values of the network density and clustering coefficient dropped sharply in phase 2 and then continued to increase in phase 3. This trend means that when the construction project rebounds from adversity, it needs to develop into a more compact (less structural holes) network (phase 3), increase the concentration, reduce the dependence on external nodes, and develop more endogenous connections. In terms of initiating collective action and promoting the rapid dissemination of information/materials/services, the project's cohesion and information sharing are restored and highlighted. Meanwhile, they ensure that the project can complete this transformation depending on the investment in trust and mutual capital in adversity, that is, adopting protective strategies, which is reflected in the increase in the number of subgroups.

Based on bridging social capital, the central idea of social capital is that individuals invest, acquire, and use heterogeneous resources in social networks to achieve the desired results [75]. In this study, the effectiveness of most individuals in adversity shows a downward trend. However, those who always maintain a high level of effectiveness or show an upward trend provide help to others to the greatest extent. The impact of adversity breaks some network bridges and increases the distance for actors to obtain resources, which makes it very important to invest in the ability to maintain existing connections and establish new connections to communicate networks and integrate resources. The engineering and technical personnel, comprehensive business management personnel of the construction unit, construction management personnel, and chief supervision engineer of the construction unit are often in the central position in the network at different phases. They either have authority or occupy the information center. The combination of authority and the central position in the network may produce a better decision-making ability and positive results. In other words, more investment in information superiority and interpersonal relationships, and a decreased loss of social identity and social influence can improve a project's resilience performance.

Among the previous literature conclusions on the resilience of construction projects, they have mainly made theoretical contributions to the preliminary understanding of the positive effect of resilience on construction projects. However, most of the conclusions are still based on the use of a single performance index to characterize resilience, and this form of post feedback lacks real-time information and effectiveness. Compared with the previous literature conclusions, this study combined the actual data of China and analyzed the influence factors of project resilience and different resource changes from the perspective of sociology to promote the success of construction projects in a more targeted and real-time way. Through social capital theory and the evolution view of resource conservation, an evaluation model of the resilience of construction projects was proposed from the two dimensions of protection and investment. The research results make up for the theoretical defects in the identification of resilience in construction projects and point out the direction for the future development of construction projects.

6. Conclusions

6.1. Theoretical Significance

Based on social network theory and social capital theory, this study revealed the emergence mechanism of project resilience. The innovation of this study is that it performed a cross-level analysis of project resilience from a dynamic perspective, and makes some theoretical contributions to the project management literature. First, social capital theory is extended to the research of project management in this study. Then, this study constructs an evaluation system for project resilience, which includes seven social capital indicators based on the two types of social capital. These research results help to deepen the understanding of the emergence mechanism of project resilience, enrich the literature on construction project management, and establish the relationship between the project and sociological research. Secondly, given the structural complexity and resource diversity of construction projects, this study proposes that project resilience should be considered at both the overall and local structural levels. Bonding and bridging social capital are inherent in the overall and local relationship of the project, which provides a new understanding for the identification and measurement of project resilience. Third, this study discusses the capital integration process of the project from a dynamic perspective. This research shows that the construction project will strengthen the trust and reciprocity and information superiority, allow the development of the interpersonal relationship ability of employees, and maintain the cohesion, information sharing, social identity, and social influence at no less than a certain level, which will provide new insights into the understanding of project resilience.

6.2. Management Significance

Our results provide some practical guidelines on the resilience of construction projects to maximize organizational and project performance. First, consideration of the evolution of the relationship network will help to shift the management of the construction industry to informal institutional arrangements, including but not limited to trust, cohesion, information sharing, and social identity, etc., to enhance the sustainability of social project governance. Secondly, this study will help practitioners fully grasp the emergence process and phase of project resilience to deal with risks and adversity pertinently and strategically, especially sudden public health events. In addition, we suggest that the project should pay attention to the development of investment capital and protect the conservation of capital. In times of adversity, the project should strengthen the trust among actors, improve the quality of the relationship, develop collective efficiency, and ensure the psychological safety and sense of belonging to a certain level, which will help loose construction projects to have better resilience and achieve their objectives.

7. Limitations

This study can be regarded as the starting point for further testing of the development of resilience in the construction industry through SNA. One of the limitations is the methodological challenge of the SNA method. Drawing social network diagrams, especially vertical continuous drawing, is a costly and time-consuming process, which requires an ingenious and thorough research design and system design. Future work is encouraged to clarify the bridge between project resilience standards and network measures, and the theoretical development of resilience measures and network evolution. In addition, this study did not consider the types of relationships (such as friend relationship, task relationship, interest alliance, etc.), and it encourages further detailed research to explore the relationship between the network dynamics and project resilience of construction projects under the background of more complex relationships.

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

Funding: This research was funded by Planning Foundation of Ministry of Education of China, grant number 21YJA630087.

Institutional Review Board Statement: Not applicable.

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

Data Availability Statement: All data generated or used in the study can be obtained from the corresponding author upon reasonable request.

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

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Predicting Employer and Worker Responsibilities in Accidents That Involve Falls in Building Construction Sites

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Abstract: Fall-related accidents have received more attention in building construction than in civil construction as fall-from-heights is more common in building construction. In addition to social costs, construction companies face a significant financial burden when fall-related accidents occur. The major portion of the direct cost of accidents that involve falls includes the compensation paid by the employer to the worker. The employer and the worker try to reach an agreement on the size of the compensation, however, most of the time the process is contentious. The objective of this study is to predict the parties' responsibilities for a fall-related accident by modeling the relationship between the employer and the worker using a multi-agent system. The research pursued a three-step method, including collection of data, development of a multi-agent model, and testing of the model. The model provides satisfactory results and can be used to quantify the employer's and the worker's responsibilities in construction fall accidents, hence avoiding any escalation to pursue arbitration or litigation.

Keywords: construction accident; construction safety; worker compensation; falls; multi-agent systems

Citation: Akcay, E.C.; Arditi, D. Predicting Employer and Worker Responsibilities in Accidents That Involve Falls in Building Construction Sites. *Buildings* **2022**, *12*, 464. https://doi.org/10.3390/buildings12040464

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 21 February 2022
Accepted: 7 April 2022
Published: 10 April 2022

1. Introduction

The construction industry is one of the most hazardous industries [1,2]. It has a poor safety record all over the world [3,4]. There were 4779 worker deaths recorded in all sectors in the U.S. in 2018, 21.1% of which occurred in the construction industry [5]. In other words, one out of every five deaths was caused by accidents on construction sites [6]. In the U.K., 111 workers lost their lives on the job between the years 2019–2020, 40 of them in construction [7]. Although there is a gradual decrease in the number of occupational incidents on construction sites thanks to preventive laws and regulations [8], the construction industry still experiences higher rates of accidents compared to other industries. This is a problem that can be resolved if adequate precautions are put in place to eliminate the most common reasons that cause accidents on construction sites.

Falls have received more attention than any other type of occupational accident as falls have been very common in the construction industry [9]. According to OSHA [10], 33.5% of total fatalities in the U.S. construction industry in 2018 were fall-related. Additionally, falls were responsible for 25% of all fatal injuries in the U.K. [7]. Besides social costs, construction companies also face a significant financial burden caused by falls. The direct cost of falls in U.S. construction sites has been estimated to be about USD 70 billion annually [11]. The economic impact of falls has been significant not only in the US but also in other countries such as the U.K. [12], European Union Countries [13], Australia [14], South Africa [15], Singapore [16], and Taiwan [17]. The prevention of fall-related accidents on construction sites is therefore of paramount importance.

The major portion of the direct cost of accidents that involve falls includes the compensation paid by the employer to the worker. When an accident occurs, the employer and the worker (or the worker's family) try to reach an agreement on the size of the compensation, however, on many occasions they fail to reach an agreement and must go to court for a settlement. In Turkey, there were 180,000 court cases between the employer and worker in the period 2017–2018 [18]. As it is extremely time-consuming to consider these many cases, the Turkish Government encourages employers and workers to settle using arbitration, and skip court. In addition to preventing the occurrence of fall-related accidents, it is important to reach a mutually agreed settlement that is fast and fair to both parties.

The arbitration process involves discussions between the employer and worker. These discussions depend to a large extent on the employer's and the worker's responsibilities for the accident. In other words, it should be easy to calculate the size of the compensation by using the rules provided by the government that make use of the employer's and the worker's responsibilities for the accident, however, it seldom is. Most of the time, the process is contentious and often results in ill feelings on the part of one of the parties. This research aims to predict the parties' responsibilities for an accident by modeling the discussion between the employer and the worker using a multi-agent system, hence skipping painful and lengthy arbitration or litigation and creating an objective and fast solution that is acceptable to both parties. This study is expected to contribute to the literature in building construction safety management and to safety practice in the building construction industry by streamlining the settlement of worker compensation in the aftermath of fall-related accidents. In addition, this study provides procedural benefits to the legal system that is routinely congested.

2. Literature Review

This research builds on and extends studies about (a) accidents that involve falls on construction site, (b) multi-agent systems, and (c) dispute resolution in construction. The issues that are encountered in fall-related accidents on construction sites, the basic principles and the pros and cons of multi-agent systems, and the studies about construction dispute resolution are briefly discussed in the next three subsections.

2.1. Fall-Related Accidents in Construction Sites

Falls on construction sites have always drawn the attention of many researchers (e.g., [9,19–24]) as falls are the leading cause of occupational injuries and fatalities on construction sites [10], especially on building construction sites.

As seen in Table 1, several studies were conducted about fall detection, fall prevention, fall protection, safety training, causes of falls, and fall-related accident patterns, each study using different methods such as statistical methods, qualitative evaluations, sensor and camera-based techniques. Despite the existence of quite a few research studies related to fall-related accidents, there was no study published in the literature that focused on modeling the interaction between the employer and the worker to predict each party's responsibility for this kind of accident. To fill this gap, this research proposes a model that simulates the discussion between employer and worker to predict the employer's and worker's responsibilities for the accident.

Table 1. Research about Fall-Related Accidents.

Topics Investigated in Research about Fall-Related Accidents	Tools Used	Selected Sources
Fall detection	Sensor-Based Technology	[25–28]
Conditions that provoke fall-related accidents	A static balance tool for proactive tracking	[29]
Fall prevention	Fall prevention index (Measuring center of posture of 30 participants)	[30]

Table 1. *Cont.*

Topics Investigated in Research about Fall-Related Accidents	Tools Used	Selected Sources
Worker safety training	The relationship between the social learning and construction workers' fall risk behaviors (Virtual Reality)	[31]
Fall protection and risk factors	Statistical techniques	[32,33]
Fall protection analysis	Evaluation of regulations, construction practices and fall protection plans	[34]
Causality patterns of unsafe behavior leading to fall hazards	Motion detection camera (Workers' unsafe behavior)	[35]
Falls in steel erection	Bayesian Network approach	[36]
Fall-related accident patterns	Statistical techniques	[24,37–40]

2.2. Multi-Agent Systems

A multi-agent system is an artificial intelligence technology that consists of autonomous intelligent agents to create an intelligent behavior within a system to achieve a common objective [41]. These intelligent agents have not only the capability to act independently according to their personal objectives, but they can also interact with each other in the same system [42]. Multi-agent systems first appeared in the 1980s, and have been extensively used in different disciplines to solve complex and dynamic problems [43]. As the construction industry is highly fragmented, it mostly involves complex and fragmented problems. Hence, multi-agent systems have been widely used in construction management for simulating different problems. As seen in Table 2, several multi-agent studies were conducted to solve supply chain problems, to simulate the negotiation process to resolve conflicts between parties, to achieve energy savings, and to simulate worker safety behavior.

Table 2. Research about Multi-Agent Systems.

Agent-Based System Applications	Selected Sources
Modeling complex negotiations in multi-echelon supply chain networks	[44]
Optimizing cost management in supply chains	[45]
Modeling scheduling workflows in supply chains	[46]
Modeling supply chain management	[47–50]
Developing framework for supply chain coordination	[51]
Improving negotiation efficiency in supply chains	[52]
Modeling the negotiation process between contractor and client about sharing cost overruns in construction projects	[41]
Resolving schedule conflicts between subcontractors	[53]
Modeling incentive contracts to regulate the relationship between risk-neutral owners and risk-averse contractors	[54]
Developing energy-saving systems	[55–58]
Proposing a model to simulate the safety behaviors of workers	[59,60]

As seen in Table 2, the first six rows concern issues encountered in supply chain management, while the remaining rows include studies as diverse as negotiation processes between parties, energy consumption, and workers' safety behaviors. Out of the eighteen papers cited in this table, only Karakas et al. [41], Kim and Paulson [53], and Hosseinian et al. [54]

used agent-based systems to resolve conflicts between parties, a topic of particular interest relative to the study presented in this paper. Karakas et al. [41] developed a multi-agent system to simulate the negotiation process between contractor and client about sharing cost overruns in construction projects, while Kim and Paulson [53] used multi-agent systems to resolve schedule conflicts between subcontractors. Hosseinian et al. [54] developed a multi-agent sharing model for incentive contracts to regulate the relationship between risk-neutral owners and risk-averse contractors. It is noteworthy that none of these studies looked into the discussion/negotiation process that takes place between contractors and workers after a fall-related accident has occurred to agree upon the compensation (if any) to be received by the worker.

2.3. Dispute Resolution in Construction

As the complexity and scale of construction projects increase, disagreements and legal disputes have been very common in recent years [61]. As seen in Table 3, a vast number of researchers have published studies about various aspects of construction disputes.

Table 3. Research About Construction Disputes.

Topics Investigated in Research about Legal Disputes in Construction Projects	Selected Sources
Identifying the major causes of disputes in the UAE	[62]
Identifying the common causes of disputes in the Indonesian construction industry	[63]
Developing dispute causal model	[64]
Proposing BIM-based claims analysis model	[65]
Identifying the major causes of dispute in the Nigerian construction industry	[66]
Identifying the causes of contractor claims in Engineering-Procurement-Construction Projects	[67]
Identifying major causes of disputes in Bahrain	[68]
Adopting machine learning models to predict the outcome of differing site condition disputes	[69]
Developing an integrated prediction model to predict the outcome of construction disputes	[70–74]
Developing a dispute resolution selection model	[75]
Offering a case retrieval approach based on text-mining to resolve disputes	[76]

A review of the literature in Table 3 reveals that research in construction disputes mostly emphasizes (a) the investigation of the causes/types/severity of disputes, and (b) the development of alternative dispute resolution methods for resolving the disputes. El-Sayegh et al. [62] who investigated the major causes of construction disputes in the United Arab Emirates stated that identifying the causes of disputes have a great importance in reducing the occurrence of disagreements and disputes between owners, designers, and contractors. While Hayati et al. [63] identified the common causes of disputes in the Indonesian construction industry, Viswanathan et al. [64] developed a dispute causal model that considered the relationships between the causes of a dispute.

Concerning the development of predictive models for construction dispute resolution, Mahfouz and Kandil [69] adopted machine learning models to predict the outcome of differing site condition disputes, whereas Pulket and Arditi [70,71] developed an integrated prediction model to predict the outcome of construction disputes. Although quite a few research studies related to dispute resolution have been conducted, only a limited number were related to construction accidents. For example, Fan and Li [76] offered a case retrieval approach based on text-mining to resolve disputes, but only in certain types of construction accidents. The literature includes several studies related to construction dispute resolution, but no study offers a multi-agent system to simulate the discussions between an employer and a worker to settle with mutual satisfaction the employer's and the worker's responsibilities in fall-related accidents.

3. Research Method

Before the arbitration or litigation process, a discussion takes place between the employer and the worker to determine the parties' responsibilities. The discussion between the worker and the employer can be thought of as a negotiation process where the parties aim to achieve their respective goals within a specified period. If the parties are not able to reach an agreement, a lengthy arbitration or litigation process starts where both parties spend considerable time/effort and incur significant cost. Given the general lack of relevant research in the literature, a multi-agent system was used to model the discussion between the employer and the worker in this research for two reasons:

1. The multi-agent system allows researchers to create agents that have their own objectives and their own strategies. These agents can make autonomous decisions based on their objectives and strategies. These decisions reflect the real-life strategies of the parties in the discussions.
2. The multi-agent system gives the flexibility to select a suitable negotiation strategy by considering the characteristics of the negotiation, which reflect the dynamic discussion process between the worker and the employer.

The objective of this study is to construct a multi-agent system to simulate the discussion between an employer and a worker to agree on the employer's and the worker's responsibilities in fall-related accidents. To accomplish this objective, this research involves three steps, including collection of data, development of a multi-agent model, and testing of the model. The flow diagram of the research method is presented in Figure 1.

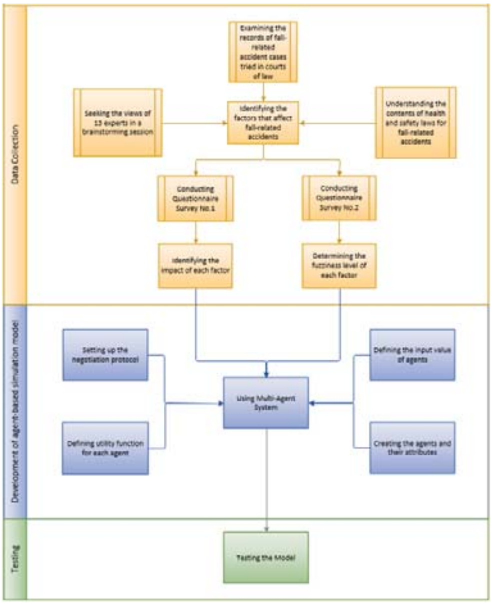


Figure 1. Flow Diagram of Research Method.

3.1. Data Collection

Data collection consisted of two stages including identification of the factors that affect fall-related accidents, and identification of the impact of each factor. It was conducted in the Turkish building construction industry and the Turkish court system.

3.1.1. Identification of the Factors That Affect Fall-Related Accidents

The identification of the factors that influence the discussions between the employer and the worker was performed by examining the records of fall-related accident cases tried in courts of law, understanding the contents of health and safety laws for fall-related accidents, and seeking the views of thirteen experts in a brainstorming session. It should be noted that all participants in the brainstorming session had been tasked at one time or another by Turkish courts to serve as experts in cases involving fall accidents. The profiles of the participants are provided in Table 4.

Table 4. Profile of the thirteen Participants in the Brainstorming Session.

Respondent ID	Profession	Years of Experience	Sector	Number of Reports Prepared for Courts
1	Civil engineer	10–15	Public	10–20
2	Lawyer	5–10	Private	<10
3	Lawyer	15–20	Private	20–30
4	Mechanical engineer	10–15	Public	10–20
5	Civil engineer	35–40	Private	>30
6	Electrical engineer	10–15	Private	10–20
7	Academic	40–45	Public	>30
8	Academic	40–45	Public	>30
9	Academic	20–25	Public	20–30
10	Civil engineer	15–20	Private	<10
11	Lawyer	20–25	Private	20–30
12	Environmental engineer	5–10	Public	<10
13	Industrial engineer	10–15	Private	10–20

The brainstorming session involved two stages. In the first stage, the participants examined a total of 27 fall accident cases and discussed the employer's and of the worker's responsibilities for each court case by examining the relevant laws. In the second stage, based on what they learned in these court cases, and with the help of their experiences, the participants identified the factors that affect the quantification of the employer's and the worker's responsibilities. They identified five factors:

1. Evidence of worker training: The first factor is whether workers have received safety training. According to the regulations, an employer should provide mandatory safety training to all workers. If an employer has evidence attesting to worker safety training, it proves that the employer has complied with government regulations. In this case, the employer has the power during the negotiations. On the other hand, if the employer is not able to present such evidence, the worker has the power;
2. Presence of site engineer: The second factor is whether the site engineer was present on the construction site. Another government regulation requires that a site engineer always be present on the construction site. If the site engineer was present on the construction site at the moment of the accident, the employer has the negotiating power. On the other hand, if the site engineer was not present on the site at the moment of the accident, the worker has the negotiating power;
3. Responsible behavior of worker: The third factor is the behavior of the worker. If the worker exhibits unsafe behavior, the employer has the negotiating power, whereas if the worker consistently demonstrates safe behavior, the worker has the power during the negotiations;

4. Safe site conditions: The fourth factor involves the safety conditions on the construction site. An employer who provides safe site conditions implies that the employer has a good sense of responsibility. In this case, the employer has the power during the negotiations. On the other hand, if the employer has failed to provide safe site condition, the worker has the negotiating power;
5. Use of protective equipment: The fifth factor involves the availability and use of worker protective equipment. In this case, the worker and the employer share the negotiation power as availability and use of worker protective equipment is considered by governmental regulations to be the responsibility of both parties. In other words, while the employer has the obligation to provide safety equipment, the worker has the right to demand that proper safety equipment be provided.

3.1.2. Identification of the Impact of Each Factor

A web-based questionnaire was prepared and administered to 48 experts to identify the impact of each factor. The demographic information of the respondents is presented in Table 5.

Table 5. Profile of the 48 Experts who responded to the Survey.

Category	Properties	Frequency	Percentage (%)
Profession	Civil engineer	12	25.0
	Lawyer	9	18.8
	Mechanical engineer	5	10.4
	Electrical engineer	4	8.3
	Academician	8	16.7
	Environmental engineer	4	8.3
	Industrial engineer	6	12.5
Years of experience	0–5	1	2.1
	5–10	4	8.3
	10–15	10	20.8
	15–20	11	22.9
	20–25	9	18.8
	25–30	7	14.6
	30–35	2	4.2
	35–40	1	2.1
	40–45	3	6.3
Sector	Public	17	35.4
	Private	31	64.6
Number of reports prepared for the court	<10	11	22.9
	10–20	13	27.1
	20–30	14	29.2
	>30	10	20.8

In this questionnaire, each expert rated each factor by using a nine-point Likert Scale where one indicates very low impact and nine indicates very high impact. A Relative Importance Index (RII) was calculated to analyze the data. The RII of each factor was calculated by using Equation (1) and helped to identify the importance of each factor relative to the perceptions of the respondents.

$$\text{RII} = \frac{\sum W}{A \times N} \tag{1}$$

where RII is the relative importance index; W denotes the weight assigned to each factor by the respondents (in this case, it ranges from one to nine); A is the highest weight (in this case, it is nine); and N is the total number of respondents.

The value of RII varies between zero and one. *A* negotiation factor that has a higher RII has larger impact compared to a factor with a lower RII. The questionnaire results, RII values, and their weighted percentages are presented in Table 6. To check the reliability and the internal consistency of the collected data, the Cronbach's Alpha coefficient was calculated. It was found that the Cronbach's Alpha coefficient of 0.892 is greater than the acceptable minimum value of 0.7 suggested by Santos [77].

Table 6. Data, RII values, and fuzziness levels.

Negotiation Factor	RATING Frequency of Responses 1	2	3	4	5	6	7	8	9	RII	Weighted Percentage (%)	Fuzziness Level
Evidence of worker training	1	2	2	4	11	14	9	4	1	0.63	17.1	Low
Presence of site engineer	1	1	1	1	5	4	9	22	4	0.77	21.1	Low
Responsible behavior of worker	1	0	4	4	7	16	9	5	2	0.65	17.8	High
Safe site conditions	0	0	6	4	4	3	4	18	9	0.75	20.6	Medium
Use of protective equipment	0	1	1	3	2	1	6	9	25	0.86	23.5	Low

As each factor involves a level of uncertainty, a level of fuzziness should be incorporated into the weight of each factor. For this purpose, another questionnaire was administered to the thirteen experts who took part in the brainstorming session at the beginning of the study (see Table 4). The questionnaire was administered orally as it was more convenient for respondents to answer. Respondents assessed the level of vagueness as low, moderate, and high. Later, these values were converted into percentage values. To reduce the range of the answers, the Delphi method was performed in two successive rounds. The Delphi method is a group decision-making and forecasting method that involves successively collating the judgments of experts with the aim of seeking consensus. The fuzziness level of each factor is shown in Table 6.

3.2. Development of a Multi-Agent System

The multi-agent system requires that a decision variable be defined at the beginning of the development process. In this study, the choices were the worker's or the employer's responsibility for the accident. Since this is a zero-sum situation, the selection of one or the other does not make any difference in the functioning of the model. In this study, the responsibility of the worker for the fall was selected as the decision variable. Therefore, the discussion between the worker and the employer was modeled to quantify the responsibility of the worker rather than the responsibility of the employer.

The agents of the multi-agent system developed in this study are the worker and the employer. The employer makes the initial determination of responsibility, typically by assuming little responsibility and assigning most of the responsibility for the fall to the worker. The worker counters with the worker's perspective, typically assigning most of the responsibility to the employer. Both agents have a "reservation value" that defines their limit in making concessions to each other. For the employer, the reservation value is the lowest worker responsibility that can be accepted by the employer, whereas for the worker, it is the highest worker responsibility that can be accepted. In other words, if the worker's responsibility is lower than the employer's reservation value, the employer's responsibility becomes so high that it is not acceptable to the employer; if the worker's responsibility is higher than the worker's reservation value, then the worker assumes such a high responsibility that it makes it unacceptable to the worker. The parties are privy to each other's reservation values. The initial determination of the employer, the initial response of the worker, and the reservation values are inputted into the system by using the fuzzy logic approach proposed by Akcay et al. [42] and Karakas et al. [41]. The initial determination and reservation value of the employer, and the initial response and the reservation value of the worker are set using Equations (2)–(5).

$$\mathrm{F_e} = \sum_{i=1}^{5} (W_{ei} + W_{si}) \times (1 + F_i) \tag{2}$$

where F_e is the initial determination of the employer; W_{ei} is the weighted percentage of the i^{th} factor where the employer has the power; W_{si} is the weighted percentage of the i^{th} factor where the power is shared; F_i is the fuzziness level of the i^{th} factor.

$$F_w = \sum_{i=1}^{5} (W_{ei} + W_{si}) \times 0.4 \quad (3)$$

where F_w is the response of the worker to the employer's initial determination; W_{ei} denotes the weighted percentage of the i^{th} factor where the employer has the power; W_{si} is the weighted percentage of the i^{th} factor where the power is shared.

$$R_e = \sum_{i=1}^{5} (W_{ei}) \times (1 - F_i) \quad (4)$$

where R_e is the reservation value of the employer; W_{ei} denotes the weighted percentage of the i^{th} factor where the employer has the power; F_i is the fuzziness level of the i^{th} factor.

$$R_w = \sum_{i=1}^{5} W_{ei} + W_{si} \quad (5)$$

where R_w is the reservation value of the worker; W_{ei} denotes the weighted percentage of the i^{th} factor where the employer has the power; W_{si} is the weighted percentage of the i^{th} factor where the power is shared.

As the discussion between the employer and the worker relative to the quantification of employer and worker responsibilities is a dynamic process, and the parties are fully informed about their respective reservation values, the Zeuthen Strategy was selected as a most appropriate settlement protocol. This strategy is performed by comparing the parties' tolerance to risk, which shows the ratio of the utility loss when a party accepts the determination of the other party and the utility loss when the party rejects the other party's determination [78]. The maximum risk acceptable to the employer and to the worker can be calculated using Equations (6) and (7), respectively.

$$R_e = \frac{U_{ee}^n - U_{ew}^n}{U_{ee}^n - U_e(C)} \quad (6)$$

where R_e denotes the maximum risk that is acceptable to the employer in round n; U_{ee}^n denotes the utility to the employer of the employer's determination in round n; U_{ew}^n denotes the utility to the employer of the worker's response to the employer's determination in round n; $U_e(C)$ is the utility to the employer of a breakdown in the discussions.

$$R_w = \frac{U_{ww}^n - U_{we}^n}{U_{ww}^n - U_w(C)} \quad (7)$$

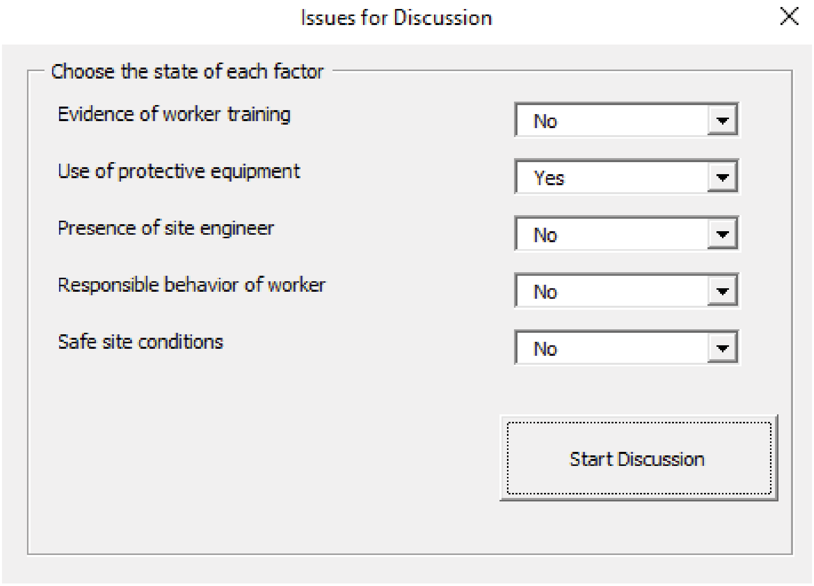
where R_w denotes the maximum risk that is acceptable to the worker in round n; U_{ww}^n denotes the utility to the worker of the worker's response to the employer's determination in round n; U_{we}^n denotes the utility to the worker of the employer's determination in round n; $U_w(C)$ is the utility to the worker of a breakdown in the discussions.

As per Karakas et al. [41], the recommended utility of the employer's initial determination and the worker's first response was set to one, whereas the utility of the reservation value for each party was set to 0.6. It should be noted that the utility curve between these two values is linear and shows the degree of the agent's satisfaction. The parties calculate their gains and losses at each round by using these functions.

The model was created by using a Java Agent Development Framework (JADE), which is one of the most widely used software environments that enable users to perform agent communications.

3.3. Case Example

In the starting interface of the program (Figure 2), the user specifies the status of the factors that affect fall-related accidents in the building project in question and clicks on the "start discussion" button. In the first round, the system calculates the initial determination of the employer agent using Equation (2), the worker agent's initial response to the employer agent's initial determination (Equation (3)), and each agent's reservation values (Equations (4) and (5), respectively) as depicted in Figure 3. The reservation values remain the same in each round.


Issues for Discussion

Choose the state of each factor

Evidence of worker training: No

Use of protective equipment: Yes

Presence of site engineer: No

Responsible behavior of worker: No

Safe site conditions: No

Figure 2. Starting Interface.


Employer Agent

Initial determination: 48.86 %

Reservation: 12.39 %

Worker Agent

Initial response: 16.48 %

Reservation: 41.20 %

Figure 3. Employer Agent's Initial Determination and Worker Agent's Response to the Initial Determination in the First Round.

After these values are calculated by the system, the discussion about the employer agent's determinations and the worker agent's responses to these determinations proceeds by using the Zeuthen Strategy. In this strategy, the parties compare the maximum risk that is acceptable to them and their opponents (using Equations (6) and (7)) in each round. The agent who has the lower acceptable maximum risk, makes the next offer. The discussion between the agents continues until the value of R_e (Equation (6)) equals to the value of R_w (Equation (7)). In this example, the system generates the responsibility of the worker for this case as 18.43%.

3.4. Performance of the Model

Seven court cases related to fall-related accidents were used to test the performance of the proposed multi-agent system. The condition of each factor and the responsibility that the court assigned to the worker were determined by examining the court records. The responsibility that the court assigned to the worker was compared with the worker's responsibility obtained by using the proposed model. The comparison was performed by calculating the percentage difference in each case using Equation (8).

$$\mathrm{D} = |E - T| \tag{8}$$

where D is the percentage difference for each case; E is the worker's responsibility obtained by using the proposed multi-agent system; T is the worker's actual responsibility of the worker assigned by the court.

Table 7 summarizes the information extracted from the court records and the output of the proposed model for each case. With the exception of the outlier, Case 4, which has a difference of 11.03%, the average differences of the remaining six cases amounts to ±4%, indicating that the performance of the model is quite satisfactory. Courts give their final decisions by considering the reports of safety experts. The minor variation in the differences between the determinations of the courts and the outcomes generated by the proposed model can be explained by the subjectivity of the experts' judgments.

Table 7. Performance Results.

Case ID	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Responsibility of Worker Assigned by the Court (%)	Responsibility of Worker Assigned by Multi-Agent System (%)	Difference (%)
Case 1	Yes	No	Yes	Yes	No	40	48.86	8.86
Case 2	No	Yes	No	No	No	20	18.43	1.57
Case 3	Yes	No	No	No	No	35	40.76	5.76
Case 4	Yes	No	Yes	No	Yes	75	86.03	11.03
Case 5	No	No	No	Yes	Yes	25	24.97	0.03
Case 6	No	No	No	Yes	Yes	30	24.97	5.03
Case 7	No	No	No	Yes	No	15	11.91	3.09

Factor 1 = Evidence of worker training. Factor 2 = Use of protective equipment. Factor 3 = Presence of site engineer. Factor 4 = Responsible behavior of worker. Factor 5 = Safe site conditions.

4. Conclusions

The construction safety literature routinely covers many aspects of fall-related accidents that frequently occur on construction sites, including the causes and consequences of these accidents, although none of the studies have ever modelled the interaction between the employer and the worker to predict each party's responsibility in fall-related accidents. Several dispute resolution methods have been developed as an alternative to lengthy and expensive litigation over the years and some of them like arbitration, mediation, and dispute review boards have been quite successful in achieving a fast, inexpensive, convenient, and fair resolution of disputes between construction owners and contractors, however, alternative dispute resolution methods have never been used to settle the parties' responsibilities over fall-related accidents. In response to this research gap, this paper proposes a multi-agent system to simulate the discussions between an employer and a worker for quantifying the responsibilities of these parties in fall-related accidents in construction sites, a major concern especially in building construction sites. Even though agent-based systems have been used by researchers to find solutions to various construction-related problems, only a few researchers attempted to regulate the relationship between contractors and their workers relative to their responsibilities in construction accidents, but never in fall-related accidents.

First, the factors that affect the discussions were identified by performing a brainstorming session with 13 experts, examining the records of 27 cases tried in courts of law, and getting closely acquainted with related laws and regulations. Second, the impact of each factor was determined by conducting a questionnaire survey administered to 48 experts. A Relative Importance Index (RII) was calculated to analyze the results. Third, another questionnaire survey was conducted to determine the fuzziness level of each factor. The Delphi method was performed to reduce the range of answers. Fourth, the model was constructed on the JADE platform by setting up the discussion protocol, creating agents, setting up the input values, and defining the utility function of each agent. Fifth, the performance of the model was assessed by comparing the output of the model and the actual court decisions in seven court cases. The model provides satisfactory results and can be used to quantify the employer′s and the worker′s responsibilities in construction fall accidents.

This research contributes to construction safety management in the context of fall-related accidents that constitute a serious problem especially in building construction sites. It also provides potential benefits to the legal system that is routinely used to settle differences between employers and workers in such accidents.

- This is the first study in the literature that offers a multi-agent system to simulate the discussions between an employer and a worker to settle with mutual satisfaction the employer′s and the worker′s responsibilities in fall-related accidents.
- This research provides fast, objective, and equitable solutions to the sensitive and usually controversial process of apportioning responsibility between employers and workers for fall-related accidents in the construction industry.
- The proposed model generates more sensitive results (two digits after the decimal point) than the traditional quantification used in court cases (integers in increments of five).
- Instead of waiting for the expert report, the courts or arbitrators can use this model to quantify the responsibilities of the parties, leading to a faster decision with a shorter stressful period for both parties. Better still, if the parties use the proposed model and settle out of court, the current case load of the severely congested court dockets can be radically reduced.
- The responsibilities for fall-related accidents can be assessed consistently for similar cases by using the proposed model. In other words, the proposed model's consistent outcomes do away with the subjectivity of the expert reports typically sought by courts of law.

It should be noted that the proposed model can be used to quantify the responsibilities of only the employer and the worker. The responsibilities of other parties such as the site engineer, the project manager, the subcontractor, etc., cannot be predicted. Simulating other parties' responsibilities in fall-related accidents can be explored in future research. In addition, the proposed model can be expanded to assess the responsibilities for other types of accidents other than falls.

Author Contributions: Conceptualization, E.C.A.; Formal analysis, E.C.A.; Investigation, D.A. and E.C.A.; Methodology, D.A. and E.C.A.; Software, E.C.A.; Supervision, D.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

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

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Safety Risk Recognition Method Based on Abnormal Scenarios

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Abstract: Construction safety monitoring is a significant issue in practical engineering. Unfortunately, specific techniques in this field still heavily depend on artificial monitoring. To detect the abnormal scenarios during the construction process automatically, a method was proposed for the detection and localization of abnormal scenarios in time and space. The method consists of three components: (1) an I3D-AE video prediction model, which extracts the video features from multiple I3Ds and reconstructs the video by 3D deconvolution; (2) a spatial localization module AS-CAM, which determines the location of abnormal areas via back-propagating the I3D-AE; (3) a temporal parameter S_t, which can calculate the abnormal time period. The effectiveness of the method was verified with the use of a dataset, and the resulting data were plotted as ROC curves. The results indicated that the proposed method exceeded 0.9 on the frame-level test and 0.76 on the pixel-level test with the use of the AUC evaluation metric. Therefore, it can be used to assist the construction managers to improve the efficiency of construction safety management.

Keywords: abnormal scenarios detection; localization; video prediction; autoencoder; construction process

Citation: Li, Z.; Song, B.; Li, D. Safety Risk Recognition Method Based on Abnormal Scenarios. *Buildings* **2022**, *12*, 562. https://doi.org/10.3390/buildings12050562

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 24 March 2022
Accepted: 25 April 2022
Published: 27 April 2022

1. Introduction

Construction is a high-risk industry in many countries, and the risks inherent in the construction industry contribute to high worker fatalities. According to the US Bureau of Labor Statistics (US BUREAU OF LABOR STATISTICS), 3.1 out of every 100 full-time construction workers in the US were injured and sick, and according to the UK National Safety Executive (HSE), 262 workers were injured per 10,000 workers in the UK construction industry in 2017 [1].

Construction site monitoring is an essential procedure in construction safety control, to minimize construction safety risks, as well as to support project managers in making strategic decisions at critical times [2]. However, the construction site environment is complex [3], and with many targets [4], so it is difficult for construction managers to monitor the construction site in real time. Since there are numerous cameras on the construction site [5], it is convenient to introduce some vision-based technologies for continuously monitoring the activities of construction sites [6–10].

However, most of the existing studies have focused on the recognition and tracking of workers' actions during the construction process. The hazards of the construction process do not arise only from workers' actions, but also from the presence of some construction workers, construction machines, or construction materials in areas and times where they should not be. For example, falling from heights are the greatest risk of death for construction workers [11,12]; on the one hand, they are due to the construction workers not wearing safety belts as required when working at heights [13], while on the other hand, the illegal presence of construction workers in some overhead areas is an important reason [14]; in construction site fire accidents, flammable construction materials in areas with a considerable amount of welding work are the main cause of fires in the construction process [15–17]. To cope with these risks, researchers have proposed intelligent methods for identifying risk scenarios [18,19].

Although the current approach focuses on specific risk recognition, in the construction site, there are many types of risks, and they change with time, so if the risks are recognized in a directional way, it is easy to cause insufficient recognition of risks; a risk recognition method that can be used for a multi-scenario recognition is also lacking. Under a sound security management system, the occurrence of risk events is generally a small probability event, i.e., an abnormal event. Abnormal events are unpredictable, and if they are recognized for this characteristic of risk events, security risks can be effectively recognized while consuming a small amount of computation. Compared with previous methods, the greatest contribution of this paper is in its exploratory attempt to use the unpredictability of risk scenarios to identify risks; this is the first time that the idea of abnormal scenarios prediction is used to recognize the safety risks of the construction process, for which only a deep learning network is needed to avoid tedious database construction.

Based on the above analysis, we proposed a 3DCNN-based encoder model to detect abnormal frames by predicting future frames, which is an end-to-end deep learning framework trained on normal video samples. Specifically, we predicted a video based on the history of video clips; to this end, we first built a prediction model that can predict future videos, and we trained it with a normal video so that it can predict future videos. In the testing phase, if the error between the truth frame and the predicted frame was small, we decided that it was a normal video, and if the error was large, we considered this frame as an abnormal frame. An effective model to predict the video is key for the task, and therefore, we used an I3D-AE encoder as the video prediction model, which consists of two parts—an encoder and a decoder. In the encoder part, we used multiple I3D [20] networks to extract video features, which have good performance in extracting video features, and we used multiple 3D deconvolutional networks in the decoder. For the abnormal scenarios localization, we proposed a module AS-CAM for the spatial information localization and a parameter S_t for the temporal information localization.

2. Related Research

2.1. Abnormal Scenario Detection Methods

Sungmin and Junseok [21] proposed a novel system that detects abnormal events. Unlike conventional methods, they considered abnormal event detection as a variation matching problem. In the application of abnormal scenarios detection, deep learning plays an irreplaceable role. Wei et al. [22] proposed an abnormal scenario detection method for monitoring abnormal activities in public places. They exploited fully convolutional neural networks (FCNs), which have been proved to be powerful in image processing, to extract the features of videos. Zhang et al. [23] introduced a more effective algorithm for detecting abnormal behaviors in narrow areas with perspective distortion. The algorithm firstly uses the adaptive transformation mechanism to make up for the distorting effect in the region of interest extraction. Then, an improved pyramid L–K optical flow method with perspective weight and disorder coefficient was proposed to extract the abnormal behavior feature that occurred in historical moving images. Abid [24] proposed a two-stream architecture using two separate 3D CNNs to accept a video and an optical flow stream as input to enhance the prediction performance. He et al. [25] proposed an anomaly introduced learning (AL) method to detect abnormal events. A graph-based, multi-instance-learning (MIL) model was formed with both normal and abnormal video data. Sabokrou et al. [26] were the first to apply deep learning to the task of abnormal scenario detection; the researchers combined two detectors into a cascade classifier and achieved good detection results. Fully convolutional networks (FCNs) were used in a pretrained model [27], combining semantic information (inherited from existing CNN models) and low-level optical flow to measure local anomalies. One of the advantages of this method is that it does not require fine-tuning of the phase.

2.2. Construction Risk Scenario Detection Methods

Duan et al. [28] proposed a method to recognize and classify four different risk events by collecting specific acceleration and angular velocity patterns through built-in sensors of smartphones. The events were simulated with anterior handling and shoulder handling methods in the laboratory. After data segmentation and feature extraction, five different machine learning methods were used to recognize risk events, and the classification performances were compared. Jeongeun et al. [29] proposed a deep convolutional neural network that automatically recognizes possible material and human risk factors in the field regardless of individual management capabilities. The most suitable learning method and model for this study's task and environment were experimentally identified, and visualization was performed to increase the interpretability of the model's prediction results. Kim et al. [30] analyzed the step-by-step process required to automate construction site safety management based on Building Information Modeling (BIM) and evaluated a specific construction site hazard using a BIM-based example. Yang et al. [31] developed a fire identification model and a real-time construction fire detection (RCFD) system. Experiments were conducted to verify the applicability of the proposed system under different environmental conditions. Xiong et al. [32] developed an automated hazards identification system (AHIS) to evaluate operational instructions generated from field videos based on safety guidelines extracted from text files by construction safety ontology. Zhang et al. [1] proposed an automatic recognition method.

3. Proposed Method

We proposed an abnormal detection method during the construction process based on future frame prediction, consisting of a model for predicting future frames, which is called I3D-AE, and using past frames in video clips to predict future frames. We proposed a module AS-CAM to locate the spatial information of abnormal scenarios and used a parameter S_t to locate the temporal information of the abnormal scenarios. The key elements of the proposed method are shown in Figure 1.

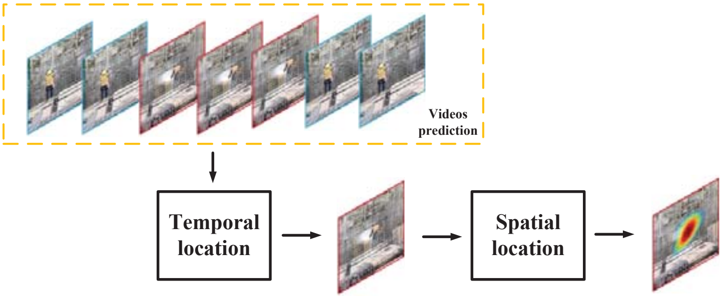

Figure 1. Key elements of proposed method.

3.1. I3D-AE Video Prediction Model

Unlike conventional autoencoders, our convolution is a 3D convolution, and multiple I3Ds were used in the encoder (two-stream inflated 3D ConvNets) [20]. One video clip was extracted from each I3D, and the video clips extracted from adjacent I3Ds were consecutive but not intersecting. The number of I3D modules can be used according to the actual situation; the number of modules used for the purposes of this paper was four. The 3DCNN is expanded from 2DCNN Inception-V1 and can use the parameters pretrained on ImageNet. The experimental results show that this model achieved the best results with this configuration on all standard datasets. The middle layer uses three fully connected layers, and the decoder has a 3D deconvolutional structure. We used a normal construction site video as the training video, as we can reconstruct the video well when the test video is a normal video, and the reconstruction error is large when the test video is an abnormal video. The model structure is shown in Figure 2.

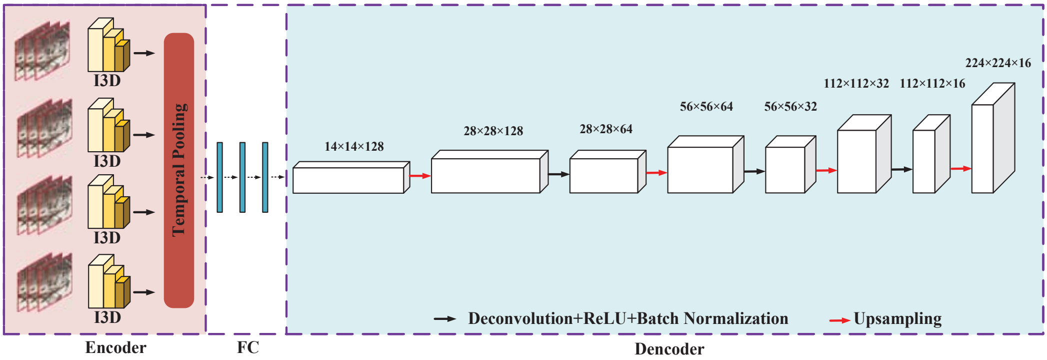

Figure 2. Structure chart of our I3D-AE.

At the beginning of the training, given an input video clip V_i and a future clip V_p, the autoencoder reconstructs the video using $I_w(F_w\ (D_w\ (V_i)))$, where I_w is an I3D integrated network with the weight parameter I_D, F_w is a fully connected layer with the parameter w_F, and the decoder D_w is a 3D deconvolutional network with the weight parameter w_D. To train this autoencoder, we used Euclidean loss as the loss function.

$$w_I, w_F, w_D = argmin \sum_i \| V_p - I_w(F_w(D_w(V_i))) \|_2^2 + \lambda \Big(\| I_w \|_2^2 + \| F_w \|_2^2 + \| D_w \|_2^2 \Big) \quad (1)$$

The first term of the objective function is the loss function, which was used to calculate the difference between the reconstructed frame and the video frame, and the second phase of the objective function is the L2 regularization, which was used to limit the complexity of the parameters in the autoencoder. In the encoder part, to reduce the model parameters, we read 64 frames of grayscale video instead of RGB video and used four I3D modules as feature extractors; the features extracted by the I3Ds were pooled in time and then entered into the fully connected layer. In the decoder part, we used four upsampling layers and three deconvolution layers, each of which contains a ReLU layer.

3.2. Spatial and Temporal Locating

3.2.1. Abnormal Scenario Spatial Localization

Since we trained normal clips as the dataset, abnormal scenarios cause a larger reconstruction error when they appear in the clips. The reason for the increased reconstruction error is due to the presence of abnormal scenarios in the clips. Therefore, it is crucial to find the pixels that cause the reconstruction error to increase, the locations of which indicate abnormal scenarios. Based on the above assumptions, we proposed an AS-CAM module to locate abnormal scenarios, which was developed based on Grad-CAM++ [33]. The flow of the AS-CAM is shown in Figure 3.

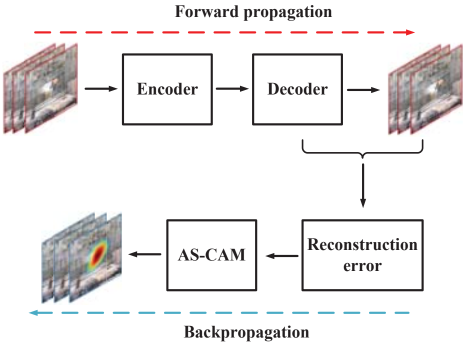

Figure 3. Flowchart of AS-CAM.

Grad-CAM++ is based on CAM [34] and Grad-CAM [35], the principle of which is to construct the weights of the action maps, and by solving for the weights, the contribution of different action maps to the reduction in the objective function is obtained; furthermore, by multiplying weights with the action maps, the heat maps are obtained to show which area contribute most to the reduction in the objective function. In our task, we needed to find out which areas contributed most to the increase in reconstruction error, which were the locations of irregular construction in the construction scenarios. The calculation formula for the abnormal location is as follows:

$$L_{ij} = \sum_{k} w_k \cdot A_{ij}^{k} \tag{2}$$

where L_{ij} is the saliency map of abnormal scenarios of spatial location (i,j), and w_k is the weight of the pixel A_{ij} in the k^{th} action map. The value of w_k can be multiplied by the pixel weights α_{ij}^{c} and the loss gradient through the negative ReLU (NReLU) activation weighting.

$$w_k = \sum_{i} \sum_{j} \alpha_{ij}^{k} \cdot \text{NReLU}\left(\frac{\partial \Delta J}{\partial A_{ij}^{k}}\right) \tag{3}$$

where α_{ij}^{k} is the weighting coefficient of pixel (i,j) when w_k is calculated; NReLU is the activation function. The calculation of α_{ij}^{k} is as follows:

$$\alpha_{ij}^{k} = \frac{\dfrac{\partial^2 \Delta J}{\left(\partial A_{ij}^{k}\right)^2}}{2\dfrac{\partial^2 \Delta J}{\left(\partial A_{ij}^{k}\right)^2} + \sum_{a}\sum_{b} A_{ab}^{k} \dfrac{\partial^3 \Delta J}{\left(\partial A_{ij}^{k}\right)^3}} \tag{4}$$

where (i,j) and (a,b) are iterators over the same activation map. NReLU is designed to activate the negative gradients, so the expression of NReLU is as follows:

$$\text{NReLU} = f(x) = \min(x, 0) \tag{5}$$

where ΔJ is the reconstruction error, with the input of V_i. It can be calculated by backpropagation of the I3D-AE, and the equation is as follows:

$$\Delta J = \parallel V_p - I_w(F_w(D_w(V_i))) \parallel_2^2 \tag{6}$$

Therefore, the saliency map of abnormal scenarios is calculated by Equation (7) as follows:

$$L = \sum_i \sum_j L_{ij} \tag{7}$$

3.2.2. Abnormal Scenario Temporal Localization

For the temporal localization of abnormal scenarios, we calculated the reconstruction error for each frame by subtracting the pixel value of each frame from the pixel value of the corresponding frame of the reconstructed video.

$$e_t = \frac{\sum_{x,y} \parallel V(x,y,t) - I(F(D(V(x,y,t)))) \parallel_2}{x \cdot y} \tag{8}$$

where $V(x,y,t)$ indicates the pixel value of a frame, $I(F(D(V(x,y,t))))$ indicates the pixel value of the reconstructed frame at that specific time; after normalizing the reconstruction error, we obtained the temporal information parameter as follows:

$$S(t) = \frac{e_t - e_{min}}{e_{max} - e_{min}} \tag{9}$$

4. Experiments

4.1. Construction Site Dataset

A dataset was taken at a construction site in Chengdu with an iPhone 13. The intention of this section is to simulate a fire scenario in a construction site, hoping to detect fire scenarios in time and space. In construction sites, fires are generally prohibited, so in order to simulate the identification of fire scenarios, in this section, we use the image of steel welding as an alternative. Since fire and smoke are generated when steel welding is drawn and welded, the characteristics of fire can be well simulated. The video in which no firelight and smoke are generated was used as the regular screen for training I3D-AE in dataset species, and the welding screen containing firelight and smoke was tested as the abnormal screen. The dataset contained a total of 62 min of video in the regular frame and 3 min of video in the abnormal frame.

4.2. Evaluation Criteria

In order to evaluate the abnormal scenarios detection method, the receiver operating characteristic (ROC curve) was used as an evaluation metric, which is based on a series of different dichotomies, (cutoff values or decision thresholds), with the true-positive rate (TPR) representing the percentage of samples that are correctly judged as positive among all samples that are actually positive, and false-positive rate (FPR) representing the percentage of samples that are incorrectly judged as positive among all samples that are actually negative. The ROC curve represents the sensitivity of different thresholds to TPR and FPR, and the fuller the curve, the better the classification. TPR and FPR are calculated as follows:

$$TPR = \frac{TP}{TP + FN} \tag{10}$$

$$FPR = \frac{FP}{FP + TN} \tag{11}$$

where false negative is FN, false positive is FP, true negative is TN, and true positive is TP. As shown in Table 1, FN indicates a sample judged to be negative but is in fact positive, FP indicates a sample judged to be positive but is in fact negative, TN indicates a sample judged to be negative and is in fact negative, and TP indicates a sample judged to be positive and is in fact positive.

Table 1. Meaning of TP, TN, FP, and FN.

	Actual Positive Samples	Actual Negative Samples
Predicted to be positive samples	TP	FN
Predicted to be negative samples	FP	TN

The effectiveness of the proposed method was evaluated from two perspectives—the pixel-level evaluation method and the frame-level evaluation method. Both methods use the area under the curve (AUC) as an evaluation metric, in addition to the ROC curve, which indicates the area enclosed by the ROC curve and the coordinate axes; the larger it is, the better the performance of the classifier.

(1) Pixel level

The ROC curves at the pixel level were designed to provide the localization ability of the proposed method in space, for which the intersection-over-unio ratio was used as a predictor. Intersection-over-unio (IOU) ratio, a concept used in target detection, is the intersection ratio of the generated candidate frames to original marker frames, i.e., the ratio of their intersection to the merged set, and is calculated as shown in Equations (1)–(12). The intersection-to-merge ratio is ideally a complete overlap, i.e., a ratio of 1. If the intersection-to-merge ratio between the localized area and the true anomaly area is greater than a threshold, the localization result under that frame is defined as a positive sample, and if the intersection-to-merge ratio is less than the threshold, the localization result under that frame is defined as a negative sample.

$$IoU = \frac{\text{area}(L) \cap \text{area}(G)}{\text{area}(L) \cup \text{area}(G)} \tag{12}$$

(2) Frame level

The ROC curves at the frame level were designed to provide the localization ability of the proposed method in time, for which the S_t value was used as a predictor.

4.3. Implementation Details

We adjusted all video clips to 224 × 224 and calculated the optical flow between each adjacent frame [36]. I3D-AE uses Adam [37] as the optimizer with a learning rate of 0.0001, a minimum batch size of 100, and an epoch setting of 200; our model was implemented on TensorFlow 1.14 and trained, with a 2080TiGPU. The model parameters are shown in Table 2.

Table 2. I3D-AE; the main parameters of the model.

Layer	Output Size	Kernel Size	Stride	Pad
FC	14 × 14 × 128			
Upsampling 1	28 × 28 × 128			
DeConv 1	28 × 28 × 64	3 × 3 × 3	2	1
Upsampling 2	56 × 56 × 64			
DeConv 2	56 × 56 × 32	3 × 3 × 3	2	1
Upsampling 3	112 × 112 × 32			
DeConv 3	112 × 112 × 16	3 × 3 × 3	2	1
Upsampling 4	224 × 224 × 16			

5. Experimental Results

5.1. Visualization of Spatial Localization Results

Figure 4 shows the experimental results of the method proposed in this study on a construction site dataset. When workers perform welding, fire and smoke cause changes in the reconstruction errors, which are localized. When there is no smoke, the proposed method locates the flame more accurately, but when there is smoke, the smoke causes an increase in the reconstruction error and the size of the localized area is larger than the real area.

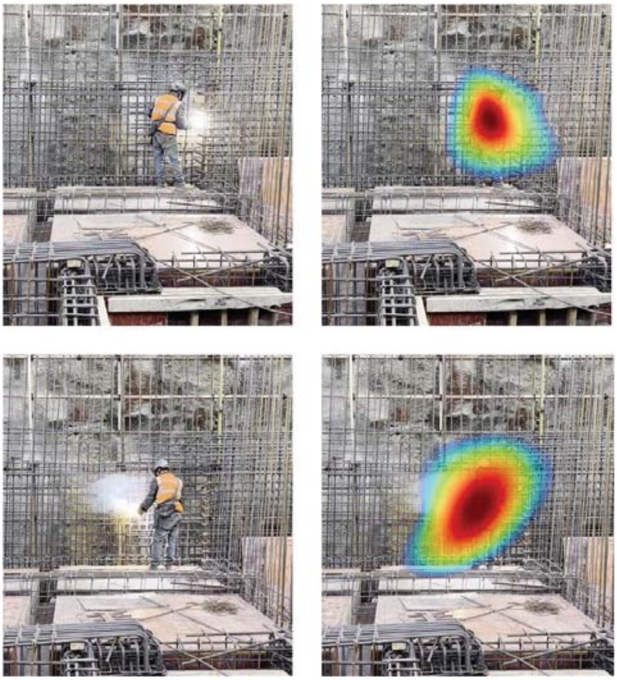

Figure 4. Experimental results of the construction site dataset.

5.2. Temporal Localization Results

Figure 5 shows variations in S_t values in the construction site dataset and distinguishes normal and abnormal frames with background colors. It can be seen from the figure that, in the normal frame, the value of S_t is small, and the curve is flat, while in the abnormal frame, the value of S_t is more prominent, and the two cases can be clearly distinguished. In both scenarios, there is an elevated value of S_t in the normal frame, but in the abnormal frame, S_t does not appear flat, indicating that the method had a mild over-recognition in recognizing abnormal scenarios. As shown in Figure 6, a ROC of 0.901 on the frame-level ROC curve indicates that S_t can distinguish between normal and abnormal frames in time well.

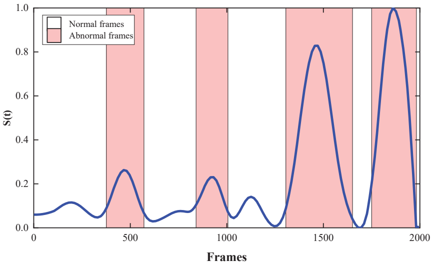

Figure 5. The *St* curves of a clip in the construction site dataset.

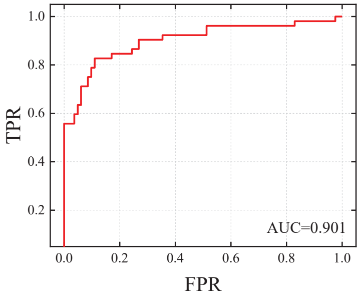

Figure 6. ROC curve at frame level.

5.3. Ablation Experiments

In this section, the effectiveness of each module of the proposed method is tested through a set of ablation experiments. The experiments are divided into two groups. In Experiment 1, the four I3D modules in the I3D-AE module were replaced with C3D models, i.e., the commonly used 3DCNN video feature extraction networks, and then the module was trained and tested with the replaced network and the construction site dataset. This experiment tested the feature extraction effectiveness of the proposed I3D-AE. In Experiment 2, AS-CAM was replaced with the reconstruction error-based localization method, i.e., the reconstruction error was used as the activation map to achieve the localization of anomalous areas, and then the replaced network and the construction site dataset were used for training and testing; this experiment tested the localization effect of the proposed AS-CAM. The ROC curves and AUC values were used to show the localization ability of the network used in the experiment.

As seen in Figure 7, the ROC curves of the proposed method are fuller than those of the C3D-based method, indicating that the proposed method outperformed the C3D-based method in locating anomalous areas. The reason for this is that the C3D-based method is weaker than I3D in video feature extraction, and I3D has the advantage of pretraining; therefore, it can capture more details in the video through multiple I3D modules in series, making it a stable and fast video feature extraction method.

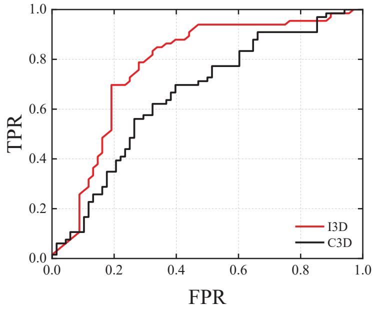

Figure 7. Pixel-level ROC curves with video feature extraction method changes.

From Figure 8, it can be seen that AS-CAM has a better localization effect based on the area surrounded by curves and axes, and the reconstruction error-based method has a larger gap than the proposed method. The reason is that, in video prediction, although a reconstruction error can represent an anomalous area, it is also affected by network depth—when the network layers are deep, the anomalous pixel area causes the error not necessarily in the mapped anomalous area; therefore, this type of method is more suitable for shallow encoder networks.

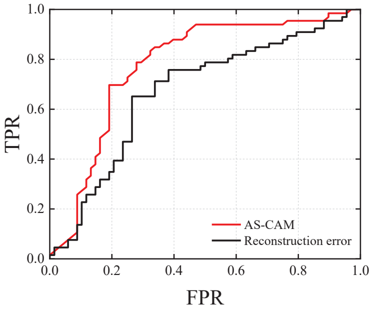

Figure 8. Pixel-level ROC curves with changes in localization method.

6. Discussion

(a) In this study, automatic recognition for potential safety risks at construction sites was investigated. The principle is to use the unpredictability that risk scenes have; thus, a video prediction model was used, and when the prediction model demonstrated anomalies, the scene was considered to have the possibility of risk.

(b) Compared with the traditional human safety risk recognition method, the proposed method is an intelligent recognition technique. Compared with the existing techniques based on intelligent algorithms, the proposed method omits the database construction of risk scenes and is a lightweight method.

(c) The proposed method provides a new way of thinking in terms of risk scenario detection. It is not necessary to detect only specific security risks; undirected detection can still be effective for risk recognition.

7. Conclusions

Construction safety has always been an important problem in the construction industry, and currently, it mainly relies on manual inspection to detect the risk of construction sites. In this paper, deep learning methods were applied to the process of construction risk detection, providing a new perspective for intelligent monitoring of construction sites as follows:

- A new abnormal scenarios detection method for construction sites was proposed, which contains a video prediction model, I3D-AE, a spatial information module, AS-CAM, and a temporal information parameter, S_t;
- By locating abnormal areas by replacing the reconstruction error with a weighted saliency map, this method can achieve a good localization effect when faced with a complex image;
- Our method was validated with a dataset, and the results show that our method can reach an advanced level at construction sites;
- The proposed approach allows for the recognition of multiple unknown risks, rather than specific risk scenarios, avoids building a database, and saves computing resources.

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

Funding: The authors are grateful for the financial support from the National Natural Science Foundation of China (NSFC), under Grant Nos. 51778104, and the Fundamental Research Funds for the Central Universities (Project No. DUT19LAB26).

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

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Safety Built Right in: Exploring the Occupational Health and Safety Potential of BIM-Based Platforms throughout the Building Lifecycle

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Abstract: This article investigates the opportunities of using digital building platforms based on Building Information Modelling (BIM) to increase occupational health and safety (OHS) in building design, construction, operation and deconstruction. The data collection followed a mixed-method approach with a systematic mapping review and focus group discussions with industry practitioners from the Swedish construction and real estate industry. Use cases were identified from both venues, as were prevailing barriers, potential facilitators, best practices and future applications. The findings highlight OHS potentials of digital building platforms for Rule-Based Checking and Design Validation, Team Building and Communication, Site Layout and Task Planning, Real-Time Monitoring, Equipment and Temporary Structures, Robotic Task Performance and Learning and Documentation. A set of principles is proposed to promote a higher degree of lifecycle and stakeholder integration: (1) technology, (2) data and information, (3) business and organization, (4) people and communication and (5) industry structure and governance aspects.

Keywords: occupational health and safety; digital twin; building information modelling; building life cycle; construction safety; design for safety; construction management; facility management

Citation: Hoeft, M.; Trask, C. Safety Built Right in: Exploring the Occupational Health and Safety Potential of BIM-Based Platforms throughout the Building Lifecycle. *Sustainability* **2022**, *14*, 6104. https://doi.org/10.3390/su14106104

Academic Editor: Srinath Perera

Received: 21 March 2022
Accepted: 11 May 2022
Published: 17 May 2022

1. Introduction

The building sector has one of the highest rates of accidents and fatal injuries each year both in greenfield construction and maintenance works. In 2020, the construction industry had the largest proportion of people reporting a workplace accident in the European Union: 4.2% compared to 2.4% for all industries combined [1]. Most commonly, accidents concern falling, slipping or interactions with machinery. In addition, factors such as stress and long-term harmful work postures further put workers' occupational health and safety (OHS) at risk [2].

While the need for safety measures is generally recognized, risk assessments are often performed by individual trades and in an ad-hoc manner. In common industry practice, the ultimate liability for accidents happening on a construction site is borne by the constructor organization, even if those accidents could have been avoided by earlier design adjustments or evaluations [3]. Frequently, risk assessment approaches are inconsistent across projects and rely on the tacit knowledge and experience of individuals [4] As a consequence, information is not passed beyond discipline silos to all affected project parties. This refers to both vertical integration along the supply chain and horizontal integration along the lifecycle of a building [5,6]. On a vertical level, collaboration with workers, cross-trade training for a broadened safety understanding and adaptive safety to reduce paperwork are encouraged [7]. Throughout the building lifecycle, the notion of lifecycle safety has been introduced [8] to "reflect safety concerns in all phases of the facility's lifecycle including programming, detailed design, construction, operations and maintenance, retrofit and decommissioning" (p. 2). In this lifecycle context, the concepts of Prevention through Design (PtD) and Design for Safety (DfS) are deemed especially impactful [9,10], given that a large share of construction accidents is related to design.

As manual, 2D-based safety planning has significant shortcomings and is prone to human error [11], recent research has focused on exploring safety technologies to support risk management. For example, emerging construction safety technologies have been clustered into applications for: project safety design and planning, visualization and image processing, project monitoring, information management and Internet of Things (IoT), automation and robotic systems, accident prevention and structure evaluation [12]. It is notable that most of the solutions are linked to (or based on) Building Information Modelling (BIM) platforms [9,13,14]. This enables more comprehensive representations; for example, hazard identification, 4D scheduling or automated safety code checking [10]. Additional applications in the operation and maintenance phase include the use of BIM tools for fire safety management and the identification of safety attributes during repair activities [5]. BIM has also been explored to help in the transfer of building system information from the design and construction to the operation stage to minimize safety risks [15]. Beyond those areas, information management and maintenance safety evaluation in the design stage have been highlighted as future research areas [16]. It should be noted that more recently advancements have been made beyond the pure semantic representation of building components and systems. Here, the concept of a Digital Twin aims at "a more holistic socio-technical and process-oriented characterization of the complex artefacts involved by leveraging the synchronicity of the cyber-physical bi-directional data flows", through the integration of BIM data with real-time data from IoT sensors or artificial intelligence (AI) [17]. However, research on the technology potential for increased OHS is to a large extent limited to the planning and construction phases, while other stages have been neglected [10,18].

As collaborative work methods have become more popular, opportunities have emerged for promoting safety throughout the building lifecycle in the context of an integrated, platform-based collaboration process. To facilitate this, there is a need to summarize and analyze the most recent research on BIM and operational health and safety (OHS). The successful implementation of digital OHS tools requires mapping not only the potential use cases (in terms of safety hazards and proposed solutions) within each lifecycle stage, but also the corresponding barriers and success factors when attempting to implement BIM methodology for OHS purposes ("BIM for OHS") in real life project settings.

Existing studies of BIM methodology have focused mainly on environmental and economic performance evaluations throughout the lifecycle [19–21]. Many existing reviews on the use cases do not specifically focus on safety implications beyond acknowledging generic benefits across the project lifecycle and stakeholder dimensions [22–24] or were performed in the context of another industry, e.g., manufacturing [25]. Available reviews of the OHS applications of BIM methodology tend to provide a cursory summary of findings, with a focus on bibliometric/scientometric analyses and reliance on article meta-data [10,18] or a provide a broad overview of OHS-related BIM opportunities without stratifying by lifecycle stage and hazard type [26].

The resultant gap in the understanding of barriers and facilitators in relation to the successful implementation of BIM for OHS has been acknowledged [26]. The single identified review that did examine success factors for BIM implementation was not specific to OHS, and also did not stratify by lifecycle stage [24]. In addition, many of the existing reviews are based on studies published more than five years ago [10,23,24,26], and there is a need to update the state-of-knowledge with the substantial number of recent developments. Clearly, there is a gap in the knowledge base about the characteristics and enabling factors of a more integrated, BIM-based safety management.

In addition to a current summary of the literature, there is a need to understand how BIM for OHS opportunities are reflected in current practice. Although there are a few studies that investigate the implementation of BIM methodology for real-life OHS applications [27,28], most of the literature base proposes processes, applications, plug-ins and opportunities with no reported implementation in project settings. In the rare instances where industry feedback for a specific solution is reported, research settings are heavily skewed towards U.S. and Chinese contexts, with little consideration of European and specifically Scandinavian perspectives. There is research indicating that BIM methodology is used in Sweden [29,30], indicating that there is an opportunity there to apply BIM methodology to improve OHS outcomes. However, the lack of published BIM implementation research for OHS in the Swedish context requires a qualitative exploratory approach that investigates the what, how and why of current industry practices directly from industry practitioners.

This paper aims to investigate how BIM-based digital platforms can be used to support OHS management. It investigates the potentials to leverage automation capabilities and platform structures for a closer collaboration between different stakeholders throughout the building lifecycle. Enablers and prevailing challenges will be identified to guide future actions for technology-based accident prevention in research and practice. To fill the previously identified research gap, the following questions are addressed:

1. What are the opportunities for lifecycle OHS management with a BIM-based digital platform, as described by the peer-reviewed scientific literature?
2. What characterizes current BIM for OHS practices in the Swedish context?

The findings of this paper set BIM methodology-based safety technology tools in the context of holistic lifecycle safety approaches. The paper will also shed light on the current state of the Swedish building industry and the common challenges encountered in practice to highlight the need for further technology development and management training. A set of principles is derived to guide this transformation and inform stakeholder decision-making and actions.

2. Materials and Methods

The study design for this paper was a mixed-method approach, incorporating both synthesis of literature sources and qualitative focus group discussions with key informants. As described by Pluye and Hong, mixed methods combines "the strengths of quantitative and qualitative methods and to compensate for their respective limitations" [31].

2.1. Literature Review

This review was structured as a systematic mapping review, as described by Grant et al [32]. Consistent with their Search, Appraisal, Synthesis and Analysis (SALSA) framework [32], the aim of this mapping analysis was to characterize research streams addressing OHS strategies linked to BIM methodology. The findings subsequently informed the workshop questions for key informants in the Swedish building industry.

2.1.1. Search and Screening Methods

A search was conducted in two main electronic published databases from: Scopus and Web of Science on 15 June 2021. Based on preliminary investigations into this literature, date limits were set for records published in 2010 and later. Full-text, peer-reviewed records in English were included. The main search terms included three conceptual groups of synonyms for "occupational health and safety", "building lifecycle stages" and "BIM". Synonyms within concept groups were combined with "OR", all conceptual groups were combined with "AND" (see Table 1 for a full list of search terms). Note that the asterisk (*) is used as a 'wildcard' operator or a placeholder which will return matches with different word endings. For example, Ergonom* will return 'ergonomics', 'ergonomist', 'ergonomic', and 'ergonomical'.

Table 1. Literature review search terms; terms within conceptual groups were combined with "OR" and all three conceptual groups were combined with "AND".

Concept 1 Occupational Health and Safety	Concept 2 Building Lifecycle Stages	Concept 3 Building Information Modelling
Occupational health Occupational safety Safety management Accident prevention Injury prevention Ergonom*	Design Construction Facilit* management Demolition	BIM Building information modelling

2.1.2. Inclusion and Exclusion Criteria

The review included peer-reviewed journal papers published in the English language, of all study designs (e.g., cross sectional and longitudinal designs, case studies and study protocols) as well as quantitative, qualitative or mixed methodologies. Given the anticipated early state of research in this area, no exclusions were made based on study quality.

Eligible records reported on the actual or future application of digital BIM with occupational health as a primary or secondary goal or benefit, within the context of building lifecycle, including design, construction, commission, operation and maintenance, renovation and deconstruction. Records investigating the building lifecycle as related to single-site, long-term (i.e., "permanent") commercial and residential buildings designed for continuous occupancy were included; infrastructure cases (e.g., railway, roads, nuclear plants) were excluded, as were temporary structures and small seasonal accommodations.

The scope of Occupational Health and Safety was considered to include the recognition, evaluation and control of hazards in relation to occupational exposure thresholds and related health effects. For example, noise levels approaching 90dB were included, but acoustic features related to speech intelligibility and annoyance were not. This interpretation of hazards extended to those onsite workers who are directly related with stages in the lifecycle; all types of construction workers, facility management and operation workers were included. To evaluate the direction and maturity of the field, primary research, reviews and editorials were included. Conference papers and study protocols that primarily described planned future research were excluded.

Identified records were screened for adherence to the inclusion criteria independently by two reviewers (MH, CT) at the title stage with any discrepancies resolved through discussion and consensus; inclusion and exclusion criteria were refined as needed based on this discussion. At subsequent abstract and full-text stages, these refined criteria were applied by at least one reviewer, with any ambiguous records reserved for discussion.

2.1.3. Data Extraction and Analysis

As there was no exclusion based on study quality features, there was no formal quality assessment. Since the studies differed considerably in their designs and characteristics, it was not considered appropriate to conduct a meta-analysis. Instead, the analysis took the form of a narrative synthesis of the main findings. The analysis of the journal papers was guided by the data categories and study characteristics outlined in Table 2. The category definitions summarized both general paper characteristics and specific use case details. An overview of this assessment for all included papers can be found in Annex Table 1. The main literature results took the form of a narrative synthesis of the main findings from primary research articles. Reviews were excluded from the analysis of primary articles, though many were cited in the discussion section to interpret the results.

Table 2. Data extraction categories and description of extracted information.

Category	Description of Extracted Information
Basic study information	- Country of study - Type of building
Solution characteristics	- Data sources - BIM applications - Linked technologies - Type of hazard addressed - Type of solution
Stakeholder integration	- Responsibilities for solution - Beneficiaries of solution
Lifecycle integration	- Lifecycle stages - Links between stages
Impact and adoption	- Facilitating factors for adoption - Barriers/weaknesses of solution

2.2. Industry Perspectives

A series of workshops and interviews were held to address the following research question: What are the experiences of current professionals in Sweden with using BIM for OHS practices in a Swedish context, both in terms of existing (technological) solutions and in terms of barriers and facilitators in the implementation? Three 2-h web-conference sessions were conducted using focus group methodology adapted to the online format. These were supplemented by three one-on-one interviews using the same questions and prompts.

2.2.1. Recruitment and Sampling

Since the goal of the workshops and interviews was to investigate the perspectives of industry professionals in the intersections of OHS and BIM, the workshops were promoted via email, LinkedIn and Twitter using the professional networks of the authors and the stakeholder advisory group. Participants were encouraged to contribute to snowball sampling by sharing the invitation within their networks. When recruiting for the interviews, experience with using BIM methodology or digital twins at the specific lifecycle stage in question was an explicit eligibility criterion. Use of BIM is not legally mandated in Sweden, so the participants represented a specialized group of industry professionals. The result was a purposive sample recruited from professionals who work with BIM-based platforms in four stages of the asset lifecycle: design, construction, operation and deconstruction (see Table 3). One of the aims was a balanced gender distribution, resulting in 33% female and 66% male participants. Although a variety of professions participated (e.g., architects, engineers, site managers, (sub-)contractors, digitalization professionals, facility managers), there was group homogeneity from shared experience within a stage of the asset lifecycle.

Workshops were held for the design phase (3 participants), construction (6 participants) and operation phases (3 participants). To accommodate participants' schedules, two supplementary interviews were held for the operation phase. Two different workshop times were scheduled and promoted for the demolition phase but were cancelled due to low registration; ultimately one interview was conducted for this phase.

Table 3. Professional roles of interview and focus group participants within each lifecycle stage.

Lifecycle Stage	Profession (n) of Workshop Participants	Profession (n) of Interview Participants
Planning and Design	Architect (1) Structural Engineer (1) Design Manager (1)	-
Construction	Architect (1) CEO for Sub-contractor (1) Construction Engineer (1) BIM Coordinator/Project Manager (2) Head of Design Team (1)	-
Operation and Maintenance	Architect (1) Health and Safety Manager (1) Property Manager (1)	Software Developer (1) Property Manager (1)
Demolition and Reconstruction	-	Sustainability Consultant (1)

2.2.2. Facilitation

Using a phenomenological framework and an inductive approach [33], questions and prompts aimed to elicit participants' direct experiences and perceptions related to their current or planned implementation of BIM methodology. The question topics regarding use cases, facilitators and barriers were selected to be comparable to the main themes of the literature review. In addition, a question about potential upcoming applications was added to ensure a transparent distinction between currently implemented real-world use cases and industry practitioners' prognoses, conjecture or hypotheses. Feedback from the construction industry steering group related to this project was also considered to ensure the questions' relevance and applicability to industry practice. The main question topics used for both workshops and interviews are shown in Table 4.

Table 4. Outline of the open-ended questions used in the industry workshop discussions.

	Question Topics
1	Please describe your use cases for BIM to enhance health and safety. What actors were involved and what were the main information sources?
2	Which factors supported the implementation of the use cases?
3	What are the main challenges to implementing BIM for safety benefits?
4	How could these barriers be overcome?
5	How (else) could BIM and digital twins be used for safety in future applications?

Workshops and interviews were led by the authors using facilitation best practices as previously published [34,35], with adaptations for the web conference format [36]. For example, in the absence of in-person body language, during workshops the facilitators endeavored to hear from all participants by using a round-robin format. Following introductions and orientation, workshops opened with a warm-up activity using Mentimeter, a web-based group polling platform that allows for open-ended responses and displays results as a word cloud or set of anonymous quotes. Participants were invited to share their main safety priorities, motivation for implementing BIM and main safety applications for BIM. This was followed by group discussion in a round-robin format with broad, open-ended questions. Interviews followed the same process, with the warm-up questions posed and answered verbally, and follow-up questions to the individual participant replacing the round-robin format. Notes were made on participant responses and reactions. Workshop and interviews were also recorded with the permission of the attendees; all participants provided informed consent prior to participating.

2.2.3. Data Analysis and Synthesis

Analysis of the workshop responses followed an inductive approach using qualitative content analysis as described by Graneheim et al. [37]. Analysis was performed by both members of the research team. One of the team members performing analysis had specific training and professional expertise concerning BIM methodology and building lifecycles (MH), while the other had corresponding training and expertise in occupational health and safety (CT). Workshop notes were first open-coded then grouped into relational categories and themes within each lifecycle phase. Direct quotations from participants were selected to illustrate each aspect of the findings and to demonstrate that the analytic interpretations were rooted in the data. The literature review and industry perspective data were compared and combined into a single synthesized visual representation of categories and themes.

3. Results

3.1. Summary of Literature Review

After removing duplicates, the literature search yielded 272 individual records. A full-text review left 79 papers that were considered related based on the defined selection criteria. A total of 51 of them were non-review articles that met the inclusion criteria and were retained for full data extraction. Figure 1 shows the results of the screening process.

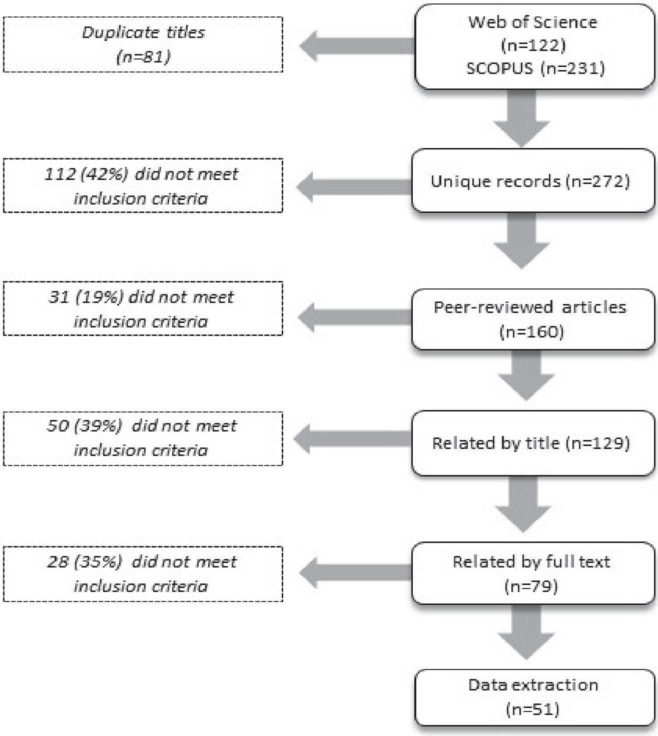


Figure 1. PRISMA diagram outlining the results of the literature search, screening and extraction stages.

The majority of the 51 primary research articles were published in 2015 (10), 2016 (7) and 2020 (11). A total of 25.5% (n = 13) of the articles included consideration of the design phase, 60.8% (n = 31) of the construction planning phase, 47.1% (n = 24) of the construction execution phase and 13.7% (n = 7) of operations phase. No papers were identified addressing hazards in deconstruction or demolition. (Note that some articles considered more than one phase). Figure 2 summarizes the distribution of the main hazards and solution types across the lifecycle stages.

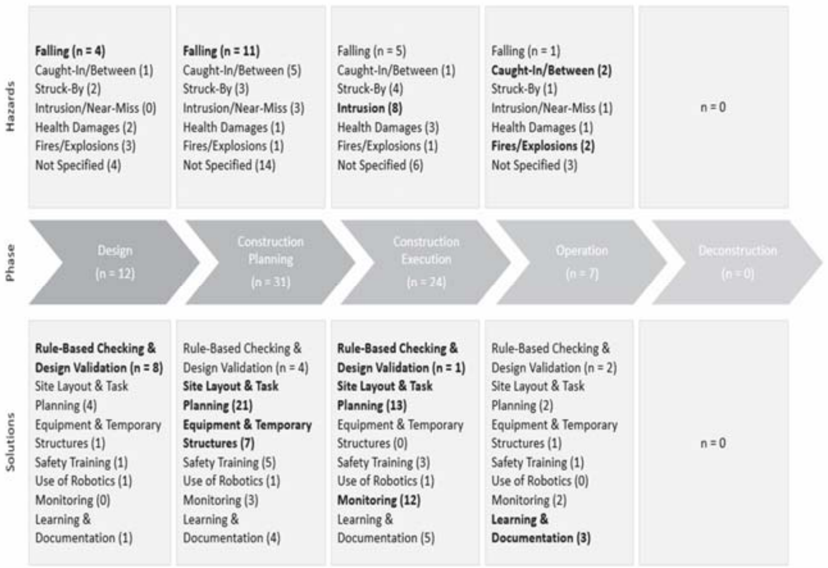


Figure 2. Hazards and BIM-based solution types with associated lifecycle phases as described in the published literature.

The use cases discussed in the literature covered a variety of solution types which can be broadly grouped into seven categories: Rule-Based Checking and Design Validation, Site Layout and Task Planning (workspace planning), Safety Training (simulation, gamification), Real-Time Monitoring (surveillance, tracking and notifications), Equipment and Temporary Structures (scaffolding, protective personal equipment), Robotic Task Performance and Learning and Documentation (knowledge management, reporting, decision-making). A full tabulation of the extracted data from the 51 records included in the review can be accessed as Supplementary Materials (Table S1).

3.1.1. Use Cases

Design

Research publications focusing on applications of BIM methodology for safety enhancements during the design stage mostly presented Design for Safety approaches for rule-based checking and validation. While the primary objective of those papers was to increase the safety of construction workers, a few solutions also aimed to improve OHS aspects for facility managers and building occupants. The tools were typically intended to support architects and engineers, for example, through automated design review and risk assessment systems [4,38,39], and simulations to optimize design choices with respect to emergency situations such as fire evacuation [40]. In addition, the use of knowledge databases was explored in an attempt to bridge the gap between construction and operation knowledge and early-stage architectural design [16,41,42]. Finally, using BIM to design for robotic construction can be considered to reduce human exposure to hazardous work [43]. The data used in the safety tools came from historical data aggregated on an industry level [38] or building level [44], safety guidelines and national building codes [40], as well as professional knowledge gathered in interviews or from project documentation [45,46].

If information was passed across lifecycle stages, it was mainly to navigate robotic equipment [43] and to validate or document as-built conditions [5,45]. The majority of the reported solutions (63%) were based on 3D BIM models and did not report the use of any other technologies to support the BIM methodology-based digital environment for safety purposes.

Construction Planning

Tools in construction planning often address the site layout and task planning (67.7%), as well as the use of equipment and temporary structures (22.6%) to prevent falls and other accidents during the work execution. As such, proposed solutions included, for instance, automated safety planning [47–49], the identification of blind spots and danger zones on site [50] as well as workspace planning and training for the interaction with machinery and the assembly of heavy elements [28]. Thereby, 4D BIM (including the link to a construction schedule), was employed in 54.8% of the articles to visualize dynamic sequences and to better account for risks related to changing site layouts and building conditions. The safety managers were described as the central actors to employ the solutions either as the sole target user or to coordinate the use with actors from the design or construction execution phase for feedback and planning validation. Fifteen of the thirty-one articles drew on professional experience as input data, historical data were used in seven cases, while safety guidelines such as OSHA were used in twelve proposed solutions. In addition, individual worker characteristics and work sequence descriptions were taken into account to plan and evaluate construction workspaces with the help of Virtual Reality (VR) [28,51].

Construction Execution

Safety during the construction execution phase was, first and foremost, addressed by BIM methodology-based solutions that enabled real-time monitoring, notifications, visualizations and warnings, as well as safety compliance checking. They aimed to increase the degree of process automation for safety tasks [51–53], prevent exposure to harmful environmental conditions [54] and improve on-site safety communication, for example through real-time reporting of unsafe conditions [55]. In addition, the aim was to improve the availability of assembly information [38]. The main hazards discussed in the literature were unauthorized intrusions and near-misses as well as falling and struck-by accidents during interactions with heavy objects. Data sources were mostly on-site real-time data (50%) or industry safety guidelines (29.2%). To date, a number of technologies have been linked to the digital platforms, including RFID tags, GPS and Bluetooth beacons for localization, drones for image production, robots for automated installation, block chain for secure credentialing of materials and approvals and IoT sensors to monitor environmental conditions such as dust or heat.

Operation and Maintenance

During the operation stage, the main hazards investigated concerned emergencies such as fires and explosions, as well as maintenance work in confined spaces [56,57]. Emphasis was also placed on the applicability of digital platforms for documentation purposes to provide guidance for inspection and maintenance tasks [5,58]. Data sources primarily included input from experienced professionals and past project reports (57.1%) as well as industry guidelines (42.9%). Since there were no dynamic changes in the building layout, all solutions in the operation stage were based on 3D BIM-based platforms. In terms of additional technologies, several solutions carried out the integration of these platforms with IoT sensors, sometimes explicitly introducing the notion of a digital building twin [56].

3.1.2. Barriers

The aforementioned use cases spanned a variety of purposes and intended benefits, but the included articles rarely reported measurements or assessments that quantified the impact of using BIM-based platforms for safety. Outside of technical simulations and hypotheticals, the barriers and facilitators of real-world implementations were based on researchers' interviews with users and hence represent subjective perspectives. Overall, the barriers reported in the academic literature can be grouped into five categories: (1) technology, (2) data and information, (3) business and organization, (4), industry structure and governance and (5) people and communication.

With regards to technology, data and information, barriers to the adoption of BIM for OHS throughout the building lifecycle concerned the technological immaturity of the solutions in terms of hazard detection and data processing capabilities. For instance, the tools fell short on accounting for interdependencies between different risk factors in the complex construction setting [45,46,59]. Commonly, solutions for falling or collisions were presented, neglecting other hazard sources such as electricity. Moreover, complementary infrastructures such as RFID antennas or a strong WiFi-network would be needed to enable, for example, cloud-based information sharing and real-time monitoring. However, this infrastructure is seldom present at today's construction sites, is itself immature (e.g., limited sensor accuracy), or requires a lot of resources and space to install [57,60]. Other barriers to BIM-based solutions include the limited user-friendliness of the software interfaces [54] and limitations of the input dataset to identify risks in the first place [39,52,61]. This latter limitation often stems from a lack of detailed accident statistics on a corporate or industry level, especially with regards to individual trades or small and medium enterprises (SMEs) [62]. In addition, the building model has to be modelled very accurately in order to automate safety-related tasks. This makes the design phase very time-consuming, especially if the information is static and does not update automatically based on identified hazards, simulations, and schedule changes [39,63]. Human intervention is hence often needed to validate outcomes and ensure their quality [62,64], resulting in a high degree of manual work and overall lower automation levels.

In terms of business and organization aspects, the main barriers to using BIM-based platforms for safety include the lack of defined evaluation metrics and difficulties to account for e.g., behavior-based safety hazards. This limits the inclusion of safety criteria in traditional time- and cost-centered decisions [51,65]. Moreover, the need for organizational changes and the currently isolated nature of BIM methodology use cases can make it difficult to scale solutions to a profitable level [43]. Many safety applications require a high level of detail of the building models, which in turn could be leveraged, for example, for more prefabrication to justify the higher upfront resource needs. From an industry structure and governance perspective, the regulatory landscape reportedly provides insufficient support for the application of BIM for OHS due to the lack of standards [4,62] or difficulties to obtain approval for the use of onsite equipment such as drones [27].

In terms of people and communication factors, Choe and Leite claim that the lack of technical skills of construction and design staff is one barrier to employing the solutions at larger scale [47]. Few professionals in the industry possess the programming skills that would enable them to customize, for example, the integration of different tools such as BIM and VR [28]. In addition, integrity concerns were stated in the context of real-time monitoring [55] or the fear of job losses and resistance to the adoption of new technologies [57].

3.1.3. Facilitators

Next to the barriers, there were also a number of factors mentioned that support the development and implementation of BIM-based platforms for safety use cases. Most commonly, these included integrated project team structures fostering communication links between actors from several lifecycle phases and organizations [38,63], as well as a high level of software interoperability [54,66]. Regarding the latter, there is evidence that a workload reduction can be achieved in a single software environment as a unified system of integrated components. In this context, several papers reported the use of established BIM software such as Revit or Navisworks as a facilitating factor [15,48], while others emphasized the importance of open standards such as IFC [40], or—beyond a sole BIM focus—the introduction of standards for Common Data Environments (CDE).

To create a more collaborative, web-based environment, cloud platform technologies as the backbone of the communication infrastructure have become increasingly popular [57,60,63]. For any of the solutions, a high degree of usability (i.e., intuitive handling, no programming knowledge requirements and ergonomic hardware) and accessibility on mobile devices (especially for fieldwork) is deemed crucial to easily retrieve safety-related information [13,28]. Other factors that can help to introduce a BIM methodology for lifecycle safety include regulatory obligations [48], the link to other use cases such as prefabrication [56] and a high level of detail about the underlying circumstances, for instance, the occupancy characteristics of a building in the case of fire simulations [44]. Finally, solutions with low implementation costs and an innovation mind-set within the project organization(s) are needed to scale the adoption in the industry [51].

Figure 3 provides an overview of all barriers and facilitators found in the literature review including their categorization into (1) technology [T, visualized in Figure 3 as blue boxes], (2) data and information [D, in green], (3) business and organization [B, in orange], (4), industry structure and governance [I, in yellow] and (5) people and communication aspects [P, in purple].

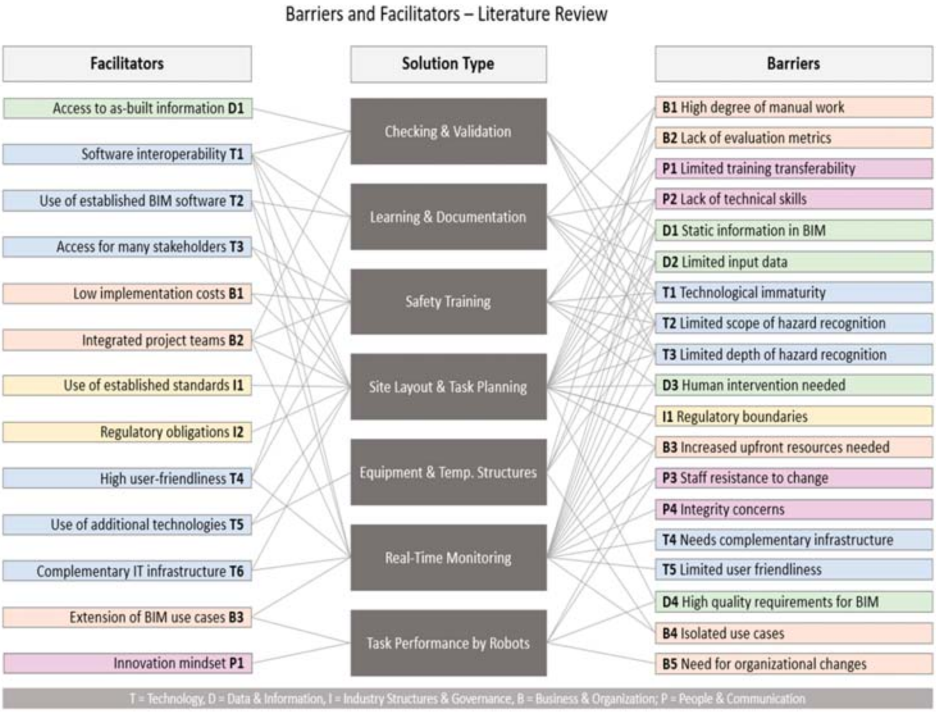


Figure 3. Barriers and facilitators as described in the published articles included in the literature review.

3.2. Summary of Industry Perspectives

Throughout the entire lifecycle, the workshop participants described perceiving the use of BIM-based platforms for safety purposes in the Swedish building industry as currently "exploited to a small extent" according to polls conducted during the sessions. Irrespective of the lifecycle stage, they are mostly adopted to realize cost and time savings. However, there was a strong potential and need seen for leveraging the potential of digital, platform-based applications for safety, especially when it comes to long-term perspectives and the connection of silos in the building ecosystem.

3.2.1. Use Cases

Design

Existing industry use cases described in the design phase primarily fall into the areas of (1) Rule-based Checking and Design Validation, as well as (2) Team Building and Communication. Typically, these solutions in the design stage are based on 3D platforms (mostly architectural elements), sometimes combined with VR tools or game engines. For instance, the creation of virtual game environments was described as a way to explore the designs in a realistic simulation about 6–12 months before the actual completion of construction works. Feedback can be given much earlier to detect and prevent hazards in a timely manner, and this can be applied in both construction and maintenance scenarios. Joint virtual explorations help designers, construction managers and facility managers to communicate and identify spatial constraints and requirements at an early project stage:

> *"We like [the construction managers] to think ahead: while we design, we want them to look at safety aspects for raising the building during construction. [. . .] Does it work the way it is designed?"*

Additional value stems from virtual walks in site areas which are typically inaccessible due to, e.g., ongoing nearby transport operations, to visualize and explore the site conditions and building dimensions. It was also reported that this gamification approach increased the team feeling and consequently the interaction and trust among the stakeholders, leading to higher perceived safety. Additionally, using BIM-based software in design meetings and visual risk assessments was reported to facilitate discussions and help to pass safety information from design to construction staff by including annotations about potential hazards and safety instructions directly in the models. Most often, the solutions described target design managers, architects, safety and construction managers. Stakeholders and information from the operation and deconstruction phase were considered less frequently to not at all.

Future use cases that were brought up by participants in the design workshop were related to the improvement of software and hardware functionalities as well as the data and information quality. Regarding technology, more automated risk assessments in tools such as Navisworks or Solibri and the integration of generative design in project workflows were perceived as useful to promote and structure the consideration of safety aspects at an early project stage. In addition, the further customization of the software interfaces was deemed important to allow for a smooth transition between different stakeholder perspectives (management, site managers, project leaders, etc.) and the related information displayed. With regards to data and information, the curation of industry databases and open information exchange based on common standards was suggested, exemplified by the idea of a "Github for the construction industry". Closely linked to this aspect was the notion of lifecycle learning, aiming to save the data relevant for safety risks and incorporate feedback from construction and operation into the design phase to increase data-based decision making and prevent hazards stemming from design choices.

> *"We should not just design good houses if we are lucky with the [project] group. There are sometimes groups that work well together, sometimes less and it is important that technology supports us in the future to find errors. Then people can still make a choice."*

Construction

On site, commonly mentioned hazards were falling from height, struck-by and dangerous environmental conditions such as dust and heat. To address them during the construction phase, BIM methodology-based solutions in the Swedish industry can be broadly clustered into applications for (1) Site Layout and Task Planning, (2) Real-Time Monitoring and (3) Learning and Documentation. While the majority are based on 3D platforms, some approaches feature connections to sensors, location tags and smart personal protection equipment or a scheduled integration for 4D BIM simulations.

Applications for site layout and task planning included the use of BIM methodology-based tools for safety workshop communication as well as the planning, evaluation and follow-up of work sequences including the corresponding placement of building materials. During workshops, BIM methodology was reported to be the basis for the dialogue with designers about assembly considerations and potential sequencing options. For instance, during the installation of MEP systems, daily logs and notes on the BIM-based platform helped the general contractor to track material and completed steps, perform tests on time and prevent potentially hazardous interferences of trades on site. Moreover, clearly planning and marking material locations in BIM increases transparency for all trades involved, reduces stress and optimizes the workers' paths to avoid collisions and spatial constraints. An example mentioned was the assembly of inner walls. The information used from the building model included the size of the pre-cut boards and their intended location in the building. The delivery packages were then grouped and placed on-site the day before the assembly without any disturbance of simultaneous ventilation and electricity works. With the use of 4D platforms, additional opportunities arise for the evaluation and visualization of spatial constraints in a more dynamic manner. However, while considered a promising option by several workshop participants, 4D BIM methodology was not reported to be currently implemented for construction sequencing beyond initial trials.

Real-time monitoring use cases included the use of wearable personal equipment such as smart helmets that help to both prevent accidents and send real-time notifications in case of a worker's fall or being struck. With the help of location markers, workers' positions are anonymously tracked and visualized in a digital building twin, which can support emergency evacuations and the monitoring of danger zones with entry restrictions. In addition, environmental sensors send real-time alerts if the air quality (e.g., humidity, dust, gases) or noise levels pose a threat to workers' health.

Finally, BIM methodology was reported to support learning and documentation efforts at inspections during and after the completion of construction works through as-built comparisons, annotations in the models and real-time sharing of information linked to the respective building locations. While it often starts with the project managers using BIM methodology, the greater safety benefits were seen from the integration of a variety of stakeholders, including cleaning personnel and subcontractors. The goal was described as:

> *" . . . to have everyone's eyes both in the building model and in the real world on site and to see potential issues."*

Concerning future use cases of BIM for OHS, workshop participants discussed a variety of potential developments. Although blockchain security has not been used to this point, it could be a useful facilitator to secure and certify data updates. As described by one informant, the data itself would become an important product particularly in digital twins:

> *" . . . [the] allegiance to [the] building over time is greater than allegiance to one property owner"*

As another example, the increased use of BIM-based game environments or VR applications could bring additional stakeholders such as architects, owners and the general public into the project to raise awareness of spatial and temporary constraints during construction. As mentioned in the design stage, the importance of a lifecycle perspective on safety and a higher degree of customization with regards to the information displayed was also stressed in a construction phase (and operation) context. The extension of BIM model dimensions to 4D further enables a more dynamic visualization of spatial and temporal implications during constructions to minimize hazards from overcrowding and a lack of coordination. In addition, potentials were identified for more prefabrication and robotics to cut hazardous on-site work performed by humans. BIM methodology is essential here as the underlying information source for manufacturing and assembly. Next to that, leveraging artificial intelligence to handle the enormous amount of data generated over time and across projects will be essential in the long run. It was however also stressed that these transformations are likely to take time and require a clear "safety first" mind set:

> *"We have to stop asking yes or no questions: If it is about using digital twins for safety, it can only have a yes answer"*

Operation

In operation, the use cases mentioned by industry practitioners can mainly be classified as solutions for learning and documentation. Since the building is completed at this point, all solutions are represented in 3D. During operation, more examples of the integration of various sensor data sources were mentioned than in construction, aiming for a shift from BIM to digital twins as a virtual duplicate of the complete asset. This includes, for example, the integration of checkpoints in the building to link check-up rounds and safety instructions to a digital twin. The underlying intention was to decouple information from single individuals and promote safety through shared information visualized in a 3D map environment. Knowledge about maintenance standards and work procedures can thus be made explicit, whereas it was previously typically trapped in software silos, on paper or in the head of individuals. Digital notations in the building model were mentioned to allow for additional remarks and follow-up tasks. Other use cases that are being explored but not yet widely implemented in Sweden at this point include the use of localization sensors to automatically filter safety information based on a worker's location. Over time, the aggregation of maintenance information to data-driven reports was suggested as a way to further promote safety by enabling more proactive operations and the timely replacement of worn-out equipment. Additionally, real-time monitoring was mentioned as a safety-related use case for digital building models. Here, sensor data linked to building locations can be used to visualize equipment breakdowns, including information about the necessary repairs. Moreover, it can trigger alerts about unhealthy air conditions to enable a timely response by the maintenance staff and/or the general public in the building.

Asked about the direction for the next five to ten years, potential was seen in the extended use of real-time data linked to building locations for more automated building system steering and control as well as for managerial decision-making. In this context, the threat of cybersecurity was mentioned, representing a new dimension of safety to be considered as buildings become smarter and more connected. Another aspect currently neglected is social safety in residential districts—a factor that was reported as not being linked to digital models yet despite being of high importance to residents. Moreover, the need for more integrated collaboration including the suppliers and other ecosystem actors was mentioned to promote safety through building platforms.

Deconstruction

At present, the use of BIM for OHS is very limited in deconstruction. In pilot projects, 4D simulations are performed by project managers to evaluate different scheduling scenarios and visualize work sequences for different stakeholders. With the increasing importance of circularity, potential synergies from the integration of lifecycle safety aspects into material databanks and a closer, optionally BIM methodology-based collaboration between circularity experts and safety managers were mentioned; however, no current use case was identified by the participants.

3.2.2. Barriers

Although linked to experiences with use cases in their respective lifecycle stages, the barriers described by industry professionals showed a lot of consistency across lifecycle stages. Therefore, the barriers to using BIM methodology for safety applications are presented here not within use cases or lifecycle stages, but according to thematic categories. Qualitative analysis of the workshops and interviews yielded five overarching categories of barriers: (1) technology; (2) data and information; (3) industry structure and governance; (4) business and organization; and (5) people and communication.

The theme of technology related to both lagging technology maturity and the limited scalability of solutions. Inconsistent platforms across firms and across lifecycle stages made it difficult to realize the benefits of a common information source. For example, it was considered faster to adopt and implement new digital tools in the design stage than in the construction phase, so the latter lags behind. Concerns about limited scalability related to the time- and effort-intensive process of building models adequate to support safety efforts; this in turn led to limited coverage of assets. In the early stages of technology maturity and usability, firms experience the labor and cost without yet benefitting from easy access to shared data. Additionally, low usability reduced the ability to make use of new technologies; it can be difficult to find the appropriate safety information in a model when needed. Most software solutions do not offer built-in workflows that facilitate safety applications, requiring external consultants or staff with specialized programming knowledge.

Barriers within the data and information theme largely described issues with acquiring safety-related (e.g., safety measures during construction, maintenance instructions, accident statistics) data in a usable format that support transferability across platforms, particularly across stages in the lifecycle. Those collecting and supplying data inputs for BIM may not be working with safety specifications in mind. The responsibilities for safety may be spread among several outsourced consultants or sub-contractors, and the ultimate decision-making power for implementing safety processes may lie within a different life-cycle stage, or with an actor from a different firm. According to workshop participants, the lack of understanding about the information needs of each lifecycle stage, and the potential for that information to have a positive safety impact, is a major barrier. For example, without key inputs from the operation and construction phases, it is not clear what safety hazards should be highlighted at the design stage, and what type of data to pass forward to future stages. There remains a lack of clear requirement definitions to guide the development of model information inputs:

> *"[OHS data for BIM] needs to become . . . an industry standard. I think we are going in that direction . . . but it is still like some of the companies have THEIR solution and other companies have THEIR solution . . . "*

At the same time, they acknowledged a trade-off between strict and detailed requirements that would increase cost, vs. loose low-detail requirements insufficient to enhance safety. In addition, public clients stressed the perceived conflict between neutral tendering documents and the implementation of standardized routines in information management.

The industry structure and governance theme described barriers related to how the industry's existing frameworks and practices impacted the implementation of BIM for OHS. For example, particularly in construction, the industry is fragmented and decentralized, with diverse and local firms contributing to a finished project; this "ecosystem web" can make it difficult to adopt new technologies and platforms without standards and regulations enforcing consistency. With small margins and considerable uncertainty over multi-month projects, this is a setting with considerable unavoidable business risk and risk aversion in terms of early adoption. Perceived financial risks were described by a construction workshop participant as a disincentive to be an early adopter:

> *"I want to test new things, but I don't want to be the first guy out."*

This industry tendency towards risk aversion is linked to the theme of business and organization, which pertained to challenges in evaluating the impact of adopting BIM for OHS, and in particular quantifiable evidence of success. Without specific metrics, "better safety" or "better workflows" are vague and intangible goals that are not very enticing from a business perspective. When queried as to what type of evidence would be useful, one operation workshop participant described:

> *"Cost and time, because that's how decisions are made at the top . . . "*

The lack of links to cash flow combined with the potential for long (or unknown) returns on investment are a particular challenge within the temporary project context of construction stage. Business and organization barriers also involve prioritizing organizational functions, allocation (and siloing) of work and the lack of a "road map" or set process for integrating BIM methodology into workflows throughout the lifecycle stages.

> *"There is a missing link: We need to use the BIM model all the way, which is not really the case in many projects today. . . . When you can connect the whole value chain all the way to operations and also follow what is done and how it is done, then quality and safety can improve."*

Technology adoption is typically driven by core productivity goals such as cost and time savings. Safety is rarely a primary organizational priority, and since high safety performance is not typically listed as a contract specification by clients, it is often one of many ancillary regulatory requirements competing for attention. An organization's work allocations can present a barrier when the workers handling digitalization and safety are in separate departments, resulting in a silo effect that inhibits the sharing of information and the development of updated work processes that meet several goals (e.g., production and safety goals).

The people and communication theme concerns barriers with human resources, and the need to further develop communication, knowledge and leadership relative to BIM for OHS. Communication gaps include how data are used and what is needed at each stage, and knowledge gaps often reflect a "myopia" within a lifecycle stage or professional role. Similarly, professionals with an artistic focus in architectural design and working in the design phase may not know many details about the construction process, building logistics and time spans; this limits the degree to which they can contribute relevant safety-related data. A lack of big-picture management capacity to identify hazardous situations in advance via coordination between highly skilled individuals was also described within the theme of "people". This would require a prioritization of leadership that incorporates generalized skills and knowledge over specific focus on one profession or stage:

> *"Everyone is working with a certain part of the project and sometimes they have excellent tools in the bigger projects [for calculating, follow-ups, model viewing], but the core construction skills and having the oversight to manage a project well is sometimes getting lost. That stops us from taking bigger steps. It is happening, but it is still slow."*

3.2.3. Facilitators and Best Practices

Facilitators for the adoption of BIM for OHS were proposed as potential tactics to mitigate the barriers named by informants; the best practices were current methods or strategies that had already been tested. The best practices and facilitators described by informants largely fit into the same five overarching themes: (1) technology; (2) data and information; (3) industry structure and governance; (4) business and organization; and (5) people and communication.

Best practices in technology related to realism, accessibility and interoperability. Success was seen with technology that provided highly realistic representations to facilitate an intuitive understanding of 3D and 4D models. Current accessibility best practices also included portable access via cloud networks on mobile devices, with suggested facilitators being availability to a large number of stakeholders to create a multi-professional team with an understanding of the digital environment and representations. For example, wider accessibility would be facilitated by technology that allows a large number of stakeholders to contribute to the development and updating of digital building models in construction and operation. User-centered interfaces should be tailored to provide the information that is needed for each user and to avoid information overload. Open-source platforms and standards could reduce friction between programs and platforms and allow for accelerated data usage and greater interoperability; ultimately this could contribute to greater collaboration and integration between firms, professions and lifecycle stages.

Informants described data and information best practices including flexibility, accessibility and information consistency. There has been success with flexible and accessible data structures that will facilitate the crowdsourcing of information (keeping models up to date) and enable transparent, shared access to a "single source of truth" which can be considered a current and trustworthy description of the asset. However, in terms of facilitators there remains a need for a clear industry-wide standardization of requirements and formats on how to collect and link high-quality data. In order to facilitate data integrity over time, data structures should be linked by location attributes and should accommodate many sources and types of data into a database that can be shared and interpreted by multiple platforms or tools. Given that, ideally, data will be created and used across many firms and lifecycle stages, there is no competitive advantage to a single proprietary platform or data ontology. Rather, there was a stated need for agreement across lifecycles stages and firms on what type of information is needed, and what formats and structures are best to encode the information. Extending the utility of, for example, the building collaboration framework (BCF) could help achieve this, as described by a participant in the design workshop:

> *" ... there can be some rules and a language, for example added to BCF, to exchange that information. Maybe [safety hazard information] can also be connected to BCF, because there you can connect different views and models. This can be a way of transferring information from one program to another. We can use [multiple current BIM and DT platforms] ... and everyone receives the same information and it is editable. BCF gives a lot of possibilities for this, [it] is not that far away".*

Best practices in industry structure and governance include repositioning the legal value of BIM documentation. For example, elevating BIM models as the highest legal document governing assets throughout the lifecycle provides an additional incentive for BIM to become the "single course of truth" regarding the asset.

In terms of business and organization, best practices related to realizing the commercial potential of BIM methodology adoption, developing Key Performance Indicators (KPIs), and incorporating cross-functional work practices. Cross-functional integration has successfully spanned lifecycle stages, gathering input from stakeholders in other stages (even end-users and building occupants). As a current best practice, traditional metrics such as time and cost are being augmented by engagement metrics such as daily active users (DAUs) of the tool, and interactions with safety-related data as an indicator of safety management performance. Additional best practices include the development of new business models and incentives for early investment that can help counteract a culture of risk aversion.

> *"The moment you can talk business about it, a lot more people will be interested to help, especially from the top."*

Proactive use and tracking of data in earlier lifecycle stages can demonstrate when there are future savings. It has proven beneficial to start small with pilots, proof-of-concept and test beds to demonstrate profitability and then to scale up. Informants reported that orientation towards innovation has grown when (best) practices shift towards experimentation, allowing for quick iterations of "fail-and-learn", but this needs to be developed further through test beds, continuous benchmarking and sharing the results:

> *"We don't take any risks at all in this business" ... "You have to fail to learn"*

Moreover, as investors and shareholders demand corporate actions on sustainability and ESG (environmental, social, governance) compliance, this is seen as another force to drive the implementation of platform-based, digital safety solutions.

Under the people and communication theme, BIM for OHS requires developing the workforce, specifically in terms of skill capacities, an innovation/digital mind set and cultivating support and leadership for BIM methodology-supported safety. In current best practice, workforce development is motivated by a shared vision of possibilities for safety supported by top management and operational staff, and by inclusive contributions from all stakeholders. This approach engenders a sense of pride; for example, in the operations phase there comes a sense of comprehensive stewardship and knowing a building inside and out, and being proactive in forestalling maintenance issues:

> *"You want to have 100% control and you can in a better way. [...] People almost start to compete with each other to have better knowledge and information connected to the digital twin."*

Mutual communication and sharing of best practices and success stories was reported as a current best practice, and also one that could be expanded further as a facilitator. There was great value seen in the promotion of both small-scale firms and high-profile "Hollywood projects" that have demonstrated the successful application of BIM for OHS; the result was that the benefits and impact of data sharing through BIM-based platforms became more widely understood. While there might be disincentives to sharing some types of best practices with competitors, informants described that this did not apply well to safety issues, since enhancing working life and attracting workers to the industry is an industry-wide issue, and not specific to any one firm. According to informants, best practice shows facilitation, support and prioritization from several stakeholders; when general contractors, top-level management and clients champion BIM for OHS, it helps promote the wider adoption of the technology. Although the implementation of BIM for OHS requires the work of many, it is currently driven by management and client demands, and in particular, demands from those who are responsible for the costs, delays and/or legal repercussions of a workplace accident. When leadership and clients understand the link between safety and project quality, their motivation for adopting BIM for OHS is increased:

> *"With intense planning and a better run project, safety will come or if you look from the other direction, if you are safety-focused, you will plan your projects better and then also lower the costs for the client in the end so the involved parties can make more money."*

Although current best practice involves developing a strong understanding of the types of data and communicating how to use it throughout the lifecycle, this needs to be further developed in order to exploit efficiencies and enhance safety. Informants proposed building the internal skills capacity to allow even small firms to go from relying on external consultants, data specialists and BIM specialists, to all actors contributing to and benefiting from BIM methodology. When properly facilitated, this capacity could grow and reach a critical mass, as described by one informant:

> *"The change will be seen in the moment where we don't need those specific roles any longer, when everybody understands what BIM means and how to use the tools we have. Like with the telephone—when it was invented, you needed a telephonist to help. When people can find information they need by themselves, the real change will happen."*

Figure 4 provides an overview of all barriers and facilitators brought up during the workshops, including their categorization into (1) technology [T, visualized in Figure 4 as blue boxes], (2) data and information [D, in green], (3) business and organization [B, in orange], (4), industry structure and governance [I, in yellow] and (5) people and communication aspects [P, in purple].

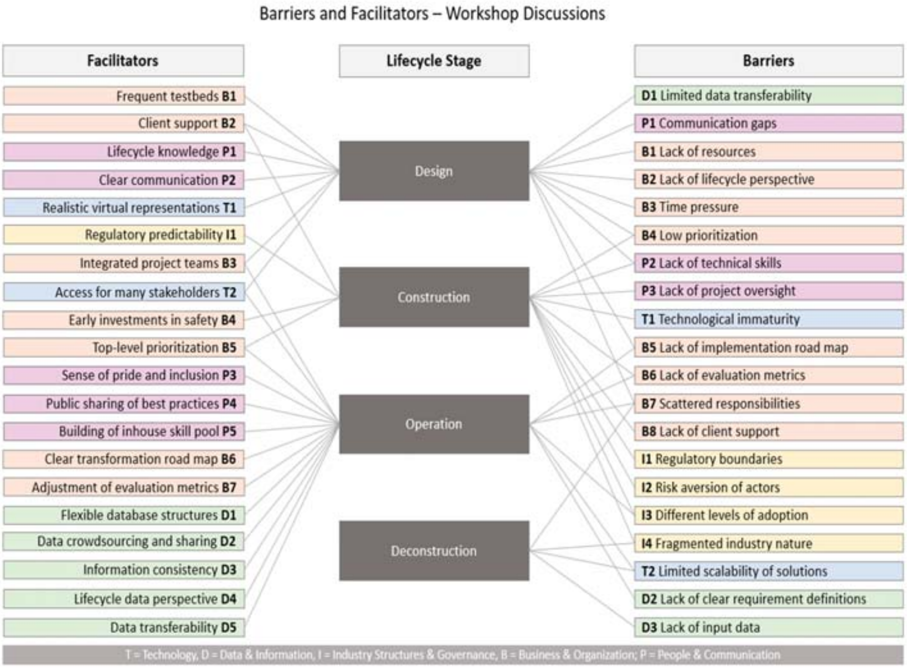


Figure 4. Barriers and facilitators as described in workshop discussions with industry professionals.

4. Discussion

4.1. Comparing the Literature Review and Focus Group Findings

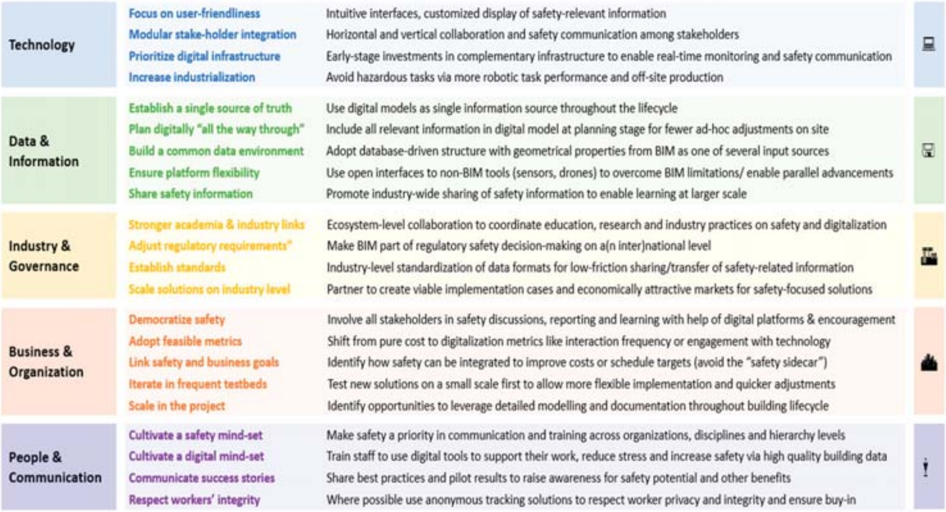
In some cases, the findings from the literature review and focus groups were consistent and/or reinforced one another. As an example, several of the barriers/facilitators were consistent between the data sources related to technology (e.g., technological immaturity), data and information (e.g., data transferability) and governance (e.g., regulatory requirements) were consistent. In addition, the low number of demolition/reconstruction use cases reported in the literature seems to correspond with the low focus group participation within this lifecycle stage; it seems reasonable to assume that this reflects the slower adoption in current practice.

However, there was also a difference in that many of the implementation challenges and proposed success factors regarding human factors highlighted by the focus groups were not found (or were less prominent) in the literature. For example, focus group participants had insights on industry-level organizational culture such as client support and the reprioritization of time and resource allocation, as well as on the need to develop BIM methodology-related skills and coordination roles. Although some of these same barriers were listed in the published research, in the literature they mainly arose from conjecture and prognosticating rather than directly from collected data. A very small proportion of published research studies have investigated the *implementation process* of BIM methodology; this may be why the barriers and facilitators gathered from the focus groups within the theme of "people and communication" were broader and more developed. This suggests an opportunity for implementation research that can evaluate and promote promising practices for the successful application of BIM for OHS goals.

4.2. Principles for the Successful Adoption of BIM for OHS

Findings from the industry discussions and systematic literature review revealed a number of potential use cases for BIM-based platforms to improve safety throughout the building lifecycle. Whether a situation becomes hazardous or not is influenced by different causal hierarchy levels: originating circumstances (e.g., safety culture, client requirements or construction education), shaping factors (e.g., design specifications, worker skills or site constraints) and immediate accident circumstances (e.g., communication, material conditions or the temporary local climate) [67]. Drawing from these risk layers [67], this article identified core examples of how digital building models can support both technical and psychological safety factors by transforming: (1) the underlying industry structures (with regards to safety culture, fragmentation and client requirements); (2) risk management strategies in construction projects and building management (e.g., clearer design specifications, industrialized construction methods and immersive worker trainings); and (3) the immediate situations in which accidents can occur (e.g., digital communication, material conditions and local climate monitoring).

Implementing BIM methodology can be considered a prerequisite to the successful application of BIM for OHS use cases. However, given this article is specific to safety use cases, the summarized principles for the successful adoption of BIM (Figure 5) focus primarily on safety applications to guide this transformation and inform stakeholder decision-making and actions. The categorization of the principles is based on the earlier detailed discussion (for reference, see Figures 3 and 4).



Technology	Focus on user-friendliness	Intuitive interfaces, customized display of safety-relevant information
	Modular stake-holder integration	Horizontal and vertical collaboration and safety communication among stakeholders
	Prioritize digital infrastructure	Early-stage investments in complementary infrastructure to enable real-time monitoring and safety communication
	Increase industrialization	Avoid hazardous tasks via more robotic task performance and off-site production
Data & Information	Establish a single source of truth	Use digital models as single information source throughout the lifecycle
	Plan digitally "all the way through"	Include all relevant information in digital model at planning stage for fewer ad-hoc adjustments on site
	Build a common data environment	Adopt database-driven structure with geometrical properties from BIM as one of several input sources
	Ensure platform flexibility	Use open interfaces to non-BIM tools (sensors, drones) to overcome BIM limitations/ enable parallel advancements
	Share safety information	Promote industry-wide sharing of safety information to enable learning at larger scale
Industry & Governance	Stronger academia & industry links	Ecosystem-level collaboration to coordinate education, research and industry practices on safety and digitalization
	Adjust regulatory requirements"	Make BIM part of regulatory safety decision-making on a(n inter)national level
	Establish standards	Industry-level standardization of data formats for low-friction sharing/transfer of safety-related information
	Scale solutions on industry level	Partner to create viable implementation cases and economically attractive markets for safety-focused solutions
Business & Organization	Democratize safety	Involve all stakeholders in safety discussions, reporting and learning with help of digital platforms & encouragement
	Adopt feasible metrics	Shift from pure cost to digitalization metrics like interaction frequency or engagement with technology
	Link safety and business goals	Identify how safety can be integrated to improve costs or schedule targets (avoid the "safety sidecar")
	Iterate in frequent testbeds	Test new solutions on a small scale first to allow more flexible implementation and quicker adjustments
	Scale in the project	Identify opportunities to leverage detailed modelling and documentation throughout building lifecycle
People & Communication	Cultivate a safety mind-set	Make safety a priority in communication and training across organizations, disciplines and hierarchy levels
	Cultivate a digital mind-set	Train staff to use digital tools to support their work, reduce stress and increase safety via high quality building data
	Communicate success stories	Share best practices and pilot results to raise awareness for safety potential and other benefits
	Respect workers' integrity	Where possible use anonymous tracking solutions to respect worker privacy and integrity and ensure buy-in

Figure 5. Proposed guiding principles for implementing BIM for safety, developed from the literature and industry workshop findings combined.

4.3. Methodological Considerations and Significance of Results

The findings presented here complement previously published work by adding an industry perspective and extending the considerations over the entire building lifecycle, from early design to deconstruction. In setting the discussion about the potential of BIM methodology-based platforms for safety into a larger context of uninterrupted information flows towards digital twins, it moves beyond isolated use case scenarios as suggested by the authors of ref. [68].

By combining both academic reports and the experience of industry professionals, this paper also contributes to a better understanding of how BIM methodology could be applied to safety management, and what the barriers and facilitators would be for realizing that potential. Given the previously recognized lack of practical BIM methodology applications [69], this unique synthesis of data sources and the subsequent development of principles for future use are a major strength of the paper. Moreover, introducing a Swedish industry perspective—a country known for its leading role in the promotion of worker safety and use of technology—represents an interesting complement to the work of the authors of ref. [70], who surveyed professionals in the United States.

The literature search included a limited date range, although since the first years of the search window did not contain any included papers, it seems unlikely that important research was missed using these date limits. It was noted that no papers were found for the demolition stage of the lifecycle; this could be the result of missing search terms needed to identify these papers. However, given that the industry workshops struggled to identify and recruit professionals in the demolition/deconstruction phase who had experience with BIM methodology, we rather consider our search to be an accurate reflection of the current level of BIM for OHS maturity in this lifecycle stage. Despite searching in international scientific publication indexing databases, we note that the included papers reflect a preponderance of research from Korea, USA and China. Although unlikely, it is possible that the English language search limits precluded important work published in other languages. The review extraction and synthesis approach used in this paper aligned best with that of a mapping review. However, the search and screening process involved the systematic application of broad search terms and clear inclusion and exclusion criteria; this rigorous methodology increases confidence that all relevant papers were included.

The phenomenological approach to the interviews was intended to temper the academic perspective on possible BIM methodology-based safety solutions with the lived experience of professionals currently practicing in this field. As with most qualitative interview studies, the samples were small and purposefully selected, which precludes both statistical analysis and any assumptions of the representativeness of the sample. Instead, the advantage of this approach is in the richness of the explanations and examples given, and the ability to generate hypotheses and frameworks for future studies to test. It should be noted that the workshops relate to the Swedish context, and that the sector's digital maturity, governance structures and the Swedish sociocultural milieu for both safety and technology are likely to have impacted the findings. While it was unfortunate not to be able to collect wide perspectives on BIM methodology within the demolition stage, we interpret this challenge to be a reflection of the lagging implementation of BIM in that stage.

Although the focus group findings fill some gaps in the current published research, the focus group methodology does not supply the data needed to make a reliable statement about similarities of Swedish practices to other countries, or differences between professions. Making those comparisons was not the original goal of this research project and would require further quantitative data collection (i.e., surveys) across professions in the Swedish industry or a comparison of practices in different countries. This is an important topic and it is hoped that the barriers, facilitators and priorities described by the focus group participants in the current study will be useful in developing survey items for future studies.

5. Conclusions

This article assessed how BIM-based digital platforms for operational health and safety during the building lifecycle, as guided by two questions: (1) "*What are the potentials for lifecycle OHS management with a BIM-based digital platform, as described by the peer-reviewed scientific literature?*" and (2) "*What characterizes current BIM-based OHS practices in a Swedish context?*". A mixed-method approach was chosen to investigate use cases, barriers and best practices in academic research and Swedish industry practice. Enablers and prevailing challenges were identified to guide future actions for technology-based accident prevention in research and practice.

BIM-related OHS solutions have the potential to improve the sustainability of both a productive construction workforce, and the healthcare systems which benefit from the reduced burden of caring for construction-related injury and illness. Such solutions are emerging in the fields of Rule-Based Checking and Design Validation (Design for Safety), Team Building and Communication, Site Layout and Task Planning, Real-Time Monitoring, Equipment and Temporary Structures, Robotic Task Performance and Learning and Documentation. BIM methodology is hence not limited to visualizing building geometry but has significant usefulness as a data source in relation to a broader data environment from which stakeholders can retrieve unambiguous information catering to their needs at any point in the building lifecycle. As a consequence, trust in shared information, real-time hazard monitoring and availability of structured documentation contribute to promoting safety in buildings. Moreover, since occupational health and safety should be a joint effort of all stakeholders, the increased cross-functional teamwork and democratization of information management enabled by BIM methodology-based solutions can be of tremendous value for safety throughout the building lifecycle.

While the academic literature mostly reports shortcomings in terms of technological immaturity and missing complementary infrastructure on building sites, the Swedish real estate and construction industry described struggles with (technical) skill shortages among their staff and the low user-friendliness of existing solutions. Finding a balance between software expertise and building construction and maintenance experience will be key to benefitting from new technologies, making informed choices and not blindly trusting auto-generated results. In addition, few BIM use cases and investments today are motivated by safety as a key driver despite its high relevance to the industry, mostly due to the lack of adequate quantitative metrics.

To promote a higher degree of lifecycle and stakeholder integration and to overcome current limitations, this paper proposed a set of principles related to (1) technology, (2) data and information, (3) business and organization, (4) people and communication and (5) industry structure and governance aspects. These findings have implications for stakeholders in building design, construction, operations and deconstruction. They can help to define the next steps in the implementation of BIM use cases for safety, identify potential pitfalls and contribute to learning from successful pilot projects and approaches. To leverage BIM for OHS, it should not be viewed as an isolated task. Instead, it must become an integral part of BIM methodology and data management discussions linking various stakeholders throughout the lifecycle. It is hoped that enhanced digital maturity in combination with an understanding of the respective product and process impacts can prevent injury and illness and thereby enhance the health, sustainability and productivity of the construction and maintenance workforce. To fully leverage BIM for OHS, more research is needed to demonstrate the quantifiable benefits that justify potential higher initial costs and provide guidance in the implementation process. It will also be important to define standards and information requirements to make safety-related data an integral part of digital building models throughout the lifecycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106104/s1; Table S1: Summarized literature review characteristics of the 51 included papers reporting BIM applications in occupational health and safety.

Author Contributions: Conceptualization, M.H. and C.T.; methodology, M.H. and C.T.; formal analysis, M.H. and C.T.; writing—original draft preparation M.H. and C.T.; writing—review and editing, M.H. and C.T.; visualization, MH and C.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AFA Försäkring, grant Dnr 170149.

Institutional Review Board Statement: Given the non-sensitive, non-personal nature of the data collected in this interview study, an institutional ethics review was not required within the Swedish Ethics framework.

Informed Consent Statement: Informed consent was obtained from all focus group participants involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: We gratefully acknowledge the review and feedback from Principal Investigator of the AFA Försäkring grant project, Professor Jörgen Eklund. We would also like to thank the industry stakeholders who contributed to this paper by participating in the focus groups.

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

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Article

How Did COVID-19 Pandemic Impact Safety Performance on a Construction Project? A Case Study Comparing Pre and Post COVID-19 Influence on Safety at an Australian Construction Site

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Abstract: COVID-19 had a significant impact on construction projects due to labor shortages and COVID-19 restrictions, yet little is known about the impact it had on construction safety. To address this gap, an Australian construction project was selected to study the impact of COVID-19 on safety performance, safety climate and safety leadership. The study collected data from safety climate surveys, leading and lagging safety indicators and used linear regression to compare safety performance pre and post the onset of COVID-19. Our results showed after the onset of COVID-19 there was a significant reduction (Pr > F at 0.05%) in incident rate, an improvement in supervisor safety leadership and safety climate, and satisfaction with organisational communication. The study identified the increase level of safety awareness due to COVID-19 did not result in an increase in the level of engagement in safety leadership. Interestingly, participation in the safety leadership activities did not improve until a change of Project Manager occurred. The study determined leaders who establish a positive safety climate within a project could negate the safety performance impact of COVID-19. The study confirms the importance of site safety leadership in maintaining engagement in risk management and the value of focused safety communication.

Keywords: COVID-19; safety performance; safety climate; safety leadership; risk management

Citation: Selleck, R.; Cattani, M.; Hassall, M. How Did COVID-19 Pandemic Impact Safety Performance on a Construction Project? A Case Study Comparing Pre and Post COVID-19 Influence on Safety at an Australian Construction Site. *Safety* **2022**, *8*, 77. https://doi.org/10.3390/safety8040077

Academic Editor: Raphael Grzebieta

Received: 21 September 2022
Accepted: 16 November 2022
Published: 22 November 2022

1. Introduction

In early 2020 the COVID-19 pandemic caused major disruption to the global and Australian construction industry. Prior to the COVID-19 pandemic, global employment within the construction industry was 7.7% and projected to contribute up to 13.4% of the GDP [1]. High COVID-19 case numbers resulted in government orders restricting movement to reduce spread of the disease and to slow transmission [2–4]. In Australia, the result was a 13.9 billion AUD annual contraction in construction work and the loss of an estimated 76,500 jobs with further reductions of 7.3% predicted in 2020/2021 [5–8]. The restrictions together with construction workers contracting COVID-19 also impacted labor supply for construction projects with an average 35–40% of a projects workforce either ill or not working whilst completing isolation requirements. The industry has also experienced supply chain disruptions, increases in the cost and shortage of building materials as COVID-19 caused factory closures and port to port shipment delays [6,7]. The European International Contractors [6] predicted economic setbacks across the industry including "insolvency of stakeholders along entire supply chains". However, the Australian Federal and State governments recognized continued investment in construction and mining sectors would buffer the Australian economy and provided stimulus to keep people working. The Federal government invested in a $1.5 billion infrastructure COVID-19 stimulus package on road and rail projects across all states [9]. Subsequently the construction, mining and resources sectors were classified as ‘essential’ industries allowing the work to continue provided mandatory COVID-19 controls were implemented.

In response, organisational COVID-19 management plans were developed to formalize compliance with Governmental mandates and internal approaches to manage the health risk to construction workers. COVID-19 management plans were developed to minimize the risk of introducing COVID-19 into the work environment and minimize spreading of the disease in the workplace. The COVID-19 management plans comprised COVID-19 policy, risk management, health factors (COVID-19 symptom monitoring, hygiene, mental wellbeing) with a heavy reliance on communication. The constant evolution of COVID-19 and the change in management response required by organization meant effective communication was critical to effective COVID-19 risk management. The workforce relied on organizations to interpret and make sense of the COVID-19 restrictions and protection measures being mandated by government agencies which kept the workforce informed throughout the evolution of the pandemic [10].

Organization COVID-19 impacts have resulted in changes to daily work routines, work methods, logistics, material supplies and resource constraints at all levels of the organization [11]. The effect of these changes has increased levels of worker anxiety and stress [12] with the associated risk to the health and safety of the workforce by the extended periods of COVID-19 conditions and distractions. To reduce worker stress and anxiety the construction organizations need to provide a safe working environment preventing the spread of COVID-19 across construction sites through health and hygiene controls, reduction in community contacts and keeping the site teams informed on the status of changes in COVID-19 controls and conditions [13]. Organizations had to develop strategies to manage the constantly changing conditions, the effects of delays in supply chains and labor shortages with project leaders under increased pressure to deliver project work schedules with reduced manning, extended hours of work and uncertainty of future COVID-19 conditions.

To meet the COVID-19 risk management objectives fly in/fly out (FIFO) workers were required to work extended rosters, adhere to minimal contact measures in the workplace and in accommodation camps. To minimize close contact work teams began working in ‘bubbles’ with enhancement of personal hygiene measures and separate meal arrangements with workers usually eating alone in their rooms at camp. For those workers who travelled internationally or interstate as travel restrictions were imposed, they had to make the decision to either stay work or return home resulting in workers being away from their family and support networks for extended durations (6 to 9 months). Changes in work schedules in response to COVID-19 including extended shifts and rosters, uncertainty of FIFO logistical arrangements, introduction of COVID-19 testing affected workers’ job satisfaction, attitude and well-being as workers attempt to cope with factors outside of their control [14]. The measures implemented to reduce potential spread and contain COVID-19 infections in the workplace and FIFO accommodation also increased social isolation for workers, a psychological risk [15] for workers already removed from their normal social networks and support arrangements. Therefore, the construction industry has mitigated the social isolation through the inclusion of mental health measures in COVID-19 management plans [10].

This paper presents the impact of COVID-19 on a construction project safety performance using actual project safety data and the moderating effect of site leadership measured through safety climate perceptions.

2. Literature Review

2.1. Impact of COVID-19 on Safety Performance

Research on the effect that COVID-19 had on the health and safety performance within the construction industry has been predominantly post the advent of COVID-19 and based on interview and/or survey techniques or a review of policies and control practices [11,13,15–17]. The early COVID-19 pandemic research [12,15,18–20] provided a better understanding of the perceptions of people working within the industry and enabled construction organizations to adapt risk management programs to prevent and/or mitigate COVID-19 effects on worker health and wellbeing. However, minimal research has measured the direct impact of COVID-19 on construction worker safety performance using actual project safety performance leading and lagging indicators.

Construction workplace safety performance measurement currently uses a variety of indicators which measure event frequency (injury and/or incident) which are considered 'lagging indicators'. Leading indicators in the form of actions taken to mitigate safety hazards (safety observations, hazard reports) and communication activities (pre-start briefing, toolbox meeting) and viewed as antecedents of events [21,22]. Incident and injury frequency rates are indirect safety performance measures as they measure the 'absence of safety' [23]. The risk of relying on incident and injury frequency rates is they fail to detect escalating risks that deteriorate safety performance until after the events have occurred [24,25]. Due to the limitations of using event rates to measure safety alternative leading indicators using measures of safety-related activity have been identified and modelled to predict safety events in a workplace [22,26,27]. Lingard [28] identified the relationship between leading indicators and event frequency is variable and depending on the timing of the measure may have a circular relationship. An event (injury) may cause an increase in safety activity (e.g., toolbox meeting), so the event predicts an increase in a leading indicator, equally the leading indicator (low frequency of the activity) may predict the event.

Measuring construction safety performance, given the decentralized organization structure [28], is complex as leading indicators are inter-related and not always directly related to the lagging indicators of incident or injury performance [29]. To measure the impact of COVID-19 on safety performance consideration needs to be given to lagging measures (incident and/or injury rates), leading indicators which measure field level risk activity (e.g., hazard reporting, critical control verifications) and the leadership behaviours which support the creation of positive safety climate (e.g., supervisor observations).

2.2. Interrelationship between Safety Performance and Safety Climate

Workplaces with more positive safety climate have a better safety performance as workers hazard recognition and safety risk perception increase [30], improve safety compliance as a function of supervisor safety leadership [31,32] and participation in safety practices [33]. Safety climate models differentiate two dimensions of safety performance; safety participation and safety compliance through determinants of performance (e.g., personal risk tolerance), performance antecedents (e.g., knowledge, skills) and measuring behaviours specifically involved in work tasks [30,34,35]. Safety compliance is the adherence to rules and procedures whereas safety participation is the engagement in safety activities to improve safety outcomes [34,36]. Significantly safety compliance is adhered to as it serves as it is cost effective and immediately available choice strategy and readily adaptable to the situation compared with more engineered solutions [37]. Whereas safety participation can be viewed as a form of safety citizenship relating to discretionary actions which contribute to organization safety outcomes [38]. Both dimensions, safety participation and safety compliance, are required in a safety management program. Compliance and discipline provide routine and reliability whilst initiative and participation improve the capacity for safe decisions and behaviours in less predictable situations [36].

2.3. Leadership Aspects Impacting Workers during COVID-19

Leaders create safety climate at the organizational and supervisory levels [32,36,39], and frontline supervisors influence the safety behaviors of their workers [40,41]. However, the organizational safety climate will modify the effects of supervisory safety climate [32,39,42]. COVID-19 was a major disruption to the relationships between project management, supervisors, and the workers. By studying pre and post COVID-19 safety climate, the factors affecting the relationships between stakeholders became more evident.

Establishing these factors enabled management to improve support to frontline leaders, in particular, to positively influence workers compliance and participation in safety processes, and the project safety performance.

Safety climate arises from individual's experiences and perceptions being shared socially in the workplace. These shared perceptions arise from two antecedents being, symbolic social interactions and supervisory leadership [43,44]. When faced with complex and potentially ambiguous work situations individuals will attempt to make sense of the situations through social interactions with others, to gain an understanding of how to interpret and respond to the situations [45]. Through the repeated social exchanges, particularly supervisors, the leader creates the safety climate as they make sense of organisational requirements and the observed supervisor actions and practices [46].

Effective leaders establish meaningful high-quality relationships with their workers and care for their wellbeing particularly in high-risk situations found on construction projects. The observed practices and social exchanges between supervisor and worker, or between workers, affect the work group safety climate perceptions and perceived priorities within the work unit, e.g., prioritizing safety over production demands [44]. Measuring safety climate builds an understanding of the social mechanisms impacting either the social interactions which build common and aligned safety attitudes within a project, or factors affecting frontline leaders at the point in time.

An early study indicated COVID-19 acted as a distraction reducing workers and line supervision capacity to focus on the day-to-day safety risks [13]. Almohassen et al. [15] identified whilst there was a general heightened awareness of core safety elements during the pandemic the importance rating of the elements was not different after COVID-19. Three exceptions were identified, 'participation in safety programs', 'report safety and health concerns', and 'identification of hazards associated with emergency and non-routine situations'. All relate to the heightened awareness of COVID-19 and the health controls imposed on construction sites to prevent spread of the disease.

The COVID-19 pandemic progressed it was a major disruption event on projects with increased pressure on site leaders to implement the COVID-19 management plan. Leaders were expected to communicate COVID-19 changes to the workforce, maintain morale, ensure hygiene measures and social distancing were applied whilst maintaining production schedules. Amidst the juggling of COVID-19 measures site leaders were responsible to maintain a positive safety climate as the project safety risks had not diminished with high-risk activities continuing to be conducted. In the absence of a positive safety climate [18,47] workers' perception of COVID-19 risks, and the systems, practices, and behaviours of leaders to manage COVID-19 risks, had the potential to increase workers anxiety or become a distraction from the high-risk work being conducted [16,17,48]. The site leaders (project manager, construction manager, supervisors) set the safety climate on the project site which directly affects the attitude and behaviours of the workers [18]. Site leaders who can establish a positive safety climate will generate higher levels of safety participation across the workforce and reduce "at risk' behaviours of the workers [32,35,49]. To achieve a reduction in risk during COVID-19 leaders needed to have the skill, knowledge, and capability to communicate changes to keep workers informed whilst balancing project schedule, materials, equipment [50]. Site leaders also need to moderate perceived increased work pressures as sites continue to meet construction schedules impacted by labor and material shortages [19]. Almohassen et al. [15] identified the changes in safety practices which occurred during the pandemic, however a greater understanding of leadership factors and safety climate which support safe outcomes would benefit site leaders managing major project disruptions like the COVID-19 pandemic.

2.4. Measuring Construction Safety Climate

Building on Mohamed's [51] safety climate measurement model designed for the construction industry Saunders [29] further developed the instrument to extend to other stakeholders (e.g., owners, engineers, subcontractors). The safety cultures which shape construction project safety 'decision-making' in Australian construction projects is complex [52] so it is important to discern differences between safety climate perceptions between organizations. The outputs of safety climate surveys provide project management an insight into organization, team and individual safety perceptions and factors influencing either the social interaction or effective supervisor modelling of positive safety.

3. Study Objectives

Insights gained from comparison of safety performance and safety climate measures pre and post COVID-19 disruptions will benefit organizations and project leaders to focus on practices and behaviours which support effective risk management throughout the disruption event.

The study aims to:

1. Evaluate COVID-19 influence on the safety climate and safety performance of a construction project.
2. Evaluate the influence of leadership on a construction project safety performance under the impact of COVID-19.

This paper is novel in that it provides insights from a construction project which experienced pre and post COVID-19 conditions and provides direct measurement of safety performance throughout the pandemic phenomenon. The data and safety perceptions of the workers reflect the journey the construction project went through learning to manage COVID-19 on site, the direct impacts on labor and material shortages, isolation of the workers and the challenges facing the site leaders. The study also provides commentary of the additional complexity facing construction project throughout COVID-19 and the decisions taken by organizations to maintain 'safe work environments' on remote sites.

4. Methods

4.1. Project Selection

An Australian construction project (Table 1) was opportunistically selected for the study as the project had mobilized to the field prior to the COVID-19 pandemic (August 2019–6 months prior to first wave) and continued for a further eighteen months through the COVID-19 pandemic for a total of 72 weeks. Two safety climate surveys were conducted one in January 2020 (pre-COVID), and one in October 2020 (post COVID). The participating organization changed out the Project Manager (Lead A) to (Lead B) at the end of week 43 which provided a comparison of the safety impact between two different leaders on the same project.

Table 1. Project Details.

Project Parameters	Details
Location	Pilbara Western Australia
Scope	Infrastructure–earthworks, rail formation, tunnel, and bridges
Contract Model	Procure, Construct
Contract Structure	Joint Venture–self perform with specialist sub-contractors
Workhours	1,120,000 with 270 persons on site at peak
Duration	Total: 23 months. On site: 16 months
Value	>$500 k AUD

4.2. Safety Climate Survey

The Saunders et al. [31] safety climate survey was selected as it had been developed for construction organizations and measured individual, team, supervisor, and management factors. The safety climate survey provided a point in time benchmarking tool measuring eleven (11) attributes of worker safety climate perceptions (Table 2) comprising 35 questions.

The safety climate survey was structured to measure organization, team, and individual safety perceptions across eleven Likert like units of questions (Table 2) with two questions of free text on safety risks and safety improvements identified by participants. The question responses were formatted into a Likert-5 level response format and uploaded to the Microsoft Forms® survey tool for digital data capture and produced in hard copy for field-based personnel.

Table 2. Structure of Safety Perception Survey.

Organizational Elements	Likert Scale Units–Group of Questions
Company (ORG Avg)	Management Commitment (MC Avg) Communication (COM Avg) Rules and Procedures (RUL Avg) Overall Safety Climate
Team (TEAM Avg)	Supportive Environment (SUP Avg) Supervisory Environment (VIS Avg) Workers Involvement (WI Avg)
Individual (IND Avg)	Personal Appreciation of Risk Work Hazard Identification (HAZ Avg) Work Pressure (WKP Avg) Competence (CMP Avg)
Context Questions	Safety Risks Safety Improvements

Participants in the survey were recruited in two ways, attendance at a site safety meeting and through an email distribution list provided by the organization. Site based surveys were facilitated by the organization, where the researcher (Selleck) attended the project work site, attended the weekly safety toolbox meeting with the workers, provided an overview of the survey aims, ethics being applied and handed out hard copy survey forms. Workers were provided time to complete the survey which were deposited by the participants anonymously in a box provided. The collection box remained available until the shift. The process was repeated for the cross shift a week later.

Personnel with access to computers were emailed the Microsoft Forms® survey link to complete the survey within the two weeks, with a reminder on day 7 and day 13. Participation in the survey was voluntary and anonymous with basic demographical information and response to questions collated into the MS Form® database for analysis. All participants were asked to provide consent on the survey forms consistent with the ethics requirements for the research and where consent was not provided to use the data, the information was excluded from the analysis. Incomplete hard copy forms were excluded from the survey results and not uploaded into Microsoft Forms® data set.

The safety climate survey was depl”yed ’wice during the study, one month after the mobilization of the project into the field prior to COVID-19 pandemic being present in the region (end of January 2020) under Leader A and repeated post COVID-19 impact on the project in October 2020 under Leader B. The survey in both instances was conducted across two weeks to capture all three crews on the project with time provided for the site team to complete during the weekly safety meeting.

The Microsoft Forms® survey analytics was used for comparative analysis and to provide a report of the response summary to the participating company.

Each participant’s Likert Scale scores were averaged using following formulas to transform data so comparative statistical analysis could be conducted on responses from the two sets of surveys.

$$\text{Average Likert Scale Score } (x) = \text{sum } (\text{Qi score} + \text{Qii score} + \ldots \text{ Qn score})/\text{n scores} \quad (1)$$

where: Qi = participant score for (i) Likert scale question, n = number of Likert questions with Likert Scale (Minimum value = 0, Maximum value = 5).

Statistical analysis was conducted to highlight the significance of the relationship between variables including organisational elements and safety perception factors.

4.3. Safety Performance

The participating organization provided two safety performance data sets; incident events and counts of risk management activities (Table 3).

Table 3. Summary of Project Safety Performance Data-Risk Management Activities (Weekly).

Measure	Unit
Personal Risk Assessments	% completed [a]
Hazard Reports	% completed
Supervisor Observations and Interventions	% completed
Major Accident Prevention (MAP) Critical Control Checks	% completed
Major Accident Prevention (MAP) Audits	% completed
Exposure hours	Count
Total number of incidents	Count
Total incident frequency rates	Frequency rate [b]

[a] % completed = (number of activities completed/planned number of activities) per 100. [b] Frequency rate = No of injuries in period per 1,000,000/exposure hours in period.

4.4. Statistical Analysis Method

The data was analyzed using R statistical package [53] applying exploratory analysis steps to understand the relationships and strength of relationships between the data set factors and the independent variables [54].

4.4.1. Safety Climate Survey Model

The Safety Climate Survey statistical model tests each of the Likert Scale like parameter to identify if there is a significant difference in the means due to the factors (COVID, Organization, Gender, Age). The model analyzed for differences in means between pre/post COVID surveys, participant Organizations (Client, Principal Contractor, Sub-Contractor), gender (male, female, non-disclosed) and age groups (<18, 18–29, 30–39, 40–49, 50–59, 60–69, >69). Each of the factors may contribute to differences in safety perception measures between the two survey events and is represented by Equation (2):

$$\begin{gathered}\text{Lm(var x} \sim \text{COVID + ORGANIZATION + GENDER + AGE, data = data set)}\\ \text{e.g., Lm(COM\_Avg} \sim \text{COVID + ORGANIZATION + GENDER + AGE, data = sc\_survey\_data)}\end{gathered} \quad (2)$$

where linear regression of the mean scores (Lm) is applied to 'var x' which represents the perception measure (Likert scale unit or Organization Element) being analysed. The linear regression model includes all four factors (COVID, Organization, Gender, Age) to determine significance (p = <0.05).

The results return regression analysis of the mean scores (F) and determines significance (Pr > F) at 0.05% significance level. Variables identified as potentially different from the exploratory analysis were fitted to linear regression model with significance calculated using multi-regression analysis (ANOVA) and checked for assumptions of normality and homoskedasticity. The effect size was for significant variables (p = 0.05) was calculated using the estimated marginal means of the variable within the statistical model (Equation (3)).

$$\begin{gathered}\text{Emmeans (var x, pairwise} \sim \text{FACTOR)}\\ \text{e.g., emmeans(COM\_avg, pairwise} \sim \text{AGE)}\end{gathered} \quad (3)$$

The significance between groups was confirmed through post hoc Tukey honest significant difference (Equation (4)) which compares other means of every factor to the means of every other factor and identifies any difference between two means that is greater than the standard error.

$$\mathrm{Qs} = (\mathrm{Y_A} - \mathrm{Y_B})/\mathrm{SE} \tag{4}$$

where $\mathrm{Y_A}$ is the larger of the two means being compared, $\mathrm{Y_B}$ is the smaller of the two means being compared, and SE is the standard error of the sum of the means.

4.4.2. Safety Performance Model

The Safety Performance model tests the factors (COVID, LEAD) which may contribute to differences in perception measures between the two survey events and is represented by Equation (5).

$$\begin{gathered}\mathrm{Lm(var\ x \sim COVID + LEAD < data = data\ set)}\\ \mathrm{e.g.,\ Lm(INCIDENT\ Rate \sim COVID + LEAD,\ data = P1\_safety\_stats)}\end{gathered} \tag{5}$$

where linear regression is applied to 'var x' which represents the perception measure (Likert scale unit) being analyzed.

Variables identified as potentially different from the exploratory analysis were fitted to linear regression model with significance calculated using multi-regression analysis (ANOVA) and checked for assumptions of normality and homoskedasticity. The effect size was for significant variables ($p = 0.05$) was calculated using the estimated marginal means of the variable within the statistical model (Equation (6)).

$$\mathrm{Emmeans\ (var\ x,\ pairwise \sim FACTOR)} \tag{6}$$

5. Results

5.1. Safety Climate Survey

The COVID-19 surveys were undertaken by a total of 194 participants across the two survey events. Sixty-eight (68) participants completed surveys in the pre-COVID survey and 126 in the post-COVID survey representing 79% and 91%, respectively of the onsite workforce, an overall response rate of 85%. Fourteen (14) surveys were incomplete, and 14 participants elected to not participate in the research leaving 166 surveys included in the study. The response rate compares favorably for similar research-based safety climate surveys including construction industry surveys [29,55–58]. Participation rate in the initial baseline safety climate survey was impacted by the rostering of workers and limited involvement by white collar workers. The post-COVID-19 survey had an increase in participation rate, however access to participants across the three different rosters was limited due to COVID-19 restrictions.

5.1.1. Demographics

A shift in the age distribution for the project's working population was observed between the two surveys. The second survey had a 11.1% reduction in the 18 to 29 age group an increase of 9.5% and 4.9% in the 40 to 49 and 50 to 59 age groups, respectively. (Figure 1).

There was a change in participation with sub-contractors representing 81.2% of the October 2020 survey participants compared to 56.5% in January 2020. (Figure 2). There was limited participation in either survey by Owner organization representatives (2 participants).

The participants surveyed were predominantly from the equipment operator and trades occupations with limited input from superintendent/construction management, engineering, catering, and administration occupations. There was a significant increase in the Equipment Operator roles between the January and October surveys. (Figure 3).

The site-based field occupations conduct high risk activities which means understanding their safety perceptions provides an opportunity for project leaders to effectively manage potential safety risks.

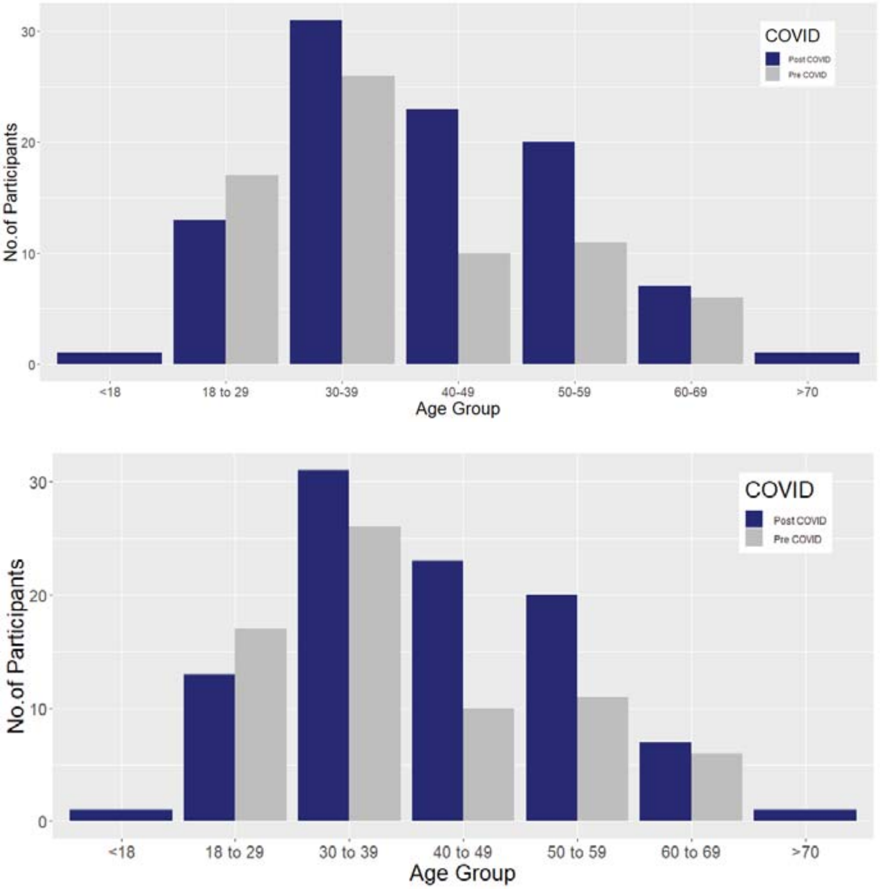


Figure 1. Comparative Age Demographic (n = 166).

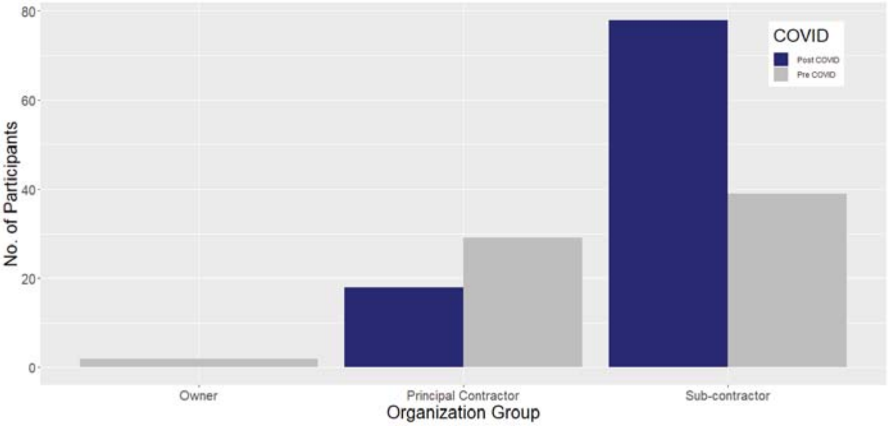


Figure 2. Participating Organizations.

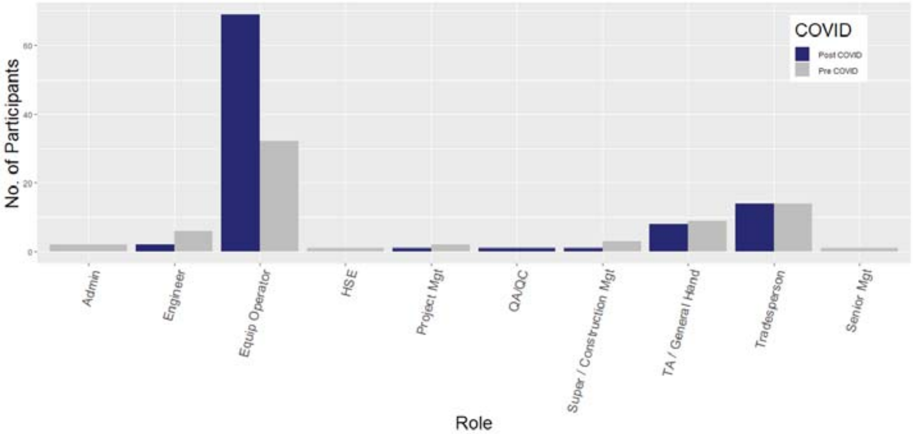


Figure 3. Comparative Participation by Roles.

5.1.2. Measures of Difference between Safety Climate Surveys–Pre/Post COVID-19

Plotting of participant scores by Likert scales identified a similar profile and spread of scores between the two surveys except for Safety Communication (COM_Avg). The average safety communication perception scores have improved between the two surveys with more participants ranking the communication higher on the Likert scale (0–5) with 0 low score and 5 high score of safety rated perceptions (Figure 4).

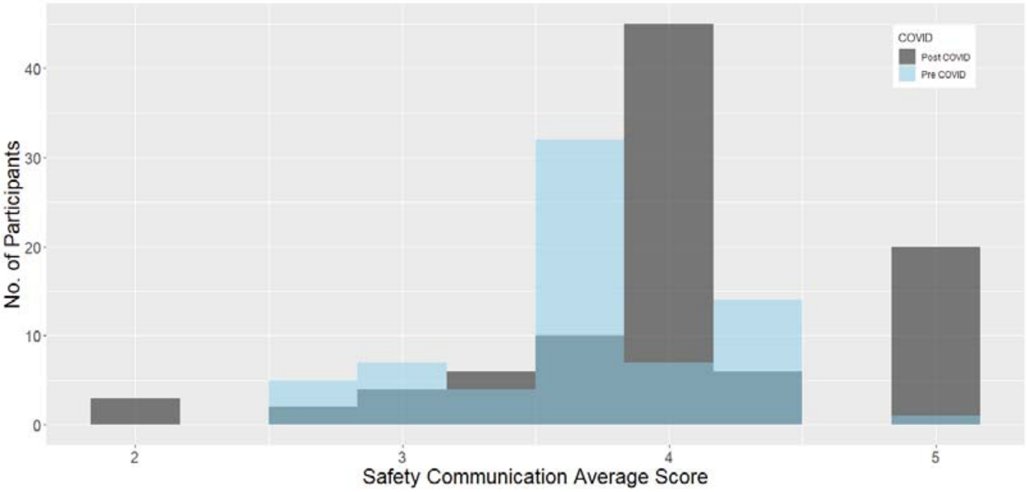


Figure 4. Safety Communication Average Scores by Participants (*n* = 166).

Linear regression models were fitted to all variables (Likert scale units) and the different organization elements (organization, team or individual) with ANOVA of the fitted means used to identify significance between the Likert scale units. The analysis identified significant difference between the survey results for Likert Scale measures of Communication, Supportive Environment, Work Hazard Identification, Worker Involvement and organization elements of Team and Individual safety perceptions (Table 4).

Table 4. Safety Climate Survey Likert Scale & Organization Elements ANOVA Results.

Factor: COVID-19 (df 1:154)					
Likert Scale	**Sum Squares**	**Mean Square**	***F* Values**	**Pr (>F)**	**Significant**
Communication	4.455	4.455	12.063	**<0.001**	Yes
Supporting Environment	0.000	0.00003	0.0001	0.994	-
Work Hazard Identification	0.058	0.058	0.107	0.744	-
Workers Involvement	0.500	0.5003	1.087	0.299	-
Individual Element	0.032	0.032	0.122	0.727	-
Team Element	0.003	0.003	0.008	0.929	-
Factor: ORGANIZATION (df 2:154)					
Likert Scale	**Sum Squares**	**Mean Square**	***F* values**	**Pr (>F)**	**Significant**
Communication	0.028	0.028	0.772	0.782	-
Supporting Environment	2.274	1.137	2.168	0.118	-
Work Hazard Identification	4.623	4.623	8.515	**0.004**	Yes
Workers Involvement	2.782	2.781	6.042	**0.015**	Yes
Individual Element	1.018	1.018	3.916	**0.049**	Yes
Team Element	2.195	2.194	6.966	**0.009**	Yes
Factor: GENDER (df 2:154)					
Likert Scale	**Sum Squares**	**Mean Square**	***F* values**	**Pr (>F)**	**Significant**
Communication	0.384	0.192	0.595	0.594	-
Supporting Environment	0.287	0.143	0.272	0.761	-
Work Hazard Identification	0.062	0.031	0.057	0.944	-
Workers Involvement	0.234	0.117	0.254	0.776	-
Individual Element	0.008	0.004	0.015	0.985	-
Team Element	0.326	0.163	0.517	0.597	-
Factor: AGE (df 6:154)					
Likert Scale	**Sum Squares**	**Mean Square**	***F* values**	**Pr (>F)**	**Significant**
Communication	3.915	0.652	1.767	0.109 *	Outliers skew
Supporting Environment	11.039	1.839	3.508	0.003	Yes
Work Hazard Identification	1.996	0.333	0.613	0.719	-
Workers Involvement	3.370	0.561	1.219	0.299	-
Individual Element	1.000	0.167	0.641	0.697	-
Team Element	3.752	0.635	1.984	0.071 *	Outliers skew

* Further model analysis required given data distribution across the groups with potential outliers skewing results.

5.1.3. Communication Safety Perceptions–COVID and Age Factor Analysis

Initial data exploration identified potential data 'outliers' in the Organization (Owners–Figure 5) and Age (<18 and >70–Figure 6) factor groups where participants of the age group were only in one of the surveys. Further analysis of the data excluded 'Owners' and the two outlier age groups.

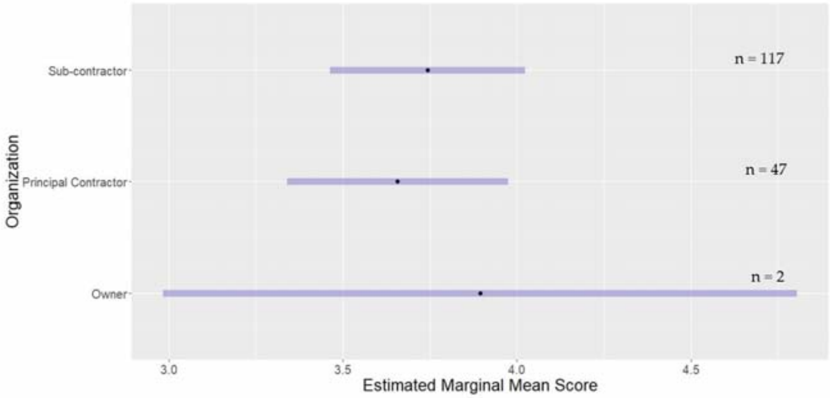


Figure 5. Estimated Marginal Means Distribution by Organization Safety Communication.

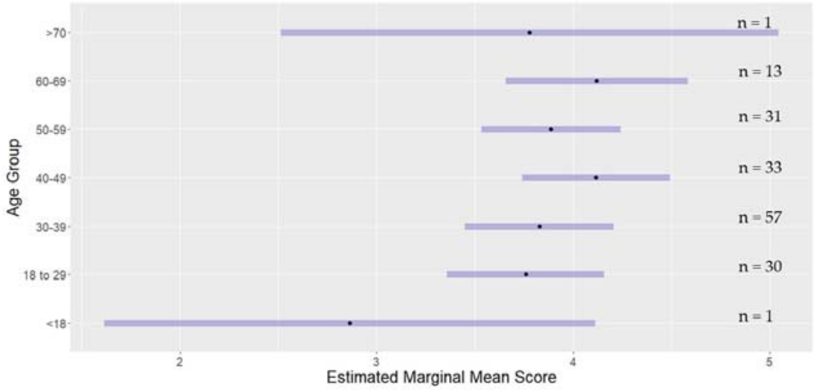


Figure 6. Estimated Marginal Means Distribution by ORGANISATION for Safety Communication.

The average safety perceptions associated with communication were affected by two factors, COVID-19 (p = <0.001) and age (p = 0.1) with the distribution of the data by age (Figure 7). The size of the effect was tested by Estimated Marginal Means with results for COVID and AGE factors shown in Table 5. ANOVA assumptions of normality and homoskedasticity were confirmed through visual inspection of residuals plots.

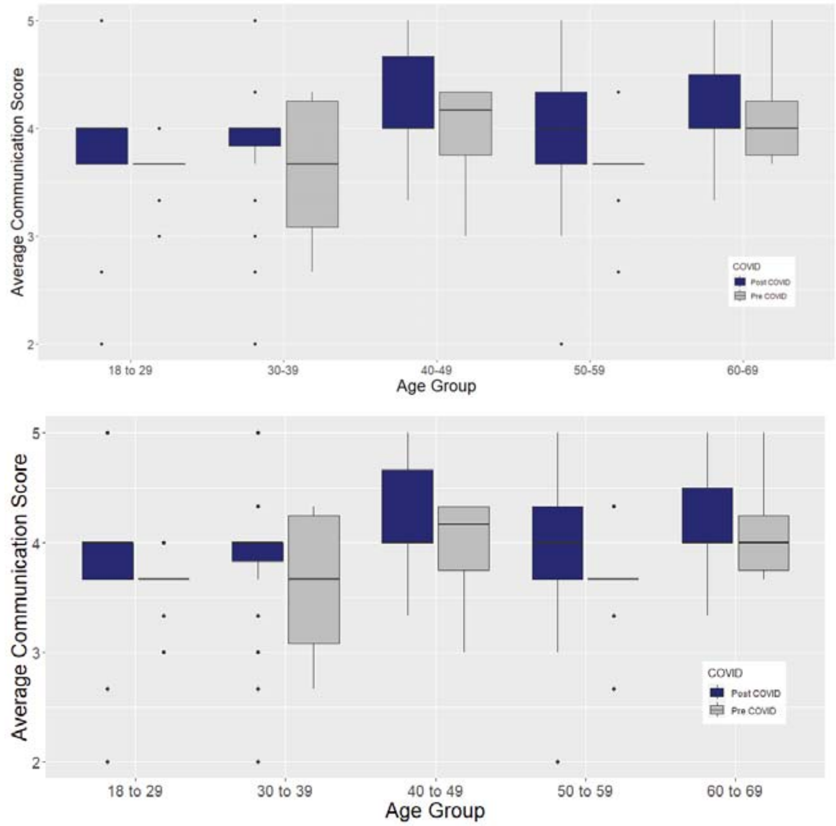


Figure 7. Communication Safety Perceptions by COVID and AGE Factors (n = 166).

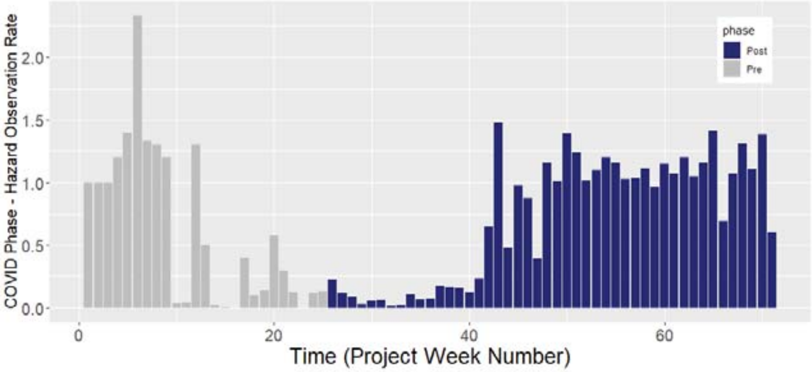
Table 5. Safety Communication by Age Group Estimated Marginal Means Across COVID Phase.

Age Group	Estimate Marginal Mean	Standard Error	*T* Value	Pr (>[t])
30–39	0.069	0.140	0.495	0.621
40–49	0359	0.160	2.246	**0.026**
50–59	0.129	0.165	0.781	0.436
60–69	0.362	0.204	1.772	0.078 [1]

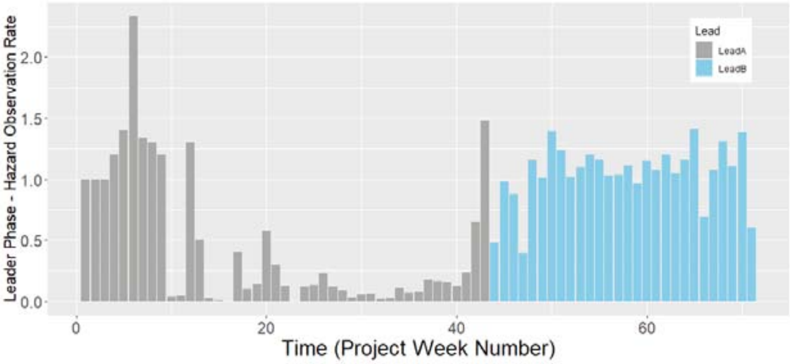
[1] significant at 10% confidence level when further tested ad hoc by Tukey (HSD).

At the 5% confidence level there is sufficient evidence (F(1, 154) = 12.38, $p = 0.0006$) to claim the mean Communication Average score between COVID groups are different. Post COVID scores are on average 0.289 units higher.

Statistical evaluation of AGE factor identified a weak correlation with Communication Average scores (F(4154) = 1.99, $p = 0.098$). The 40–49 age group (group a) were significantly different (t = 2.246, $p = 0.026$) and confirmed through post hoc Tukey analysis (Figure 8). The 18–29 age group was not significant at the 5% confidence level, however, was identified as a separate group (group b) in post hoc Tukey analysis (Figure 7). The other age groups (group ab) were not differentiated from each other, however, was identified through post hoc Tukey analysis as being different from both the 18–29 age group and 40–49 age group (Figure 7).



(**a**)



(**b**)

Figure 8. (**a**) Hazard observation rate by COVID Phase, (**b**) Hazard observation rate under different Project Leaders.

5.1.4. Supportive Environment Safety Perceptions–Age Factor Analysis

Data analysis without the outlier age groups (<18 and >70) identified a significant difference in the average safety perceptions around Supportive Environment between age groups (F(4154) = 4.53, $p = 0.0017$) at the 5% confidence level. Post hoc analysis (Tukey HSD mean = 3.85) identified three different sub age groups. The 40–49 and 60–69 formed group a with average supportive environment score > 4. The 30–39 and 50–59 age groups (group b) had the lowest average scores with the 30–39 age group having the widest variance in mean scores. The 18–29 age group (group ab) was differentiated from the other ages with a median average score and moderate variation in mean scores.

5.1.5. Organization Factor Analysis–Work Hazard Identification and Workers Involvement

The exclusion of outliers (Owner, age groups) was applied to the linear regression model for both Work Hazard Identification and Workers Involvement sets of Likert Scale data with size effects measured by Estimated Marginal Means.

Safety perceptions for Work Hazard Identification and Workers Involvement were significantly different between Principal Contractor and Subcontractor organizations at the 5% confidence level confirmed through post hoc Tukey analysis. Principal Contractor average scores are lower than Subcontractor average scores (Table 6).

Table 6. Safety perceptions for Work Hazard Identification and Workers Involvement.

Likert Scale	*F* Value	Pr > (F)	Emmeans (Principal Contractor/Subcontractor)
Work Hazard Identification	8.515	0.004	−0.428
Workers Involvement	6.042	0.016	−0.298

5.1.6. Organization Factor Analysis–Team and Individual Safety Perception Elements

The exclusion of outliers (Owner, age groups) was applied to the linear regression model for both Team and Individual elements data for ANOVA analysis with size effects measured by Estimated Marginal Means (Table 7).

Table 7. Organizational Factors for Team and Individual Elements of Safety Perceptions.

Likert Scale	*F* Value	Pr > (F)	Emmeans (Principal Contractor/Subcontractor)
Team	6.984	**0.009**	−0.304
Individual	3.916	**0.049** *	−0.214

* Confirmed not to be different when measured by post hoc Tukey analysis.

Safety perceptions for Team was significantly different between Principal Contractor and Subcontractor at the 5% confidence level and confirmed by post hoc Tukey analysis. Individual average safety perception scores were not different when measured by post hoc Tukey analysis.

5.1.7. Safety Climate Survey Summary

The safety climate perceptions were significantly influenced by COVID, Organization and Age factors (Table 8). COVID influenced Communication safety perceptions which varied by age group as did Supportive Environment. Differences in safety perceptions between Principal Contractor and Subcontractors was identified for Work Hazard Identification, Worker Involvement and Team attributes. Results identified COVID-19 adversely impacted management safety communication which as Table 8 shows also influences organizations and different age groups safety perceptions.

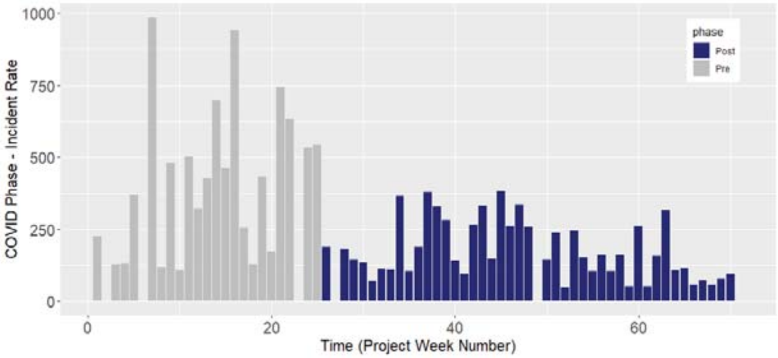
Table 8. Summary of Significance by Safety Climate Measure and Project Factors.

Safety Climate Measure	Project Factors			
	COVID	Organization	Age	Gender
Safety communication	Yes	Yes	Yes *	-
Supporting environment	-	-	Yes	-
Work Hazard Identification	-	Yes	-	-
Worker Involvement	-	Yes	-	-
Individual	-	Yes	-	-
Team	-	Yes	-	-

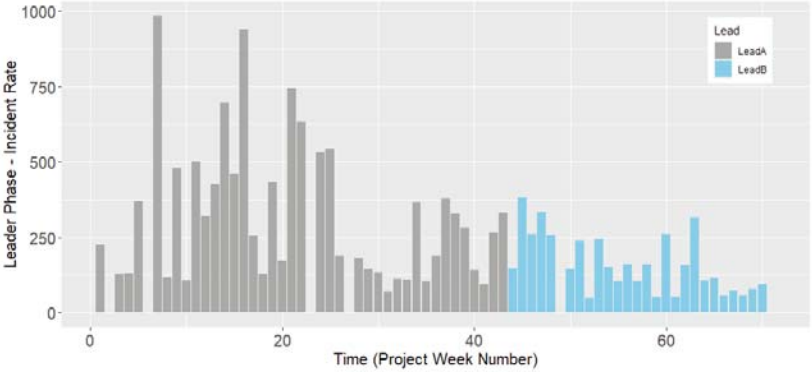
* Specific age groups.

5.2. Safety Performance Results

The leading and lagging safety performance measure trends over time were graphed for the COVID and LEAD factors for exploratory analysis. Visual trends were observed for Hazard Observations (Figure 8a,b), incident rate (Figure 9a,b), Supervisor Observation & Interventions (Figure 10a,b) and MAP checks (Figure 11a,b) and were selected for statistical analysis.

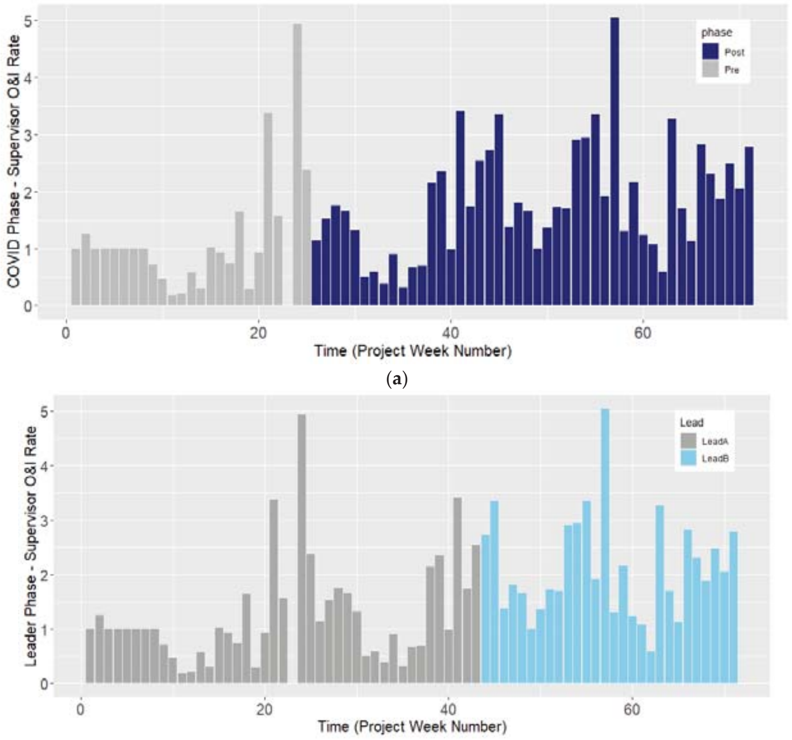


(**a**)



(**b**)

Figure 9. (**a**) Total incident rate by COVID Phase, (**b**) Total incident rate under different Project Leaders.



(**a**)

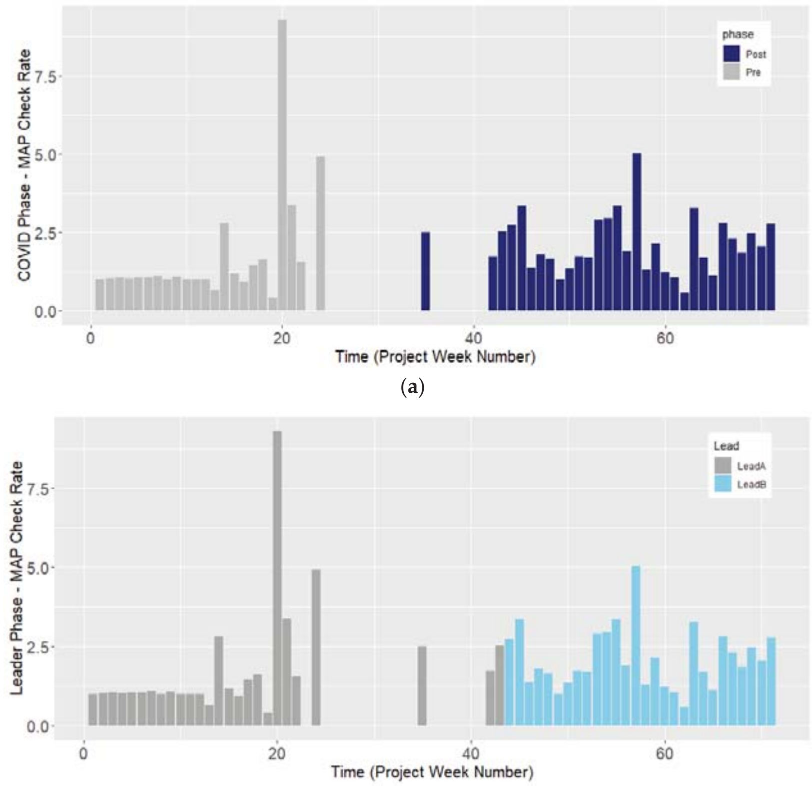
(**b**)

Figure 10. (**a**) Supervisor observation & intervention rate by COVID Phase, (**b**) Supervisor observation & intervention rate under different Project Leaders.

Each selected safety performance parameter was fitted to linear regression model for ANOVA to test significance by COVID and Leader factors with Estimated Marginal Means used to assess the scale of the difference. ANOVA assumptions of normality and homoskedasticity were confirmed through visual inspection of residuals plots. A summary of the ANOVA outputs by safety performance parameter are provided in Table 9.

Table 9. Safety Performance for COVID and LEADER Factors–ANOVA Results.

Factor: COVID-19 (df 1:68)					
Performance Indicator	**Sum Squares**	**Mean Square**	***F* Values**	**Pr (>F)**	**Significant**
Hazard Observations	0.164	0.164	0.819	0.369	-
Supervisor Observations	7.769	7.769	8.192	**0.0056**	Yes
Critical Control Verifications	0.543	0.543	0.295	0.589	-
Total Incident Rate	703,387	703,387	19.937	$\mathbf{3.096 \times 10^{-5}}$	Yes
Factor: ORGANIZATION (df 2:154)					
Performance Indicator	**Sum Squares**	**Mean Square**	***F* values**	**Pr (>F)**	**Significant**
Hazard Observations	7.624	7.624	38.687	$\mathbf{3.49 \times 10^{-8}}$	Yes
Supervisor Observations	6.401	6.401	6.749	**0.011**	Yes
Critical Control Verifications	33.737	33.737	18.356	$\mathbf{5.905 \times 10^{-5}}$	Yes
Total Incident Rate	19,059	19,059	0.540	0.469	-



(**a**)

(**b**)

Figure 11. (**a**) MAP check rate by COVID Phase, (**b**) MAP check rate under different Project Leaders.

5.2.1. COVID-19 Effect

The project safety performance as measured by Total Incident rate improved significantly in the eight weeks post COVID-19 affecting site operations (Figure 9a). The incident rate deteriorated again and plateaued but did not return to the original levels and was on average significantly lower post COVID-19. The mean incident rate between Pre and Post COVID was different (F(1,68) = 19.9, $p = 3.1 \times 10^{-5}$) where the post COVID incident frequency rate is on average 183 units lower.

The Supervisor Observation (SO&I) rate was significantly different between Pre and Post COVID (F(1,18) = 8.2, $p = 0.0056$) with the Post COVID rate being on average 0.23 units higher than Pre-COVID rate.

5.2.2. Leader Effect

Leaders influenced frontline risk management practices of Hazard Observations (HAZOB), Supervisor Observations (SO&Is) and Critical Control verification (MAP Check) rates. On average Leader B improved the rate of all frontline risk management practices, HAZOBs by 0.83 units (F(1,68) = 38.7, $p = 3.5 \times 10^{-8}$), SOIs by 0.76 units (F(1,68) = 6.7, $p = 0.11$) and Critical Control verification rate by 1.75 units (F(1,68) = 18.36, $p = 5.905 \times 10^{-5}$).

The times series graphs (Figure 8a,b, Figure 10a,b and Figure 11a,b) for each of the risk management practices show a similar trend with risk management practices slowing down or ceasing in the case of MAP Checks with the onset of COVID-19 impacts (week 25) and not increasing again until under the influence of Leader B.

In summary the project had a significant improvement in incident rate and SOIs post COVID. Leader B improved the rate of leading indicators including Hazard Observations, Supervisor Observations & Interventions and MAP Checks.

6. Discussion

The research evaluated the effect of COVID-19 on a construction project by comparing pre and post COVID-19 safety performance and the influence of leaders on the worker safety perceptions. The project was operational prior to COVID-19 and had completed a baseline safety climate survey to compare post COVID-19 results. The results are unique as the data shows the project throughout the COVID-19 transition period and operating under the new COVID-19 conditions and provides direct comparative data pre and post COVID-19.

COVID-19 as a factor was identified in total incident rate and supervisor observations and worker perceptions around safety conversations. Leaders influenced the frontline risk management activities of hazard observations, supervisor observations and critical control verifications (MAP Checks). Project leadership was not static during the study as the Project Manager (primary leader) was changed by the organization in response to deteriorating safety performance and broader management of COVID-19 effects on the project. The statistical modelling did factor in the change to ensure the effects of COVID-19 were not over-estimated due to the change in leaders. The analysis does provide insights into the safety climate dynamics operating within a construction site when external stress events are introduced.

The overall reduction in incident rate following the impact of COVID-19 is consistent with other studies where COVID-19 heightened the risk awareness of workers [10–12,15]. The decentralization of construction organizations [28] with management control at site directed through the Project Manager and supervisors has meant front line leaders have a direct influence of on safety performance [59]. The supervisor role is pivotal on a construction project as it directly influences work group safety attitudes and risk-taking behaviour [48] resulting in a reduction in injuries [29]. Alruqi [59] supported this view when comparing safety climate to safety performance within the construction industry whereby supervisor behaviour is important in improving safety climate and reducing injuries.

6.1. Influence of Leadership through COVID-19 and Safety Perceptions

Studies have also reported the heightened level of risk awareness by workers due to COVID-19 has also applied to other safety management practices [11,36]. The results from this study differ from previous findings as the frontline risk management practices do not increase worker risk management practice in response to COVID-19 but decrease under Leader A. However, the trend does reinforce the relationship between supervisors and the safety climate set on the project. Supervisors responded to COVID-19 by increasing the SOIs with the workers including associated safety orientated communication. The engagement by supervisors was recognized by the workers in the safety climate surveys where workers perceived there was an increase in ‘safety communication’ post COVID-19 than pre-COVID-19.

The increased worker engagement through SOI’s by supervisors in the post COVID-19 period and prior to the commencement by Leader B did not result in an increase in other risk management activity by the workers as measured by hazard observations (HAZOBs). The increase on average of worker hazard observations (HAZOBs) and re-instatement of supervisors completing Critical Control (MAP Check) verifications was associated with the influence of Leader B. The safety climate at the site is set by the Project Manager (Leader A/Leader B) who can influence positively by providing support for supervisors and their work teams or negatively with a focus on production and ongoing perceived production pressure by supervisors and the workers [18].

Project supervisors and workers will perceive to be under greater production pressure due to delays caused by material and labor shortage, disrupted rosters and imposed COVID-19 control activities [12]. In the absence of pro-active and positive safety leadership under COVID-19, the project safety climate will deteriorate and a reduction in worker safety motivation, participation in safety programs and safety compliance will occur [18,29]. The decline in worker hazard observations (HAZOBs) and Critical Control verifications post COVID-19 under Leader A supports Guo's [47] safety climate prediction.

Post COVID-19 when the project was under stress due to the health, logistics and supply issues the perceived safety climate improved. Initially under Leader A as the continuous changes, due to COVID-19 increasing rate of spread, were communicated, and then improved even further under Leader B. In the post COVID-19 period the change in safety communication positively influenced the perceived safety climate and safety participation as the frequency of risk management activities (HAZOBs, MAP Checks) increased, a finding consistent with previous research [29,32,47]. Leader B in the post COVID-19 period set up the communications and actions required to re-instate supervisor interactions improving the 'social support' for the workers and establish a positive 'supporting environment'. COVID-19 factors including increased work pressure arising from shortage of labor and restricted logistics arrangements initially caused a deterioration in worker safety participation and safety compliance. Under Leader B's guidance the perceptions related to work pressure improved, workers became more involved and work hazard identification improved. By increasing the rate of supervisor observations (SOIs) and Critical Control (MAP Check) verifications, Leader B re-instated the social interactions and supervisory leadership both antecedents of a shared safety climate [43,44]. COVID-19 was a major disruption on the project which caused a drop in frontline risk activities after the initial three-week period. However, Leader B demonstrated generating a positive safety climate through communication and committed risk management actions offset the impact of the COVID-19 disruption and improved safety performance. A similar conclusion was reached in an oil and gas COVID-19 study recommending 'companies should maintain a positive perception of health and safety culture to improve workplace safety even during the pandemic' [60].

6.2. Influence of Age on Safety Perceptions

Safety communications across the project were influenced by age group of the workers with younger personnel (18–29-year-old group) having a lower perception on the effectiveness of safety communication and the supporting environment than other age groups. Younger worker safety perceptions are influenced by organisational relationships, mental stress, and job security [61] all of which were subject to changes and the associated pressure due to the COVID-19 impact on the project. The 'supporting environment' provides the organisational structure and support to safely undertake work under instruction from the supervisor and guidance of the work team. This age group safety perception of the 'supporting environment' was on average > 1.05 units lower than all other age groups surveyed and reflects the dependency younger construction workers have on stable organisational support.

Older construction workers, (in this instance > 30 years old) safety perceptions are dominated by factors of workload and job satisfaction [61–63]. Two age groups (40–49 and 60–69 years old) perceived safety communication on average at a higher level than the other age groups. One theory is these groups represent supervisory or management roles and have a more positive perspective as they are directly engaged in the safety communication processes on projects. This was unable to be validated due to limitations of the data set.

6.3. Influence of Organization on Safety Perceptions

Organisational factors, specifically differences between principal contractor and subcontractor safety perceptions were identified for Work Hazard Identification, Worker Involvement and Team factors with subcontractors on average having a higher safety perception. Subcontractors are used on construction projects to undertake specific scopes of work relevant to the specific skill sets of the contracting company and usually operate independently of other subcontractors with oversight provided by principal contractor representatives. In working within self-contained teams, the subcontractor leaders have more direct contact with their workers. The higher level of perceived safety by subcontractors reflects this organisational structure with subcontractor leaders directly influence frontline risk management activities, engaging with the workers and engendering a team environment.

The differences Identified in safety perceptions between principal contractor and subcontractors reflects the complex social ecosystem which exists within a construction project. Principal contractor representatives in Australian construction industry were found to be more focused on getting the job done given the range and scope of the project than consulting or communicating with subcontractor personnel to resolve schedule clashes or other issues or ensuring safe work practices [64]. The safety attitudes and behaviours are shaped by professional; organization and industry cultures which influence the operations at site, and it is common for misalignment between organizations, even to the point there is no shared view of safe practices [64].

Leadership attributes were potentially more pronounced due to COVID-19 given the pressures on resources, time and schedule COVID-19 introduced which resulted in a change of Project Manager during the study. The change in leaders however also provided an opportunity to model the effect of different leaders under COVID-19 conditions.

Two disruption events occurred during the study, COVID-19 and change in project leaders, resulting in transition periods as the project personnel learned how to 'normalize' the effect of the change in day-to-day work. The data indicates during the transition periods (3 to 4 weeks) the change had an exaggerated short-term effect on the performance measure (e.g., MAP checks, incident rate) which was not quantified. Further analysis is required to explore the impact of "transitions" on safety performance

COVID-19 presented a major disruption event to the study project with increased level of stress within the organizations involved through impacts to workers, labor shortage, supply chain and increased schedule pressure. Organizations have become entrenched in 'administering' safety with a focus on producing 'pieces of paper' and by default the pieces of paper have become more important than the activities which produce them [65]. The comparative difference between the project leaders in the study emphasized the importance frontline leaders have in delivering safety outcomes primarily through worker engagement and effective communication on safety priorities. Organizations looking to manage through disruption events, and, by extension, catastrophic incidents would benefit from 'checking in' with the worker safety perceptions and how to improve worker engagement to ensure the wellbeing and safety of workers.

6.4. Limitations

There are a few limitations of the study which need to be acknowledged. First the study was limited to one construction project operating under fly in: fly out manning in remote Western Australia with personnel experiencing long periods of isolation physically away from immediate personal support networks. Managed under joint venture management structures with stringent client COVID-19 imperatives which constantly changed, a level of misalignment occurred between organizations not usually present within a construction project. While the study confirmed the importance of site leaders in setting the safety climate identified in previous research [32,40] further longitudinal research is needed to validate the inter-relationships identified. Second, under the unique circumstances the aspects directly related to participation rates (high rates) and misaligned safety perceptions between organizations, these should not be extrapolated as typical construction project work arrangements. Further research to across multiple projects is needed to test the results from this study. Third, the safety climate survey used was modelled and validated through research [29] to test inter-organization and supervisor level safety climate factors, while the safety climate measures were sensitive enough to detect differences in real test situations further validation across multiple case study sites is needed. Finally, COVID-19 was a significant disruptive event and while being a focus of the study also introduced a potential bias in perceptions relevant to management commitment as organization management were not able to have a present on the work site.

7. Conclusions

Safety performance as measured by incident rate improved under the effect of COVID-19 which is consistent with the inherent increase in safety awareness due to COVID-19 reported in previous studies [10,11]. The increased safety and wellbeing awareness due to COVID-19 did not result in an increased level of engagement in front-line risk management activities. The frontline risk management activities reduced over time under the influence of COVID-19 and did not improve until a change of Project Manager occurred. The study identified the effect of leadership and power of setting a positive safety climate to increase worker motivation, participation in risk management processes and compliance to safety requirements.

The safety climate on a project is perceived differently by different organizations working with the site environment or by different age groups. The dynamics with the construction site organizations collectively shape the safety climate on site with the subcontractors having a more direct relationship with their worker generating a more positive safety climate than the principal contractor. Younger members of a construction workforce perceive the safety climate more negatively than older work-force members.

The study benefits construction frontline leaders managing disruption events, either externally imposed (e.g., COVID-19) or internally (e.g., organization changes), the positive impact of worker engagement and consistent safety communication has on safety climate and safety performance. Through positive engagement frontline leaders enable workers to build resilience and maintain a focus on risk management practices.

Author Contributions: Conceptualization, R.S.; methodology, R.S. and M.H.; investigation, R.S.; formal analysis, R.S.; resources, R.S.; supervision, M.C. and M.H.; writing original draft, R.S.; writing—review and editing, M.C. and M.H.; validation, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by an Australian Government Research Training Program (RTP) Scholarship.

Institutional Review Board Statement: The research has been conducted in accordance with Edith Cowan University Human Research Ethics Committee (HREC) approval for Project number 20293 Selleck granted on 12 June 2018 (valid from 12 June 2018 to 31 March 2022) which meets the requirements of the National Statement on Ethical Conduct in Human Research.

Informed Consent Statement: Consent was obtained from participants to use the safety climate survey responses as part of the survey method. Safety performance statistics provided by the participating company were de-identified prior to being provided to the researcher. No harm has resulted from the safety climate survey or other participation in this research.

Data Availability Statement: Restrictions apply to the availability of these data. Data was obtained confidentially from four third party construction companies and is available upon request from the corresponding author with the permission of participating companies.

Acknowledgments: The authors would like to express thanks to the construction company which provided access to the construction project site, provided safety performance data, and participated in this research.

Conflicts of Interest: The authors confirm there are no competing interest associated with this research.

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A Mathematical Modeling of Evaluating China's Construction Safety for Occupational Accident Analysis

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Abstract: China has seen a rapid increase in its construction industry in recent years; however, safety conditions of their workers have not improved owing to low education levels and increasing age trend of construction personnel. This study analyzed construction occupations in China from 2010 to 2018 using descriptive analysis, ANOVA and factor analysis. The results showed May, July and August as the deadliest months during the peak of construction activities in the year. No particular day was established as having a higher risk than other days in the week. The most vulnerable times of the day are from 9 AM to 10 AM and 2 PM to 4 PM. A mathematic modeling based on factor analysis, which is the construction safety evaluation score equation, was developed to illustrate regional distribution, and Qinghai Province ranked the worst in construction safety in China. Problems such as poor labor and environment safety management procedures and false reporting or concealed reporting of construction accidents were revealed. Suggestions for improving China's construction safety were also generated. This study enriched statistical analysis results of construction accidents in China and evaluation modeling with an abundant database will serve as a reference for stakeholders and researchers to improve the construction safety situation in China.

Keywords: construction in China; construction safety; construction accidents; statistical analysis

Citation: Ma, Q.; Lusk, J.W.; Tan, F.H.; Parke, M.E.; Alhumaidi, H.M.; Clark, J.D. A Mathematical Modeling of Evaluating China's Construction Safety for Occupational Accident Analysis. *Appl. Sci.* **2022**, *12*, 5054. https://doi.org/10.3390/app12105054

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin, Anil Sawhney and Edyta Plebankiewicz

Received: 8 April 2022
Accepted: 16 May 2022
Published: 17 May 2022

1. Introduction

Construction is a labor-intensive industry based on manual labor [1,2] and therefore, the education and skill level of the workforce mainly determine the safety and quality of its products. However, the average annual salary of these workers was 60,501 yuan (approximately USD 9300) in 2018, which was less than the average annual salary of China's total workforce [3]. It is hard to attract a younger, more educated workforce with high technical skill to consider construction as a vocation. The education level of 87.1% of construction workers was equal or lower than senior high school [3]. Additionally, according to the China Construction Industry Association, the average age of construction workers increased by ten years from 2007 (33.2 years) to 2017 (43.1 years). The low skill level [4], low educational level [4,5] and increased age trends of construction workers in China increase the likelihood of accidents as compared to those of workers with the same trends in other industries. In addition, characteristics of complexity [6,7], dynamic workplace [8], staff mobility [8,9] and external weather effects [2,10] that exist in the construction industry also increase the risk of accidents that construction workers encounter. Specifically, there were 5255 construction accidents and 6392 worker deaths in China during the period from 2010 to 2018, reported by the annual construction accident report from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHUOURD) [11]. Therefore, it is urgent to evaluate construction safety in China, which will contribute significantly to reduce death and financial loss due to construction accidents.

Statistical analysis and mathematical modeling, which depicted abundant information regarding safety and risk level [12], such as assessment and prediction of injuries and fatalities in construction, have been applied to civil engineering [13,14]. Im et al. studied 10,276 fatal occupational injuries' characteristics in Korea through several statistical analyses and offered suggestions to reduce death due to the most frequent accident types, such as falling, structural collapse and electric shock in Korea's construction industry [15]. Cheng et al. carried out correlation coefficient analysis and ANOVA on 1546 occupational accidents for small construction enterprises in Taiwan and suggested occupational accident occurrence was highly related to age, profession, unsafe acts by workers and unsafe conditions [16]. Wangberg et al. used linear regression to test the null hypothesis that there is no statistical relationship between quality performance indicators and safety performance indicators and found strong positive correlations between injury and rework and first aid rate and defects [17]. Winge and Albrechtsen used incident concentration analysis (similar to descriptive epidemiology) to identify clusters with common characteristics of 176 construction accidents in Norway. It was reported that work type, hazard and energy difference in energy models contributed together to the difference in the distribution of accident types [18]. The studies mentioned above demonstrated the feasibility of using statistical analysis and mathematical modeling in estimating and assuming safety performance in construction engineering.

Studies have also been carried out on construction accidents in mainland China for construction accident prevention. Tam et al. conducted a questionnaire survey among 200 construction firms in China to examine construction safety in China and revealed defects of safety management including lack of provision of PPE, regular meetings and safety training [4]. Zhang et al. compared usability and validity of four accident causation models (STAMP, AcciMap, HFACS and 2-4 Model) when analyzing a construction accident case in China and recommended the 2-4 Model for construction accident analysis owing to its characteristic of connecting accident causes, management and safety culture [5]. Guo et al. formed a Bayesian network (BN) model based on 287 construction accident cases in China to reveal that unsafe behaviors greatly contributed to certain accident types in critical groups. The importance of safety training for both workers and managers/engineers was also suggested [19]. Xu et al. devised an approach to extract typical safety risk factors using text mining (TM) technology from construction accident reports and applied it to a case study reporting critical safety risk factors in China including surrounding environment, safety management, construction technology, construction personnel, materials and equipment [20]. However, sample sizes in current research were not large, and some of them were outdated since fresh data are updated. Although some studies have illustrated construction accident patterns in China based on abundant new database, a more comprehensive study with more information is required rather than investigating construction fields merely because China is a huge country with different developmental levels and safety climates in different regions.

This study aimed at overcoming deficiencies of limited sample size in current research for time scales and building a standard construction accident evaluation model by combing indices of construction safety, finance, labor and building construction scale for different regions in China. Data for construction accidents in China during the period from 2010 to 2018 were collected from MOHURD [11] and local websites in Henan Province [21]. Frequency analysis and analysis of variance (ANOVA) were used to explore time distribution characteristics for construction accidents in time scales regarding year, month, day of week and hour of day. Then, factor analysis was conducted to combine various indices into two factors and build a standard construction accident evaluation model for different regions in China. Finally, suggestions for improvement of construction safety were generated for local government and companies regarding results of the time-regional distribution of construction accidents.

2. Data and Methods

2.1. Data Source

MOHURD collects and publishes construction accident information monthly, quarterly and annually. Construction accident reports can be accessed by entering the document library of MOHURD [11], then filtering parameters by clicking "Department of supervision on construction quality & safety" (relevant department of construction accident) and "Statistical data" (relevant document type). Construction accident number and worker death toll per year, month, region and accident cause can be obtained. However, these reports contain little information and more detailed description of each accident is needed for further study. There was an accident bulletin board in MOHURD which displayed more specific time and accident types of worker fatalities for relevant stakeholders of numerous construction accidents, but it is no longer available as of 2019. Thanks to a local website in Henan Province [21] which collected and recorded reports from the accident bulletin board. Construction accident number and worker death toll per day of week and hour of day were obtained through extracting key information from reports on the accident bulletin board. Note that although there might be some deviation of data owing to concealment or delay of reporting from some local authorities to MOHURD or updates of data over time, analysis results in this study can still reveal patterns of construction accidents in China and serve as a reference which contributes to improving construction safety in China. Building areas under construction, construction gross domestic product (GDP) and construction employee population in each region were collected from annual *China Statistical Yearbooks* (for example, [22]).

Data from MOHURD are relevant to building and civil construction accidents. According to the work safety commission office of the State Council of China [23], the scope of building and civil construction is defined in Table 1.

2.2. ANOVA

Analysis of variance (ANOVA) is a test statistic to test the hypothesis that the p distributions from which the samples were drawn are actually the same [24]. Two hypotheses are supposed as follows:

H0: *There is no significant diversity between observations among different samples.*

H1: *The hypothesis H0 is not true.*

Variation between n observations can be partitioned into two smaller sums of squares: sum of squares will measure variation between the p different samples (S^2_{Resid}), and the other sum of squares will measure the variation between observations within each of the samples (S^2_{Betw}). These two sums of squares are defined as follows:

$$S^2_{Resid} = \sum_{i=1}^{p} \sum_{j-1}^{n_i} \left(X_{ij} - \overline{X}_{i+}\right)^2, \tag{1}$$

$$S^2_{Betw} = \sum_{i=1}^{p} n_i \left(\overline{X}_{i+} - \overline{X}_{++}\right)^2, \tag{2}$$

In which,

$$\overline{X}_{++} = \frac{1}{n} \sum_{i=1}^{p} \sum_{j=1}^{n_i} X_{ij} = \frac{1}{n} \sum_{i=1}^{p} n_i \overline{X}_{i+} \tag{3}$$

A test statistic that will tend to be larger if H1 is true than if H0 is true. Supposing H0 is true, the ratio of two sums of squares (U^2) will have the F distribution with $p - 1$ and $n - p$ degrees of freedom. Therefore, whether or not observations come from the same sample can be identified through comparing significant values of U^2 with critical values. U^2 is defined Equation (4):

$$U^2 = \frac{S^2_{Betw}/(p-1)}{S^2_{Resid}/(n-p)} \tag{4}$$

Table 1. Scope of building and civil construction.

Category	Subcategory
Building construction	Residential buildings Commercial buildings Hotels, restaurants and apartments Offices Schools and hospitals Passenger waiting rooms at airports, wharves, railway stations and bus stations Indoor stadiums and entertainment venues Workshops and warehouses
Civil engineering construction	Subway, light rail and tramcar subgrade track laying Urban municipal and ordinary highways Urban roads, streets, sidewalks, overpasses, underpasses, squares, parks and traffic barriers Subway and municipal road tunnels Municipal road bridges and urban flyovers Waterworks and sewage treatment works Water treatment system installation Gas and heat supply facilities Solid waste treatment works Urban landscapes, greenbelts and street lighting Urban pipelines and transfer stations
Mechanical installation	Electric wiring, lighting and electric equipment Signal appliances Telecommunication lines and equipment Water pipes and equipment Gas supply lines and equipment Heating pipelines and equipment Air conditioning equipment Fire detection devices Anti-theft devices Insulation and fireproof devices Elevators
Architectural components installation	Doors, windows and glass Floor treatment Wall and ceiling treatment and whitewash Paint Indoor woodworking and metalworking services Building repair and maintenance
Others	Preparation Construction equipment and operator service

2.3. Factor Analysis

Factor analysis is utilized to represent the underlying information of a set of variables using a smaller number of variables [25]. An indices system was built and principal component analysis (PCA) was carried out to extract information from the original data sets regarding construction accidents, finance, labor and building construction scale and combine them into two composite indices called factors. A score function and a mathematical model based on the result of factor analysis were built. Statistical Product Service Solutions (SPSS 23.0) was utilized for completing factor analysis, ANOVA and other statistical functions.

3. Results

3.1. Descriptive Analysis

Data from the annual construction accident report in MOHURD [11] suggest that the number of building and civil construction accidents decreased during the period from 2010 to 2015 and increased during the period from 2015 to 2018 (see Figure 1). The fewest accidents were 442 in 2015. The corresponding worker deaths exhibited the same pattern. The State Council of the People's Republic of China categorizes four levels of accidents based on the number of fatalities per accident [26]. Accidents that result in less than three worker deaths are regarded as low. These levels rise with the increased number of fatalities to medium (3–10), high (10–30) and very high (30+). In the following sections, moderate- to high-fatality (MHF) accidents refer to accidents that result in no fewer than three worker deaths (medium, high and very high number of fatalities). Therefore, the number of worker deaths is greater than that of construction accidents annually in Figure 1 due to the occurrences of multiple fatalities associated with the MHF accidents.

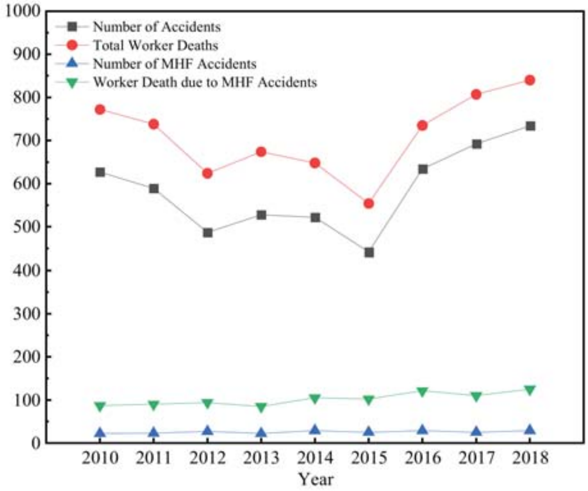

Figure 1. Building and civil construction accidents.

Change in construction industry gross domestic product (GDP) in China is a primary factor leading to patterns of construction accidents in Figure 1. China's construction industry has played an important role in the process of the country's economic growth and is a major contributor to China's GDP. According to the annual *China Statistic Yearbooks* (for example, [22]), the construction industry increased its contribution to GDP from 3.8% in 1978 to 6.9% in 2018, and 7.2% of China's workforce were construction workers in 2018. Figure 2 displays the number of construction accidents and construction industry GDP in China during the period from 2010 to 2018. Note that the dip in the number of building and civil construction accidents in Figure 2 is due to the decrease in the growth rate of construction industry GDP during the period from 2010 to 2015 (2.29% in 2015). Therefore, lower construction activity in 2015 resulted in fewer accidents. Then, from 2015 to 2018, construction accidents began to increase. The dip in construction accidents can also be explained by the change in the total number of construction contracts and building construction areas (see Figure 2). Both lines also exhibit the same pattern as the number of construction accidents. The above-mentioned information establishes a relationship between cost, investment, profit and safety within the construction industry. The period from 2011 to 2015 was the 12th Five-Year Plan of China, during which China expected a shift to a consumption-driven economy [27]. Therefore, China's economic structure was adjusted, and the development model changed from 2010 to 2015, leading to the deceleration of the construction industry. In this case, the number of construction accidents decreased as well.

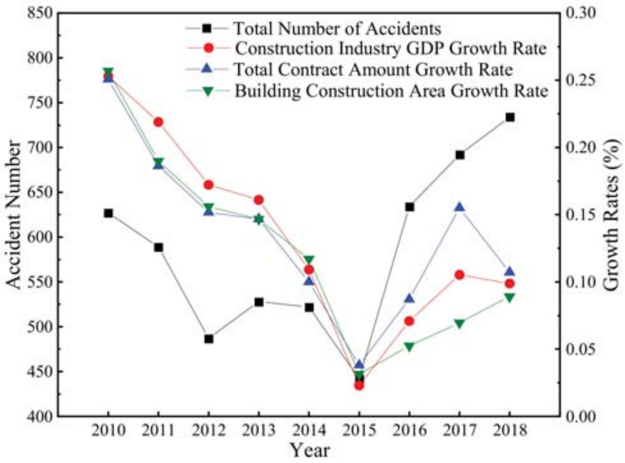

Figure 2. Comparison between number of accidents and other indices.

Construction industry profit improved after 2015 and construction accidents accordingly increased during that period. Additionally, MOHURD published a notification to local authorities prohibiting delay in reporting or concealment of construction accidents in 2015 [28], which also contributed to the increase in accidents after 2015. Number of construction employees increased every year except for 2011 (for example, [22]). Despite the increased number of workers, a decrease in construction accidents indicates that safety improved during that period. Therefore, a combination of economic conditions and safety measures could explain the construction accident change.

Figure 3 illustrates total number of construction accidents (during the period from 2010 to 2018) among 31 regions in China (excluding Hong Kong, Macao and Taiwan). Regions with higher GDP, such as Jiangsu Province, Zhejiang Province and Guangdong Province, have the most accidents. Additionally, relatively underdeveloped regions such as Shanxi Province, Ningxia Province and Tibet Autonomous Region have the fewest accidents. Figure 4 depicts a scatter plot between the total construction accident number and the total construction industry GDP of different regions, from which a positive linear relationship can be observed. The Pearson's Correlation Coefficient of 0.777 (−1 to +1 range) indicates that there is a high positive correlation between these two indices [24].

Regarding accident causations, approximately 51.6% of total construction accidents were due to "falls", 13.8% were "struck by objects", 12.46% were "struck by objects" and 12.46% were "collapsed structures". "Falls" are China's predominant cause of construction accidents (the same as for many other parts of the world) [6,15,18].

3.2. Time Distribution of Construction Accidents

3.2.1. Construction Accident Number per Month

Figure 5 depicts the number of construction accidents per month from 2010 to 2018. A similar change of accident number in each month within every year can be observed. ANOVA was employed to test if there is a correlation between number of construction accidents and the month in which they occur. Two hypotheses (not significant and significant) were established and data in Figure 5 were tabulated into 12 groups by month of the year. The significance value from the ANOVA table is 0.000 (<0.05), suggesting there is a significant diversity between construction accident number in different months. Therefore, correlation between these two variables was identified.

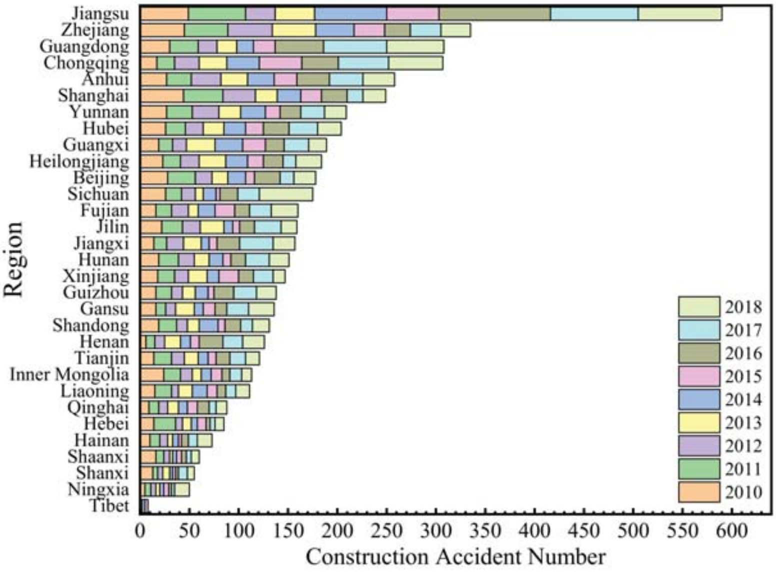

Figure 3. Total construction accidents in 31 regions of China.

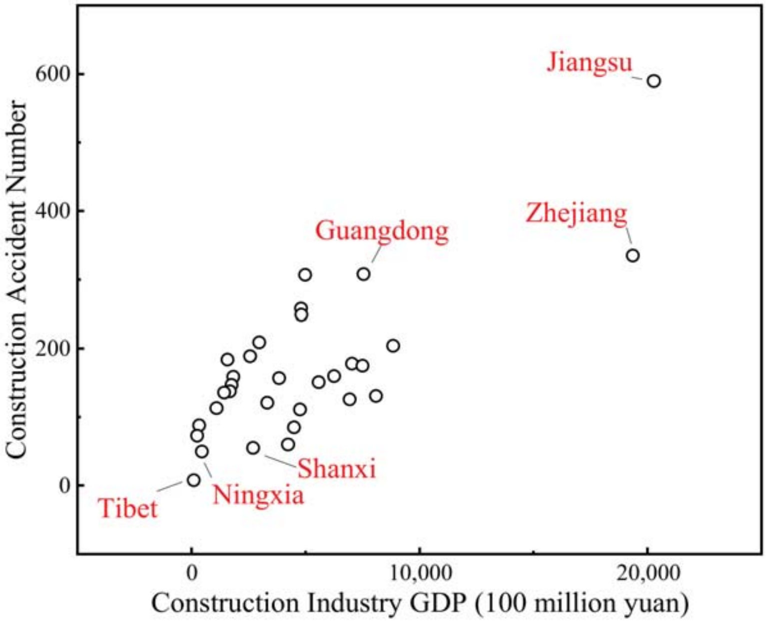

Figure 4. Scatter plot of construction accidents and construction industry GDP.

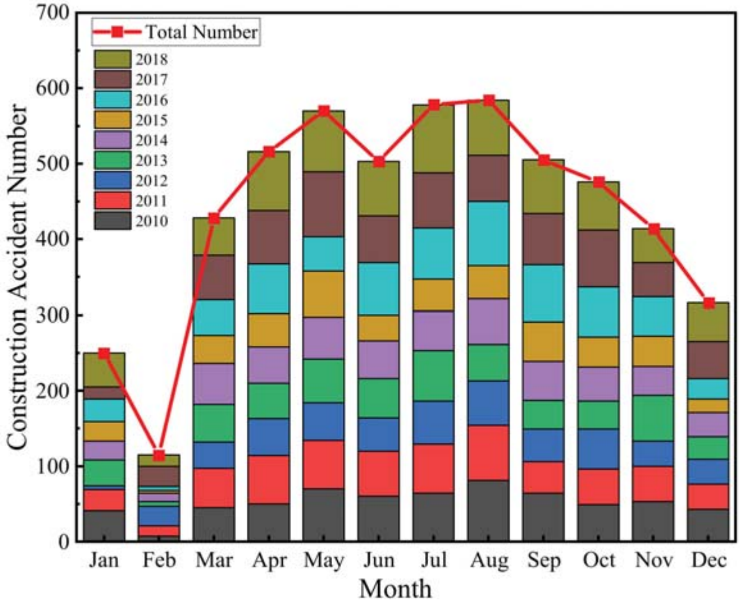

Figure 5. Number of construction accidents per month.

The most frequent occurrences of construction accidents take place in May and from July to August, and the least from January to February (see Figure 5). The Chinese New Year is in February during this period and most construction workers are on vacation. Therefore, the number of accidents in February is less than the other months. In March, as construction workers return to work, the number of accidents starts to increase. Although this number reaches a peak in May, it decreases in June. Two reasons could account for this as follows: first, an activity known as Safety Production Month of China is held by MOHURD in June every year. During this month, construction companies conduct safety training programs for workers and construction managers; this will improve safety aspects during construction operations. Second, most labor forces in the construction industry are from rural areas owing to urbanization in China [29–31], and most workers return home to engage in farming activities in June, which is the summer harvest in China. In July and August, to prevent potential delay caused by the summer harvest, managers may add workloads to workers [31]. Thus, construction workers will work overtime or extended hours. However, in July and August, during the summer season, bad weather including high temperatures and heavy rain (especially in south regions) may cause poor working conditions for construction and increase work intensity for construction workers. In this case, there is a negative impact on the physical and mental state of workers [32,33]. Thus, accident number reaches another peak in July and August. In autumn, i.e., in September and October, the weather becomes moderate, leading to a weakening of thermal impact on construction workers. Additionally, after the completion of construction projects, several construction activities cease, and a decrease in construction accident number is observed owing to combination of these two facts. In November and December, the weather starts to become colder. Winter construction is difficult, especially for construction involving concrete. Some construction companies in China's northern regions begin to stop working, and others work indoors. At this time, most construction jobs are related to lighter work, such as wall plastering and ceiling work, leading to a decrease in construction accidents.

3.2.2. Construction Accident Number per Day of Week

Correlation between the number of accidents and the day of the week was tested using ANOVA using data for accidents per day of the week. To establish correlation between day of the week and the number of accidents, accident data were tabulated into seven groups by day of the week. ANOVA testing was performed to establish the significance of the day of week as a factor of time to the number of construction accidents. However, a significant value of 0.767 (greater than 0.05) was obtained, indicating that there is no correlation between the day of week and the number of accidents. Figure 6 shows a scatter plot between day of week and construction accident number, in which points are distributed discretely and there is no linear correlation between the two variables.

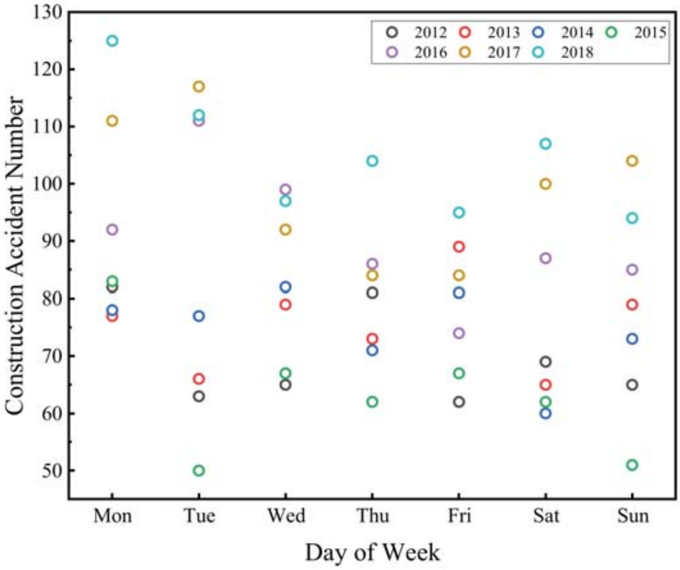

Figure 6. Scatter plot between day of week and construction accident number.

Although previous studies have proposed a theory of "Monday effect" in which more occupational accidents occur on Monday since it is hard for workers to pay attention to hazard in work on the first day after finishing weekend breaks [34], a different result based on collected data was found. This may be explained by the working habits of construction workers. Generally, some construction workers in China may work on weekends because current construction activities in China still rely on manual labor. According to annual reports of the National Bureau of Statistics (for example [35]), the average working days per month for rural migrant workers are approximately 25.2 (more than 20) during the period from 2013 to 2016. Interviews that were conducted with ten construction employees who worked in construction companies in different regions in China revealed that these construction companies allow their workers to work seven days per week. Furthermore, the daily workload for them is constant. These working conditions might have affected their behavior, where they would have been exhausted and losing focus on the safety aspects of construction operations. This might have led to the occurrence of construction accidents on any day of the week. Therefore, no correlation is observed between the day of week and the number of accidents, and there is no significant day of the week that points to a higher risk for construction accidents.

3.2.3. Construction Accident Number per Hour of Day

The final step in this section is to identify the correlation between the hour of day and the number of accidents. Figure 7 displays number of construction accidents by hour. Time of accident for each year was divided into 24 groups, in which each group contained the same hours (from 0 to 23). The outcome of ANOVA yields a rejection of hypothesis that diversity between construction accident number among different months is not significant. Therefore, a strong correlation between construction accident number and the hour of day is identified. A double-hump distribution with 12 o'clock axis of symmetry is obtained in Figure 7, and most accidents took place from 7 AM to 10 AM and 2 PM to 5 PM. In China, construction workers start working at 7 AM and continue with their work until noon. Accidents happened frequently during this time period, reaching a peak at around 10 AM. Then they had a one-hour lunch break. At 1 PM, when the temperature is the highest in the day, workers returned to work. In the afternoon, most accidents occurred from 2 PM to 5 PM, reaching their peak at around 3 PM. Most workers finish working at 6 PM, leaving only a few workers on duty at night. The number of accidents is low during nighttime and nearly zero around midnight.

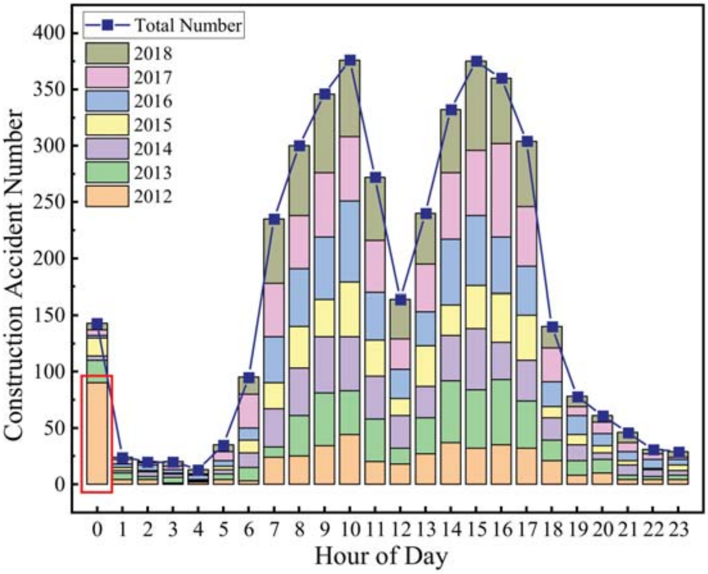

Figure 7. Number of construction accidents per hour of day.

Note that an abnormally high number of accidents were reported between 0:00 to 0:59 AM, as evidenced in Figure 7. Only the year 2012 saw a high number of accidents occurring at midnight (marked with rectangular box), accounting for more than 50% of the total accidents at that time from 2012 to 2018. The number of accidents in the evening (5 PM to 11 PM) and midnight (1 AM to 5 AM) hours are low. Therefore, this high number can be regarded as a virtual peak which is attributed to the fact of false reporting or concealed reporting of accidents [36]. Frequently, when a construction worker dies because of an accident, some construction managers would first contact their family and pay them to compensate for their loss. If the family was satisfied with the amount of compensation for the loss, this accident would be concealed. Although the Chinese government requires that the accident should be reported to local government within one hour [37], some construction managers did not report accidents in order to avoid penalty. However, if they failed to reach a settlement with the worker's family, they were required to report the accident to local government, which delayed the report for several days after the accident.

By then, no witnesses remembered the accurate time of the accident and simply picked 0:00 as the time of death in the report, leading to the virtual peak at midnight.

3.3. Regional Distribution of Construction Accidents

3.3.1. Indices

In this section, a construction safety performance evaluation index system is introduced with six indices: accident number (X_1), worker deaths (X_2), death rate per 1,000,000 m^2 (X_3), death rate per 100,000,000 yuan (X_4), death rate per 100,000 employees (X_5) and moderate- to high-fatality (MHF) accident rate (X_6).

Note that the first and second indices are the two intuitive indices from MOHURD as a foundation for the others. According to requirement regarding occupational safety work of Chinese government, death rate per million tons is an index for safety evaluation in the coal mining industry [38]. Similarly, death rate per 100,000 m^2 describes a relationship between worker deaths and workload in the construction industry, which have been used in past studies. Death rate per 100,000,000 yuan (approximately USD 15 million) and death rate per 100,000 employees are indices for occupational fatal accidents suggested by the Chinese government [38]. MHF accident rate is also considered in this study since it reveals the damage level to the construction industry owing to its higher fatality level characteristics. In the U.S., the commonly used index is hour-based rates. According to the U.S. Bureau of Labor Statistics [39], hour-based rates measure fatal injury risk per standardized length of exposure and are generally considered more accurate than employment-based rates. For example, fatal injury rate per 100,000 full-time workers is a typical rate used in the U.S. However, working-hour data in China is not currently available. Therefore, the hour-based rate will not be used in this system and a construction accident evaluation index system was built based on six indices described above.

3.3.2. Construction Safety Performance Evaluation

Values of each of the six indices for 31 regions in China (excluding Hong Kong, Macao and Taiwan) were compiled and tabulated in Table 2.

Data from Table 2 is employed in the SPSS program to implement the factor analysis. The KMO (Kaiser–Meyer–Olkin) test for sampling adequacy reveals a value of 0.623, which is higher than 0.500, indicating that there are sufficient partial correlations among these variables. The independence of these variables (indices) was rejected, leading to sufficient correlations among them. On this condition, these six variables satisfy the requirements of factor analysis. Principal component analysis (PCA) (one method to extract the factors) was performed in this study to reduce the dimensionality of a large data set of variables to a smaller one that still contains the practical information of the original data set. Two factors are extracted from the six indices in the index system. The rotation sums of the squared loadings approach were employed to establish the contribution rate of a factor to other principal components. The variance contribution rate of the first factor (F_1) to all others is 48.735% while the rate of the second factor (F_2) is 39.053%. Cumulative variance contribution rate of these two factors yields 87.788% (more than 80%), which means they are sufficient to describe the construction accidents of the 31 regions in China.

A subsequent analysis involves the evaluation of construction accidents in 31 regions in China. A prediction model for the first factor is shown as follows:

$$F_1 = -0.020X_1 - 0.045X_2 + 0.330X_3 + 0.343X_4 + 0.344X_5 - 0.178X_6 \tag{5}$$

where F_1 is the response variable that represents the impact score of the first factor and $X_{1\ldots6}$ are the dependent variables representing the six components. The equation for the second factor yields:

$$F_2 = 0.396X_1 + 0.378X_2 + 0.031X_3 + 0.061X_4 + 0.019X_5 - 0.369X_6 \tag{6}$$

where F_2 is the response variable that represents the impact score of the second factor and $X_{1\ldots6}$ are the dependent variables representing the six components. The equation of final impact score was created based on variance contribution rates of these two factors, which yielded the following:

$$F = \frac{45.729}{45.729 + 39.256} \times F_1 + \frac{39.256}{45.729 + 39.256} \times F_2 \tag{7}$$

Table 2. Construction accident indices in 31 Regions.

Region	Accident Number	Worker Deaths	Construction GDP/ 100 Million Yuan	Death Rate/ 1,000,000 m^2	Death Rate/ 100 Million Yuan	Death Rate/ 100,000 Employees	MHF Accident Rate (%)
Beijing	178	212	63,348.59	0.04	0.003	5.22	2.81
Tianjin	121	135	29,896.04	0.10	0.005	3.37	2.48
Hebei	85	120	40,455.19	0.03	0.003	1.20	10.59
Shanxi	55	83	24,245.96	0.05	0.003	1.49	9.09
Inner Mongolia	113	151	9869.41	0.16	0.015	5.81	8.85
Liaoning	111	158	42,773.41	0.04	0.004	1.42	10.81
Jilin	159	188	16,514.94	0.17	0.011	4.99	3.77
Heilongjiang	184	209	14,186.72	0.31	0.047	6.32	3.26
Shanghai	249	273	43,339.15	0.08	0.006	3.89	2.41
Jiangsu	590	660	182,534.48	0.03	0.004	1.13	2.71
Zhejiang	335	372	174,241.97	0.02	0.002	0.66	1.19
Anhui	258	306	43,196.30	0.08	0.007	2.30	3.10
Fujian	160	182	56,282.13	0.03	0.003	0.81	3.13
Jiangxi	157	192	34,527.97	0.07	0.006	1.83	5.10
Shandong	131	186	72,807.82	0.02	0.003	0.80	9.92
Henan	126	178	62,468.14	0.03	0.003	0.90	9.52
Hubei	204	257	79,593.16	0.04	0.004	1.60	6.37
Hunan	151	180	50,221.89	0.04	0.004	1.23	3.97
Guangdong	308	372	67,939.10	0.07	0.006	2.21	5.52
Guangxi	189	209	23,095.61	0.11	0.009	2.80	3.70
Hainan	73	79	2266.13	0.38	0.035	13.41	1.37
Chongqing	307	323	44,896.36	0.12	0.007	2.25	1.30
Sichuan	175	214	67,523.55	0.04	0.003	0.97	6.86
Guizhou	138	186	15,156.00	0.12	0.002	4.28	7.97
Yunnan	209	241	26,707.86	0.16	0.009	3.05	2.87
Tibet	8	16	891.80	0.32	0.018	5.84	12.50
Shaanxi	60	79	38,106.77	0.03	0.002	0.89	10.00
Gansu	136	155	12,865.92	0.17	0.012	3.60	2.21
Qinghai	88	102	3055.06	1.09	0.033	12.09	4.55
Ningxia	50	66	4070.99	0.17	0.016	7.75	8.00
Xinjiang	147	169	15,749.77	0.15	0.011	6.13	5.44

After substituting index values of each region into the equations the final score results were obtained and tabulated in Table 3. A score map displayed in Figure 8 was created to visualize the result, which shows Qinghai, Hainan and Heilongjiang as provinces have the highest scores. Since all these indices are reversed, construction accidents in places with higher scores are the worst. One can see that from all the regions in China, these three provinces call for immediate attention to improve construction-related safety issues. This construction safety evaluation score can serve as a reference for stakeholders to assess risk of construction in different regions in China.

Table 3. Construction Accidents in 31 Regions (2010 to 2018).

Region	F_1	F_2	F	Score Ranking
Qinghai	3.36	−0.17	1.73	1
Hainan	2.58	−0.03	1.37	2
Heilongjiang	1.90	0.58	1.29	3
Jiangsu	−0.71	3.20	1.09	4
Chongqing	−0.09	1.32	0.56	5
Zhejiang	−0.61	1.53	0.38	6
Shanghai	−0.05	0.83	0.36	7
Yunnan	0.09	0.56	0.30	8
Anhui	−0.24	0.88	0.28	9
Jilin	0.36	0.14	0.25	10
Gansu	0.34	0.12	0.24	11
Guangdong	−0.46	0.99	0.21	12
Xinjiang	0.37	−0.15	0.13	13
Beijing	−0.05	0.32	0.12	14
Guangxi	−0.05	0.28	0.10	15
Tianjin	−0.03	−0.08	−0.05	16
Ningxia	0.66	−1.07	−0.14	17
Inner Mongolia	0.31	−0.69	−0.15	18
Jiangxi	−0.38	−0.07	−0.24	19
Hubei	−0.63	0.20	−0.25	20
Fujian	−0.55	0.10	−0.25	21
Hunan	−0.50	−0.02	−0.28	22
Guizhou	−0.31	−0.48	−0.39	23
Sichuan	−0.73	−0.16	−0.47	24
Tibet	0.54	−1.85	−0.56	25
Henan	−0.88	−0.75	−0.82	26
Shandong	−0.93	−0.75	−0.85	27
Liaoning	−0.83	−1.00	−0.91	28
Shanxi	−0.71	−1.25	−0.96	29
Hebei	−0.87	−1.20	−1.02	30
Shaanxi	−0.89	−1.36	−1.10	31

Table 3 shows that Qinghai Province ranked first in construction accidents in the period from 2010 to 2018. Thus, in this paper, construction practices in this province are elaborated upon. The construction industry in this province mostly involved residential and infrastructure construction. The annual *China Building Industry Yearbook* (for example, [40]) suggested that affordable housing under construction increased steadily every year during the period from 2010 to 2016. Approximately 55% of accidents happened in this building category involving local construction companies.

Geographically, Qinghai Province is located in a higher-elevation region with lower oxygen levels and lower temperatures. Such conditions may have an influence on the performance of labor and equipment. Specifically, the altitude stress may have affected the physical and mental state of workers and thus decreased productivity. In these conditions, the likelihood of accidents is increased [41,42]. Additionally, the capacity and productivity of engine/equipment is decreased at high altitudes because of inadequate combustion [43]. Lack of management and technical skills are also important issues for Qinghai Province. For example, the *China Building Industry Yearbook* reported that there were 144,900 employees in Qinghai Province in 2016, but only 16,500 (11.4%) possessed technician skill level [40]. Qinghai is an underdeveloped province where transportation is often an issue because of high altitude. Therefore, it is difficult to attract skilled managers and technicians to work there. The main force of construction workers in Qinghai Province is migrant workers from rural areas who often encounter management issues. For example, workers are likely to ignore contractual obligations, and the labor relation between workers and management is loose [44], which will contribute to the cause of accidents. Such a loose labor relation allows companies to save money on insurance and safety training, especially combined with the absence of contracts with workers. Migrant workers in Qinghai Province tend not to be controlled by the company by not signing a contract with the company so they would have more freedom of mobility. The problem is that when an accident occurred, workers would not have financial and medical support.

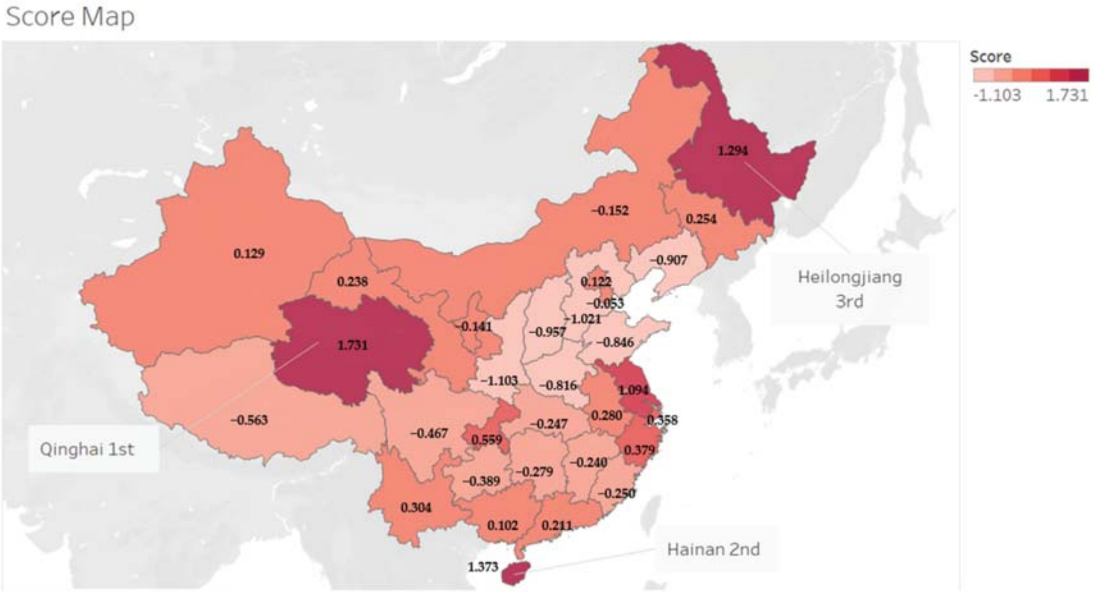

Figure 8. Construction accident evaluation score of 31 regions in China.

4. Discussion

In this study, ANOVA analysis revealed the time distribution of construction accidents in China. From time distribution results, a problem of poor construction environment management was revealed. Specifically, natural conditions such as exceedingly high temperatures and heavy rain in summer increased construction accident numbers significantly. Increased workloads led to exhaustion of construction workers, which in turn contributed to a higher risk of construction accidents. Since there are interactive relationships between person, environment and behavior [45], providing a safe environment is necessary to ensure the safe behavior of construction workers. A safety plan developed by carefully examining project activities and preventing associated hazards is a tool for facilitating such a task [46]. For example, regular inspections and audits to identify hazards, reduction of workload for workers when natural condition is poor and avoidance of overtime works. Additionally, no evidence existed to support any day of the week being more dangerous than any other days, which is not consistent with the “Monday effect” theory [34]. However, the finding was built on existing data and similar results that workers may work continuously can also be found in the past study [31]. An improved labor manage plan should be conducted; for example, scheduling an adequate number of workers on construction sites during high workload hours. For accident number per hour, the virtual peak of accidents at midnight revealed cases in which some construction managers concealed the accidents and did not immediately report them to the local authority [36]. In this case, polices regarding monitor of accidents reporting should be generated by the Chinese government to prompt construction companies to improve safety management. Questionary [46,47] would be a good method for supervision and inspection of safety situations on site.

A mathematical modeling based on factor analysis, which is the construction safety evaluation score equation, was developed to illustrate regional distribution of construction accidents in China. Qinghai Province ranked the worst in construction safety because of hazards of construction in high-altitude regions [41–43]. The low education/skill level of construction workers in Qinghai Province also contributed to the bad safety performance since the workers may ignore contractual obligations and exhibit lack of safety awareness. When construction workers become more aware of their responsibilities for hazard prevention, they will exhibit more interest in maintaining a safe and healthy work site [47]. Thus, construction safety and health training for construction workers should be conducted to improve construction safety in Qinghai Province [48,49]. Virtual and Augmented Reality (VR/AR) have been suggested by past studies [50,51] for such a training. Through creating forgiving environments for visualizing complex workplace situations, building up risk-preventive knowledge and undergoing training, hazard perception skills of construction workers will be improved. For example, VR/AR can be introduced in Qinghai Province to stimulate natural working conditions for construction workers to enhance their cognitive abilities, such as decision-making, attention, reaction time, contrast sensitivity and visual pursuit [52]. Since traditional measurement of safety is after-the-fact measurement, which means evaluations always took place after the fatal or injured accidents occurred, it has the problem of lagging indicators [46,53]. Therefore, this modeling is able to reflect current construction safety situation among different regions in China, which will serve as a reference for the government to create regulations to prevent demonstrated hazards in the future. Additionally, this model will exhibit economic benefit for stakeholders such as the owner and construction manager. They can increase investment and carry out construction activities in regions with higher construction safety to reduce the likelihood of financial loss because of construction accidents. Finally, researchers in other nations can use this model to explore native construction safety situations to help reduce accidents.

Based on the analysis above, suggestions for the government to improve construction safety in China are as follows: first, increase supervision of construction companies lacking a contractual agreement between workers and companies and mandatory reporting of accidents. Second, instead of merely introducing Safety Production Month activity in June, the government should consider conducting safety production activities more frequently and encourage enterprises to improve the safety awareness of construction workers, especially during time intervals with bad weather conditions and high workloads. Finally, the government should consider creating policies to attract technicians to work in the construction industry (for example, increased salary, rental allowance or education for migrants' children), especially in underdeveloped regions such as Qinghai, and to improve the safety and health of construction employees and their families.

For China's construction companies: first, generation of a safe plan to indicate hazards on site to mitigate construction risks. Second, implementation of a labor management plan, especially with respect to the deadliest time intervals during extreme weather conditions and high workload periods. Finally, improvement of their competitiveness by enhancing their technology and incorporating advanced construction equipment to overcome local environmental and climate issues (for example, higher elevation in Qinghai Province).

5. Conclusions

Construction jobs remained one of the most hazardous occupations. This study revealed time distribution and regional distribution of construction accidents in China based on fatal construction accidents. Close correlation between construction industry GDP in China and construction accidents is also observed. A mathematical modeling based on factor analysis, which is the construction safety evaluation score equation, is built to serve as a reference for suggestions regarding improvement of construction safety in China.

Author Contributions: Conceptualization, Q.M. and J.W.L.; methodology, Q.M.; software, Q.M.; validation, Q.M., F.H.T., M.E.P. and H.M.A.; formal analysis, Q.M.; investigation, Q.M.; resources, Q.M.; data curation, Q.M.; writing—original draft preparation, Q.M.; writing—review and editing, J.W.L. and F.H.T.; visualization, Q.M.; supervision, J.D.C.; project administration, F.H.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data used in this study are available within this article.

Acknowledgments: The authors wish to acknowledge Jianwei Zang and many other construction employees from numerous construction companies in China, whose comments have contributed greatly to the study in this paper. Participants of the weekly seminars in the construction program at The Ohio State University, Fei Yang, Omar Algonaian, Yanting Chen, Guowei Du, Taylor Cooper and Aziz Al-Zugair provided valuable comments and suggestions for this study.

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

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ISBN 978-3-0365-7639-8