buildings

Special Issue Reprint

Green Building Design and Construction for a Sustainable Future

Edited by
Yongtao Tan, Peng Mao, Xiaolong Gan and Hui Xu

mdpi.com/journal/buildings

MDPI

Green Building Design and Construction for a Sustainable Future

Green Building Design and Construction for a Sustainable Future

Guest Editors

Yongtao Tan
Peng Mao
Xiaolong Gan
Hui Xu

MDPI

Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

Guest Editors
Yongtao Tan
School of Engineering
RMIT University
Melbourne
Australia

Peng Mao
College of Civil Engineering
Nanjing Forestry University
Nanjing
China

Xiaolong Gan
School of Economic and Management
Southwest University
Chongqing
China

Hui Xu
School of Economic and Management
Chongqing University of Posts and Telecommunications
Chongqing
China

Editorial Office
MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

This is a reprint of the Special Issue, published open access by the journal *Buildings* (ISSN 2075-5309), freely accessible at: https://www.mdpi.com/journal/buildings/special_issues/QOV1YKM83N.

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

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

ISBN 978-3-7258-4575-0 (Hbk)
ISBN 978-3-7258-4576-7 (PDF)
https://doi.org/10.3390/books978-3-7258-4576-7

Contents

buildings

MDPI

Review

Sustainable Design and Operations Management of Metro-Based Underground Logistics Systems: A Thematic Literature Review

Dandan Gong [1], Jiajia Tian [2,*], Wanjie Hu [3,*], Jianjun Dong [4], Yicun Chen [5], Rui Ren [1] and Zhilong Chen [1]

1 College of Defense Engineering, Army Engineering University of PLA, Nanjing 210007, China; gdd07724129@126.com (D.G.)
2 College of Civil Engineering, Nanjing Tech University, Nanjing 211800, China
3 Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing 100124, China
4 School of Science, Nanjing University of Science and Technology, Nanjing 210094, China; dongjj@njust.edu.cn
5 Institute of Defense Engineering, Academy of Military Sciences PLA, Beijing 100850, China
* Correspondence: 202161226069@njtech.edu.cn (J.T.); steve_hu@emails.bjut.edu.cn (W.H.)

Abstract: Sustainable urban development relies on forward-looking infrastructure development. As an emerging infrastructure system that incorporates green technologies, the Metro-based Underground Logistics System (M-ULS) enables sustainable transportation of passengers and freight within cities collaboratively by sharing rail transit network facilities. M-ULS can effectively save non-renewable energy and reduce pollution to the ecological environment, and the comprehensive benefits of the system make an outstanding contribution to sustainable urban development. The purpose of this study is to provide a systematic review of M-ULS based on different perspectives and to present the development of the M-ULS network integration concept. By employing bibliometric analysis, the four dimensions of M-ULS related literature are statistically analyzed to discover the knowledge structure and research trends. Through thematic discussions, a development path for developing the concept of M-ULS network integration was established. The main findings of this study are summarized as follows: (i) A comparative analysis shows that the metro system has a high potential for freight use; (ii) Improvements in metro freight technologies are conducive to urban economy, environment, and social sustainability; (iii) Network expansion is an inevitable trend for implementing underground logistics based on the metro; (iv) The interaction among public sectors, metro operators, logistics corporations, and users plays a critical role in promoting the development of M-ULS. (v) It is worth mentioning that the planning of green infrastructure should fully consider its comprehensive contribution to the sustainable development of the city. This study visualizes the current status and hotspots of M-ULS research. It also discloses frontier knowledge and novel insights for the integrated planning and operations management of metro and urban underground freight transportation.

Keywords: sustainable development; underground logistics system; green infrastructure; design and operations management; stakeholders; literature review

1. Introduction

City logistics, also known as urban freight transportation, significantly affects the viability of the economy and the environment [1]. According to studies, the primary forces behind the development of city logistics are the ongoing innovation in industrial ecosystems, transportation systems, business and economic models, and mass consumption habits [2]. In the context of booming e-commerce, the traditional logistics system based on road network is far from being able to meet the explosive growth of urban freight demand. The current problem of fragmentation, decentralization and disorder in city logistics is becoming more and more serious, and their detrimental effects are now a major issue for livelihood, the economy, and society [3]. Especially during emergency situations such as COVID-19, the drawbacks of traditional freight delivery models have become increasingly apparent. The concept of synchronized ecological, economic, and social development promotes a comprehensive change in city logistics and transportation system [4,5]. Strengthening the construction of green infrastructure and using green technologies innovatively have emerged as crucial means for the logistics industry to promote sustainable development [6,7].

The Underground Logistics System (ULS), a new type of urban transportation infrastructure system that relies on underground tunnels or pipelines for the transportation of goods, is characterized by underground installation along with the overall function of freight transfer, handling and distribution [8]. Traditional urban logistics has numerous drawbacks in terms of transportation mode, service quality and social impact [9]. First of all, the traditional logistics transportation method is singular, and the demand for labor is extremely high. Secondly, the system has a low degree of informatization, making it difficult to visualize the full freight transit process. Further, last-mile urban delivery, which is mainly carried out by electric vehicles, is costly and inefficient, and has a significant impact on social security [3]. More seriously, trucking's activity worsens environmental issues such as noise pollution, exhaust vapors, and traffic congestion. Obviously, this strategy runs counter to initiatives to support urban sustainability [10]. To address the aforementioned issues, making use of underground space for freight transportation has become an unavoidable solution. ULS optimizes the distribution routes with the help of big data analysis through the establishment of an information platform, realizing the visualization of the whole process and improving the efficiency of logistics operation [11]. The application of artificial intelligence technology effectively lowers labor costs and improves service quality. Compared with traditional urban logistics, the utilization of green and clean energy is a reflection of the advantages of ULS, such as being all-weather, disturbance-free, low-carbon, having energy-saving features and bringing positive social benefits [12].

The Metro-based Underground Logistics System (M-ULS), by sharing the network infrastructure with the metro, enables the synergistic transportation of passengers and freight within the city [13]. Initially, the integration of urban public transport with freight networks was proposed [14]. Several European cities that have since developed a variety of practices using trams for freight transport, such as CarGoTram [15] and GüterBim [16], have acknowledged the feasibility of rail-based freight transportation. The development process has been significantly hampered by the protracted construction time and high cost of dedicated ULS. Hu et al. [17] mentioned that metro infrastructure can be expanded and utilized to fully assume the function of urban underground logistics. Therefore, M-ULS has been widely discussed as a feasible solution for ULS at this stage. In addition, it is also considered to be one of the many forms of ULS with high performance and efficiency [18]. The findings of Dong et al. [13] further demonstrate, once again, that this novel type of infrastructure system fully exploits the potential of underground tunnels and subway stations and considerably lowers the construction costs of ULS. To reduce the impact on passenger transit following the introduction of freight, the metro system should modify the infrastructure in accordance with the various operation modes. Additional logistics functional areas and equipment systems should be installed on the platforms to support freight operations such as loading and unloading, unpacking, sorting, and warehousing [19]. For the stations of trans-shipment, additional temporary storage areas are required. The installation of dedicated package storage cabinets at metro stations can be taken into consideration as a solution to the last-mile delivery problem [20].

Environmental, social and economic factors create a context around sustainable development [21]. As an important strategy for achieving sustainable urban development, previous studies have conducted systematic literature reviews [22] around green logistics and green infrastructure, respectively. The review studies on the topic of green infrastructure demonstrate that the field focuses on the relationship of green infrastructure with ecosystems and human health, as well as the construction, evaluation, and management of green infrastructure [6]. Sustainability and management, freight transportation and carbon emissions, and green supply chains are the three most commonly discussed subjects in research on green and sustainable logistics [23]. M-ULS integrates the dual characteristics of green infrastructure and sustainable logistics. To the authors' knowledge, there is no systematic review of the theory and practice of this system in the literature.

The purpose of this study is to review the state of research and development trends by conducting a comprehensive review of the relevant literature on the topic of M-ULS. One of the novelties of this work is that the review is being undertaken in a small, unexplored field of knowledge. Specifically, firstly, a descriptive analysis is carried out on four aspects: year of literature inclusion, journal distribution, keywords, and research methods. Secondly, while summarizing the M-ULS operation model, the drivers and barriers of M-ULS are discussed based on the theory of sustainable urban development, followed by the construction of the path of M-ULS networked concept integration. Furthermore, from the perspective of stakeholders, the relationships between multiple stakeholders have been explored, and recommendations have been provided. Finally, the contribution of M-ULS to sustainable urban development is illustrated through an exploration of its combined benefits. This paper is intended to provide a reference for the research frontier and emerging trends in this field.

The remainder of this paper unfolds as follows. In the next section, a brief overview of the research perspective used in this article is provided, including an overview of M-ULS development and two underlying theories. The research methodology is described in Section 3, which offers a systematic descriptive analysis in four dimensions. Then, in Section 4 of the article, different research themes based on M-ULS are discussed. Finally, the main findings, research limitations and possible future directions are derived in Section 5.

2. Research Perspectives

The rational planning of urban spatial structure as the carrier of the urban economy will play a crucial role in the sustainable development of cities [24]. M-ULS has evolved from conventional trams to a networked and integrated concept, which is a shift in the concept of sustainable urban development planning. Additionally, from a strategic management standpoint, the implementation and management of M-ULS usually relies on the support and participation of stakeholders [17]. Due to these factors, this study is based on stakeholder theory and urban sustainability theory. The overview of M-ULS development practice is followed by a brief description of the underlying theory in this section.

2.1. M-ULS Development Overview

The integration of freight networks and public transportation is one of the major prospects for city logistics, and Freight on Transit (FOT) is an implementation of this idea [25]. FOT refers to operational strategies that use urban public transportation vehicles or infrastructure to move goods. Cochrane et al. [26] explored the challenges and opportunities of FOT using a Delphi survey in the context of Toronto and analyzed the potential benefits of using these assets for goods movement.

With the growth of the public transport line network and the accumulation of operational experience, several European countries have experimented with the use of tram networks for freight transport [27]. Examples of representative practices include the GüterBim project in Vienna and the Dresden CarGoTram system [28]. The city's existing ground transportation lines are used by CarGoTram's freight trams to deliver automobile parts. The GüterBim train, which was made up of a tractor car and a trailer container, was used to deliver wear-and-tear components including seats, tires, and batteries between the material depots of each vehicle division on a weekly basis [16]. Unfortunately, the initiative was abandoned after two years of trial operation due to high running expenses and a lack of policy backing.

The practice of employing trams to convey freight has not impacted the operational or infrastructure frameworks. It has also been shown that it is feasible to convey goods utilizing other light rail infrastructure. Dampier et al. [29] developed an event-based simulation model of the Newcastle Metro system to analyze the feasibility of track and platform utilization and determine the advantages of transporting urban goods on urban tracks. Unlike trams, freight is not only thought to be delivered by dedicated trains, but also by linking freight cars behind passenger trains or by sharing space with passengers during off-peak hours. Serafini et al. [30] investigated the attitudes of Rome metro commuters towards using train space for crowdsourced deliveries. The Sapporo subway experiment by Kikuta et al. [31] demonstrated that shared carriages were well-liked and successfully enhanced the flow of goods transportation by integrating public subway services and conventional freight car operations.

In fact, urban rail systems such as subways, which operate mainly underground, are also a form of underground freight transport (UFT), which can be an alternative to existing modes of freight transport such as road, rail and water transport [32]. Most of the earliest applications of underground urban freight transportation systems were for transporting energy or small materials in underground pipes, which were then defined as “freight pipes” [33]. Depending on the type and characteristics of the technology, there are different nomenclatures in the literature, such as Underground Physical Goods Distribution System [34], CargoCap [35] etc. It is currently known as ULS, a dedicated logistics infrastructure with a high cost and prolonged construction period. Therefore, M-ULS, also known as metro-integrated logistics systems (MILS), which is built on the existing metro network, has gradually attracted the attention of the academic community [36].

2.2. Sustainable Development Theory

Green building is an integral part of low-carbon ecological city construction, in which the emerging infrastructure system plays an important scale effect [37,38]. The development of green building is not only the vision of the country and society, but also the objective requirement of sustainable development [39]. Therefore, the theory of sustainable urban development was chosen as the primary theoretical basis of this paper. The World Watch Institute in the United States first coined the term “sustainable development” in the 1870s [40]. The United Nations World Commission on Environmental Development (WCED) publicly endorsed the concept in its 1987 report, “Our Common Future”. Strictly speaking, urban sustainability theory and sustainable development theory are approximately identical, with the exception that urban sustainability theory research takes a more specific and grounded approach to their analysis.

Sustainable urban development encompasses not only growth in the economy but also growth in terms of resource utilization, environmental protection, social ecology, and the use of space available [41]. In fact, construction has long been considered a resource-intensive and energy-consuming industry [42]. As the overall foundation and backbone of the urban building system, urban infrastructure is directly or indirectly involved in the production and living processes of the city in specific ways [43]. With the concept of sustainable urban development gaining more and more attention, green infrastructure has been well received by governments around the world as a strategy to improve sustainability in the construction industry [44]. Not only that, a large number of scholars have also begun to value the important contribution of urban form and spatial organization to sustainable development [45]. Based on the aforementioned arguments, it is gradually becoming a consensus that developing infrastructure underground provides more energy-saving advantages than planning infrastructure above ground [46]. Future sustainable urban development could greatly benefit from this.

The M-ULS plan is an implementation of this fundamental concept, and the urban form that utilizes public infrastructure to connect the urban core to the outlying villages and tribes has been acknowledged as such. The need for sustainable transformation of urban infrastructure further contributes to the innovation of logistics systems [47]. On the one hand, it is an emerging infrastructure that supports sustainable urban development; on the other hand, it applies green technologies and enables digital operations through an intelligent platform [48]. Generally speaking, M-ULS is not only an effective way to realize the logistics and transportation system for sustainable urban development, but also an effective way to improve the accessibility of urban cargo transportation [49]. Additionally, it weakens the antagonistic relationship between traditional logistics' economic development and environmental pollution, brings social and environmental benefits while optimizing the economic structure of the whole city, which is a new idea to promote sustainable urban development.

At this stage, the research content of urban sustainable development theory mainly focuses on system coordination theory, resource carrying theory, system renewal theory and circular economy theory [50]. In Section 4, we will construct the development path of M-ULS concept integration based on the perspective of urban sustainable development theory. Then, we will illustrate the significant benefits of M-ULS in sustainable development on three different levels: technical, economic, and socio-environmental benefits.

2.3. Stakeholder Theory

The second theoretical viewpoint in this paper is stakeholder theory. First, it is believed that the city's stakeholders are crucial groups to evaluate when determining the future direction of sustainable urban development, and second, the stakeholders are key decision-makers in the M-ULS implementation process [51]. To discover new possibilities for sustainable urban development, they must examine the difficulties associated with the project's entire life cycle of construction from a variety of perspectives [52]. In summary, stakeholder theory was also selected as the foundational theory for this paper.

The term "stakeholder" initially appeared in the 1860s. Stakeholder theory steadily shifted from the periphery to the fore of management study in the 1970s with the rise of Corporate Social Responsibility research [53]. As the flagship of stakeholder theory, Freeman published his classic book Strategic Management: A Stakeholder Approach in 1984, which is also regarded as the founding work of stakeholder theory [54].

There are a variety of definitions of stakeholders. According to the book mentioned previously, the traditional definition is "all individuals and groups that have the potential to affect how an organization achieves its goals or who are impacted by that process". Freeman (1984) did not create the idea of stakeholders, but he was the one who first systematized it in terms of strategic management [54]. The underlying paradigm of the individual as the research perspective can be credited to Freeman's stakeholder management theory, and the theoretical framework he provided has evolved into the fundamental foundation for subsequent scholars to analyze stakeholder issues.

Stakeholder theory has been incorporated into different fields of study in extremely beneficial ways. We discovered a substantial corpus of scholarly work applying stakeholder theory in strategic management [55], sustainable supply chain management [56], and corporate social responsibility [21] after reviewing the academic literature on the subject. In addition, Stakeholder theory proposes that treating all stakeholders well creates a sort of synergy [57]. As a result, it is impossible to build a project without the input and involvement of numerous stakeholders. By balancing the cooperative or competitive relationships among multiple stakeholders, the inclusion of each stakeholder in organizational decision making helps to enhance the overall advantage.

To the best of the authors' knowledge, M-ULS has not been studied in the early literature from the perspectives of numerous stakeholders, and the implementation of M-ULS requires the joint role of urban subject decision-makers. Based on the theory of stakeholder management, we identify the key players in the implementation of M-ULS in this article, and we offer recommendations after taking factors such as drivers and barriers into account.

3. Methodology

3.1. Overview of Review Protocol

The bibliometric analysis method, an effective inquiry tool, is commonly used to analyze the literature on a certain topic and discover the structure of knowledge and research trends, e.g., green buildings [58], green and sustainable logistics [23]. This method uses statistical analysis of multiple dimensions of the literature to objectively evaluate contributions and make predictions with few external constraints [59]. In this paper, all searchable M-ULS literature are statistically measured in four dimensions, year, journal, keyword and research methodology, in order to grasp the knowledge system and establish a framework for its evolution. The methodological procedure is depicted in Figure 1 from literature retrieval through discussion.

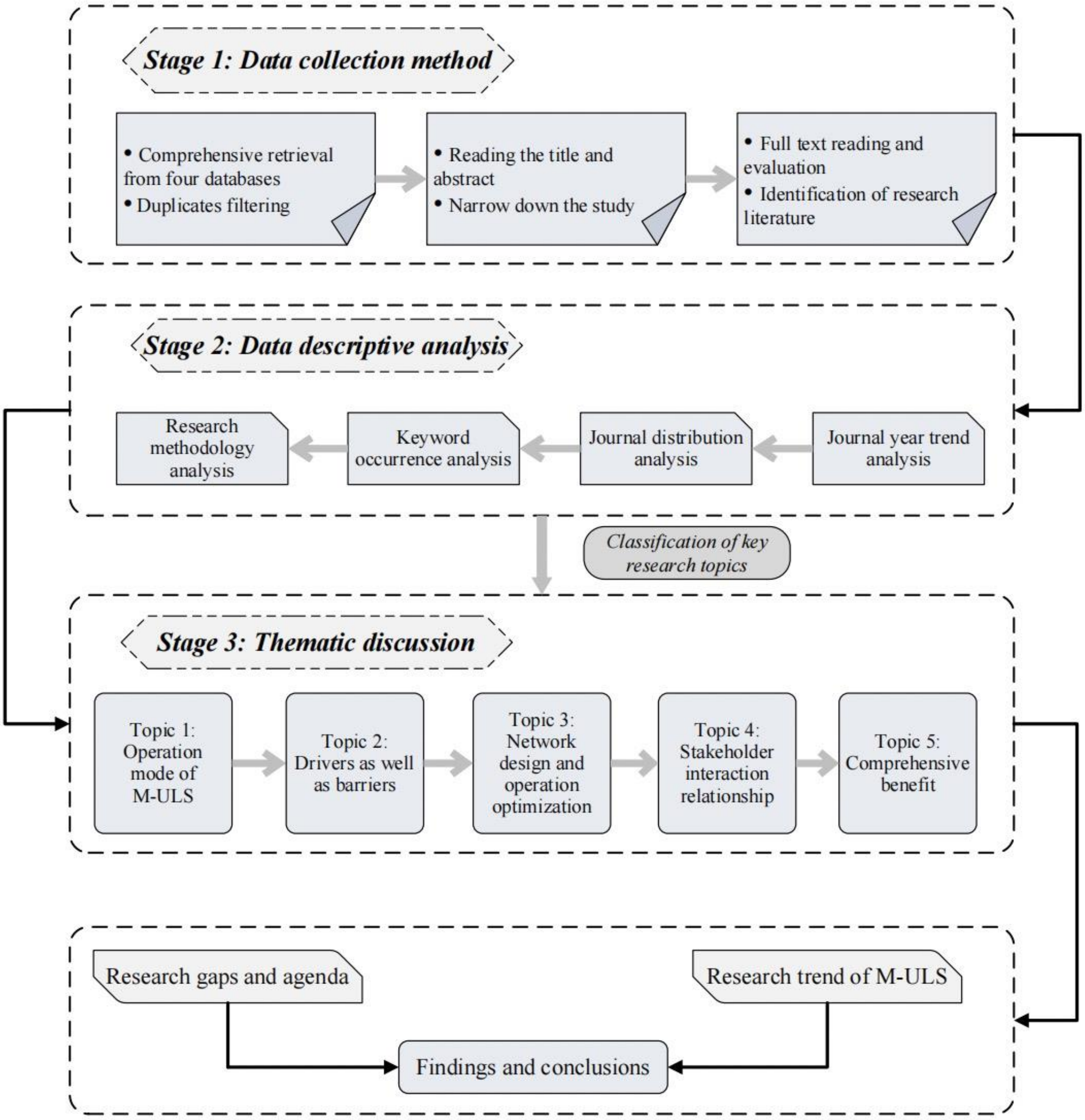


Figure 1. Flow chart of literature review.

In Step 1, comprehensive material retrieval utilizing keywords across four databases was completed and subsequent screening criteria were made to determine the eventual scope of the article research.

Four descriptive analyses of the data were designed and carried out in stage 2. These included the following: the year of publication, the distribution of the literature by journal, keyword analysis, research methodology and theme analysis.

In Step 3, five different topics were discussed for M-ULS based on the results of the descriptive analysis. Finally, the findings of the article and the gaps were summarized.

3.2. Data Collection and Selection

Keyword selection and inclusion criteria. We defined the year of search for the literature in the four databases as 2010 and beyond since theoretical study on M-ULS only formally started at the beginning of the twenty-first century [60]. A comprehensive literature search was carried out using the following logical statement, as given in Table 1. Subsequently, Endnote (X7 ver.) software was used to undertake the initial screening of the literature in each database and remove duplicate items. Following these steps, Elsevier, Web of Science Core Collection, Scopus, and Engineering Village, respectively, yielded 204, 65, 83, and 97 documents.

Table 1. Results of literature retrieval and selection.

Database	Elsevier	Web of Science Core Collection	Scopus	Engineering Village
Logical statement	TI = ((“metro” OR “subway” OR “rail”) AND (“logistics” OR (”underground” AND “logistics”)) OR ((“freight” OR “goods” OR “cargo”) OR (“mixed” AND “passenger”) AND (“transport” OR “transportation” OR” delivery” OR “distribution”))) AND Language: (English) AND Time span (2010–2022)			
Inclusion criteria	(i) articles, proceedings papers, review articles, conference papers; (ii) literature obtained through a retrospective search strategy despite not being in the database			
Initial records	204	65	83	97
Exclusion criteria	(i) brief article with less than six pages; (ii) lack of references or full text; (iii) unrelated to the topic of the study (e.g., energy, design field)			
Final records	52			

Review of the title and abstract for secondary screening: The aforementioned procedures resulted in the acquisition of a total of 310 documents, which were then reviewed for their titles and abstracts. We tried to screen out articles whose content did not fit well with the research topic through this step. For example, several of them, such as tunneling technology, energy, transportation management, and research, were from areas completely unrelated to the research topic. There were 73 papers in total that were chosen.

Full paper reading and evaluation to establish the ultimate study scope: At this stage, 73 papers from the literature were read thoroughly. Some of the articles were less than six pages in length, although their titles were related to M-ULS. There were also some articles containing research content unrelated to the topic, such as technical research on driverless trains or model design for subways. In addition, some articles were not directly searched in the database, but the references of some articles caught our attention according to the principle of retrospective search [31]. Finally, 52 articles were selected for our review.

3.3. Data Descriptive Analysis

3.3.1. Journal Year Trend

According to the growth and aging laws of scientific and technological literature, an annual statistical study of the number of pertinent articles released can indicate the state of the subject and forecast its future development. Figure 2 shows an annual summary of the 449 items of data from the initial screening and the 52 finalized pieces of literature for the period from 2011 to 2022. Both are generally developing in an upward trend. We primarily concentrated on the annual status of change for the final 52 works of literature examined. It was clear that until 2017, research on M-ULS was basically stagnant. It was clear that until 2017, M-ULS research did not attract the attention of a wide range of scholars, with the number of published articles per year being no more than three. During this period, the discussion topics of most articles then focused on the establishment of dedicated ULS. However, starting in 2018, the idea of constructing underground transportation systems based on the metro gained traction, and the number of papers published on M-ULS progressively rises, peaking at ten in 2022, which is nearly comparable to the total of all the prior numbers in 2017. Combined with the moving average line, it can be seen that the research topics of M-ULS show an upward trend in terms of number and agreement.

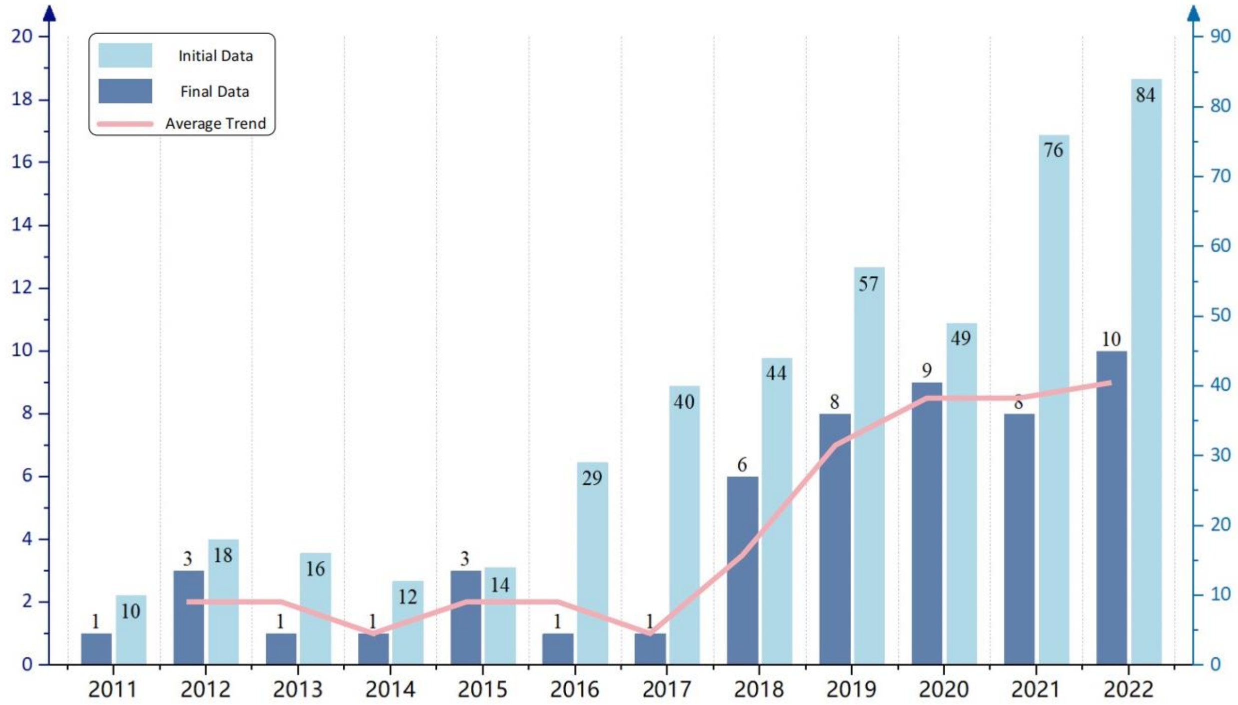


Figure 2. Year distribution of M-ULS literature.

3.3.2. Journal Distribution

As shown in Figure 3, all 52 publications were from a total of 31 different journals, and each journal's total number of publications is indicated in the lower left corner of the picture. Subsequently, in order to capture the distribution of academic journals in this research topic across countries, we counted the number of journal publications in the country of the first author. The image's bottom right corner displays the number of articles published in each nation. In order to visualize the geographical distribution, we have marked the general location of each country and shown the corresponding data with a background global map. Scholars from 18 different nations have contributed to the research on this topic. Among them, the number of countries distributed in Europe reaches ten and the vast majority of journal publishers originate from here as well. In terms of the number of literature distributions, although the number of Asian countries is only half that of Europe, a team of authors from China contributed more than half of the total number of articles.

Further, Figure 4 depicts the major journals that published two or more articles. Although about 42% of the journals published only one article on the topic of M-ULS, there is no shortage of journals that contain very high impact factors, such as Transportation Research Part A. The journal with the highest number of published articles is Tunnelling and Underground Space Technology (seven), followed by Sustainability (five) and IEEE Access (four), respectively. Despite the short period of research on the topic of M-ULS, the classification of journals shows that the research topic spans different fields such as transportation planning [32], logistics management [19], underground space [61] and engineering construction [62]. This indicates that M-ULS research is multidisciplinary in nature and spans a wide variety of fields.

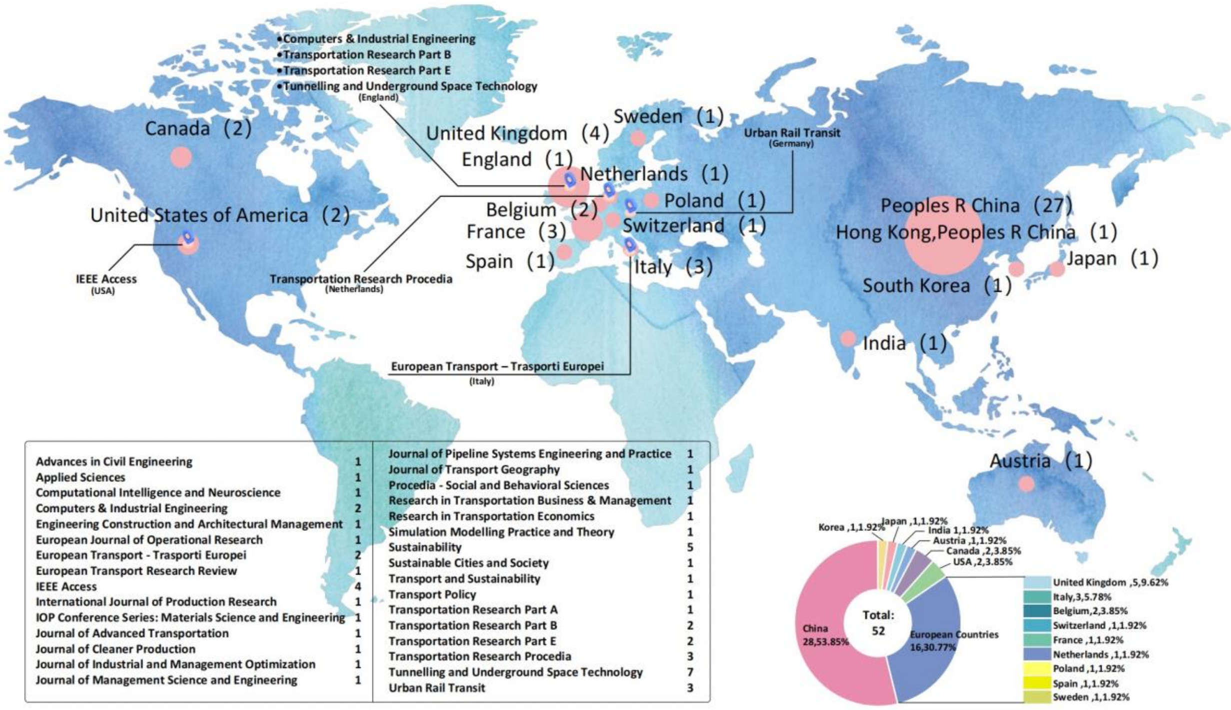
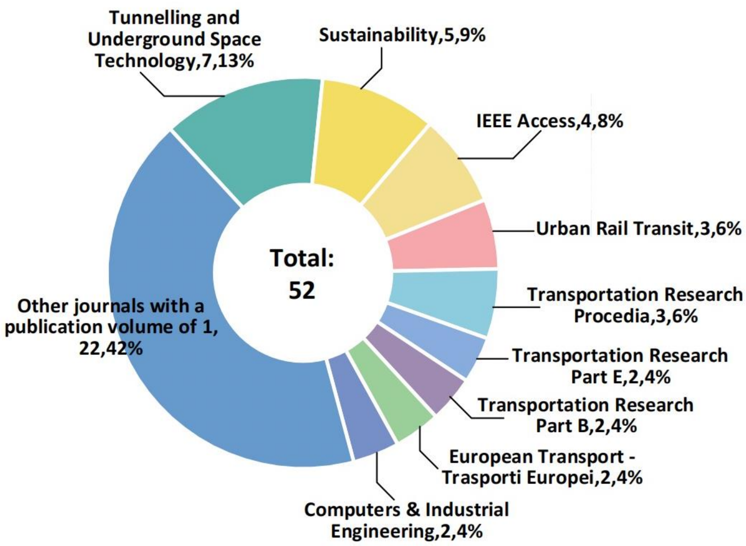


Figure 3. Regional distribution of periodicals.



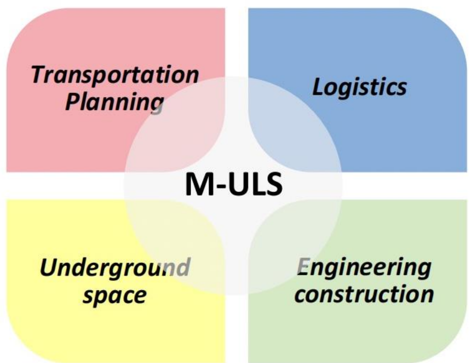


Figure 4. Distribution of literature journals.

3.3.3. Keyword Occurrence Analysis

The co-word analysis method uses the co-occurrence of lexical pairs or noun phrases in a collection of literature to ascertain the connections between the subjects covered by the collection of literature [59]. In order to better summarize the key elements of the current research on the topic, we have integrated and analyzed the keywords or high-frequency words of the articles using scientific text analysis. As previously mentioned, this study was organized around a critical review of a small scoping field of knowledge. Considering that there were only 52 publications chosen, some crucial information might be overlooked if only the original keywords of the journals are reviewed. As a result, we used text analysis tools to statistically examine the data for the phrases in each article. The Python environment was initially loaded with unstructured text data. Tokenization was then used to separate the textual data into groups of words or phrases. During this process, keywords with the same meaning, such as "transport" and "transportation" were merged. Finally, deactivated words such as "is" and "a" were removed before performing word frequency data. After sorting according to the frequency of occurrence, the top five high-frequency terms or phrases that differ from the keywords of the articles were extended to our final analysis. On the basis of word frequency analysis, CiteSpace helps us identify clusters of keywords that reflect different themes. Following the aforementioned steps, the top ten that ultimately appeared more frequently were divided into three approximate clusters. The first cluster includes "city logistics", "carbon emission", and "sustainability", as the background of the majority of the literature almost always discusses an array of environmental issues brought on by urban freight transportation, and the sustainability of logistics is also a hot topic supported by scholars. The second cluster consists of the terms "network design", "model", and "optimization and management". Network design, operation and management are the current focus of M-ULS, and mathematical modeling is a key tool in this process. The third cluster incorporates "freight transportation", "infrastructure", "passenger and freight", and "underground space". In truth, it is easy to see that M-ULS is an ideal choice to make full use of the underground space to build a new type of freight infrastructure and put the idea of passenger and freight synergy into reality.

3.3.4. Research Methodology Analysis

The research method section of the literature is a tool for the author to reveal the inner laws of the research thrust. Therefore, according to Lagorio et al. [63], we classified the research methodologies into "Review", "Conceptual Paper", "Questionnaire Survey", "Empirical Paper", "Mathematical Modelling", and "Hybrid Method" after reviewing the research content of each paper (see Table 2). The results showed that Mathematical Modelling was the most applied, with a total of 29 articles. While identifying the research methodologies in the literature, the author made a more detailed classification for the literature that took the Mathematical Modelling approach. Generally, Mathematical Modelling contains four types of modeling, which are Evaluation Model, Optimization Model, Classification Model, and Predictive Model. In the scope of this review study, the first two modeling types are widely used by various scholars, and in particular, the mixed integer nonlinear programming model is the most commonly used modeling approach in optimization problems. In addition, the combination of qualitative and quantitative analysis is also the most commonly used strategy for this research topic; for example, eight papers use the Hybrid Method, which includes the combination of mathematical modeling and questionnaires, or the combination of literature review and empirical analysis.

Table 2. Materials classified by research methodology.

No.	Research Methodology		Description	Count
1	Review		Research that reviews and analyses the content and trends of published literature	4
2	Conceptual paper		A study that focuses on conceptual content and design framework	5
3	Questionnaire survey		A research instrument consisting of a series of questions related to the topic to obtain information about the interviewee's answers	2
4	Empirical paper		An article that tests a proposed theory or hypothesis based on collected data	4
5	Mathematical modelling	Evaluation model	A study that builds a mathematical model aimed at conducting an evaluation of the project objective	15
		Optimization Model	A study that builds a mathematical model aimed at optimizing the project objective	14
6	Hybrid method		A study that uses two or more of the methods mentioned above	8

3.4. Literature Classification

The literature was tagged and categorized during the reading of the entire body of work in order to facilitate the categorization discussion in Section 4 based on various research themes. Researchers can swiftly and easily comprehend the current knowledge structure in this study field thanks to the classification of academic papers into various research topics. The operating models, logistics and distribution systems, node location studies, drivers as well as barriers, stakeholder interactions and comprehensive benefits may all be found in the examined study on M-ULS. The detailed results of the analysis will be discussed in Section 4.

4. Discussion

4.1. Operation Mode

As a consequence of the M-ULS concept being clarified, numerous teams both domestically and internationally have conducted research on the M-ULS operating mode and mechanism, as shown in Figure 5, where we explain the relevant definitions and depict the features of the existing schemes.

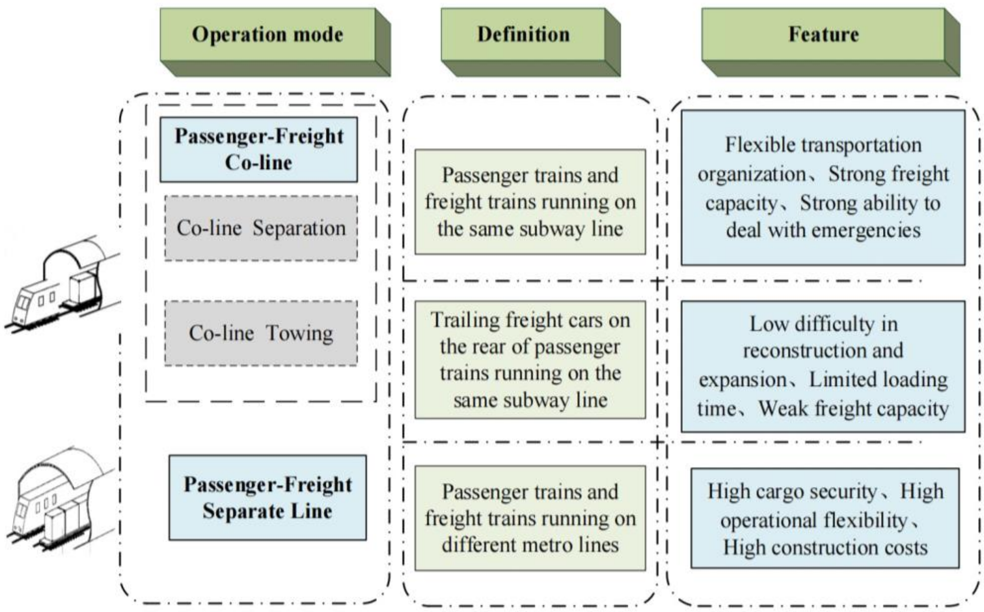


Figure 5. Characteristic diagram of different operation modes' definition.

To piggyback cargo during the metro's flat-peak operation, some academics initially advocated dedicated logistical rooms inside the passenger locomotives that could be movably segregated. Based on the operational times, Marinov1 [64] recommended "dedicated night deliveries", "dedicated day deliveries", and "combi day deliveries". An empirical investigation about its viability was undertaken by Motraghi and Marinov [65]. The findings demonstrate the model's benefits of easy operational scheduling and minimal disturbance to passenger transportation. Due to the small volume of freight and the stricter requirements for carrying cargo, it can only share the city's meager freight pressure.

Consequently, drawing on the operation mode of intercity train passenger and freight synergy, this form of transportation can often be separated into two synergistic operating modes, namely, passenger-freight co-line (P-F CL) and passenger-freight separate line (P-F SL) [66]. In Table 3, the benefits and drawbacks of the various modes of operation are compared. Although passenger and freight separation lines increase freight safety and operational flexibility, they are substantially more complex to alter and expensive to build, therefore, only conceptual design feasibility exists as a result [13]. The terms "Co-line Separation" (CL-S) and "Co-line Towing"(CL-T) refer to two different types of passenger and freight co-lines. CL-S is flexible in how it organizes its transportation and is well able to deal with unforeseen circumstances. A broader freight time window can be obtained by configuring the platform level of the distribution line, which effectively increases freight capacity and locomotive loading rate [67]. When the conditions need to be avoided, implementing rapid and slow train operation can considerably boost freight capacity. The CL-T is relatively easier to arrange and extend the station than the CL-S. However, the highest limit of its freight supply capacity is determined by the limited space for trailer cars and the loading and unloading operating times.

Table 3. Comparison table of characteristic features of locomotive co-location.

	Description	**Passenger-Freight Separate Line (P-F SL)**	**Co-Line Separation (CL-S)**	**Co-Line Towing (CL-T)**
Construction cost	Consider the stage from the design phase to the official commissioning	High	Medium	Low
Modification difficulty	Consider construction technology and existing infrastructure conditions	High	Low	Medium
Operations management	Consider train scheduling and collaboration between stakeholders	Low	Medium	High
Impact on passenger	Consider the impact on passenger travel during construction and operation	Low	Medium	High
Freight capacity	Consider the maximum daily cargo transportation capacity	High	Medium	Low

Overall, the choice of M-ULS transportation mode must take into account the real freight features as well as technical implementation considerations including site modification and growth limits [68]. It is undeniable, however, that the current locomotive synergy is primarily focused on passenger-freight co-line. Both types of passenger-freight co-lines are the focus of the current study since they have a larger freight potential. Additionally, a review of the literature may show that the development of conceptual hypotheses and feasibility analyses are the extent of the research on the M-ULS transport mode to date. However, the combination scheduling of passenger and freight trains, the layout of logistics functional areas in metro stations, and the parametric design of train equipment systems may be the key factors affecting the M-ULS's implementation. The literature that is accessible is solely valuable as a reference. In future research, standard specifications for cooperative transportation and the determination of vehicle parameters will be essential.

4.2. Drivers and Barriers for M-ULS

In the second part of the paper, we mentioned the theory of urban sustainability, in which the sustainability of urban systems can be illustrated through economic, social and environmental perspectives. In order to encourage the adoption of M-ULS as a new kind of urban transportation facility based on the urban sustainability theory, this paper will analyze the drivers and barriers of M-ULS from three perspectives: technical, economic, and socio-environmental benefits. It will also explain how these three perspectives interact with one another.

4.2.1. Drivers

As shown in Table 4, at the technical implementation level, the transportation rail network in large and medium-sized cities has been gradually expanded and developed [69], and the metro network has a wide coverage area and reasonable distribution plan for each station, so the location of M-ULS and the layout of facilities can be taken from the metro system. In addition, the relatively constant frequency of urban railways ensures prompt and effective goods transit [70]. The ability to integrate transportation in metropolitan areas using metro is also made possible by the research and development expertise of numerous paradigm ULS projects, intelligent logistics technology, and subterranean engineering construction technology [71]. At the economic level, research cases using Beijing, China, Seoul, South Korea, Madrid, Spain, and Toronto, Canada show that intermodal systems operating in a network have a good cost advantage over conventional ground freight and dedicated ULS networks [61]. Because of its operational flexibility, lack of ground freight interruption, and "contactless distribution", intermodal systems have exceptional logistical advantages, particularly in unexpected situations such as epidemics [3]. The implementation of M-ULS reduces truck use somewhat on a socio-environmental level, which in turn reduces the consumption of natural resources such as gasoline and the emission of polluting gases such as CO2 and NOx. Urban traffic congestion is also being significantly decreased, which has significant positive social and environmental effects. The findings of Kikuta et al. [31] and others, indicate that intelligent, intensive, and environmentally friendly multimodal transport systems are widely accepted in society [20].

Table 4. Multi-perspective analysis table for M-ULS implementation.

Perspectives		Detailed Categories	Representative References
Socio-environmental perspective		Reduction in harmful gas emissions and noise pollution	Chen et al. [18]; Miller et al. [12]; Langhe [72]; Hu et al. [11]
		Effectively alleviate traffic congestion and reduce the probability of traffic accidents	Langhe [72]; Chen et al. [73]
		Safety of freight transport and the intelligence of intermodal systems	Kikuta et al. [31]; Behiri et al. [74]; Chen et al. [73]
Economic perspective		Improving logistics performance	Xu et al. [3]; Visser [75]
		Cost benefits of intermodal systems	Cochrane et al. [26]; Zheng et al. [70]
		Benefits of energy savings	Hu et al. [48]; Chen et al. [73]; Pan et al. [76]
Technical perspective	Engineering technology	Infrastructure renovation and metro interior layout design	Hu et al. [19]
		Mature intelligent logistics and underground engineering construction technology	Shalaby et al. [14]; Harten et al. [77]
		Complexity of system networking	Behiri et al. [74]; Hu et al. [78]
	Operational organization	Last-mile delivery	Villa and Monzon [1]; Gatta et al. [20]
		Scheduling of the train	Li et al. [14]; Hu et al. [48]
		Operation flow of logistics	Shahooei et al. [35]; Hu et al. [79]

4.2.2. Barriers

Firstly, M-ULS adoption is still hampered by concerns about the safety of freight and the effect on passenger traffic [75]. There are tighter restrictions on the items that can be transported because the metro is used for passengers, which restricts the kinds of goods that can be moved. Secondly, there are not any fully successful operational cases from a technical standpoint that can offer a wealth of experience. Relying on the subway for freight transport also necessitates close coordination between the logistics industry and the subway sector, as well as careful scheduling management [14]. Finally, the urban metro system's network coverage typically uses the urban area as its focal point and extends in all directions. However, the end area is typically broad and fragmented, and the "last mile" of urban distribution is carried out manually [80]. The public might not be prepared to take their own packages home if the last pickup point is established in the train station because it will affect residents' behaviors to some extent.

Although there are challenges in implementing M-ULS, as indicated in Figure 6, these obstacles can be properly overcome by creating corresponding measures from various perspectives. By optimizing the logistics operation flow and designing a reasonable station, for instance, the impact on passenger flow can be significantly decreased [78]. By reducing turnaround times, saving on transportation, and increasing freight volume, reasonable network planning and operation scheduling can also improve logistics and society [81]. The relevant departments should research public acceptance of the last-mile delivery issue beforehand, enhance publicity, and work to prevent the issues that the public rejects the most in order to increase local acceptance and market awareness. Furthermore, there is a need for intensive study and development of intelligent delivery systems such as drones.

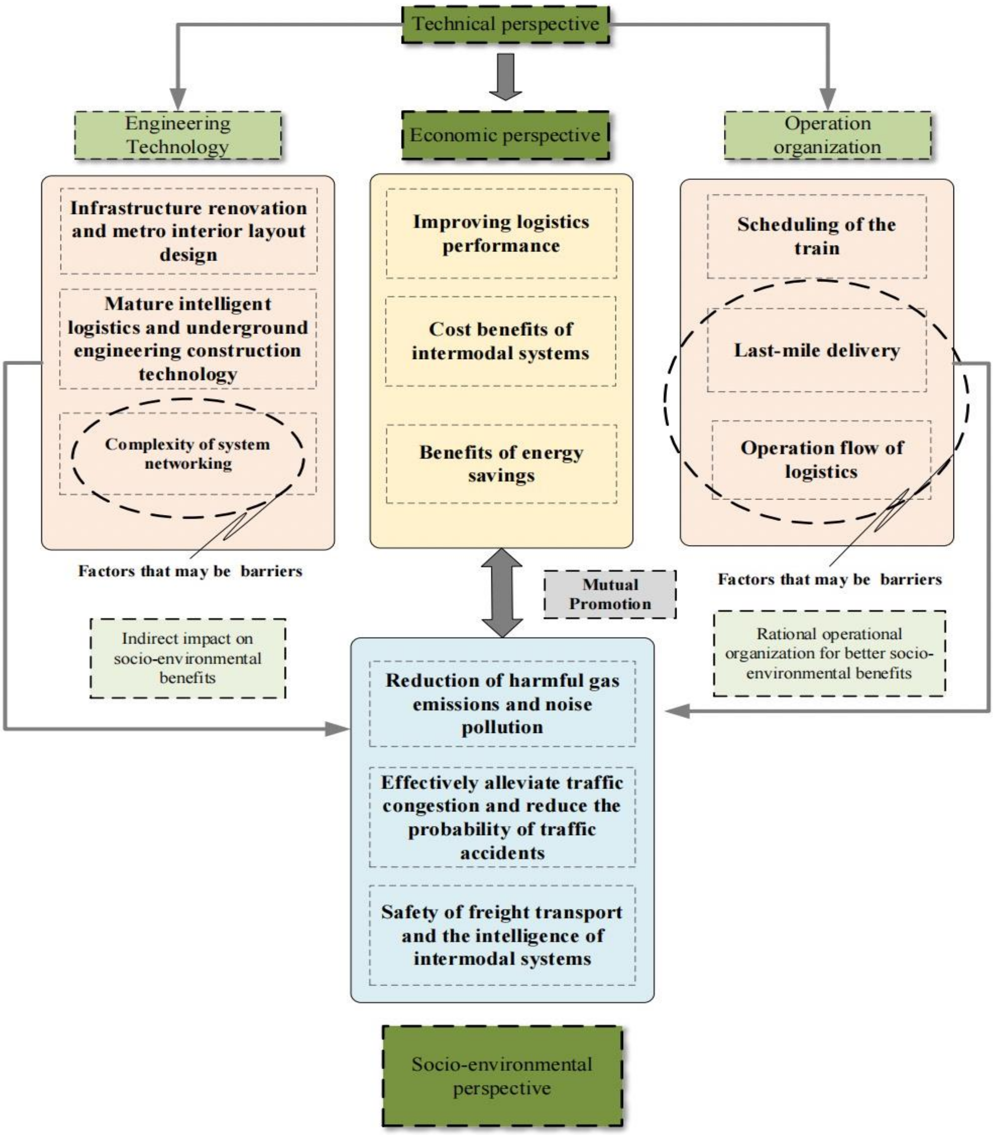


Figure 6. Multi-perspective analysis framework for M-ULS implementation.

Technology enhancement is a direct driver to improve the economic, social and environmental benefits of cities. High levels of automation and effective freight transportation management are required for the functioning of intelligent logistics systems [79]. Currently, there is little research literature related to intelligent equipment systems and management with M-ULS as a theme. If transportation devices such as technologically sophisticated drone delivery are developed, they will perfectly solve the difficult last-mile problem and also transform the obstacle factor into a driving factor. In addition, most of the scholars' studies on benefits are based on dedicated ULS and are qualitative in nature, so quantifying the benefits generated by M-ULS is also a future research trend.

4.3. System Network Design and Operation Optimization

In addition to the above-mentioned analysis of operation models and affecting factors, studies on the design and operational optimization of the system network with M-ULS as the theme have been undertaken. On the one hand, this is due to the academic community's ongoing network-based analysis and empirical research of the M-ULS program, on the other hand, it is due to the advancement of planning theories and system development strategies.

4.3.1. Node Network Design

The initial research concentrated on single-line routes, which are the fundamental layout form of M-ULS [82]. Numerous empirical studies have been conducted in the literature around its conceptual design, site selection, distribution path optimization and other issues, providing theoretical support for the implementation of M-ULS pilot projects [70]. However, too singular transportation paths limit the service scope of cargo transportation as well as transportation capacity, making it difficult to generate economies of scale. Subsequently, the concept of multilane intermodal transportation network was proposed [83].

The service range of transportation based on the original infrastructure, which may initially implement large-scale distribution in urban peripheral logistics parks and central metropolitan areas, is substantially improved by multilane intermodal transport networks [77]. Existing research frequently takes into consideration factors such as construction costs, traffic patterns, logistics demands, and industrial layout [84]. These studies then recommend network formation in regions with significant negative externalities and a pressing need for urban freight transportation by judiciously optimizing key metrics such as travel distance, travel cost, and utilization rate. However, studies have shown that "riders", with a low degree of intensification and intelligence, continue to dominate the end-of-line distribution of multilane networks. As a result, the demand for logistics cost reduction and efficiency cannot be effectively realized, and a number of new traffic issues for freight demand areas are created, such as passenger and freight lane grabbing, poor freight safety, etc. [68]. It is also far from being a practical solution to logistics issues because of the rise in multilane intermodal transit, which will result in higher transportation costs and longer travel times. Thus, there is currently an agreement that the network should be operated to maximize the benefits of intermodal transportation systems and boost their efficiency, and Figure 7 depicts the evolution of the proposed M-ULS networked concept.

4.3.2. System Operations Management

Studies on system operation optimization are currently scarce and largely concentrated on two areas: designing a collaborative dispatching scheme for passengers and freight, and improving the internal station operating flow. Visual simulation modeling of freight stations was used by Hu et al. [66] to propose an optimization scheme for internal logistics functional area layout and station operation flow. Li et al. [14], Behiri et al. [74], and Ozturk and Patrick [85] optimized the collaborative transportation scheme from the perspectives of cost–benefit, capacity constraint, distribution time, and dynamic time window, respectively. The development of secondary underground freight sub-networks in freight-intensive locations in order to create an extended M-ULS network has emerged as a new research trend based on the existing metro mainline freight network. Based on this, the operational schedule will be more complicated after adding an underground freight sub-network, and the relevant study is still in need of completion.

In general, the multilane intermodal network already in existence is unable to support the high-quality growth of an underground logistics system, therefore, network development is a necessary part of the implementation of underground logistics based on metro. Although M-ULS network design is the issue that has received the most attention in the literature so far, the mechanism of M-ULS network expansion is still unclear. The realization of networked services is directly impacted by the aforementioned trends. In this process, the assessment of project investment, operational performance and external benefits are dynamically changing. There is a lack of papers in the literature that further investigate the above issues.

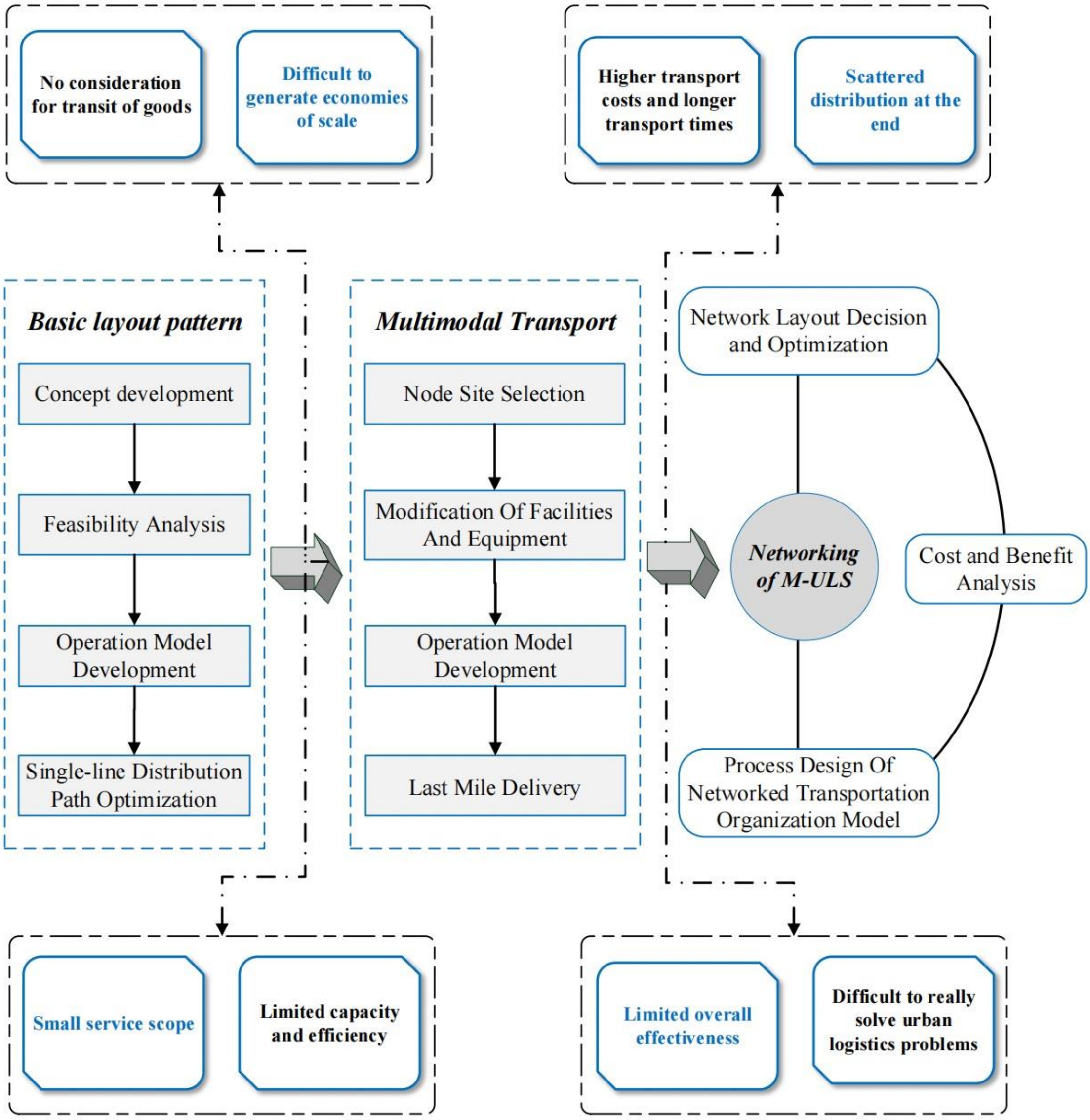


Figure 7. Integration of a networked M-ULS concept.

4.4. Stakeholder Interaction Relationship

The government, metro operating firms, logistics companies, and users are the key direct stakeholders in M-ULS from the perspective of the entire project building process [86]. The findings of Villa and Monzon [1] demonstrate that the introduction of an urban freight metro has enormous potential advantages for urban transportation. M-ULS suggests lower external costs for local governments, including social and environmental factors, which range from 11.16% to 14.72% less than in the existing model. Additionally, the mixed transport strategy results in cheaper operating costs for logistics organizations, which increases profitability. Utilizing the metro's extra capacity for cargo transportation also generates additional revenue for the firms who operate the metro. Finally, the punctuality and efficiency of cargo delivery with M-ULS is a substantial advantage for users, particularly in emergency situations such as epidemics.

Stakeholder theory's core view is that organizations should balance the needs of various stakeholders in an integrated way rather than solely focusing on performance [57]. A project should concentrate on its own external societal benefits in addition to its internal rewards [87]. In order to facilitate the development of M-ULS, stakeholders should develop initiatives as shown in Figure 8 based on the analysis of the three themes mentioned above.

The numbers in the ellipses are the statistical values of the 52 articles in the literature that are focused on or can reflect the corresponding themes, respectively. According to Hu et al. [88], system performance will be improved by early government backing and regulatory mechanisms between pricing, supply and demand levels, and investment. As a result, since this is a novel sort of urban infrastructure, the government ought to take the lead in deciding how to proceed and implement the plan. Additionally, the government should oversee and regulate the market, assisting all stakeholders in agreeing on how to distribute benefits along the logistical process. Metro operators must establish a strong working relationship with logistics firms in order to schedule trains for both passenger and cargo service. The rebuilding of metro infrastructure and the planning of trains for passenger and cargo transportation should fall more on the metro operating firms. However, metro operators need to forge a strong collaboration with logistics firms in order to participate in the standardized process of cargo transportation. Moreover, logistics firms must adopt the ideal delivery strategy and consider the needs of customers in the final mile of delivery. Finally, users must actively promote and adopt this new mode of transportation while taking advantage of M-ULS.

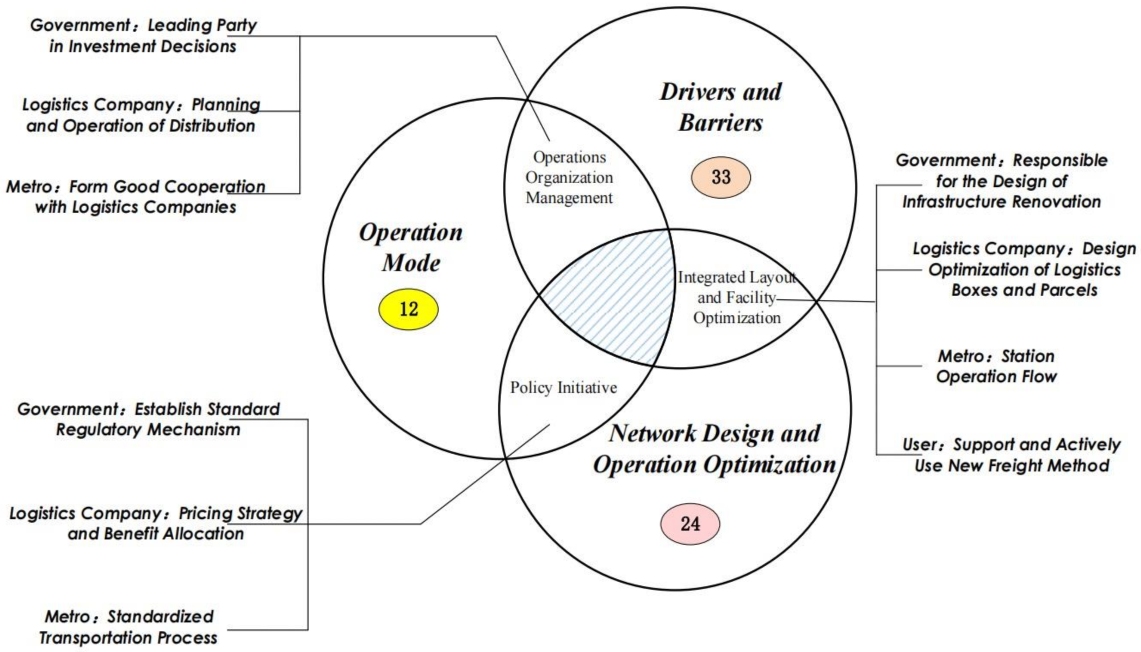


Figure 8. Stakeholder interaction relationship.

The current model of collaboration between logistics companies, service providers, and other stakeholders will unavoidably alter when new infrastructure is introduced. M-ULS has different stages of development from project planning to formal operation. Research on the demands of stakeholders and dynamic game behavior at every stage of the complicated contract logistics relationship is still lacking. Research on how to form a new logistics cooperation model and how to balance the interests between the parties also deserves in-depth discussion.

4.5. Comprehensive Benefit

Sustainable urban development requires that the construction and operation of infrastructure is needed to meet the coordinated development of economic, social and environmental benefits at the same time. When making the development plan for a public infrastructure project, the project's external benefits are always considered critical factors that motivate political support. The establishment of the M-ULS comprehensive benefit assessment system can offer government officials and decision-makers a deeper understanding of urban land utilization benefits and facilitate the selection of financing strategies.

Taking the Beijing urban rail transit system as a case study, Hu et al. [19] considered five aspects of benefits: transportation, energy, environment, land conservation, and safety. Their findings demonstrated that the M-ULS exhibits competitive advantages in terms of service capacity and profitability. Furthermore, the study's results revealed a significant impact of government funding intensity on the performance of M-ULS in terms of construction progress, benefits, and profits. Based on previous benefit studies, Pan et al. [76] constructed a benefit evaluation system containing 13 indicators using the service cost replacement method to quantitatively study the comprehensive benefits of M-ULS in transportation, logistics, environment and society. The research findings indicate that M-ULS can mitigate the negative impacts of road freight on urban sustainability and enhance the proportion of underground urban space. What is more, the application of green and intelligent technologies enables it to replace a substantial amount of labor and distributed logistics facilities, thereby fostering urban sustainable development. A model with three interrelated modules is proposed by Chen et al. [89]. In addition to quantifying the benefits in various aspects mentioned above, they also took into account the comprehensive benefits of emergency support for multi-functional logistics systems, providing a reference decision-making mechanism for the network expansion of M-ULS. In this study, energy efficiency benefits rise fastest with the promotion of underground urban freight, followed by logistics economies of scale. Once again, the significant contribution of green infrastructure planning to sustainable urban development was confirmed.

The Strategic Research Agenda for the European Underground Construction Sector has explicitly stated that the vision for its development is to put infrastructure underground and free up the surface for citizens. M-ULS initiatives stand on the maximum utilization of urban infrastructure and underground space resources to meet diverse logistics needs and compatibility for sustainable urban development. By summarizing the literature on the topic of M-ULS benefits, it becomes evident that its contribution to society is substantial. The comprehensive benefits of M-ULS are positively correlated with network scale. Therefore, the planning of M-ULS should consider the overall impact on urban sustainable development. As a matter of fact, the roles of governments and logistics companies in financing and operations are expected to evolve at different stages of ULS development. Increasing financial support in the early stages of the project can significantly accelerate system expansion. Indeed, adopting a flexible and diversified financing strategy can greatly facilitate the implementation of ULS. By encouraging the participation of various stakeholders in institutional development, it can foster the sustainable development of both the public and city logistics industries, ultimately benefiting society at large.

5. Conclusions

M-ULS is an intelligent and automated goods transportation system that is oriented toward sustainable urban development. It enhances the quality of logistics services and reduces negative externalities in cities through the application of green technologies such as smart warehousing, automated sorting, and distribution. This article reviews the current status, trends, and gaps in M-ULS research based on a bibliometric analysis of 52 relevant studies selected from four well-known databases. Following that, the main findings are presented.

First of all, as shown by the moving average trend graph for the year of journal publication, there is an increasing trend in the number and consistency of research themes in M-ULS, which indicates a gradual recognition of the innovative construction of green infrastructure. Then, the categorization of the publications demonstrates that the research topics cover a variety of industries, including engineering construction, logistics management, environmental ecology, subsurface space exploration, and transportation planning. This suggests that M-ULS research is multidisciplinary in nature and spans a wide variety of topics. Moreover, according to the statistical analysis of keywords in the literature, the creation of intelligent logistics systems integrated with subway infrastructure networks proves to be a favorable tool for the sustainable development of urban freight transportation. In the context of urban logistics advocating sustainable development, M-ULS is an ideal choice to make full use of the underground space to build a new type of freight infrastructure and put the idea of passenger and freight synergy into reality. Last but not least, within the scope of this review study, Mathematical Modelling is the most applied research method. In particular, the mixed integer nonlinear programming model is the most commonly used modelling approach in optimization problems. Moreover, the combination of qualitative and quantitative analysis is also the most commonly used strategy for this research topic.

- Subsequently, this paper summarizes the M-ULS operation model while exploring the drivers and barriers of M-ULS based on urban sustainability theory, and subsequently constructs a path for the conceptual integration of M-ULS networking. What is more, the relationships between multiple stakeholders are explored and recommendations are given from the stakeholder's perspective. Finally, the impact of the comprehensive benefits of M-ULS on urban sustainable development is explained. The key points are summarized as follows.
- Firstly, the existing operation modes mainly include P-F SL and P-F CL. According to the composition of train cars, P-F CL can be further divided into CL-S and CL-T types. A comparative analysis shows that P-F CL has higher freight potential and is the mainstream of current research. Secondly, technical, economic, and socio-environmental advantages are the three levels at which we analyze the drivers and barriers of M-ULS. The findings indicate that by taking the appropriate steps, the barriers can be transformed into drivers. Technical improvements can theoretically improve the economic, social and environmental benefits of cities. Thirdly, the concept of M-ULS network integration has gone through multiple stages of derivation. Multiline intermodal networks cannot achieve high quality development of ULS, and network expansion is an inevitable trend for implementing underground logistics based on metro. Furthermore, the government, metro operating businesses, logistics corporations, and users are the primary direct stakeholders in M-ULS. Each stakeholder participant should develop corresponding actions to help the development of M-ULS. In the end, as an emerging urban infrastructure system, M-ULS demonstrates comprehensive benefits in various aspects, including social, environmental, economic, logistics, transportation, energy, and emergency support. It is worth mentioning that the planning of green infrastructure should fully consider its comprehensive contribution to the sustainable development of the city. The comprehensive benefits of M-ULS are positively correlated with the network scale, and stakeholders can adopt different strategies at different time periods to control the development scale of M-ULS, thereby enhancing the overall benefits of the system.
- This study evaluates the relevant literature on the topic of M-ULS and visualizes the research trends. Importantly, it proposes new ideas and requirements for the development of M-ULS through the discussion of different topics. This study offers a systematic and comprehensive review. On a theoretical level, the findings provide a basis for researchers to identify gaps for future research. On a practical level, this study serves as a strong reference for practitioners to use already-known information and analyze the conditions that facilitate the implementation of M-ULS. It will make it easier for academics and practitioners to assess the current status of M-ULS and to grasp the future direction. Inevitably, there are some limitations to this study, such as the fact that the literature was searched only in four major databases based on the "title" field, a strategy that may have led to partial omission of literature. Additionally, due to the short period of research in this field and the small amount of literature, these factors may partially limit the descriptive analysis of the data.

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

Funding: This work was supported by the National Natural Science Foundation of China (grants nos. 52102392, 72271125 and 71971214) and the Natural Science Foundation of Jiangsu Province (grant no. BK20210437).

Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Villa, R.; Monzón, A. A Metro-Based System as Sustainable Alternative for Urban Logistics in the Era of E-Commerce. *Sustainability* **2021**, *13*, 4479. [CrossRef]
2. Zahed, S.E.; Shahandashti, S.M.; Najafi, M. Financing Underground Freight Transportation Systems in Texas: Identification of Funding Sources and Assessment of Enabling Legislation. *J. Pipeline Syst. Eng.* **2018**, *9*, 06018001. [CrossRef]
3. Xu, Y.; Dong, J.; Ren, R.; Yang, K.; Chen, Z. The impact of metro-based underground logistics system on city logistics performance under COVID-19 epidemic: A case study of Wuhan, China. *Transp. Policy* **2022**, *116*, 81–95. [CrossRef] [PubMed]
4. Anderson, V.; Gough, W.A. Enabling Nature-Based Solutions to Build Back Better-An Environmental Regulatory Impact Analysis of Green Infrastructure in Ontario, Canada. *Buildings* **2022**, *12*, 61. [CrossRef] [PubMed]
5. Kasznar, A.P.P.; Hammad, A.W.A.; Najjar, M.; Qualharini, E.L.; Figueiredo, K.; Soares, C.A.P.; Haddad, A.N. Multiple Dimensions of Smart Cities' Infrastructure: A Review. *Buildings* **2021**, *11*, 73. [CrossRef]
6. Ying, J.; Zhang, X.J.; Zhang, Y.Q.; Bilan, S. Green infrastructure: Systematic literature review. *Econ. Res. Ekon. Istraz.* **2022**, *35*, 343–366. [CrossRef]
7. Lyu, Y.; Ji, Z.; Liang, H.; Wang, T.; Zheng, Y.Q. Has Information Infrastructure Reduced Carbon Emissions?-Evidence from Panel Data Analysis of Chinese Cities. *Buildings* **2022**, *12*, 619. [CrossRef]
8. Vernimmen, B.; Dullaert, W.; Geens, E.; Notteboom, T.; T'Jollyn, B.; van Gilsen, W.; Winkelmans, W. Underground logistics systems: A way to cope with growing internal container traffic in the port of antwerp? *Transp. Plan. Technol.* **2007**, *30*, 391–416. [CrossRef]
9. Kilibarda, M.; Andrejić, M.; Popović, V. Research in logistics service quality: A systematic literature review. *Transp. Vilnius* **2020**, *35*, 224–235.
10. Dong, J.J.; Xu, Y.X.; Hwang, B.G.; Ren, R.; Chen, Z.L. The Impact of Underground Logistics System on Urban Sustainable Development: A System Dynamics Approach. *Sustainability* **2019**, *11*, 1223. [CrossRef]
11. Hu, W.; Dong, J.; Hwang, B.-G.; Ren, R.; Chen, Z. Hybrid optimization procedures applying for two-echelon urban underground logistics network planning: A case study of Beijing. *Comput. Ind. Eng.* **2020**, *144*, 106452. [CrossRef]
12. Miller, B.; Spertus, J.; Kamga, C. Costs and benefits of pneumatic collection in three specific New York City cases. *Waste Manag.* **2014**, *34*, 1957–1966. [CrossRef] [PubMed]
13. Dong, J.; Hu, W.; Yan, S.; Ren, R.; Zhao, X. Network Planning Method for Capacitated Metro-Based Underground Logistics System. *Adv. Civ. Eng.* **2018**, *2018*, 6958086. [CrossRef]
14. Li, Z.; Shalaby, A.; Roorda, M.J.; Mao, B. Urban rail service design for collaborative passenger and freight transport. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *147*, 102205. [CrossRef]
15. Strale, M. The cargo tram: Current status and perspectives, the example of Brussels. *Transp. Sustain.* **2014**, *6*, 245–263. [CrossRef]
16. Arvidsson, N.; Browne, M. A Review of the Success and Failure of Tram Systems to Carry Urban Freight: The Implications for a Low Emission Intermodal Solution Using Electric Vehicles on Trams. *Eur. Transp. Trasporti Eur.* 2013. Available online: https://www.openstarts.units.it/entities/publication/d494a1dc-3e54-443b-b4d0-ac712d159fcb/details (accessed on 21 July 2023).
17. Hu, W.; Dong, J.; Hwang, B.-G.; Ren, R.; Chen, Y.; Chen, Z. Using system dynamics to analyze the development of urban freight transportation system based on rail transit: A case study of Beijing. *Sustain. Cities Soc.* **2020**, *53*, 101923. [CrossRef]
18. Chen, Y.; Dong, J.; Chen, Z.; Zhao, X.; Shang, P. Optimal carbon emissions in an integrated network of roads and UFTS under the finite construction resources. *Tunn. Undergr. Space Technol.* **2019**, *94*, 103108. [CrossRef]
19. Hu, W.; Dong, J.; Hwang, B.-G.; Ren, R.; Chen, Z. A preliminary prototyping approach for emerging metro-based underground logistics systems: Operation mechanism and facility layout. *Int. J. Prod. Res.* **2020**, *59*, 7516–7536. [CrossRef]
20. Gatta, V.; Marcucci, E.; Nigro, M.; Serafini, S. Sustainable urban freight transport adopting public transport-based crowdshipping for B2C deliveries. *Eur. Transp. Res. Rev.* **2019**, *11*, 13. [CrossRef]
21. Jabbour, A.B.L.D.; Jabbour, C.J.C.; Sarkis, J.; Latan, H.; Roubaud, D.; Godinho, M.; Queiroz, M. Fostering low-carbon production and logistics systems: Framework and empirical evidence. *Int. J. Prod. Res.* **2021**, *59*, 7106–7125. [CrossRef]
22. Denyer, D.; Tranfield, D. Producing a systematic review. In *The Sage Handbook of Organizational Research Methods*; Sage Publications Ltd.: Thousand Oaks, CA, USA, 2009; pp. 671–689.
23. Ren, R.; Hu, W.; Dong, J.; Sun, B.; Chen, Y.; Chen, Z. A Systematic Literature Review of Green and Sustainable Logistics: Bibliometric Analysis, Research Trend and Knowledge Taxonomy. *Int. J. Environ. Res. Public Health* **2019**, *17*, 261. [CrossRef]
24. Zevgolis, I.E.; Mavrikos, A.A.; Kaliampakos, D.C. Construction, storage capacity and economics of an underground warehousing-logistics center in Athens, Greece. *Tunn. Undergr. Space Technol.* **2004**, *19*, 165–173. [CrossRef]

25. Xie, C.; Wang, X.; Fukuda, D. On the Pricing of Urban Rail Transit with Track Sharing Freight Service. *Sustainability* **2020**, *12*, 2758. [CrossRef]
26. Cochrane, K.; Saxe, S.; Roorda, M.J.; Shalaby, A. Moving freight on public transit: Best practices, challenges, and opportunities. *Int. J. Sustain. Transp.* **2016**, *11*, 120–132. [CrossRef]
27. Alessandrini, A.; Site, P.D.; Filippi, F.; Salucci, M.V. Using rail to make urban freight distributionmore sustainable. *Eur. Transp. Trasp. Eur.* **2012**, *50*, 1–17.
28. Hörl, B.; Dörr, H.; Wanjek, M.; Romstorfer, A. METRO.FREIGHT.2020—Strategies for Strengthening Rail Infrastructure for Freight Transport in Urban Regions. *Transp. Res. Procedia* **2016**, *14*, 2776–2784. [CrossRef]
29. Dampier, A.; Marinov, M. A Study of the Feasibility and Potential Implementation of Metro-Based Freight Transportation in Newcastle upon Tyne. *Urban Rail Transit* **2015**, *1*, 164–182. [CrossRef]
30. Serafini, S.; Nigro, M.; Gatta, V.; Marcucci, E. Sustainable crowdshipping using public transport: A case study evaluation in Rome. *Transp. Res. Procedia* **2018**, *30*, 101–110. [CrossRef]
31. Kikuta, J.; Ito, T.; Tomiyama, I.; Yamamoto, S.; Yamada, T. New Subway-Integrated City Logistics Szystem. *Procedia Soc. Behav. Sci.* **2012**, *39*, 476–489. [CrossRef]
32. Shahooei, S.; Mattingly, S.P.; Shahandashti, M.; Ardekani, S. Propulsion system design and energy optimization for autonomous underground freight transportation systems. *Tunn. Undergr. Space Technol.* **2019**, *89*, 125–132. [CrossRef]
33. O'Connell, R.M.; Liu, H.; Lenau, C.W. Performance of Pneumatic Capsule Pipeline Freight Transport System Driven by Linear Motor. *J. Transp. Eng.* **2008**, *134*, 50–58. [CrossRef]
34. Kashima, S.; Nakamura, R.; Matano, M.; Taguchi, T.; Shigenaga, T. Study of an underground physical distribution system in a high-density, built-up area. *Tunn. Undergr. Space Technol.* **1993**, *8*, 53–59. [CrossRef]
35. Shahooei, S.; Najafi, M.; Ardekani, S. Design and Operation of Autonomous Underground Freight Transportation Systems. *J. Pipeline Syst. Eng.* **2019**, *10*, 8. [CrossRef]
36. Zhao, L.; Li, H.; Li, M.; Sun, Y.; Hu, Q.; Mao, S.; Li, J.; Xue, J. Location selection of intra-city distribution hubs in the metro-integrated logistics system. *Tunn. Undergr. Space Technol.* **2018**, *80*, 246–256. [CrossRef]
37. Assefa, S.; Lee, H.-Y.; Shiue, F.-J. Sustainability Performance of Green Building Rating Systems (GBRSs) in an Integration Model. *Buildings* **2022**, *12*, 208. [CrossRef]
38. Liu, F.; Zhang, Y.; Zhang, J. Foundation Treatment in Urban Underground Engineering Using Big Data Analysis for Smart City Applications. *Comput. Model. Eng. Sci.* **2022**, *132*, 153–172. [CrossRef]
39. Li, G.; Ma, X.; Song, Y. Green Building Efficiency and Influencing Factors of Transportation Infrastructure in China: Based on Three-Stage Super-Efficiency SBM–DEA and Tobit Models. *Buildings* **2022**, *12*, 623. [CrossRef]
40. Lin, C.-L. Evaluating the urban sustainable development strategies and common suited paths considering various stakeholders. *Environ. Dev. Sustain.* **2022**, *24*, 14033–14073. [CrossRef]
41. Lombardi, M.; Berardi, D.; Galuppi, M.; Barbieri, M. Green Tunnel Solutions: An Overview of Sustainability Trends in the Last Decade (2013–2022). *Buildings* **2023**, *13*, 392. [CrossRef]
42. Liberalesso, T.; Oliveira Cruz, C.; Matos Silva, C.; Manso, M. Green infrastructure and public policies: An international review of green roofs and green walls incentives. *Land Use Policy* **2020**, *96*, 104693. [CrossRef]
43. Dai, Y.; Solangi, Y.A. Evaluating and Prioritizing the Green Infrastructure Finance Risks for Sustainable Development in China. *Sustainability* **2023**, *15*, 7068. [CrossRef]
44. Chan, A.P.C.; Darko, A.; Olanipekun, A.O.; Ameyaw, E.E. Critical barriers to green building technologies adoption in developing countries: The case of Ghana. *J. Clean. Prod.* **2018**, *172*, 1067–1079. [CrossRef]
45. Chan, I.Y.S.; Chen, H. Towards an integrative analysis of underground environment and human health: A survey and field measurement approach. *Eng. Constr. Archit. Manag.* **2023**. [CrossRef]
46. Mavrikos, A.; Kaliampakos, D. An integrated methodology for estimating the value of underground space. *Tunn. Undergr. Space Technol.* **2021**, *109*, 103770. [CrossRef]
47. He, B.-J.; Zhao, D.-X.; Zhu, J.; Darko, A.; Gou, Z.-H. Promoting and implementing urban sustainability in China: An integration of sustainable initiatives at different urban scales. *Habitat Int.* **2018**, *82*, 83–93. [CrossRef]
48. Hu, W.J.; Dong, J.J.; Hwang, B.G.; Ren, R.; Chen, Z.L. Network planning of urban underground logistics system with hub-and-spoke layout: Two phase cluster-based approach. *Eng. Constr. Archit. Manag.* **2020**, *27*, 2079–2105. [CrossRef]
49. Sun, X.; Hu, W.; Xue, X.; Dong, J. Multi-objective optimization model for planning metro-based underground logistics system network: Nanjing case study. *J. Ind. Manag. Optim.* **2021**, *19*, 170–196. [CrossRef]
50. Yang, B.; Xu, T.; Shi, L. Analysis on sustainable urban development levels and trends in China's cities. *J. Clean. Prod.* **2017**, *141*, 868–880. [CrossRef]
51. Wuni, I.Y.; Shen, G.Q.P. Critical success factors for management of the early stages of prefabricated prefinished volumetric construction project life cycle. *Eng. Constr. Archit. Manag.* **2020**, *27*, 2315–2333. [CrossRef]
52. Li, G.; Cui, L.L. Analysis of urban green building and sustainable development. *Agro. Food Ind. Hi-Tec.* **2017**, *28*, 1031–1035.
53. de Gooyert, V.; Rouwette, E.; van Kranenburg, H.; Freeman, E. Reviewing the role of stakeholders in Operational Research: A stakeholder theory perspective. *Eur. J. Oper. Res.* **2017**, *262*, 402–410. [CrossRef]
54. Freeman, R.E.; McVea, J. *A Stakeholder Approach to Strategic Management*; Wiley: Hoboken, NJ, USA, 1984.

55. Guarnieri, P.; Silva, L.C.E.; Levino, N.A. Analysis of electronic waste reverse logistics decisions using Strategic Options Development Analysis methodology: A Brazilian case. *J. Clean. Prod.* **2016**, *133*, 1105–1117. [CrossRef]
56. Amaya, J.; Delgado-Lindeman, M.; Arellana, J.; Allen, J. Urban freight logistics: What do citizens perceive? *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *152*, 102390. [CrossRef]
57. Harrison, J.; Freeman, R.E.; Cavalcanti Sá de Abreu, M. Stakeholder Theory As an Ethical Approach to Effective Management: Applying the theory to multiple contexts. *Rev. Bus. Manag.* **2015**, *17*, 858–869. [CrossRef]
58. Li, Y.; Li, M.; Sang, P.; Chen, P.-H.; Li, C. Stakeholder studies of green buildings: A literature review. *J. Build. Eng.* **2022**, *54*, 104667. [CrossRef]
59. Hu, W.; Dong, J.; Hwang, B.-G.; Ren, R.; Chen, Z. A Scientometrics Review on City Logistics Literature: Research Trends, Advanced Theory and Practice. *Sustainability* **2019**, *11*, 2724. [CrossRef]
60. Zhang, H.; Lv, Y.; Guo, J. New Development Direction of Underground Logistics from the Perspective of Public Transport: A Systematic Review Based on Scientometrics. *Sustainability* **2022**, *14*, 3179. [CrossRef]
61. Guo, D.; Chen, Y.; Yang, J.; Tan, Y.H.; Zhang, C.; Chen, Z. Planning and application of underground logistics systems in new cities and districts in China. *Tunn. Undergr. Space Technol.* **2021**, *113*, 103947. [CrossRef]
62. Singh, M.; Gupta, S. Urban rail system for freight distribution in a mega city: Case study of Delhi, India. *Transp. Res. Procedia* **2020**, *48*, 452–466. [CrossRef]
63. Lagorio, A.; Pinto, R.; Golini, R. Research in urban logistics: A systematic literature review. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 908–931. [CrossRef]
64. Kelly, J.; Marinov, M. Innovative Interior Designs for Urban Freight Distribution Using Light Rail Systems. *Urban Rail Transit* **2017**, *3*, 238–254. [CrossRef]
65. Motraghi, A.; Marinov, M.V. Analysis of urban freight by rail using event based simulation. *Simul. Model. Pract. Theory* **2012**, *25*, 73–89. [CrossRef]
66. Hu, W.; Dong, J.; Yang, K.; Hwang, B.-G.; Ren, R.; Chen, Z. Modeling Real-time operations of Metro-based urban underground logistics system network: A discrete event simulation approach. *Tunn. Undergr. Space Technol.* **2023**, *132*, 104896. [CrossRef]
67. Hu, W.J.; Dong, J.J.; Yang, K.; Ren, R.; Chen, Z.L. Network planning of metro-based underground logistics system against mixed uncertainties: A multi-objective cooperative co-evolutionary optimization approach. *Expert Syst. Appl.* **2023**, *217*, 119554. [CrossRef]
68. Zheng, C.; Zhao, X.; Shen, J. Research on Location Optimization of Metro-Based Underground Logistics System With Voronoi Diagram. *IEEE Access* **2020**, *8*, 34407–34417. [CrossRef]
69. Li, Z.; Mao, B.; Bai, Y.; Chen, Y. Integrated Optimization of Train Stop Planning and Scheduling on Metro Lines with Express/Local Mode. *IEEE Access* **2019**, *7*, 88534–88546. [CrossRef]
70. Zheng, C.; Gu, Y.; Shen, J.; Du, M. Urban Logistics Delivery Route Planning Based on a Single Metro Line. *IEEE Access* **2021**, *9*, 50819–50830. [CrossRef]
71. Ren, M.; Fan, Z.; Wu, J.; Zhou, L.; Du, Z. Design and Optimization of Underground Logistics Transportation Networks. *IEEE Access* **2019**, *7*, 83384–83395. [CrossRef]
72. De Langhe, K. The importance of external costs for assessing the potential of trams and trains for urban freight distribution. *Res. Transp. Bus. Manag.* **2017**, *24*, 114–122. [CrossRef]
73. Chen, Y.; Guo, D.; Chen, Z.; Fan, Y.; Li, X. Using a multi-objective programming model to validate feasibility of an underground freight transportation system for the Yangshan port in Shanghai. *Tunn. Undergr. Space Technol.* **2018**, *81*, 463–471. [CrossRef]
74. Behiri, W.; Belmokhtar-Berraf, S.; Chu, C. Urban freight transport using passenger rail network: Scientific issues and quantitative analysis. *Transp. Res. Part E Logist. Transp. Rev.* **2018**, *115*, 227–245. [CrossRef]
75. Visser, J.G.S.N. The development of underground freight transport: An overview. *Tunn. Undergr. Space Technol.* **2018**, *80*, 123–127. [CrossRef]
76. Pan, X.; Dong, J.; Ren, R.; Chen, Y.; Sun, B.; Chen, Z. Monetary evaluation of the external benefits of urban underground logistics System: A case study of Beijing. *Tunn. Undergr. Space Technol.* **2023**, *136*, 105094. [CrossRef]
77. van der Heijden, M.C.; van Harten, A.; Ebben, M.J.R.; Saanen, Y.A.; Valentin, E.C.; Verbraeck, A. Using Simulation to Design an Automated Underground System for Transporting Freight Around Schiphol Airport. *Interfaces* **2002**, *32*, 1–19. [CrossRef]
78. Hu, W.; Dong, J.; Hwang, B.-G.; Ren, R.; Chen, Z. Is mass rapid transit applicable for deep integration of freight-passenger transport? A multi-perspective analysis from urban China. *Transp. Res. Part A Policy Pract.* **2022**, *165*, 490–510. [CrossRef]
79. Hu, W.; Dong, J.; Xu, N. Multi-period planning of integrated underground logistics system network for automated construction-demolition-municipal waste collection and parcel delivery: A case study. *J. Clean. Prod.* **2022**, *330*, 129760. [CrossRef]
80. Ma, M.; Zhang, F.; Liu, W.; Dixit, V. A game theoretical analysis of metro-integrated city logistics systems. *Transp. Res. Part B Methodol.* **2022**, *156*, 14–27. [CrossRef]
81. Hai, D.; Xu, J.; Duan, Z.; Chen, C. Effects of underground logistics system on urban freight traffic: A case study in Shanghai, China. *J. Clean. Prod.* **2020**, *260*, 121019. [CrossRef]
82. Lundgren, T.S.; Zhao, Y. Aerodynamics of electrically driven freight pipeline system. *J. Transp. Eng.* **2000**, *126*, 263–270. [CrossRef]
83. Rezaeifar, F.; Najafi, M.; Kaushal, V.; Huff, B. Development of a Model to Optimize the Operations of an Intermodal Underground Logistics Transportation. *J. Pipeline Syst. Eng.* **2022**, *13*, 04022039. [CrossRef]
84. Janbaz, S.; Shahandashti, M.; Najafi, M. Life Cycle Cost Analysis of an Underground Freight Transportation (UFT) System in Texas. *J. Pipeline Syst. Eng.* **2017**, *2017*, 134–143.

85. Ozturk, O.; Patrick, J. An optimization model for freight transport using urban rail transit. *Eur. J. Oper. Res.* **2018**, *267*, 1110–1121. [CrossRef]
86. Marchau, V.; Walker, W.; van Duin, R. An adaptive approach to implementing innovative urban transport solutions. *Transp. Policy* **2008**, *15*, 405–412. [CrossRef]
87. Zwikael, O.; Salmona, M.; Meredith, J.; Zarghami, S.A. Enhancing project stakeholder communication under insufficient knowledge of project management concepts. *Eng. Constr. Archit. Manag.* **2022**. [CrossRef]
88. Hu, W.; Dong, J.; Yuan, J.; Ren, R.; Chen, Z.; Cheng, H. Agent-based modeling approach for evaluating underground logistics system benefits and long-term development in megacities. *J. Manag. Sci. Eng.* **2022**, *7*, 266–286. [CrossRef]
89. Chen, Z.; Hu, W.; Xu, Y.; Dong, J.; Yang, K.; Ren, R. Exploring decision-making mechanisms for the metro-based underground logistics system network expansion: An example of Beijing. *Tunn. Undergr. Space Technol.* **2023**, *139*, 105240. [CrossRef]

buildings

MDPI

Article

Evaluation of Safety Management of Smart Construction Sites from the Perspective of Resilience

Yutong Qian, Hui Liu, Peng Mao * and Xiaodan Zheng

College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China; qianyt@njfu.edu.cn (Y.Q.); liuhui@njfu.edu.cn (H.L.); zhengxiaodan90@163.com (X.Z.)
* Correspondence: maopeng@njfu.edu.cn; Tel.: +86-138-0517-1820

Abstract: In the context of green, low-carbon, and sustainable construction, the safety management of smart construction sites has been a key issue. Current related research mainly focuses on the application of technology, but lacks methods to evaluate the safety management level. Therefore, this research aims to construct a smart construction site safety management evaluation model from a resilience perspective. First, this research identified and screened the indicators initially based on the 4R resilience characteristics and 4M theory by analyzing the policy texts of smart construction site safety management. Then, through expert consultation, the ISM model of resilience indicators was established to determine the evaluation indicator system of smart construction site safety management. Next, the weight of each indicator was determined with the help of the analytic network process, and the evaluation criteria of the indicators were formulated according to the existing specifications and expert interviews; then, the evaluation model of smart construction site safety management was established. Finally, the feasibility of the model was proved through a case study. The findings of the research show that in terms of weights, management has the highest score, followed by media, man, and machine. However, more resilience measures are used for the safety management of machine than the other three in policy texts. Obviously, there is a deviation between weights and resilience characteristics. These findings help reveal the current situation of safety management at smart construction sites, which is of great significance for improving resilience. The findings also help smart construction sites to realize the upgrading of safety, efficiency, and greenness, and promote the sustainable development of smart construction sites as well as the construction industry.

Keywords: smart construction site; safety management; resilience; evaluation

1. Introduction

Under the guidance of the sustainability goals, sustainable urban development is gradually being emphasized [1]. Infrastructure construction, as a necessary part of urban development, is changing from high energy consumption and high emissions to a new model of digitalization, intelligence, and greening. The smart construction site is one of the typical representatives of the transformation path of construction mode. At present, a variety of new technologies in the smart construction site have greatly improved the efficiency, management level, and serviceability of the construction site operation.

Generally speaking, construction sites have been plagued with long-standing safety problems, such as complex environments, difficulties in personnel management, frequent occurrence of safety accidents, difficulties in investigation and evidence collection, and difficulties in machinery safety management [2,3]. The construction industry continues to be one of the most dangerous industries [4]. Therefore, safety management is a theme that must be considered in the construction site management process. The smart construction site is a new type of construction means built on a high degree of informationization. Compared with the traditional construction site, the construction scale of the smart site is increasing, and the introduction of new technologies and the integration of multiple subsystems make the construction site more and more complex. It can be seen that although there are differences in technical applications and management means between smart construction sites and traditional construction sites, their safety management is still the top priority [5]. Nowadays, despite the existence of many smart construction site management platforms in the market, they face huge uncertainties in information interaction and have poor risk resistance [6]. When some of the functions of the management system are damaged due to emergencies, the system can easily be completely paralyzed if it lacks backup modules or fails to replenish them in time. This will result in a delay in the overall construction schedule and an unnecessary waste of manpower and resources. In addition, the smart construction site management system is more complicated than the traditional management system, making it difficult to ensure a reasonable deployment of emergency resources to maximize benefits. It is also hard to return to a certain functional level in a relatively short period of time after the occurrence of emergencies. Therefore, it is one-sided and costly to rely only on traditional safety management tools to protect against risks. Resilience theory not only takes into account the ability of the thing itself to resist risk, but also focuses on the whole change process in the whole system, so that the system can return to its prior state more quickly [7]. At the same time, resilience theory can learn from the experience of the impact of shocks or disturbances, improve the adaptive capacity to uncertain events [8], and optimize the system in the direction of greenness and efficiency. As a result, it is urgent to improve the recovery and adaptive capacity of safety management systems from a resilience perspective.

The scientific community has also conducted a wealth of research on smart construction site safety management, which mainly emphasizes the application of technology and system frameworks to achieve the goal of smart construction site safety management. However, it is not enough to improve safety management only by upgrading technical means. Existing studies have not yet systematized the indicators of smart construction site safety management. In addition, there is no proper model to evaluate the current state of smart construction site safety management. Resilience considers the recovery and adaptive capacity of a system, but construction project safety management systems have not yet emphasized resilience, and smart construction sites have paid even less attention to this concept. Although some results have been accumulated on resilience evaluation research of safety management, little attention has been paid to the safety management of smart construction sites.

To overcome these shortcomings, this research aims to develop a smart construction site safety management evaluation method based on the perspective of resilience. Specifically, it explores the following questions: (1) What is the evaluation system of smart construction site safety management, based on the perspective of resilience? (2) What are the evaluation indicator criteria for smart construction site safety management? (3) How can the evaluation of smart construction site safety management be realized? To achieve the above objectives, this research first analyzed the policy texts using Nvivo. Based on resilience characteristics and 4M theory, initial indicators of smart construction site safety management were identified and selected. Secondly, the ISM model was constructed based on expert consultation, and the interrelationships between the indicators of smart construction site safety management were sorted out. Final direct indicators were obtained and the evaluation indicator system was constructed. Then, after determining the weights of the indicators and evaluation criteria, the evaluation model of smart construction site safety management was constructed. Finally, the feasibility of the model was verified by taking a smart construction site as an example.

The main contributions of this research are in the following aspects: (1) Introduce a new perspective, the resilience perspective, to discuss smart construction site safety management. (2) Combine the 4R resilience characteristics and the 4M theory to code the policy text at three levels and construct a smart construction site safety management indicator system. (3) Develop an evaluation model of smart construction site safety management to assess the current situation of the safety management level. The findings of the research help improve the safety management level of the smart construction site, make it more resilient, and avoid falling into the dilemma of simple superposition of technical means. At the same time, through the scientific management measures of personnel and media, it helps to improve the safety management efficiency of the smart construction site, promote its green upgrading, and further promote the sustainable development of the smart construction site.

The rest of the research is structured as follows. Section 2 contains the literature review. Section 3 details the method used in this research. Section 4 describes the construction of the evaluation model for smart site safety management. Section 5 proves the feasibility of the constructed model with the help of a real case study. Sections 6 and 7 present the discussion and the conclusions, respectively.

2. Literature Review

2.1. Smart Construction Site Safety Management

Concepts such as smart cities and smart districts are emerging to achieve the sustainable development targets [9]. As one of the components of a smart city, a smart construction site integrates information technologies such as BIM, cloud computing, big data, the Internet of Things, and smart devices into various fields such as construction organization management and construction site management [10,11] to promote the upgrading of the traditional construction site and achieve fine site management. Construction safety has long been a thorny issue in the development of the construction industry. It is vital to ensure the safety of personnel and machinery at construction sites. Therefore, safety management is also a research hotspot of smart construction site management. With the development of smart construction sites, more and more smart technologies are being used at smart construction sites, providing a large number of system models and countermeasure suggestions for smart construction site safety management. For example, Rey proposed a digital system for construction site safety condition inspection using UAVs to provide timely information for site decision making [12]. Zhang established a framework for the construction site information management system based on blockchain and smart contracts to guarantee the safety supervision of projects [13]. Zhang proposed a method that combines computer vision and a real-time location system for proactive site safety management [14]. Thus, it can be seen that many achievements have accumulated in smart construction site safety management at this stage, but most of the research is limited to safety risk warning systems and the detection of site safety [5]. However, there is still a lack of methods and tools that can judge the application of technology in smart construction site safety management, namely the current state of smart construction site safety management. Therefore, it is urgent to develop an evaluation model of smart construction site safety management. The scientific community has noticed the necessity to conduct research in this area; for example, Liu identified indicators for the evaluation of smart construction site safety management based on BIM technology [15]. However, the occurrence of safety accidents is not only related to technology and equipment, but also closely linked to humans, the environment, and management. This is also proved by the 4M theory of risk source. In the 4M theory, four main factors, Man, Machine, Media, and Management, are considered together [16,17]. Most traditional construction site safety management research is also based on the 4M theory [18]. These four factors work together throughout the process of the smart construction site being disturbed. Therefore, the 4M theory helps guide the safety management evaluation of the smart construction site.

2.2. Feasibility of Safety Management Research Based on Perspective of Resilience

Traditional safety management aims to reduce the number of accidents [19], while safety management that only focuses on resisting the occurrence of risks is one-sided and costly. In complex and uncertain work environments, it is important to take a fresh perspective on safety and anticipating risks [20] and take proactive measures to deal with unexpected events. Resilience is a new perspective that can achieve these goals. The concept of resilience is derived from the adaptive cycle model proposed by Holling and Gunderson and applied to various fields such as mechanics, psychology, and social sciences [21]. Resilience considers how to improve the "recovery" and "adaptation" capabilities of a system in unexpected situations, reduce recovery costs and time, and prepare for future emergencies [22]. At present, most of the research on resilience is focused on the field of public management [23]. With the depth of research, resilience has gradually been introduced into the safety management of construction projects in recent years [24,25]. For example, Rodrigues combined the concept of resilience engineering and unmanned aircraft systems technology for safety planning and control on construction sites to facilitate safety management [26]. In the field of resilience evaluation, some scholars have also conducted research, mainly focusing on the elements [27], properties [28], and influencing factors of resilience [29]. Of course, there are some research results in the evaluation of the resilience of safety management. For example, Zhu proposed a theoretical framework and key safety management factors for a construction safety management system based on resilience theory [30]. Wang established a safety management evaluation indicator system comprising 25 indicators for high-speed railroad construction projects in mining areas based on the concept of resilience and constructed a resilience evaluation model [31]. Zhang identified indicators through the literature and expert opinions and established a sewer network resilience evaluation framework [32]. In general, the most mainstream evaluation principle in resilience theory at this stage is the 4R principle proposed by Bruneau in 2003, which contains the four main characteristics of robustness, resourcefulness, redundancy, and rapidity [33]. Robustness refers to the system's ability to reduce the potential for accidents before a shock and to mitigate the negative consequences caused by an emergency when a shock occurs. Resourcefulness means that the system has a certain reserve of emergency resources and can use them rationally to maximize the benefits. Redundancy means that a system has a certain amount of replaceable spare modules, so that when the functions of some equipment in the system are seriously affected by the shock, the spare parts can participate promptly to make the whole system operate normally. Rapidity represents the ability to recover quickly after a shock [33]. However, the application of resilience in the construction safety management system has not yet received enough attention [34], and there is even less involvement in smart construction site safety management. Therefore, it is of great importance to explore the evaluation model that affects the smart construction site safety management in the resilience background.

2.3. Research Gap

With the emergence of smart construction sites, scholars have researched smart construction site safety management. But most of them only emphasize the application of information technology and lack specific methods to judge the current situation of smart construction site safety management. Considering the shortcomings of traditional safety management, resilience can not only reduce the occurrence of risks, but also improve the recovery ability of safety management systems. Although resilience is gradually used for the safety management of construction projects, it is rarely involved in smart construction site safety management. As a result, an evaluation model for smart construction site safety management based on a resilience perspective is required.

3. Methods

The research framework of this research is shown in Figure 1.

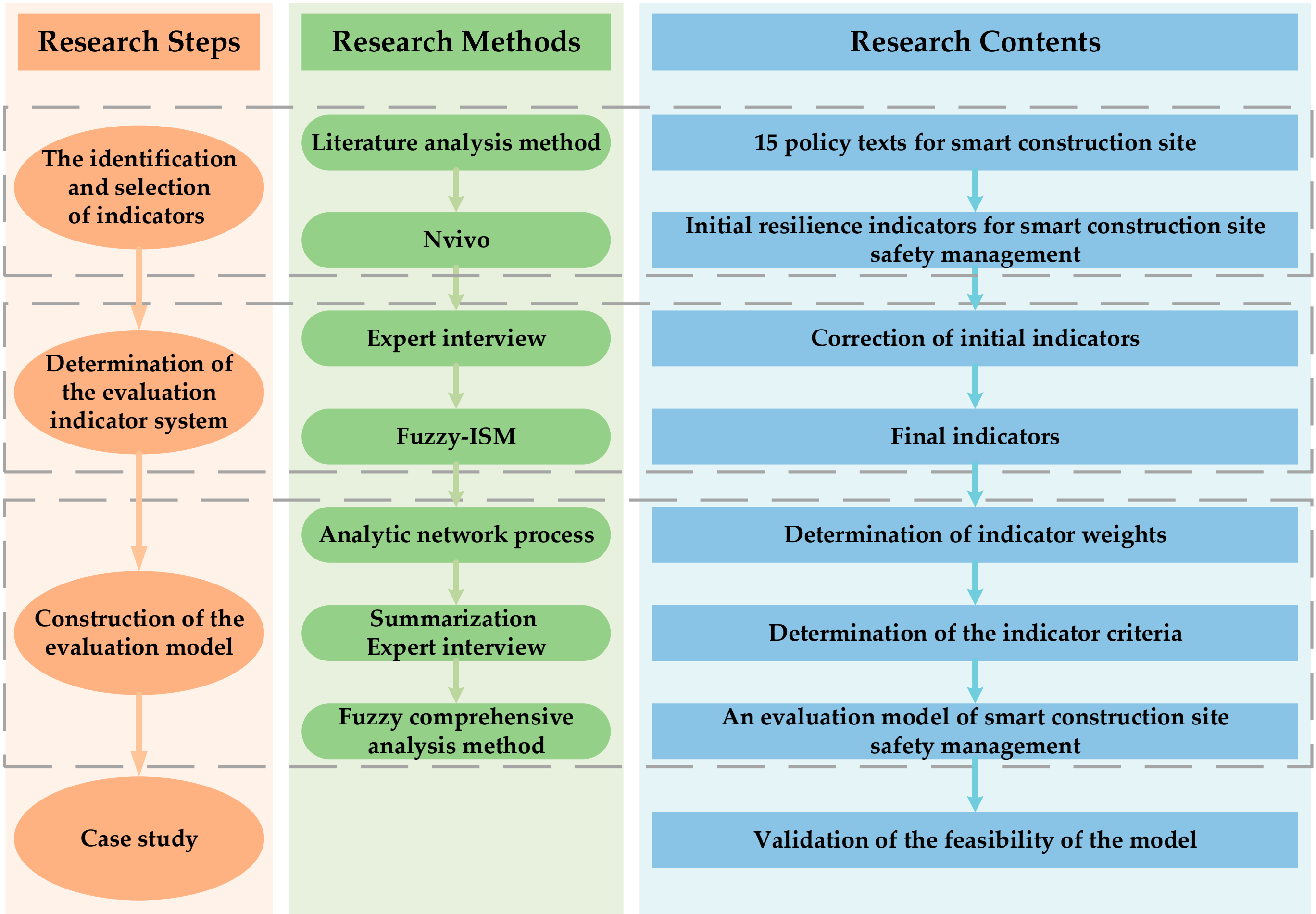


Figure 1. Research framework.

The first step is the identification and selection of indicators. First, 15 policy texts related to smart construction sites were found based on the literature analysis method. Second, this research applied Nvivo 12 Plus to obtain initial resilience indicators for smart construction site safety management. In this step, a randomly selected portion of 15 policy texts were imported into Nvivo. Based on the resilience theory, keywords and phrases in the texts involving 4R resilience characteristics were then extracted and conceptually named to form an open coding. Subsequently, main categories were created by integrating and deleting previously subsidiary conceptual categories to complete the axial coding. At last, according to the 4M theory, core categories consisting of 4M factors were determined by systematic analysis. During this step, the selective coding was completed [35]. In order to ensure the accuracy and reliability of the results, finally, a saturation test was required. Specifically, the remaining policy texts were required to be coded at three levels. If no new category appears after coding, the data are considered saturated [36]. After the saturation test, the indicator framework was derived, and the initial resilience indicators for smart construction site safety management were obtained.

The second step is the determination of the evaluation indicator system. To ensure the validity and accuracy of the indicators, 18 experts were invited to revise the initial indicators. Fuzzy-ISM utilizes fuzzy numbers instead of 0 and 1 to describe fuzzy relationships between indicators and it can transform complex content into a hierarchical system and demonstrate the hierarchical relationship between indicators clearly [37]. Therefore, Fuzzy-ISM was used to determine the final smart construction site safety management indicator system. In addition, the hierarchical relationship between the indicators can be obtained when conducting Fuzzy-ISM. It is the necessary information for the subsequent step of constructing the network structure in the ANP method.

The next step is the construction of the evaluation model. First, it is necessary to determine the weight of each indicator. The analytic network process (ANP) can measure the interrelationship of indicators in the system objectively and obtain the weights and total ranking of indicators [38]. Thus, it was used to determine the weights of the indicators in this research. Next, the evaluation criteria needed to be established. Since there are no evaluation criteria for smart construction site safety management, the criteria for these evaluation indicators were determined by summarizing the standard texts and discussing them with experts. Finally, with the help of the fuzzy comprehensive analysis method, the evaluation model of smart construction site safety management was constructed based on the determination of weights and evaluation indicators. The fuzzy comprehensive analysis method was used because it not only considers the hierarchy of evaluation objects but also gives full play to human experience, which can make the evaluation results more reliable [39,40].

Finally, we used a case study. Constructing an evaluation model requires verifying its feasibility and validity. Evaluations conducted only at the theoretical level are ultimately weak [41]. Therefore, Project A was selected for the evaluation of smart construction site safety management in this research.

4. Model Development

4.1. Identification and Selection of Indicators

The policy texts under implementation will better reflect the reality of smart construction site safety management and resilience than the past literature, and the construction standards of smart construction sites have not yet been unified. In addition, this research focused on the safety management of smart construction sites in China. Therefore, this research was based on the keywords (1) safety management ("safety guidelines", "regulatory approaches", "technical standards", etc.), (2) "smart construction site", "construction informationization", "smart construction", etc. Fifteen relevant policy texts were finally selected from the official websites of housing and construction departments of Chinese provinces and cities.

On the one hand, resilience theory can deepen the understanding of the components of the smart construction site safety management system. Enhancing the resilience of the system can avoid the occurrence of accidents while reducing the damage caused by shocks [42], and effectively improve the safety of the smart construction site. On the other hand, the source of accidents is largely attributed to the hazard source [43]. As a result, the evaluation of smart construction site safety management can be based on risk source theory, which considers the resilience of the system from man, machine, media, and management perspectives. However, in the actual response to the entire risk process, the indicators of these four perspectives often work together. Therefore, it is necessary to establish a two-dimensional matrix between the 4R resilience characteristics and the 4M theory, and to obtain the smart construction site safety management evaluation indicators from the two dimensions together.

4.1.1. Based on the 4R Resilience Characteristics

In this research, the judgment criterion for selecting smart construction site safety management indicators based on the 4R resilience characteristics was to ensure that the selected indicators must satisfy one of the characteristics of resilience. Taking "Person identification" as an example, in the smart construction site safety management system, the function can ensure personnel safety supervision by identifying whether construction personnel wear protective equipment such as safety helmets and vests. It can also assist in the efficient conduct of professional supervision through the automatic identification of the personnel number and the project progress. It emphasizes the safety of construction personnel, thus reducing construction accidents. Therefore, "Personnel identification" can be considered to be consistent with robustness. In indicator selection, Nvivo was used to perform open coding on 12 policy texts that were randomly chosen from a pool of 15, and the remaining 3 policy texts were used as data for the saturation test. After coding, 29 initial indicators were obtained. To generalize the indicators, axial coding was performed based on open coding, and 13 main categories and their corresponding subcategories were obtained. The classification nodes of each indicator's 4R resilience characteristics and the categories are shown in Table 1.

Table 1. Resilience indicators of smart construction site safety management system.

Main Category	Subcategories	R1	R2	R3	R4
Auxiliary personnel management	Personnel hierarchical authorization	√	√		
	Person identification	√			
	Personnel information management		√		
Analytical support for decision making	Assistance to personnel in decision making		√		√
	Visual aid analysis		√		
Promotion of personnel communication and collaboration	Communication skills		√		√
	Collaboration skills		√		√
Equipment failure resilience	Partial function substitutability of equipment	√		√	
	Equipment and system vandalism prevention	√		√	
	Equipment with fast response capability		√		√
Backup and expansion capability	Backup capability	√		√	√
	Expansion of functions and potential	√	√		
Early warning and emergency capability	Emergency response capability				√
	Early warning capability	√			√
Data analysis and processing capability	Adoption of cloud architecture		√		
	Positioning function		√		√
	Data acquisition and transmission		√		
	Data processing and management		√		
	Data hierarchical storage and processing		√		
Education of employees	Employee safety education	√	√		
	Employee skills training	√	√		
Ability to integrate functions	Integration of environmental monitoring	√			
Real-time environmental data	Real-time acquisition		√		√
	Real-time processing		√		√
Harsh environment resistance	Large operating temperature range	√	√		
	Inconsistent ability of equipment to resist harsh environments	√	√		
Accuracy of environmental monitoring	High environmental monitoring accuracy and fast response				√
Richness of monitoring points	Monitoring with redundancy			√	
	Multiple environmental monitoring points			√	
Total (number of nodes)		204	204	94	179

Note: R1 represents "Robustness"; R2 represents "Resourcefulness"; R3 stands for "Redundancy"; R4 stands for "Rapidity".

4.1.2. Based on the 4M Theory

As mentioned in the previous section, the indicators classified by their resilience characteristics were obtained. The final step in text coding analysis is selective coding. Therefore, based on the 4M theory, the codes were summarized and organized with the help of Nvivo. Finally, four selective codes were obtained, namely man, machine, media, and management, as shown in Figure 2. The three policy texts left behind were tested for theoretical saturation, and no new category appeared in the results. Therefore, the constructed indicators are saturated and can be analyzed next [36].

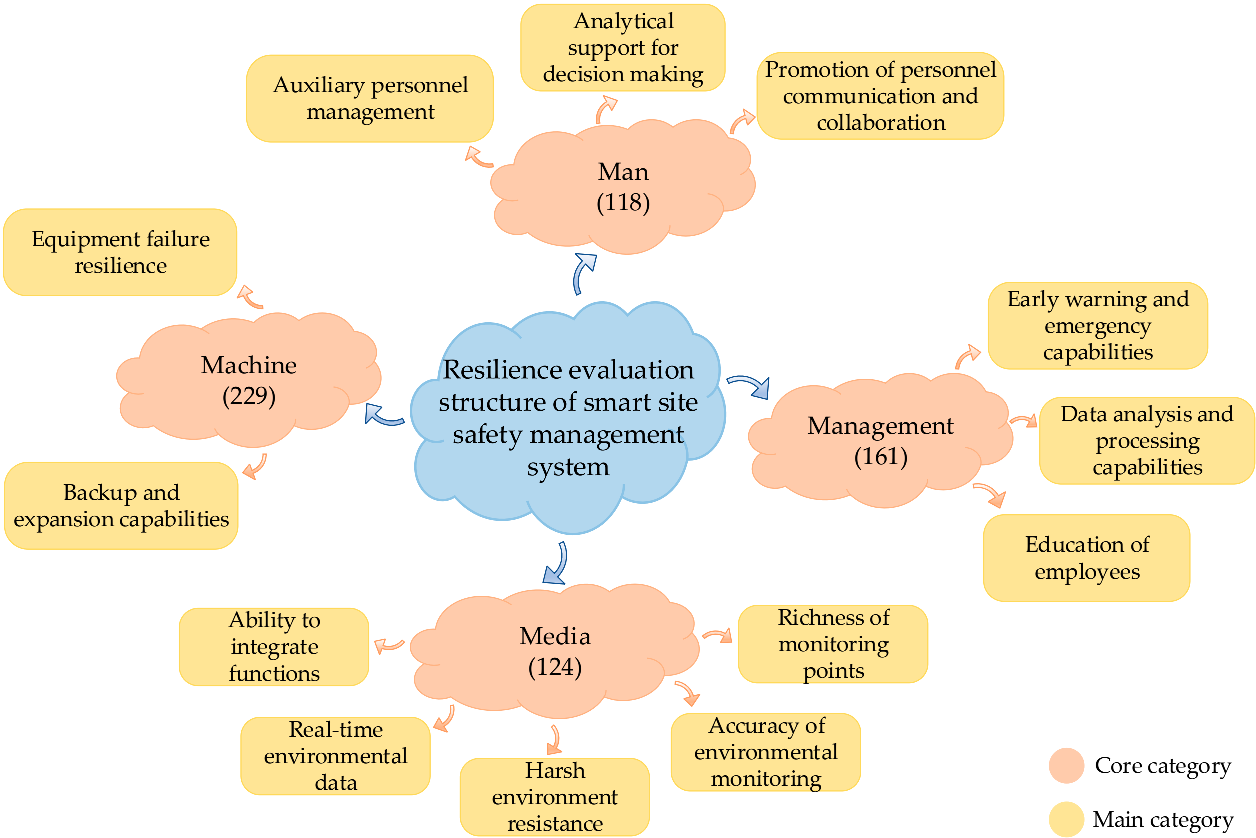


Figure 2. Resilience indicators by 4M classification.

After completing the classification of the indicators of smart construction site safety management, through quadratic matrix coding, the reflection of the 4R resilience characteristic under each 4M factor was further examined, as shown in Table 2.

Table 2. The reference point of the resilience characteristic under each 4M factor.

	Robustness	**Resourcefulness**	**Redundancy**	**Rapidity**
Man	12.31%	57.64%	0.35%	29.70%
Machine	32.93%	17.13%	30.08%	16.22%
Media	32.67%	10.17%	19.60%	37.57%
Management	29.24%	41.28%	0%	29.48%

As can be seen from the above table, the current policy texts pay more attention to the resourcefulness of man and management, which means the optimization of relevant decisions and the reasonable deployment of resources under limited resource reserves. At the same time, there are requirements for the robustness of machine and the rapidity of media, meaning the ability to absorb and resist shocks and the ability to respond and recover quickly. Combined with the ratio and the code number, the robustness of machine and the resourcefulness of man are more considered. As a smart construction site safety management system mainly serves to ensure the safety of people and machines, it is very important for a construction site to make machines more robust and people more resourceful. On the one hand, it enables people to make better decisions and improves the overall resource allocation of the system. On the other hand, it improves the resistance of machines to better cope with shocks and minimize the damage caused by risks.

4.2. Construction of the Evaluation Indicator System

As discussed in the preceding section, the Fuzzy-ISM model uses fuzzy numbers instead of 0-1 relationships to form a matrix that can effectively describe the possible fuzzy relationships among the indicators [44]. Therefore, the method was chosen in this research to explore the indicators of smart construction site safety management and the hierarchical relationship between the indicators to ensure that the final evaluation indicators can accurately reflect the resilience of smart construction site safety management. The methodological steps of the Fuzzy-ISM are specified in Figure 3.

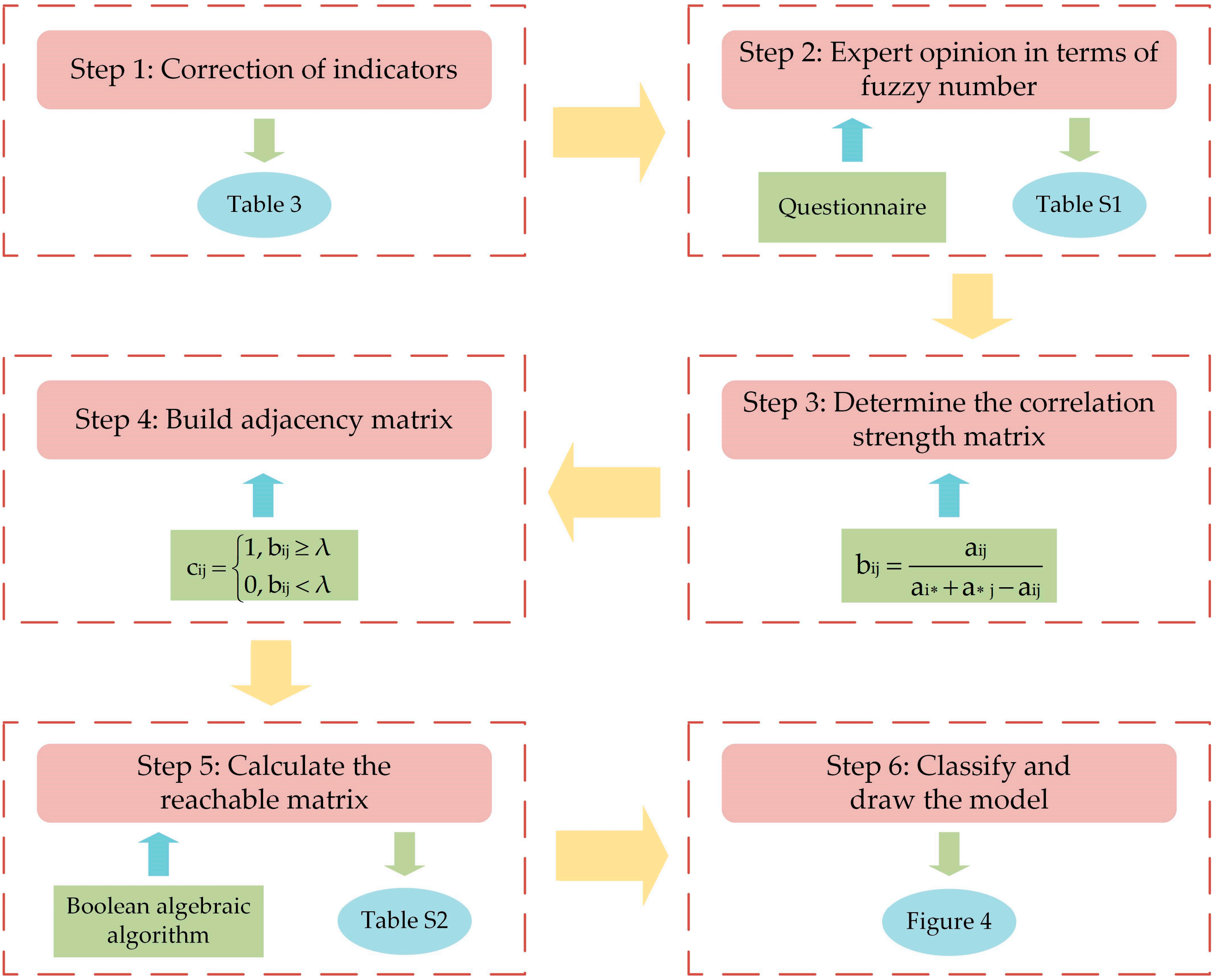


Figure 3. The process of Fuzzy-ISM. Note: (1) In the formula for step 3, a_{ij} is the value of row i and column j in the fuzzy correlation matrix, which is shown in Table S1; a_{i*} is the summation of the elements of row i of the matrix; a_{*j} is the summation of the elements of column j of the matrix. In step 4, a threshold λ is set to remove less influential relationships. Through expert consultation and experiments, λ = 0.052 was finally chosen in this research. (2) The final revised indicators are shown in Table 3. Table S2, detailed in the Supplementary Material, revealed the relationship between indicators.

Table 3. The revised indicators.

Category	Code	Indicators
Man	S1	Analytical support for decision making
	S2	Personnel management
	S3	Person identification
	S4	Promotion of personnel communication and collaboration
Machine	S5	Backup and replacement capability
	S6	Expansion of functions and potential
	S7	Equipment and system vandalism prevention
	S8	Equipment with fast response capability
Media	S9	Ability to integrate function
	S10	Richness of monitoring points
	S11	Accuracy of environmental monitoring
	S12	Harsh environment resistance
	S13	Real-time environmental data
Management	S14	Education of employees
	S15	Early warning and emergency capability
	S16	Adoption of cloud architecture
	S17	Positioning function
	S18	Data management

The process of indicator correction, questionnaire completion, and threshold λ determination in the above steps involved experts. Some research suggests that 10–18 experts are appropriate for a Delphi group [45]. Thus, 18 experts were invited to participate in this segment who are engaged in related work on smart construction sites. Among them, 15 experts have been working for more than 5 years. In terms of the nature of their work, there are six professors from universities, six corporate personnel who undertake the business of smart construction sites, and six government personnel.

It is not a good idea to use too many indicators in the evaluation process [46]. Therefore, experts were invited to make further corrections to the above indicators. After expert discussion, "Personnel hierarchical authorization" and "Personnel information management" in the subcategories were merged into "Personnel management". "Backup capability" and "Partial function substitutability of equipment" were merged into "Backup and replacement capability". "Data processing and management", "Data hierarchical storage and processing", and "Data acquisition and transmission" were combined into "Data management". The final revised indicators are shown in Table 3. The fuzzy correlation matrix of indicators and the reachable matrix calculated are shown in Tables S1 and S2 in the Supplementary Material. According to concepts such as reachable set and prior set, the indicators of smart construction site safety management were hierarchically divided. The final interpretative structural model of the indicators of smart construction site safety management is shown in Figure 4.

Due to the long influence path of the root layer indicators, the impact on smart construction site safety management is slow. Therefore, the apparent layer and middle layer indicators were determined as the final evaluation indicators. The graph of the final constructed evaluation indicator system of smart construction site safety management is shown in Figure 5. The number below the indicator in Figure 5 represents the code number corresponding to the indicator under different resilience characteristics.

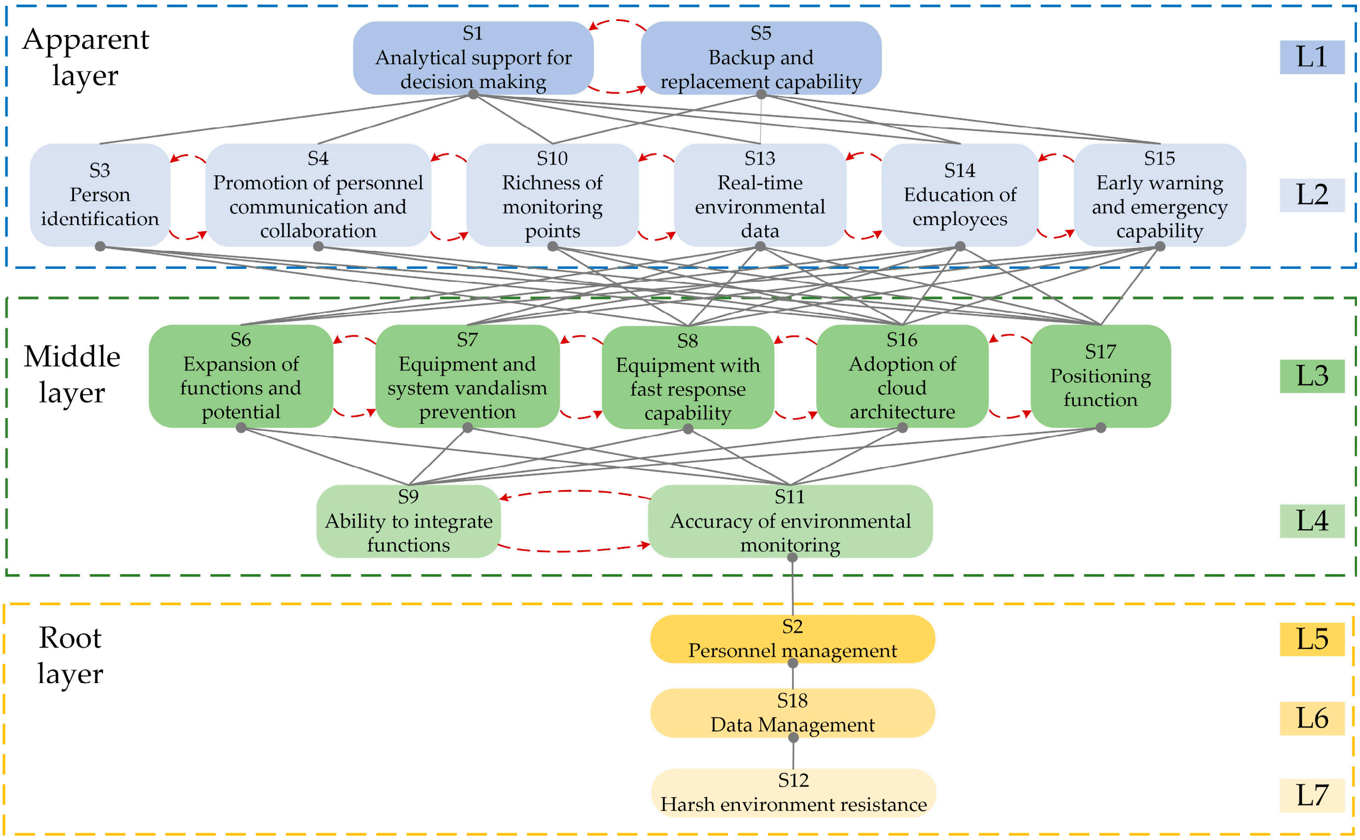


Figure 4. Interpretation structure model of indicators of smart construction site safety management.

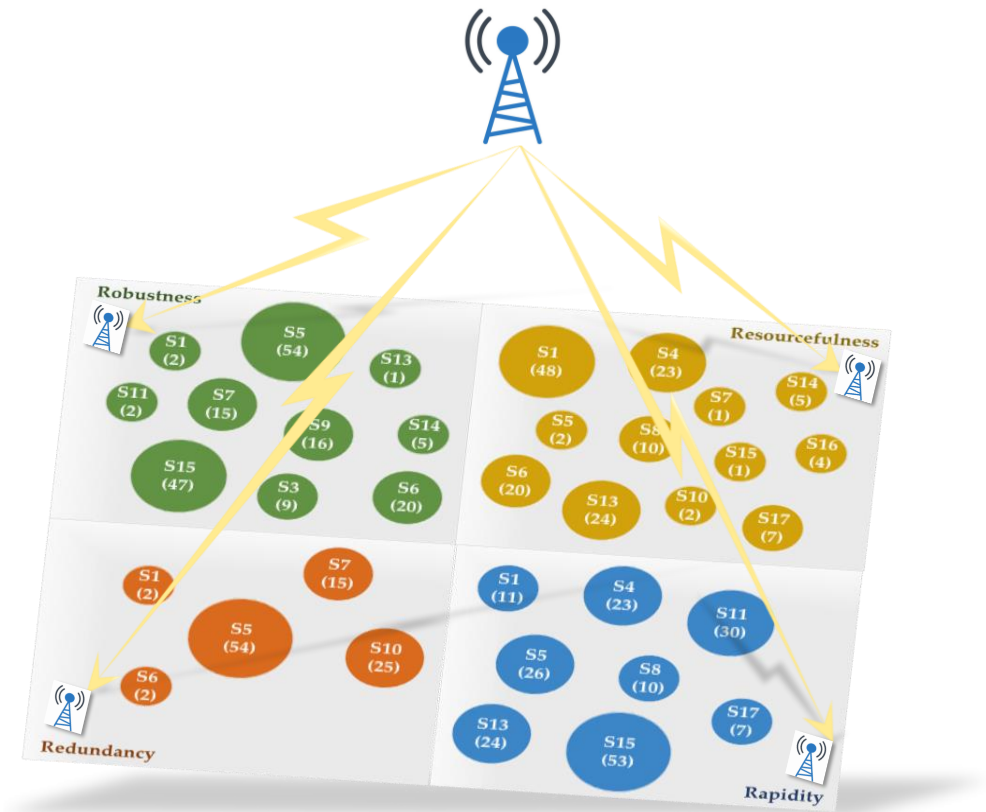


Figure 5. Evaluation indicator system.

4.3. Construction of the Evaluation Model

4.3.1. Determination of Weights

After constructing the smart construction site safety management indicator system, the next step is the calculation of weights. An analytic network process was selected to determine the weight of each indicator. The basic steps are as follows.

Step 1: The expert interviews were used to determine whether the indicators were internally independent, and the dependency and feedback relationship of each indicator.

Step 2: The correlations among the indicators were input into Super Decision to construct the network structure.

Step 3: The comparison matrices of secondary indicators (man, etc.) and tertiary indicators (S15, etc.) were constructed to form the secondary and tertiary indicator importance questionnaire.

Step 4: The experts were invited to complete the questionnaire, and the importance degree was assigned using the 1–9 scale method.

Step 5: The questionnaire results were analyzed using Super Decision software, and the hypermatrix was constructed to calculate the weights.

The experts in the steps were the same as those selected for the construction of the indicator system. Eighteen experts discussed the interpretative structure model diagram obtained previously and the fuzzy correlation matrix between the indicators, and finally complemented the correlations between S1 and S13; S4 and S13, S14; and S5 and S1, S13. After the experts completed the questionnaire, the ratings were summarized and averaged to obtain the final comparison matrices. To ensure the validity of the questionnaire results, a consistency test was required. According to previous research, the comparison matrix is consistent only if the value of the consistency ratio (CR) is less than 0.1 [47]. Therefore, the CR was calculated for all comparison matrices and the results show that values of CR were all less than 0.1, indicating that the consistency test was passed. Finally, the weights of the indicators were obtained by processing the data through the software and are shown in Table 4.

Table 4. Weight of each indicator.

Category	Weight	Indicator	Weight
Man	0.247672	S1 Analytical support for decision making	0.005057
		S3 Person identification	0.210437
		S4 Promotion of personnel communication and collaboration	0.032178
Machine	0.128442	S5 Backup and replacement capability	0.009634
		S6 Expansion of functions and potential	0.024269
		S7 Equipment and system vandalism prevention	0.019844
		S8 Equipment with fast response capability	0.074695
Media	0.295949	S9 Ability to integrate functions	0.109917
		S10 Richness of monitoring points	0.028938
		S11 Accuracy of environmental monitoring	0.112172
		S13 Real-time environmental data	0.044922
Management	0.327938	S14 Education of employees	0.051581
		S15 Early warning and emergency capability	0.052841
		S16 Adoption of cloud architecture	0.133831
		S17 Positioning function	0.089685

4.3.2. Determination of the Evaluation Criteria

Since there is less research on the evaluation of smart construction site safety management at this stage, the corresponding evaluation criteria have not yet been formed. Therefore, according to the Technical Standard for Information Systems of Construction Site Supervision And Management (JGJ/T 434-2018) [48], the Technical Standard for Intelligent Safety Supervision of Building Construction (DB32/T 4175-2021) [49], the Technical

Standard of Implementing Smart Construction Sites (DB13(J)/T 8312-2019) [50], Technical Standard for Smart Construction Sites (DB64/T 1684-2020) [51], and the Technical Specification for Smart Construction Sites (DB11/T 1710-2019) [52], combined with relevant case investigations, the preliminary evaluation criteria for safety management of smart construction sites were summarized. To enable the feasibility of the constructed evaluation criteria, the 18 experts were invited once again to judge and comment on the criteria. The evaluation criteria were then revised according to experts' comments and the revised criteria were fed back to the experts again. The experts had no disagreement with the revised evaluation criteria this time. Finally, the evaluation criteria of smart construction site safety management were obtained, shown in Table 5.

Table 5. The final evaluation criteria.

Category	Indicator	Evaluation Criteria
Man	S1 Analytical support for decision making	The number of areas covered with the ability to perform statistical analysis of information data
	S3 Person identification	The number of smart and biometric modules offered, and the number of scenes in which they are used
	S4 Promotion of personnel communication and collaboration	The number of participants involved in the multi-collaborative management of engineering construction
Machine	S5 Backup and replacement capability	The number of modules with automatic data backup, video history replay, and video download functions
	S6 Expansion of functions and potential	Whether it is possible to realize the expansion of system functions by adding business modules according to actual needs
	S7 Equipment and system vandalism prevention	Whether the designed software has encryption, whether the hardware has waterproof and drop-proof functions
	S8 Equipment with fast response capability	Responsiveness of the platform and critical equipment in terms of page response, backup/restore time of logs
Media	S9 Ability to integrate functions	The number of interface support tools for various types of IoT monitoring equipment at construction sites
	S10 Richness of monitoring points	The number of types that reflect the amount of redundancy in product design
	S11 Accuracy of environmental monitoring	Technical parameters related to the efficiency of key equipment used on sites (cameras, various sensors)
	S13 Real-time environmental data	The number of devices that can automatically monitor, display in real time, and synchronize the transmission of environmental data on sites
Management	S14 Education of employees	Whether to provide employee education-related online training, course exam management, and richness of content
	S15 Early warning and emergency capability	The number of types of warnings provided by the sites
	S16 Adoption of cloud architecture	The number of types of users involved in the platform
	S17 Positioning function	The number of types of positioning technology

Among them, S1, S3, S4, S5, S9, S10, S13, S15, S16, and S17 were quantitative indicators, and S6, S7, S8, S11, and S14 were qualitative indicators. To avoid the influence of indicator attributes on the evaluation, all indicators needed to be normalized. For quantitative indicators, taking S16 "Adoption of cloud architecture" as an example, the measure of this indicator is the number of types of users involved in the platform. According to the relevant standard texts, it is found that the user layer is generally divided into six categories, i.e., competent departments, construction units, design and survey units, construction companies, supervisory units, and practitioners. When S16 = n ($n \leq i$, i = 6), the evaluation value of the indicator is equal to n/i. When S16 > i, the evaluation value is equal to 1. The evaluation values for the remaining indicators were obtained in the same way. The value of each quantitative indicator i was verified as appropriate by the experts, and the results are shown in Table 6. For qualitative indicators, the evaluation set was determined first, and [0, 1] was divided into five subintervals corresponding to the evaluation set, and the average value was taken as the evaluation value of the indicator after scoring by experts. The criteria for determining the evaluation value of qualitative indicators are shown in Table 7.

Table 6. Each quantitative indicator's i-value.

Indicator	i-Value	Indicator	i-Value
S1	9	S3	3
S4	7	S5	8
S9	10	S10	12
S13	9	S15	7
S16	6	S17	7

Table 7. Criteria for the evaluation value of qualitative indicators.

Indicator	Evaluation Value				
	0.8–1	0.6–0.8	0.4–0.6	0.2–0.4	0–0.2
S6	high	relatively high	average	relatively low	low
S7	high	relatively high	average	relatively low	low
S8	high	relatively high	average	relatively low	low
S11	high	relatively high	average	relatively low	low
S14	high	relatively high	average	relatively low	low

4.3.3. Model Construction

In order to obtain the evaluation level of smart construction site safety management, the fuzzy comprehensive evaluation method was used to construct the model based on the determination of the indicator weight. The key steps of the method are as follows.

Step 1: The set of evaluation indicators was determined.

Step 2: Five evaluation levels were determined according to the qualitative indicator evaluation value table [53]. The following evaluation set V can thus be established: {V1, V2, V3, V4, V5} = {excellent, good, average, poor, very poor}. The range of affiliation values for each level is shown in Table 8.

Table 8. The range of affiliation values for each level.

Affiliation Value	[0.8, 1]	[0.6, 0.8)	[0.4, 0.6)	[0.2, 0.4)	[0, 0.2)
Evaluation Level	excellent	good	average	poor	very poor

Step 3: Each evaluation indicator was quantified to obtain the evaluation value, and the fuzzy relationship matrix was obtained.

Step 4: The weight vector was determined according to the following formula:

$$W = (\omega_1, \omega_2, \ldots, \omega_n). \tag{1}$$

where W represents the weight vector and ω indicates the weight of each indicator.

Step 5: Based on the weight vector and the fuzzy relationship matrix, the evaluation result vector was calculated from the equation below:

$$B = W \cdot R. \tag{2}$$

In this equation, B is the evaluation result vector and R represents the fuzzy relationship matrix. The evaluation level was obtained according to the principle of maximum affiliation.

5. Case Study

To verify the feasibility of this evaluation model, a typical smart construction site was selected as the evaluation object in this section, which had the value of analysis and evaluation because the smart business of the site was entrusted to an excellent enterprise with a certain scale, mature management, and certain praise in the industry.

5.1. Case Overview

Project A is located in Chengdu, Sichuan, China, and its main function is as an office building and commercial package. The project consists of a seventh-floor office building and a second-floor commercial building with a total construction area of 165,600 m^2. The building heights of the project are 31.85 m and 11.75 m, respectively. Construction of the project started in March 2019 and ended in May 2022. The smart business of the project is undertaken by a national high-tech enterprise. Specifically, from the four aspects of man, machine, media, and management, the status of each aspect of Project A is as follows.

5.1.1. Man

This smart construction site system uses the real-name access control system to collect and manage information such as workers' access to the site. It ensures multi-unit collaboration through platform docking and linkage technology, and supports seven types of file sharing such as project electronic drawings. It provides seven types of summarization functions such as data mining by statistical analysis data warehouse to assist personnel in analyzing and making decisions.

5.1.2. Machine

The system has good stability and reliability, and functions such as effective transfer or rapid recovery can be guaranteed in case of faults. The system retains interfaces for connection with other automation systems while taking into account future scientific developments and the application of new technologies as much as possible. A variety of auxiliary functions are added to the equipment to prevent it from being easily damaged. There are five types of modules with automatic data backup functions.

5.1.3. Media

The access sensor equipment adopts fingerprint collection, and the smart construction site system realizes checking the body temperature condition of personnel within 3 s. The system provides six types of interfaces such as environmental monitoring interfaces. It provides five types of parameter collection functions such as particulate matter concentration. Furthermore, it retains some leeway in the control capacity of the project equipment, involving ten categories of available backup equipment.

5.1.4. Management

The smart construction site system is mainly for four main subjects: competent departments, construction units, construction companies, and practitioners. It realizes two types of positioning functions for personnel and materials. Basically, it provides three types of warnings in terms of progress, environmental monitoring, and defense zone shots. It uses the Internet and multimedia display to develop the traditional party-building work into an intelligent and integrated management mode.

5.2. Evaluation Process

The actual value of the quantitative indicator was determined through on-site investigation, combined with the solution announced by the enterprise. The quantitative indicator was calculated based on the formula n/i. For the qualitative indicator, the original 18 experts were invited to score, and the average value was finally taken as the qualitative indicator evaluation value. The detailed results are shown in Table 9.

Table 9. Summary of the evaluation indicator data for the smart construction site case study.

Category	Indicator	Actual Value	Evaluation Value
Man	S1	7	0.7778
	S3	2	0.6667
	S4	7	1.0000
Machine	S5	5	0.6250
	S6	/	0.3150
	S7	/	0.4900
	S8	/	0.7250
Media	S9	6	0.6000
	S10	10	0.8333
	S11	/	0.5050
	S13	5	0.5556
Management	S14	/	0.7050
	S15	3	0.4286
	S16	4	0.6667
	S17	2	0.2857

Note: "/" shows that the indicator has no actual value.

The fuzzy relationship matrix of man, machine, media, and management was constructed using the evaluation values as follows:

$$R_{Man} = \begin{bmatrix} 0.7778 \\ 0.6667 \\ 1.0000 \end{bmatrix},\ R_{Machine} = \begin{bmatrix} 0.6250 \\ 0.3150 \\ 0.4900 \\ 0.7250 \end{bmatrix},\ R_{Media} = \begin{bmatrix} 0.6000 \\ 0.8333 \\ 0.5050 \\ 0.5556 \end{bmatrix},\ R_{Management} = \begin{bmatrix} 0.7050 \\ 0.4286 \\ 0.6667 \\ 0.2857 \end{bmatrix}$$

The weight vectors of each secondary indicator were the following:

$$W_{Man} = (0.02042, 0.84966, 0.12992)$$

$$W_{Machine} = (0.075, 0.18895, 0.1545, 0.58155)$$

$$W_{Media} = (0.37141, 0.09778, 0.37902, 0.15179)$$

$$W_{Management} = (0.15729, 0.16113, 0.4081, 0.27348)$$

The results of the fuzzy single-indicator evaluation can be obtained:

$$B_{Man} = 0.7123,\ B_{Machine} = 0.6037,\ B_{Media} = 0.5801,\ B_{Management} = 0.5302$$

The results of the fuzzy single-indicator evaluation were used to construct a fuzzy relationship matrix for the second-level fuzzy comprehensive evaluation:

$$R = \begin{bmatrix} 0.7123 \\ 0.6037 \\ 0.5801 \\ 0.5302 \end{bmatrix}$$

The weight vector of the primary indicator was

$$W = (0.247672, 0.128441, 0.295949, 0.327938)$$

Finally, the second-level fuzzy comprehensive evaluation result was obtained (B = 0.5995). Therefore, the smart construction site safety management level is "average".

6. Discussion

Overall, in terms of weights, "Management" (0.3279) > "Media" (0.2959) > "Man" (0.2477) > "Machine" (0.1284). However, in terms of the number of resilience codes, "Machine" has 229, the highest number, and the code number of indicators with higher weights is all relatively small. From the perspective of the model application, for Project A, its safety evaluation scores are higher for "Man" and "Machine", and lower for "Media" and "Management". This indicates that there is a certain deviation between the current policy texts related to smart construction site safety and the present safety management measures and the actual importance degree of indicators. Resilience characteristics in current policy texts are not sufficiently considered, focusing mainly on "Machine", especially in terms of robustness and redundancy. These resilience characteristics mainly act on the initial stage of risk to resist the occurrence of risk [54], which further verifies that the current smart construction site is influenced by traditional safety management thinking and lacks a resilience perspective to deal with the new situation in an informationization context. Therefore, in the subsequent policy release, attention should be paid to the further refinement of "Man", "Media", and "Management", thus balancing the content of the relevant standards in distribution.

6.1. Man

In the evaluation model constructed, the indicator of "Man" accounts for 0.2477 of the weight, which is usually considered the most important indicator in traditional safety management. However, the platform, hardware, and software of the smart construction site can alleviate problems such as human error and low cultural level to some extent, so it is not prominent in the weight analysis. Specifically, the weight of "Person identification" is the largest (0.2104), followed by "Promotion of personnel communication and collaboration" (0.0322), and lastly, "Analytical support for decision-making" (0.0051). "Person identification" is the basis of personnel safety under the smart construction site. For example, face recognition systems, equipment for real-time monitoring of site personnel movements, Bluetooth personnel positioning, and functions of platform alarms, capture maps, and voice prompts are based on person identification [55,56]. Realizing the improvement in person identification ability can effectively strengthen the dynamic management of construction workers and reduce the accident rate, which plays a vital role in guaranteeing safety. However, the number of resilience codes and the corresponding evaluation value in the case of this indicator are the lowest, indicating that inadequate resilience measures of person identification are reflected in relevant policy texts on the current safety management of smart construction sites, and the problem of insufficient safety assurance ability may arise. The weights of "Promotion of personnel communication and collaboration" and "Analytical support for decision-making" are not high, but the number of codes corresponding to both of them is large, which shows that the two indicators are currently given more importance in smart construction sites.

Combined with the actual case, the evaluation value of "Promotion of personnel communication and collaboration" earns a perfect score. Investigation shows that the site shares alarm systems and video resources with supervisory units through platform docking and linkage technology to ensure that multiple units work in collaboration with each other. It provides an enterprise-level smart construction site platform to meet the control of smart construction sites in each project department. It supports the uploading of enterprise or project standard data specifications, electronic drawings, and so on, with a total of seven types of file sharing. The above measures are worth learning for other smart construction site managers. The ratings of "Person identification" and "Analytical support for decision-making" are both good, with values of 0.6667 and 0.7778, respectively. It shows that this smart construction site performs well in terms of "Man", but there is still room for improvement. In terms of "Person identification", the biometric module of various ways should be added and applied. To "Analytical support for decision-making", the operator should be assisted in visualizing the operation. Also, by providing more devices and platforms with instant communication capabilities, the statistical analysis results can be better reported and shared.

6.2. Machine

"Machine" has the lowest weight of 0.1284, but this does not directly indicate that it is not important. The reason for this is that the robustness, redundancy, and other durable and replaceable aspects can be achieved to some extent by improving the quality of the equipment at the site and increasing the number of spares and replacements available. "Machine" includes "Equipment with fast response capability", "Expansion of functions and potential", "Equipment and system vandalism prevention", and "Backup and replacement capability", with weights of 0.0747, 0.0243, 0.0198, and 0.0096, respectively. The weight of "Equipment with fast response capability" is the largest, but its code number ranks last in "Machine", which indicates that the current smart construction site policy texts need to increase requirements for equipment quality. When the equipment has a shorter response and backup recovery time, the quality of smart construction sites can be increased. The other three indicators have relatively balanced weight scores and relatively high code numbers, which confirm that nowadays, smart construction sites pay enough attention to "Expansion of functions and potential", "Equipment and system vandalism prevention", and "Backup and replacement capability".

From the model application, the indicator "Equipment with fast response capability" has a value of 0.7250, which is a good rank and consistent with its higher weight. The indicator "Backup and replacement capability" with the highest number of resilience codes has a good value rating (0.6250), but it has the lowest weight, ranking only 14th in the weights of all indicators. The indicator "Expansion of functions and potential", which is in the middle of the list, has a poor value rating (0.3150). The value of the indicator "Equipment and system vandalism prevention" is 0.4900. This shows that the smart construction site needs further improvement and enhancement in the area of "Machine".

In summary, although the weight of the "Machine" is low, the overall evaluation level of smart construction site safety management can still be improved by enhancing the storage time of construction site data, supporting multiple image signal inputs, reserving more interfaces for future devices, increasing additional measures to prevent theft and vandalism in construction sites [57], and improving the ability of devices to withstand adverse weather conditions.

6.3. Media

"Media" accounts for 0.2959 of the weight and deserves to be considered as a major focus in smart construction site safety management. In the case of "Media", the safety management evaluation level is average (0.5801). As the site environment is more complex than other places, dust, too high or too low temperature, and rainfall will affect the collection and transmission of network data processing [58,59]. Thus, it will largely harm the platform and related software and hardware, resulting in a decline in the security capacity, the stability, and the practicality of smart construction sites. It is also important to have a set of information technology testing equipment and systems that meet the requirements of the site environment where they are located.

"Media" mainly includes "Accuracy of environmental monitoring", "Ability to integrate functions", "Real-time environmental data", and "Richness of monitoring points", with weights of 0.1122, 0.1099, 0.0449, and 0.0289, respectively. "Accuracy of environmental monitoring" requires faster accuracy and recognition speed of environmental factors by the relevant sensors and model systems [60]. This indicator can be a good way to improve the efficiency of the smart construction site in safety management, improve the quality of services, and improve the security capacity of safety. However, it has the lowest evaluation value in the case and needs urgent attention from managers. There is little difference in the number of resilience codes corresponding to the four indicators. The first three indicators with higher weights have evaluation scores between 0.5 and 0.6 in this case, and the scores are not high overall, with small differences. Yet, the lowest weight "Richness of monitoring points" has an excellent evaluation value (0.8333) in this case. The reason for the high evaluation value may be that the smart construction site retains some leeway in the control capacity of the equipment so that new control points can be modified in the system.

Improving the score of the indicators in "Media" can significantly improve the safety management level of smart construction sites. Measures include using high-precision and high-performance equipment [61], increasing the data interfaces of various IoT detection devices, and increasing the types of environmental parameters collected for monitoring.

6.4. Management

"Management" (0.3279) is the most heavily weighted of the four factors, reflecting the emphasis on the need to address management inefficiencies and achieve multi-party collaborative management. The safety management platform of the smart construction site is also a management-based platform, with systems such as schedule, quality, and cost management, to achieve the protection of people, materials, and the environment [62,63]. However, in the case of "Management", the evaluation score of safety management was average (0.5302). Although current smart construction sites have been more commonly used in information technology, information management for securing the safety of smart construction sites is still not systematic and has been in a fragmented state for a long time, so it is also necessary to strengthen the development and integration of applications related to smart construction site safety management in the future.

The largest weight in "Management" is "Adoption of cloud architecture" (0.1338), followed by "Positioning function" (0.0897), "Early warning and emergency capability" (0.0528), and "Education of employees" (0.0516). This indicates that "Adoption of cloud architecture" is the most important management indicator. Cloud architecture is the use of information technology on the original construction site management infrastructure for different service targets and different project-related parties to expand the architecture and functions of the management platform. By adopting the cloud model, the dynamic situation and data of each aspect of safe construction can be uploaded to the integrated platform in real time to realize the intelligent management of the whole chain and transparent construction, which can support the safety of the smart construction site [64]. In the case of the model application, the indicator scored 0.6667, showing its good performance on the smart construction site. The lowest weight "Education of employees" has the highest evaluation score among management indicators. There is also a certain separation between resilience characteristics and site management measures and weights.

"Positioning function", which is ranked second in weight, has a resilience code of only 14 and the lowest security score in the case (0.2857). The investigation shows that the smart construction site operation platform can realize the positioning of personnel at the site, as well as the anti-theft and anti-mobile GPS positioning function of materials, combined with the camera. There are two types of positioning functions. In the future, it can provide positioning capability for key machines and real-time positioning for personnel working in deep pits and other dangerous places, so that dangerous situations can be found in time. The indicator "Early warning and emergency capability" with a lower case score (0.4286) can be improved by strengthening the operation of special site equipment and the monitoring and warning measures for the working status of construction personnel [65]. "Education of employees" has the highest score (0.7050) in this smart construction site management indicator. Although the weight is low, the creation of a smart party-building platform system is worth introducing at each smart construction site.

7. Conclusions

With the general trend of digital change in the construction industry, smart construction sites have gradually received attention. In order to improve the safety management capability and promote the sustainable development of smart construction sites, it is urgent to construct a smart construction site safety management evaluation method based on the resilience perspective. Firstly, this research obtained preliminary indicators through 15 policy texts in China by combining two dimensions of 4R resilience characteristics and 4M theory. With the help of a fuzzy interpretive structural model, 15 evaluation indicators were finally determined and the evaluation indicator system of smart construction site safety management was constructed. The weight of each indicator was determined by ANP. The results show that the importance ranking according to experts is management, media, man, and machine, especially the three indicators of person identification, adoption of cloud architecture, and accuracy of environmental monitoring. However, despite the fact that machine has the lowest weight, the analysis of policy texts shows that more resilience measures are used for the safety management of machine. Meanwhile, resilience measures for the three indicators with the highest weights mentioned before are rarely emphasized in policy texts. Due to the deviation between the resilience characteristics and the weights of indicators at present, in the future policy text, it is necessary to refine the content of the indicators of management, media, and man more reasonably, so that the resilience and safety management level of smart construction sites can be improved. Specifically, for example, smart construction sites should consider adding equipment and systems for face recognition, and emphasis should be placed on the accuracy of environmental monitoring equipment and the establishment of a cloud platform for multiple service recipients. Secondly, the evaluation criteria for smart construction site safety management were proposed through standard screening and two rounds of expert consultation. Thirdly, the evaluation model was constructed after determining weights and evaluation criteria. To verify the feasibility of the model, a case study was conducted for analysis. The results of the case study show that the safety management score of the selected case is 0.5995, which corresponds to the safety management level of "average". Safety management capability can be improved by increasing monitoring and warning equipment and emphasizing the positioning of key construction machinery and personnel. Therefore, the model constructed in this research is a valid method to evaluate the current situation of smart construction site safety management. The findings of this research can effectively assess the safety management level, improve the resilience and safety management level of smart construction sites, and thus promote the efficient and green development of smart construction sites.

Although this research has achieved certain results, there are still limitations in the research process. In selecting indicators, it is not possible to use the software to extract indicators from all the policy texts of smart construction sites, as there are too many texts involved. Therefore, the study refers to the theoretical saturation adopted by most scholars as a criterion to end the coding, and there may be some criteria that are not involved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13092205/s1. Table S1: Fuzzy correlation matrix of indicators; Table S2: The reachable matrix.

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

Funding: This research was funded by the National Natural Science Foundation of China, grant number 72071115.

Data Availability Statement: The data presented in this research are available upon request from the corresponding author. The data are not publicly available due to privacy.

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

References

1. Mocák, P.; Matlovičová, K.; Matlovic, R.; Pénzes, J.; Pachura, P.; Mishra, P.; Kostilníková, K.; Demková, M. 15-Minute City Concept as a Sustainable Urban Development Alternative: A Brief Outline of Conceptual Frameworks and Slovak Cities as a Case. *Folia Geogr.* **2022**, *64*, 69–89.
2. Soltanmohammadlou, N.; Sadeghi, S.; Hon, C.K.H.; Mokhtarpour-Khanghah, F. Real-time locating systems and safety in construction sites: A literature review. *Saf. Sci.* **2019**, *117*, 229–242. [CrossRef]
3. Li, X.; Liao, F.; Wang, C.; Alashwal, A. Managing Safety Hazards in Metro Subway Projects under Complex Environmental Conditions. *J. Risk Uncertain. Eng. Syst. Part A Civ. Eng.* **2022**, *8*, 04021079. [CrossRef]
4. Carter, G.; Smith, S.D. Safety hazard identification on construction projects. *J. Constr. Eng. Manag.* **2006**, *132*, 197–205. [CrossRef]
5. Xiahou, X.; Wu, Y.; Duan, T.; Lin, P.; Li, F.; Qu, X.; Liu, L.; Li, Q.; Liu, J. Analyzing Critical Factors for the Smart Construction Site Development: A DEMATEL-ISM Based Approach. *Buildings* **2022**, *12*, 116. [CrossRef]
6. Chen, B.; Wan, J.; Shu, L.; Li, P.; Mukherjee, M.; Yin, B. Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges. *IEEE Access* **2017**, *6*, 6505–6519. [CrossRef]
7. Kameshwar, S.; Cox, D.T.; Barbosa, A.R.; Farokhnia, K.; Park, H.; Alam, M.S.; van de Lindt, J.W. Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network. *Reliab. Eng. Syst. Saf.* **2019**, *191*, 106568. [CrossRef]
8. Brunetta, G.; Ceravolo, R.; Barbieri, C.A.; Borghini, A.; de Carlo, F.; Mela, A.; Beltramo, S.; Longhi, A.; De Lucia, G.; Ferraris, S.; et al. Territorial Resilience: Toward a Proactive Meaning for Spatial Planning. *Sustainability* **2019**, *11*, 2286. [CrossRef]
9. Neumannová, M. Smart Districts: New Phenomenon in Sustainable Urban Development. *Case Study of Špitálka in Brno, Czech Republic. Folia Geogr.* **2022**, *64*, 27–48.
10. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Delgado, J.M.D.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441. [CrossRef]
11. Štefanič, M.; Stankovski, V. A review of technologies and applications for smart construction. *Proc. Inst. Civ. Eng. Civ. Eng.* **2019**, *172*, 83–87. [CrossRef]
12. Rey, R.O.; de Melo, R.R.S.; Costa, D.B. Design and implementation of a computerized safety inspection system for construction sites using UAS and digital checklists—Smart Inspecs. *Saf. Sci.* **2021**, *143*, 105430. [CrossRef]
13. Zhang, Y.; Wang, T.; Yuen, K.V. Construction site information decentralized management using blockchain and smart contracts. *Copmut. Aided Civ. Infrastruct. Eng.* **2021**, *37*, 1450–1467. [CrossRef]
14. Zhang, J.; Zhang, D.; Liu, X.; Liu, R.; Zhong, G. A Framework of on-site Construction Safety Management Using Computer Vision and Real-Time Location System. In Proceedings of the International Conference on Smart Infrastructure and Construction 2019 (ICSIC), Cambridge, UK, 8–10 July 2019; pp. 327–333.
15. Liu, P. Research on Site Safety Management by BIM Technology Based on Fuzzy Intuition Set. *Secur. Commun. Netw.* **2022**, *2022*, 7289440. [CrossRef]
16. Bowo, L.P.; Prilana, R.E.; Furusho, M. A Modified HEART—4M Method with TOPSIS for Analyzing Indonesia Collision Accidents. *TransNav* **2020**, *14*, 751–759. [CrossRef]
17. Sulistiyono, A.B.; Mutmainnah, W.; Furusho, M. 4M Study to Support Indonesia's Maritime Tourism Development. *TransNav* **2017**, *11*, 723–728. [CrossRef]
18. Huang, G.; Sun, S.; Zhang, D. Safety Evaluation of Construction Based on the Improved AHP-Grey Model. *Wireless Pers. Commun.* **2018**, *103*, 209–219. [CrossRef]
19. Hollnagel, E. Is safety a subject for science? *Saf. Sci.* **2014**, *67*, 21–24. [CrossRef]
20. Patterson, M.; Deutsch, E.S. Safety-I, Safety-II and resilience engineering. *Curr. Probl. Pediatr. Adolesc. Health Care* **2015**, *45*, 382–389. [CrossRef]
21. Pecillo, M. The concept of resilience in OSH management: A review of approaches. *Int. J. Occup. Saf. Ergon.* **2016**, *22*, 291–300. [CrossRef]
22. Sapeciay, Z.; Wilkinson, S.; Costello, S.B. Building organisational resilience for the construction industry: New Zealand practitioners' perspective. *Int. J. Disaster Resil.* **2017**, *8*, 98–108. [CrossRef]
23. Gilmore, B.; Ndejjo, R.; Tchetchia, A.; de Claro, V.; Mago, E.; Diallo, A.A.; Lopes, C.; Bhattacharyya, S. Community engagement for COVID-19 prevention and control: A rapid evidence synthesis. *BMJ Glob Health* **2020**, *5*, e003188. [CrossRef]
24. du Plessis, E.M.; Vandeskog, B. Other stories of resilient safety management in the Norwegian offshore sector: Resilience engineering, bullshit and the de-politicization of danger. *Scand. J. Manag.* **2020**, *36*, 101096. [CrossRef]
25. Bergström, J.; Van Winsen, R.; Henriqson, E. On the rationale of resilience in the domain of safety: A literature review. *Reliab. Eng. Syst. Saf.* **2015**, *141*, 131–141. [CrossRef]
26. Santos de Melo, R.R.; Costa, D.B. Integrating resilience engineering and UAS technology into construction safety planning and control. *Eng. Constr. Archit. Manag.* **2019**, *26*, 2705–2722. [CrossRef]
27. Fox-Lent, C.; Bates, M.E.; Linkov, I. A matrix approach to community resilience assessment: An illustrative case at Rockaway Peninsula. *Environ. Syst. Decis.* **2015**, *35*, 209–218. [CrossRef]
28. Xiahou, X.; Chen, J.; Zhao, B.; Yan, Z.; Cui, P.; Li, Q.; Yu, Z. Research on Safety Resilience Evaluation Model of Data Center Physical Infrastructure: An ANP-Based Approach. *Buildings* **2022**, *12*, 1911. [CrossRef]

29. Xu, W.; Xiang, L.; Proverbs, D.; Xiong, S. The Influence of COVID-19 on Community Disaster Resilience. *Int. J. Environ. Res. Public Health* **2020**, *18*, 88. [CrossRef]
30. Zhu, Z.; Yuan, J.; Shao, Q.; Zhang, L.; Wang, G.; Li, X. Developing Key Safety Management Factors for Construction Projects in China: A Resilience Perspective. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6167. [CrossRef]
31. Wang, H.; Zhou, J.; Dun, Z.; Cheng, J.; Li, H.; Dun, Z. Resilience Evaluation of High-Speed Railway Subgrade Construction Systems in Goaf Sites. *Sustainability* **2022**, *14*, 7806. [CrossRef]
32. Zhang, C.; Oh, J.; Park, K. Evaluation of sewer network resilience index under the perspective of ground collapse prevention. *Water Sci. Technol.* **2022**, *85*, 188–205. [CrossRef] [PubMed]
33. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; von Winterfeldt, D. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
34. Ranasinghe, U.; Jefferies, M.; Davis, P.; Pillay, M. Resilience Engineering Indicators and Safety Management: A Systematic Review. *Saf. Health Work-Kr.* **2020**, *11*, 127–135. [CrossRef]
35. Siccama, C.J.; Penna, S. Enhancing Validity of a Qualitative Dissertation Research Study by Using NVIVO. *Qual. Res. J.* **2008**, *8*, 91–103. [CrossRef]
36. Corbin, J.M.; Strauss, A. Grounded theory research: Procedures, canons, and evaluative criteria. *Qual. Sociol.* **1990**, *13*, 3–21. [CrossRef]
37. Dube, A.S.; Pati, N.; Gawande, R.S. Analysis of green supply chain barriers using integrated ISM-fuzzy MICMAC approach. *Benchmarking* **2016**, *23*, 1558–1578. [CrossRef]
38. Balaji, M.; Dinesh, S.N.; Vikram Vetrivel, S.; Manoj Kumar, P.; Subbiah, R. Augmenting agility in production flow through ANP. *Mater. Today Proc.* **2021**, *47*, 5308–5312. [CrossRef]
39. Ml, Z.; Wp, Y. Fuzzy Comprehensive Evaluation Method Applied in the Real Estate Investment Risks Research. *Phys. Procedia* **2012**, *24*, 1815–1821. [CrossRef]
40. Chen, G.; Zhang, S.; Yan, B.; Miao, S. Environmental safety evaluation of geopark based on CPTED concept and fuzzy comprehensive analysis. *PLoS ONE* **2021**, *16*, e0260316. [CrossRef] [PubMed]
41. Ylikoski, P.; Zahle, J. Case study research in the social sciences. *Stud. Hist. Phil. Sci.* **2019**, *78*, 1–4. [CrossRef] [PubMed]
42. Zhou, H.; Wang, X.; Wang, J.a. A Way to Sustainability: Perspective of Resilience and Adaptation to Disaster. *Sustainability* **2016**, *8*, 737. [CrossRef]
43. Peng, J.; Song, Y.; Yuan, P.; Xiao, S.; Han, L. An novel identification method of the environmental risk sources for surface water pollution accidents in chemical industrial parks. *J. Environ. Sci.* **2013**, *25*, 1441–1449. [CrossRef] [PubMed]
44. Sindhu, S.; Nehra, V.; Luthra, S. Identification and analysis of barriers in implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach. *Renew. Sust. Energ. Rev.* **2016**, *62*, 70–88. [CrossRef]
45. Okoli, C.; Pawlowski, S.D. The Delphi method as a research tool: An example, design considerations and applications. *Inform. Manag. Amster.* **2004**, *42*, 15–29. [CrossRef]
46. Sonar, H.; Khanzode, V.; Akarte, M. Investigating additive manufacturing implementation factors using integrated ISM-MICMAC approach. *Rapid Prototyp. J.* **2020**, *26*, 1837–1851. [CrossRef]
47. Saaty, T.L. Some Mathematical Concepts of the Analytic Hierarchy Process. *Behaviormetrika* **1991**, *18*, 1–9. [CrossRef]
48. *JGJ/T 434-2018*; Technical Standard for Information Systems of Construction Site Supervision And Management. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2018.
49. *DB32/T 4175-2021*; Technical Standard for Intelligent Safety Supervision of Building Construction. Jiangsu Province Market Supervision Administration: Nanjing, China, 2021.
50. *DB13(J)/T 8312-2019*; Technical Standard of Implementing Smart Construction Sites. Hebei Provincial Department of Housing and Urban-Rural Development: Shijiazhuang, China, 2019.
51. *DB64/T 1684-2020*; Technical Standard for Smart Construction Sites. Department of Housing and Urban-Rural Development of Ningxia Hui Autonomous Region and Department of Market Supervision and Administration of Ningxia Hui Autonomous Region: Yinchuan, China, 2020.
52. *DB11/T 1710-2019*; Technical Specification for Smart Construction Sites. Beijing Municipal Commission of Housing and Urban-Rural Development, Beijing Municipal Administration of Market Supervision: Beijing, China, 2019.
53. Yang, J.; Shen, L.; Jin, X.; Hou, L.; Shang, S.; Zhang, Y. Evaluating the quality of simulation teaching in Fundamental Nursing Curriculum: AHP-Fuzzy comprehensive evaluation. *Nurse Educ. Today* **2019**, *77*, 77–82. [CrossRef]
54. Okasha, N.M.; Frangopol, D.M. Redundancy of structural systems with and without maintenance: An approach based on lifetime functions. *Reliab. Eng. Syst. Saf.* **2010**, *95*, 520–533. [CrossRef]
55. Yu, H.; Liu, F.; Wang, Y. Construction and Evaluation of Construction Safety Management System Based on BIM and Internet of Things. *Secur. Commun. Netw.* **2022**, *2022*, 9757049. [CrossRef]
56. Jiang, W.; Ding, L.; Zhou, C. Cyber physical system for safety management in smart construction site. *Eng. Constr. Archit. Ma.* **2020**, *28*, 788–808. [CrossRef]
57. Pan, Y.; Zuo, L.; Ahmadian, M. A half-wave electromagnetic energy-harvesting tie towards safe and intelligent rail transportation. *Appl. Energy* **2022**, *313*, 118844. [CrossRef]

58. Wan, J.; Xiong, N.; Zhang, W.; Zhang, Q.; Wan, Z. Prioritized degree distribution in wireless sensor networks with a network coded data collection method. *Sensors* **2012**, *12*, 17128–17154. [CrossRef] [PubMed]
59. Zhang, W.; Chang, J.; Xiao, F.; Hu, Y.; Xiong, N.N. Design and Analysis of a Persistent, Efficient, and Self-Contained WSN Data Collection System. *IEEE Access* **2018**, *7*, 1068–1083. [CrossRef]
60. Alateeq, M.M.; Fathimathul Rajeena, P.P.; Ali, M.A.S. Construction Site Hazards Identification Using Deep Learning and Computer Vision. *Sustainability* **2023**, *15*, 2358. [CrossRef]
61. Su, Y.; Mao, C.; Jiang, R.; Liu, G.; Wang, J. Data-Driven Fire Safety Management at Building Construction Sites: Leveraging CNN. *J. Manag. Eng.* **2021**, *37*, 04020108. [CrossRef]
62. Park, J.; Cai, H.; Dunston, P.S.; Ghasemkhani, H. Database-Supported and Web-Based Visualization for Daily 4D BIM. *J. Constr. Eng. Manag.* **2017**, *143*, 04017078. [CrossRef]
63. Elghaish, F.; Abrishami, S.; Abu Samra, S.; Gaterell, M.; Hosseini, M.R.; Wise, R. Cash flow system development framework within integrated project delivery (IPD) using BIM tools. *Int. J. Constr. Manag.* **2019**, *21*, 555–570. [CrossRef]
64. Liu, T.; Hou, J.; Xiong, G.; Nyberg, T.R.; Li, X. Smart Cloud-based Platform for Construction Sites. In Proceedings of the 2016 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI), Beijing, China, 10–12 July 2016; pp. 168–173.
65. Yi, W.; Chan, A.P.C.; Wang, X.; Wang, J. Development of an early-warning system for site work in hot and humid environments: A case study. *Autom. Constr.* **2016**, *62*, 101–113. [CrossRef]

buildings

MDPI

Article

Climate-Adaptive Design Strategies of Sports Stadia in a Hot Summer and Cold Winter Zone: A Case Study of Nanjing

Dongxu Xiong [1,*], Kai Cheng [2] and Jingjing Chen [1]

[1] Nanjing Institute of Technology, College of Architecture and Engineering, Nanjing 211167, China; chenjingjing@njit.edu.cn
[2] Jiangsu Institute of Urban & Rural Planning and Design Co., Ltd., Nanjing 210019, China; chengkai@jspdg.com
* Correspondence: xiongdongxu@njit.edu.cn; Tel.: +86-181-5100-7981

Abstract: Urban planning and design, with the objectives of energy efficiency and climate adaptation, is receiving more and more attention as urban energy consumption keeps rising. As technical representatives with large spans and high difficulties, sports stadia have a broad range of energy conservation and emission reduction compared with traditional buildings and have an extremely close relationship with the energy consumption of the building environment and urban microclimate, so it is necessary to study the climate adaptation design strategy of sports stadia. However, climate adaptive design has not given much thought to sports stadia nowadays. And the energy-saving strategies of sports stadia rely mostly on engineering expertise without taking into account the effect of sports stadia layout, shape, and structure on the urban microclimate. This paper investigates the energy-saving and climate-adaptive design techniques of sports stadia in the hot summer and cold winter zone of China using the layout of sports stadia as the research object. Firstly, we construct a climate adaptive design framework of sports stadia of "layout-shape-structure" based on the characteristics of sports stadia. Secondly, combined with typical examples of large-scale sports stadia in hot summers and cold winters, we establish an abstract model of architectural layout, shape, and structure based on climatic environment. In order to provide climate-adaptive design methods for sports stadia in hot summer and cold winter zones, the ventilation of the external and internal spaces of sports stadia is simulated, quantified, and compared using CFD software. The study's findings suggest that the layout of sports stadia should take into account the direction of the local wind, that the goal of low energy consumption should guide the choice of building form, and that the internal wind and temperature environment should be stabilized during construction. The study's findings can serve as a guide for comparable designs that aim to construct sports stadia with reduced carbon footprints.

Keywords: sports stadia; hot summer and cold winter zone; design strategies; climate adaptation; CFD simulation

1. Introduction

The idea that climate change could have a significant impact on energy demand is generally acknowledged. China is currently the top emitter of greenhouse gases in the world as a result of its expanding energy consumption. At present, China actively participates in international efforts to reduce emissions and has set its own emission reduction targets of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 [1]. An important contributor to the nation's economy, the building sector, is responsible for a sizeable portion of urban energy use. According to reports, 67% of the world's energy needs comes from buildings [2]. Therefore, a significant stakeholder that may be successful in accomplishing this goal is the building industry. The issue of energy use and carbon emissions in public structures, particularly sizable public structures, is very apparent when looking at the construction business [3]. Previous studies have revealed that large-scale public buildings consume 2~4 times more energy than small-scale public buildings [4] and 10~20 times more energy than residential buildings in China [5]. Sports stadia, as typical large-scale public buildings, are typical representatives of large space and high performance in terms of building form, with unique volume and energy demand. For example, sports facilities consume about 8% of building energy in Europe [6]. In terms of the construction scale, according to China's most recent Sixth National Stadium Census in 2013, there were 1.69 million sports facilities nationwide, with an area of 1.99 billion square meters [7]. In recent years, the "Healthy China 2030" plan has emphasized the need to improve people's health by strengthening the construction of sports facilities [8]. It can be seen that under the impetus of the policy, the construction of sports stadia shows a rapid growth trend in the future. Therefore, there is an urgent need for the low-carbon development of sports stadia.

Climate change affects building energy consumption mainly through changes in heating and cooling demand. However, the impacts of climate change vary in different regions. For example, in hot climates, the built environment is challenged by drought and overheating, whereas this challenge does not exist in cold coastal climates [9]. In China, the climate strip of the hot summer and cold winter zone is characterized by scorching heat in summer and severe cold in winter. At the same time, the large capacity of public space in sports stadia leads to a large heating and cooling demand. The above reasons cause the energy consumption of sports stadia in hot summer and cold winter areas to be large [10]. In response to this problem, the state has promulgated policies and regulations on energy conservation in residential buildings. However, policies and regulations on sports stadia for hot summer and cold winter areas are still lacking, which makes the study of sustainable design of sports buildings in this area a meaningful exploration.

As global heating increases, all cities need to adapt to climate change. For the building industry, a range of measures are being taken to change building design and urban planning and to adapt existing buildings to climate change. In this process, climate-resilient design is emerging as an effective means of greening and low-carbon buildings. For example, Cerra (2016) proposed a framework for climate-resilient design applicable in non-coastal areas [11] and Liu et al. (2017) made recommendations for the climate-resilient design of new rural housing in their study area based on a literature review and field survey [12]. After a preliminary case study on the design of urban multi-family buildings at an early stage, Shen et al. (2020) proposed to incorporate future climate scenarios into the initial building design of two representative sites in Rome, Italy and Stockholm, Sweden [13]. Depending on the focus of the study, research on climate-resilient design can be broadly divided into three themes: (1) climate zoning, climate characteristics, and design responses [14,15]; (2) theoretical models for evaluating human thermal adaptation to spatial environments and thermal comfort [16,17]; (3) adaptation relationships between architectural spaces, urban spaces, and regional climates [18,19]. The first two themes focus on strengthening the climate adaptation of architectural spaces by analyzing the regional climate and meteorological conditions as well as the human physiological and psychological perception of the thermal environment and are mostly concerned with the determination and optimization of design principles and evaluation criteria. The third theme is mainly for the research of specific architectural spaces, generally based on specific cases such as design practice and actual engineering and around specific design methods and technologies.

In general, the design of climate-resilient buildings should consider building form and envelope [20]; climate and thermal comfort [21]; passive heating and cooling [22]; site planning [23]; windows, doors, and lighting [24]; natural ventilation [25]; adaptive low-energy technologies [26] to creatively answer the local climate and ecology through design. In the climate-adapted design process, corresponding design tools such as CFD (Computational Fluid Dynamics) simulation methods [27–29], Energy Plus [13,30], Radiance [31,32], Fluent 2016 software [33,34], and airflow network [35,36] can help to create a more climate-resilient building from the outset. Compared with residential buildings, there are fewer studies on the climate-adaptive design of public buildings at this stage. However, some scholars have paid attention to public buildings in recent years. For example, Qi and Wei (2020) proposed a climate-adaptive natural ventilation design adapted to the local climate and quantitatively evaluated the ventilation performance of the design using CFD [27]. Additionally, climate-adaptive design for public buildings is more often combined with green buildings. For example, Xu (2020) proposed a set of performance optimization design strategies for green public buildings adapted to the marine climate after analyzing the relationship between green public buildings and the external environment as well as the functional space design of coastal green public buildings [37]. Xue et al. (2016) explored the ventilation patterns of workplaces in order to optimize the passive climate-adaptive design strategies for green buildings in high-density tropical or subtropical cities on individual health perception; the results showed that the hybrid ventilation design could enable people to get in touch with nature [38]. Jing et al. (2021) proposed a cold-climate-adapted green public building design using the Chinese Pavilion of the 2019 World Horticultural Expo in Beijing, China as a research object [39]. Although more fruitful results have been accumulated on climate adaptation of public buildings, there are fewer studies on climate adaptation of buildings in hot summer and cold winter regions. At the same time, more studies have focused on office buildings and fewer studies have related to large-scale public buildings such as sports stadia. In addition, due to the lack of effective climate quantification tools and mature climate building strategies, a large number of architects rely on mechanical equipment when solving problems such as the difficulty of natural ventilation and lighting brought about by large spans, the difficulty of air intake demand brought about by large volumes, and the difficulty of coordinating the spatial arrangement of the grandstand and ventilation organization. They give less consideration to the impact of the layout of the sports stadia on the urban microclimate and the requirements of the energy saving of the built environment. Therefore, it is necessary to alleviate the problem of high energy consumption by strengthening the method of climate design.

To fill the research gap, this study intends to give systematic and practical design solutions for a new construction and restoration of sports stadia, as well as to improve the sports stadia climate adaption to hot summer and cold winter zones. This study begins with three aspects of building layout, building form, and building structure and uses typical examples of large sports stadia in hot summer and cold winter zones as the basis for refining a set of representative standardized abstract models based on the three main objectives of climate environment, low energy demand, and climate control. The "simulation-quantification-comparison" method is then used to conduct a comparative analysis of the design measures for sports stadia in order to develop a set of recommendations for climate-resilient design strategies for sports stadia. This study investigated the climate-adaptive design of sports stadia in hot summer and cold winter regions. The findings of this research can help provide architects with unique perspectives on designing and evaluating sports stadia and serve as a reference for carrying out similar designs in order to promote the decarbonization of sports stadia.

2. Climate-Adaptive Design Principles and Key Points

2.1. Design Principles for the Climatic Adaptation of Buildings in Hot Summer and Cold Winter Zones

Climate adaptive design is also known as climate design of buildings. In the stage of building scheme design, the climate environment of the area where the building is located is effectively and reliably analyzed; after considering the selection of appropriate climate adjustment measures, the design technology of better comfortable building space is achieved by using favorable climate factors and offsetting adverse climate factors [40]. From a climatic perspective, climate-responsive architecture not only responds to climatic factors through building site selection, community layout, building units, and architectural design details but also considers the impact of climatic factors on the indoor physical environment and comfort [41,42]. The climate conditions in China's hot summer and cold

-winter zone are harsh, with most areas experiencing sultry summers and high-temperature extremes, wet and cold winters, high annual precipitation, and high humidity in both winter and summer [43]. The extremes of climate create different thermal environmental needs in the region in winter and summer. In summer, there is a need to reduce the absorption of solar radiation, increase building shading, promote outdoor ventilation, and increase wind speed, which requires the provision of open spaces to guide ventilation and carry heat away from the building envelope; in winter, there is a need to increase the absorption of human solar radiation, reduce building shading, weaken outdoor ventilation, and reduce wind speed, which requires the provision of barriers to protect against wind and avoid the intrusion of cold winds into the building interior. Winter protection and warmth and summer ventilation and insulation are therefore key considerations in the design of buildings in the hot summer and cold winter zone [44]. This is also a contradiction in the design of buildings and climate adaptive design is the optimal solution to this contradiction. The advantage of this is that the design of buildings can be designed in such a way to shield the building from excessive solar radiation and to enhance natural ventilation, so that excess heat and humidity can be removed while blocking external heat intrusion as much as possible, indirectly affecting the temperature and humidity of the air and thus achieving better thermal comfort in the space. Therefore, according to the statements mentioned above, two principles of climate-adaptive design of sports stadia in hot summer and cold winter zones are proposed below:

- Actively prevent external adverse climatic factors.

Climate adaptability is not passive, rather actively optimizes the microclimate environment of the building (which is conducive to energy saving) and attaches importance to and utilizes various climatic factors, such as the dominant wind direction, topography, landform, and other natural factors in summer and winter.

- Balance the demand of buildings in different climates.

The climate adaptability design of buildings in hot summer and cold winter areas can not only meet the needs of one side and ignore the needs of the other but is necessary to reasonably deal with the different needs of winter and summer. Carefully analyze the contradictory subjects and explore the best design method without affecting the basic needs of both parties, balance the thermal comfort of the two, and achieve the purpose of building energy conservation and climate adaptability.

2.2. Key Points for the Climatic Design of Sports Stadia in Hot Summer and Cold Winter Zones

Sports stadia are buildings used for competition, teaching, entertainment, exercise, and other activities, with the characteristics of large investment, complex technology, large volume, and long service life. This research focuses on climate adaptation strategies in large spaces and complex structures, so the sports stadia in this research mainly consist of stadiums and various gymnasiums. Stadium refers to the building that can provide outdoor venues and provide users with certain seats for watching the games. Gymnasium refers to an indoor building that contains certain activity functions, commonly including swimming pools, basketball halls, badminton, etc. In the schematic design process of a gymnasium, the design process of "planning layout–shape design–structure modeling" is generally followed, so these points will be closely integrated in the climate adaptation design. The space of a sports stadia consists of two parts—the external space and the internal space—which are divided by the skin of the building. In terms of the areas of focus for the study of external and internal spaces, the focus of this study is on the public space for public use, as the aim of climate design is to provide a spatial environment with good thermal comfort for users. In this study, the external space is focused on the building layout and building shape.

Numerous studies have shown that the external layout form of a sports center has an important impact on the wind environment of its external space [45]. Although the architectural layout of the sports center is rich and diverse, it can be briefly considered from the location relationship between the buildings and the final formation of the architectural layout of the sports center that is the result of several basic layout forms combined with adjusting the orientation of groups and individuals; the more common basic layout forms are the "one-line layout" and the "triangle layout". The shape of a gymnasium is rich in variations and, from the examples of sports buildings, both planes and curved surfaces are used in the shape design. It is worth noting that, according to the authors' practical experiences, it is found that the gymnasium has the physical characteristics of a very large external surface and the roof is the most important part for its heat exchange. Therefore, in the shape of the gymnasium, the roof form is most closely related to the thermal environment. Meanwhile, except for special structure stadia, the functions of stadia are generally more fixed; all are grandstands arranged around the internal center field and the shape is generally oval or nearly oval. Therefore, when analyzing the shape, this study does not consider the shape of the stadium. The structural form of sports stadia has the characteristics of large selectivity, deep influence, and strong acceptability, e.g., the canopy form, which, with greater selectivity, is taken as the research object. On the one hand, because the infield wind environment defined by the canopy is an important factor affecting the quality of on-site exercise and game use, on the other hand, because the canopy form has a more obvious and intuitive impact on the sports stadia structure, it is one of the exploration forms that unifies design form and physical properties. Therefore, the key points of climate adaptation design for sports stadia are shown in Figure 1.

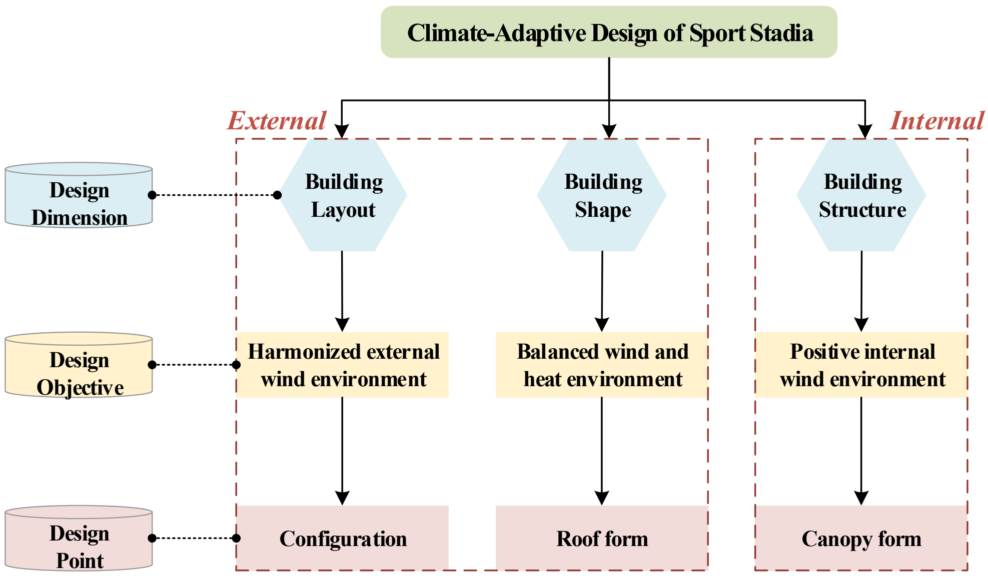


Figure 1. The design framework for the climate adaptation of sports stadia in hot summer and cold winter zones.

The unique massing and energy requirements of sports stadia lead to more pressing climate-resilient design needs than typical buildings. In general, starting from "planning layout–shape design–architectural modeling", the design points of climate-adaptive design of sports stadia in hot summer and cold winter zones are proposed below. (1) In order to cope with the impact of climate factors on the regional environment of sports stadia, it is necessary to fully consider the particularity of regional climate, seek a reasonable layout mode of the sports stadia, and realize the unity of ventilation and wind protection. (2) In order to cope with the impact of climate factors on the outside of the gymnasium, it is necessary to seek a reasonable form to balance the wind and heat environment inside the gymnasium. (3) In order to cope with the disturbance of the wind environment inside the sports stadia caused by climate factors and combine the design requirements of architectural aesthetics, it is necessary to conduct reasonable discussions through reasonable structural design.

3. Methods

3.1. Overview of the Study Area

According to the standard of climatic regionalization for architecture, diverse climates are divided into five main zones in China, including the severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and temperate zone [46]. Among them, climate-adapted building design in the hot summer and cold winter zone faces the greatest conflicts and challenges because of the region's hot and humid summers, cold and wet winters, high precipitation, high air humidity, and high average annual temperatures leading to a conflicting heat–light balance and a balance between insulation and openness throughout the year [47].

According to the statistics of the sixth national sports stadia survey, there are 1093 large-scale sports stadia in China, of which 300 are distributed in the hot summer and cold winter zone, accounting for 27.4% of the total number of sports stadia in the country, showing a clear trend of "dense in the east and sparse in the west" and "more in the south and fewer in the north" (Figure 2). Therefore, the hot summer and cold winter zone is the most active region for sports stadia construction. As economic growth in the hot summer and cold winter zone increases, so do people's expectations of thermal comfort and the energy consumption of sports stadia.

Figure 2. Distribution of large sports stadia in China.

Therefore, Nanjing (118.76 E, 32.04 N), a typical large city located in the hot summer and cold winter zone of China (Figure 3), was chosen for the simulation study. Nanjing has abundant rainfall; annual temperature extremes range from a maximum of over 40 °C to a minimum of below 0 °C [48] and there is a clear wind shift between winter and summer, with northeasterly winds predominating in winter, easterly and southeasterly winds in summer, southeasterly and easterly winds in spring, and northeasterly winds in autumn, with some typhoon weather.

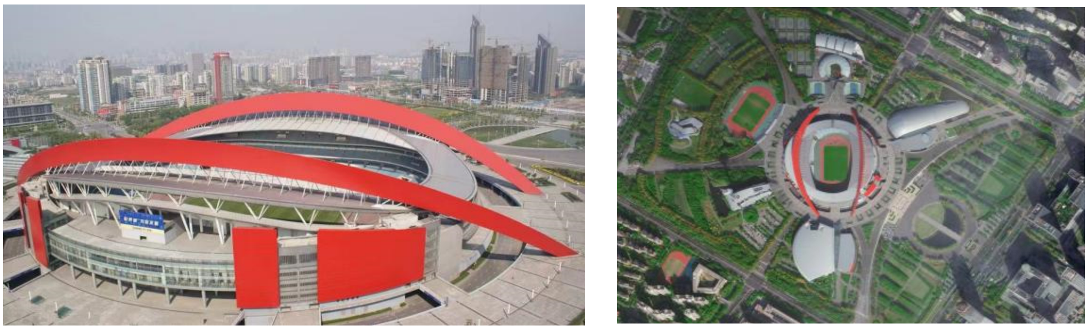
Figure 3. Location of the study area.

3.2. Architectural Examples and Abstract Models

3.2.1. Selection of Architectural Examples

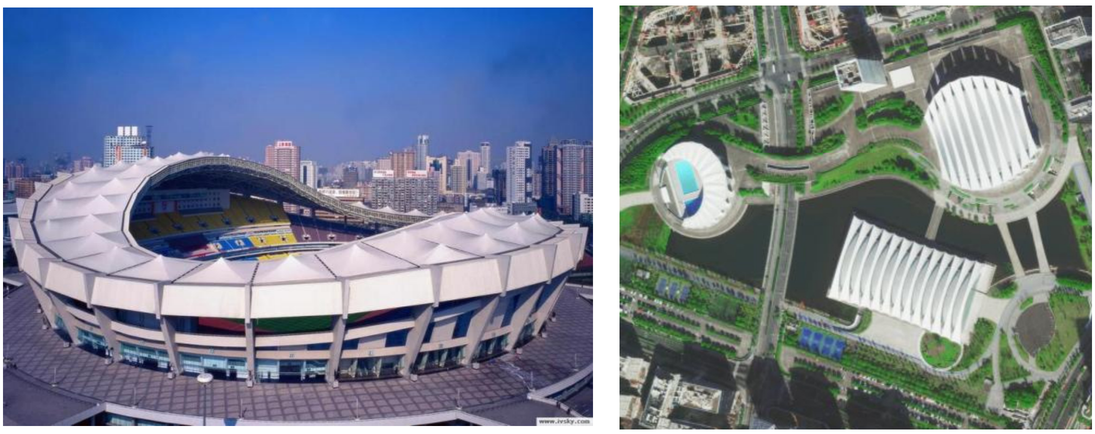
With a number of major sporting events taking place, a range of sports stadia have been built throughout the hot summer and cold winter zone, including sports centers, stadiums, gymnasiums, and swimming pools, with a wide range of types, sizes, and functions. The existence of these buildings provides excellent conditions for the study of climate design. In this study, the following representative sports centers and stadiums that have hosted major events in the hot summer and cold winter zone of China were selected as prototypes for the abstract study: Nanjing Olympic Sports Center (Figure 4a), Wuhan

Sports Center (Figure 4b), Shanghai Stadium (Figure 4c), and Hangzhou Olympic Sports Center (Figure 4d).

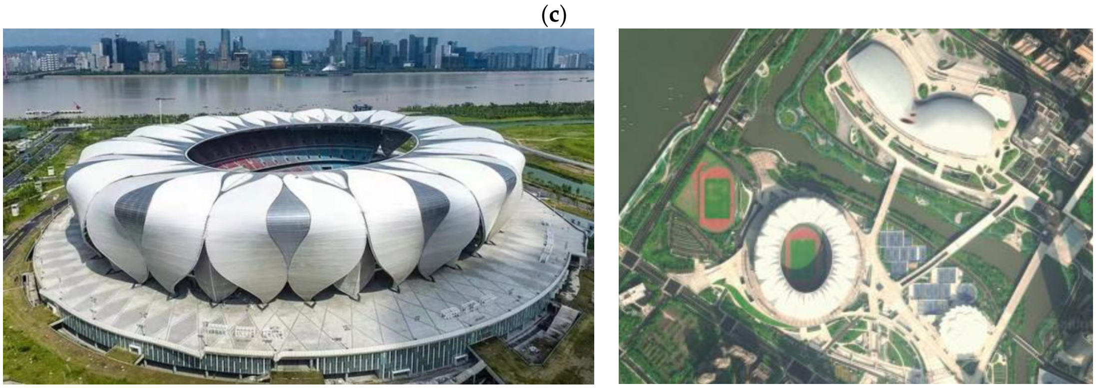


(**a**)

(**b**)



(**c**)



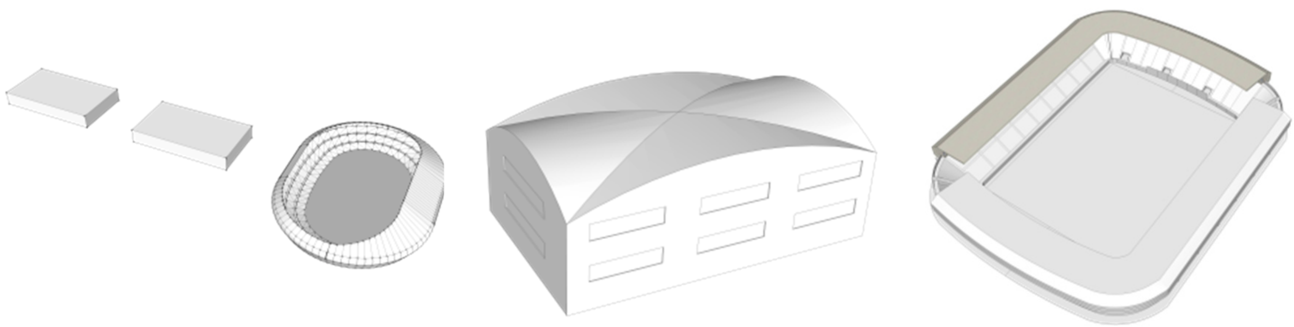
(**d**)

Figure 4. Architectural examples. (**a**) Nanjing Olympic Sports Center. (**b**) Wuhan Sports Center. (**c**) Shanghai Stadium. (**d**) Hangzhou Olympic Sports Center.

The selected architectural examples are geographically located in Nanjing, Shanghai, Hangzhou, and Wuhan in the hot summer and cold winter zone. The stadia cover the classical shapes of sports stadiums and have strong typicality and orientation, which can comprehensively reflect the shape profile of sports stadia in the hot summer and cold winter zone.

3.2.2. Construction of Abstract Models

Quantitative research using abstract models of sports stadia can better circumvent some of the problems that exist in simulation research using architectural examples, such as the research object being too dissimilar in volume, the influencing elements being too complex, and the simulation parameters being too uncontrollable. The main focus of this study is on the coordination with the layout, shape, and the structure of the sports stadia. The abstract models of Nanjing Olympic Sports Center, Wuhan Sports Center, Shanghai Stadium, and Hangzhou Olympic Sports Center were used as the basis and a set of control models were generated by controlling the variables to be studied. For example, the layout is based on the same layout as the Wuhan Sports Center, while the building shape is extracted from the Shanghai Stadium and the building structure is generated from the Nanjing Olympic Sports Center. The specific abstract model is shown in Figure 5.



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

Figure 5. Abstract model of sports stadia. (**a**) Building layout model. (**b**) Building shape model. (**c**) Building structure model.

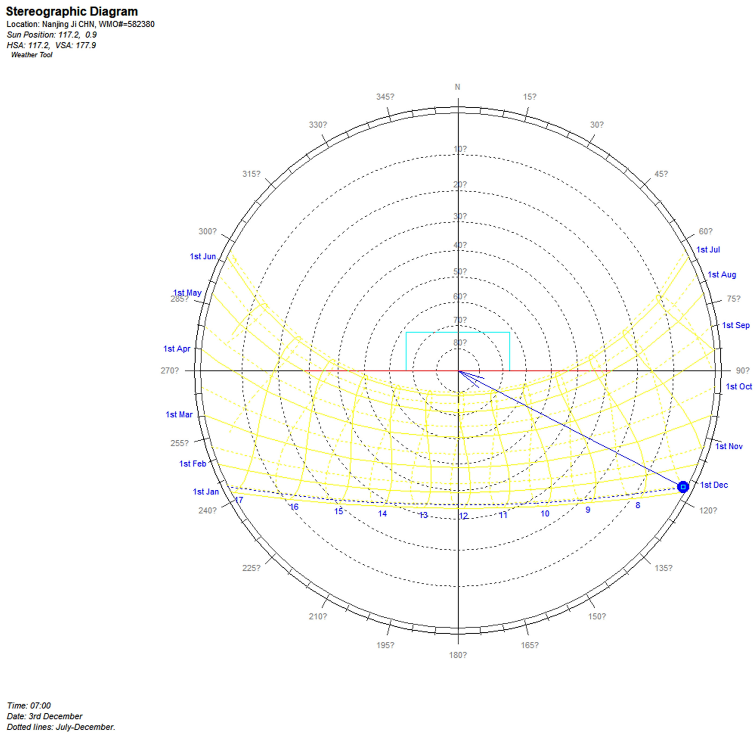
3.3. Tools for Simulation Experiments

3.3.1. Software Introduction

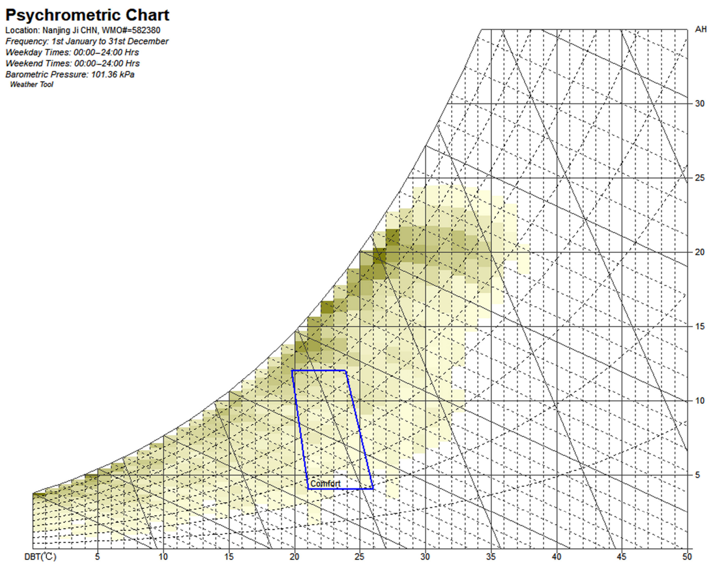
The wind environment of the building layout and building form is simulated using Phoenics. In accordance with the boundary conditions set, quantitative wind data such as wind speed and wind direction are calculated for each location in the building space in the undisturbed steady state. Tecplot 2021 software is used to select points in the wind environment and measure the wind speed at a single point. The combination of Phoenics 2016 and Tecplot 2021 allows for more accurate measurement of the wind speed in the field under different conditions. Using Ecotect 2011 analysis, five parameters—heat transfer coefficient, access coefficient, solar absorption coefficient, decay time, and delay time—are set to simulate the thermal radiation conditions of each building form and to measure the radiant heat increment outside the building under different conditions.

3.3.2. Basic Meteorological Parameter Setting

For the simulation of built environment spaces, the accurate setting of initial conditions is fundamental to the success of the simulation. Meteorological conditions are particularly important for the accuracy of the simulation results as they are an important initial condition. Although the building examples in this study are located in different parts of China's hot summer and cold winter zone, the climatic conditions are generally very similar, despite slight differences. Also, the aim of this study is to investigate climate adaptation strategies for sports stadia in Nanjing. Therefore, all the simulations in this study choose uniform meteorological data as the initial condition setting, i.e., the meteorological data of Nanjing city is used to start the simulation study in order to facilitate a uniform standard cross-sectional comparison and to avoid errors arising from different meteorological parameters (as shown in Figure 6). In this paper, the weather tool is used to obtain the meteorological data of Nanjing and the data time is obtained as the average wind speed and sunshine radiation between 08:00 and 20:00 during the summer solstice in Nanjing in 2022.

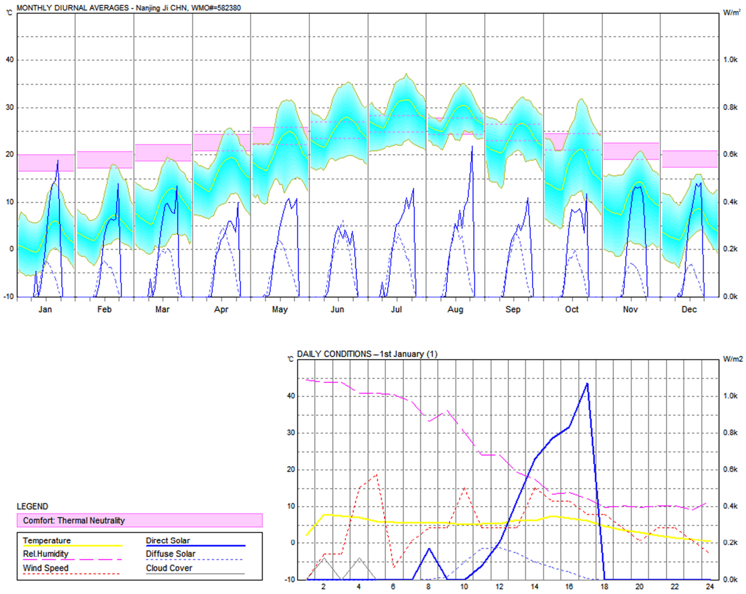


(**a**)

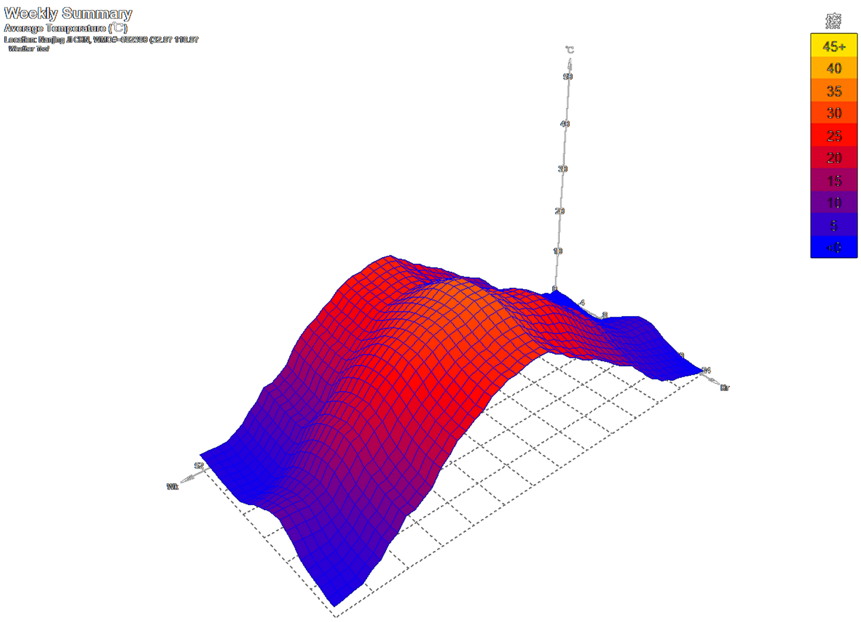


(**b**)

Figure 6. *Cont.*



(**c**)



(**d**)

Figure 6. Nanjing meteorological data. (**a**) Analysis of solar orbit in Nanjing. (**b**) Enthalpy humidity map of Nanjing. (**c**) Average daily climatic conditions in Nanjing. (**d**) Analysis of weekly average sunshine radiation in Nanjing.

4. Result

4.1. Simulation Analysis of Building Layout

4.1.1. Construction of Layout Abstract Model

Among the selected examples of sports stadia, the gymnasiums are rich in form, with a great variety of shapes, styles, and volumes. The richness of the architectural forms is derived from the basic plan forms. In the architectural examples, the planned form of the stadiums is predominantly oval and the planned form of the gymnasium is predominantly rectangular. Therefore, the shape of the stadium abstract model is regarded as an oval and that of the gymnasium abstract model is determined as a rectangle. According to the analysis of the actual case of the sports center, it can be found that the layout of the sports center is mostly in the form of a one-line layout and a triangle layout. Therefore, in the abstract simulation of the overall planning layout, the abstract model is constructed for these two categories. The dimensions of the oval stadium are 270 × 170 × 32 m with a height of 32 m, while the dimensions of the gymnasium are 180 × 100 × 25 m.

As can be seen from the architectural examples, there are multiple ways of orienting the whole of both layout forms. In order to clarify the impact of the change in orientation of the general layout on the external environment, the simulation experiment chooses eight directions, including east, south, west, north, southeast, northeast, southwest, and northwest, as orientation variables for specific assignments. Among them, the direction of the square opening of the triangle layout is the orientation direction of the layout as a whole; the direction of the stadium of the one-line layout is the orientation direction. The final abstract model is shown in Figure 7.

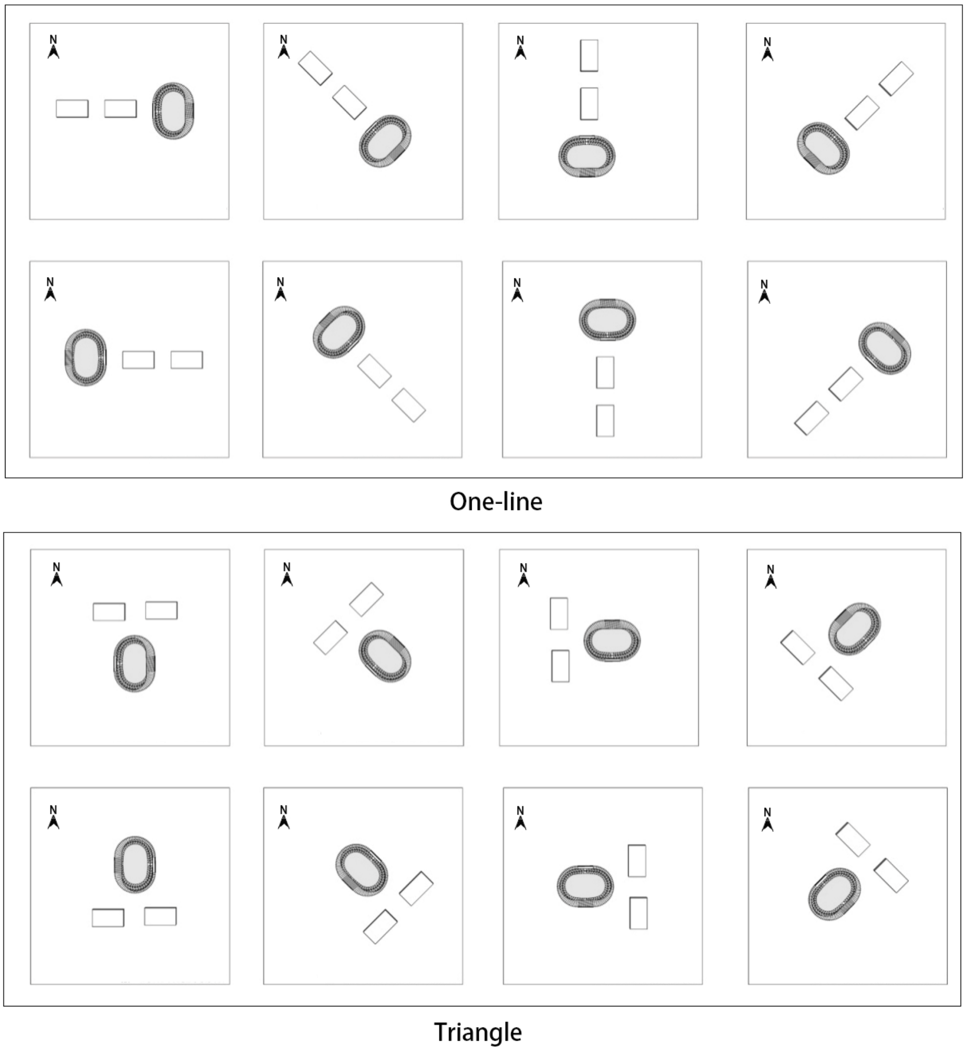
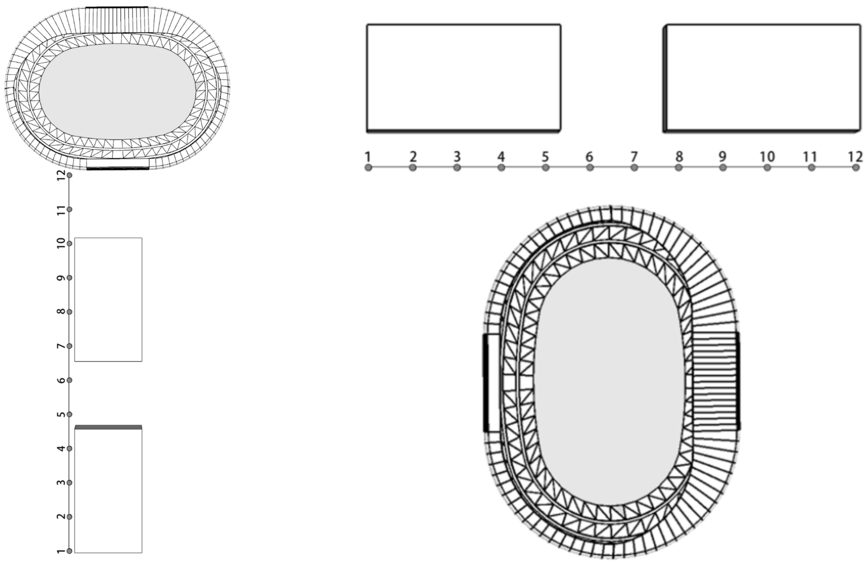


Figure 7. Abstract model of the building's orientation.

4.1.2. Simulation Condition Setting of Layout Abstract Model

For the overall planning layout, the 3D heat flow CFD Phoenics 2016 software is used to simulate the outdoor airflow velocity, atmospheric pressure, and wind profile index in order to quantify the degree of impact of different layout strategies on the environment of the arena area. In the specific simulation process, typical climate data of Nanjing city throughout the year are selected as the atmospheric boundary conditions and wind speed data are set with an initial wind speed of 6.2 m/s and a wind direction of 45° (northeast). The model grid is set at 130 × 130 × 30, the simulation time is 120 s, and the time interval is 0.1 s. The simulation analysis of the planning layout and climate environment uses the wind speed distribution map and the wind speed data at the sampling point as the measurement parameters. The sampling points are located on the symmetry axis of the site layout and are named in order of orientation. In this simulation study, we first carry out 20 sampling points, 12 sampling points, and 8 sampling points for simulation calculation comparison. From the results point of view, the analysis results of the 12 sampling points are better, that is, the data are clearer and do not cost a lot of computing power, so the one-line layout is set with 12 sampling points and the triangle layout is set up with 12 sampling points. The data of the sampling point can better reflect the wind environment of the stadium surrounding the square space and can intuitively show the square wind environment of the stadium under different climatic conditions. The specific locations of the sampling points are shown in Figure 8.



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

Figure 8. Sampling point diagram of layout abstract model. (**a**) Sampling points for one-line layout. (**b**) Sampling points for triangle layout.

4.1.3. Simulation Results of Layout Abstract Model

(1) Orientation and wind speed distribution in a triangle layout

The Tecplot 2021 software is used to sample the wind speed at 12 points selected from the enclosed plaza of the sports center in a triangle layout and the data are summarized in Table 1.

Table 1. Wind speed at sampling points for different orientations of the triangle layout (m/s).

Triangle	1	2	3	4	5	6	7	8	9	10	11	12	Mean
West	1.1240	2.3026	3.3661	3.9591	6.1118	6.9458	4.1777	0.5960	1.0135	1.1755	1.0886	4.3785	3.0199
North-west	3.3597	3.4807	3.2984	3.2633	5.9160	4.6497	2.4513	0.0290	1.2746	1.2624	3.3347	7.3372	3.3047
South-west	6.4813	3.6839	3.1583	3.6070	3.1768	4.1301	6.8990	7.1124	6.2923	4.4333	4.3215	4.2796	4.7980
East	3.1531	2.2143	2.0123	1.9072	0.7247	4.0019	5.3377	6.5161	4.5740	4.4639	1.2511	0.8291	3.0821
South	2.1364	2.2169	2.0169	3.9117	6.1773	3.1606	2.1056	2.2995	2.1469	2.2165	2.7288	6.9369	3.1712
North-east	2.4357	3.4518	3.3858	6.0058	7.0543	4.9270	3.9398	3.9857	3.8140	3.8187	5.7679	7.4711	4.6715
South-east	6.1784	2.8213	3.2078	3.2245	4.0664	4.3949	5.0112	6.1106	4.4713	5.7440	5.2246	3.9264	4.5318
North	4.6896	0.8117	0.5561	0.1453	2.5813	3.1586	4.0602	1.7527	2.1475	1.9764	0.2658	0.6105	1.8963

As can be observed from the wind speed and distribution maps of the sampling points in Table 1, the average wind speed at each sampling point in the triangle layout of the square ranges from 1.8963 m/s to 4.7980 m/s, with an overall average value of 3.5594 m/s.

The average wind speed in descending order of orientation is southwest > northeast > southeast > northwest > south > east > west > north. Under the wind speed condition of 6.2 m/s, wind environment simulations are carried out for eight different orientations of the triangle layout model, respectively, and the wind speed distribution is obtained (as shown in Figure 9).

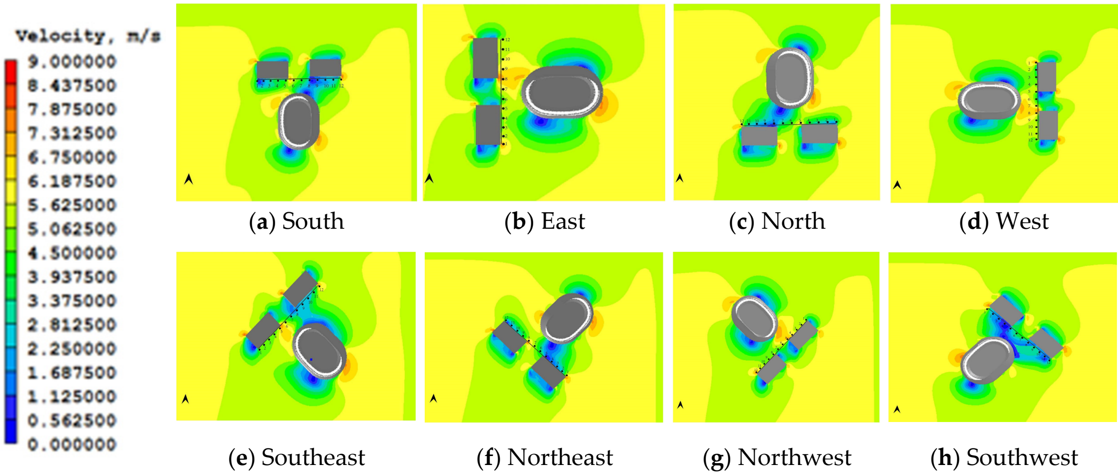


Figure 9. Site wind speed of triangle layout with different orientations.

It is found that, when the axis of the triangular layout is southwest, the wind speed in the field is the largest, at about 4.7980 m/s. Followed by the northeast direction, the wind speed is about 4.6715 m/s. The wind speed in the north direction is the lowest, at only 1.8963 m/s. It can be said that, from the demand for ventilation in the field, the wind environment of the oblique layout is better than the positive layout and the wind blowing from the side of the square can make the square space obtain the maximum wind speed. When the axis of the field is north, the average wind speed of the field is the smallest; it is found that this is due to the air inlet and outlet being blocked by the stadium. Therefore, when choosing the overall orientation of the triangle layout, if ventilation is the main choice, priority can be given to the site axis parallel to the prevailing wind direction and the square space can be opened on the windward side, so that the external wind environment can pass through the site with less obstruction.

(2) Orientation and wind speed distribution in one-line layout.

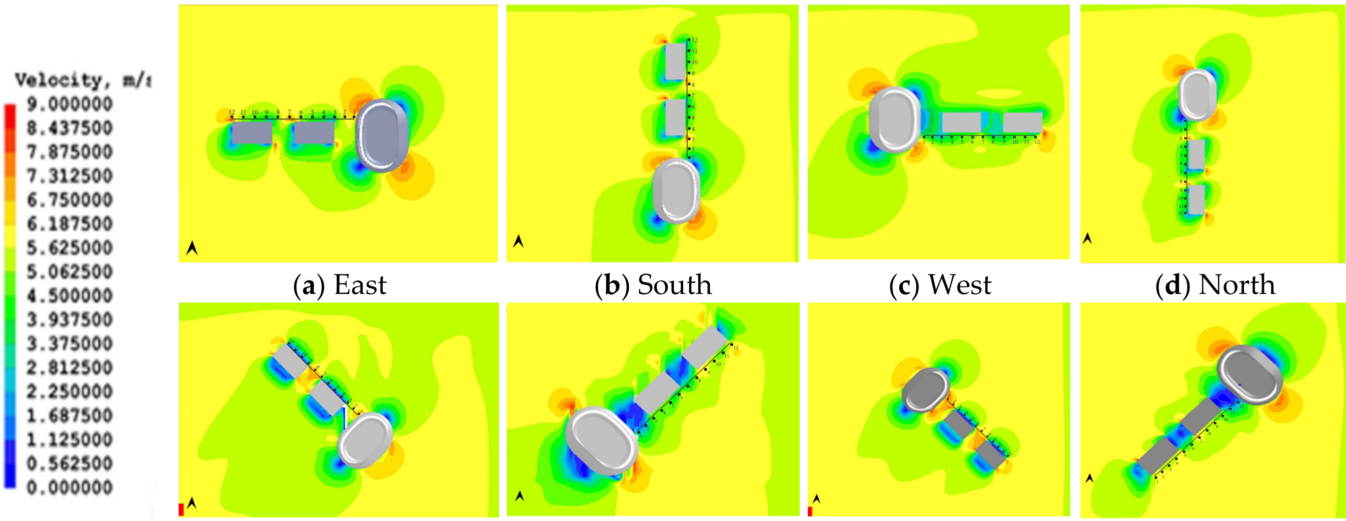
Using tecplot 2021 software, 12 points are selected for wind speed sampling in the enclosed plaza of the sports center in the one-line layout; the data are summarized in Table 2.

Table 2. Wind speeds at sampling points for different orientations of the one-line layout (m/s).

One-Line	1	2	3	4	5	6	7	8	9	10	11	12	Mean
West	5.1336	4.4904	1.8738	2.0535	3.5404	4.6226	6.1842	3.1762	2.5093	2.1775	2.8553	7.2744	3.8243
North-west	2.3688	3.1397	1.8360	2.1574	2.1527	2.0383	1.6648	1.2617	2.2783	3.1833	1.0099	1.3089	2.0393
South-west	0.0841	3.6942	6.4835	2.7246	3.4653	2.3127	3.5129	6.5852	2.0103	1.5581	1.4178	1.5651	2.9511
East	0.1229	1.4414	5.5715	5.2004	4.3755	3.3247	3.7901	5.2892	5.9661	5.2646	3.0602	4.9990	4.0338
South	1.4221	2.2812	1.3613	2.3496	5.0230	5.2598	3.1831	2.3583	3.3252	3.9116	3.1572	3.3424	3.0812
North-east	6.9264	5.1715	2.2512	1.0136	1.0575	1.0888	5.2789	4.4423	1.1880	1.0440	1.1334	2.4343	2.5025
South-east	1.0559	2.6347	5.9798	3.2081	3.4736	2.6593	3.0876	5.8560	2.0369	3.4842	3.7081	1.7132	3.2414
North	3.1743	3.0250	3.1612	3.7297	3.8136	3.2218	7.1507	4.1784	4.5189	3.7767	1.4931	1.2749	3.5432

As can be observed in Table 2, from the wind speed and distribution map of the sampling points, the average wind speed in the square with the one-line layout ranges from 2.0393 to 4.0338 m/s, with an overall average value of 3.1521 m/s; the average wind speed in descending order of orientation is east > west > north > south-east > south > south-west > north-east > north-west.

As shown in Figure 10, under the condition of a wind speed of 6.2 m/s, eight one-line layout models are simulated and calculated to obtain wind speed distribution diagrams. It can be found that, when the axis of the one-line layout is east-west, the wind speed of the site is up to 4.0338 m/s; after analysis, it is found that this is due to the wind direction crossing the site (the wind blows from the side of the site and the square space obtains a larger wind speed). At the same time, when the axis of the one-line is northeast and northwest, the axis of the sports stadia is parallel to the field and the wall of the gymnasium blocks most of the wind, so the wind speed of the site is minimal and the wind effect is significantly lower than that of other directions. Therefore, when choosing the orientation of the one-line layout, it is necessary to cross the site axis at 45° with the prevailing wind direction.



(**e**) Southeast (**f**) Southwest (**g**) Northwest (**h**) Northeast

Figure 10. Site wind speed of the one-line layout with different orientations.

4.2. Simulation Analysis of Building Shape

4.2.1. Construction of Shape Abstract Model

The construction of sports stadia in the hot summer and cold winter zone is at a leading level and the construction of stadiums has also developed rapidly, with the completion of a number of gymnasiums such as the Nanjing Olympic Sports Center and the Hangzhou Olympic Sports Center. The design of these gymnasiums is innovative and the roof forms of the buildings are abundant. In order to systematically study nine types of roof interface forms of gymnasiums, such as flat roofs, four-pitch roofs, and gable roofs,; individual details are ignored (e.g., jagged simplified into corresponding sloping or curved surfaces, etc.). Then, based on the average dimensions of major gymnasium, a flat roof form of $65 \times 40 \times 22$ m is used as the basic form and a set of abstract models of gymnasiums regarding the variation of roof forms is formed based on the unification of the nine types of gymnasiums in terms of internal volume, as shown in Figure 11.

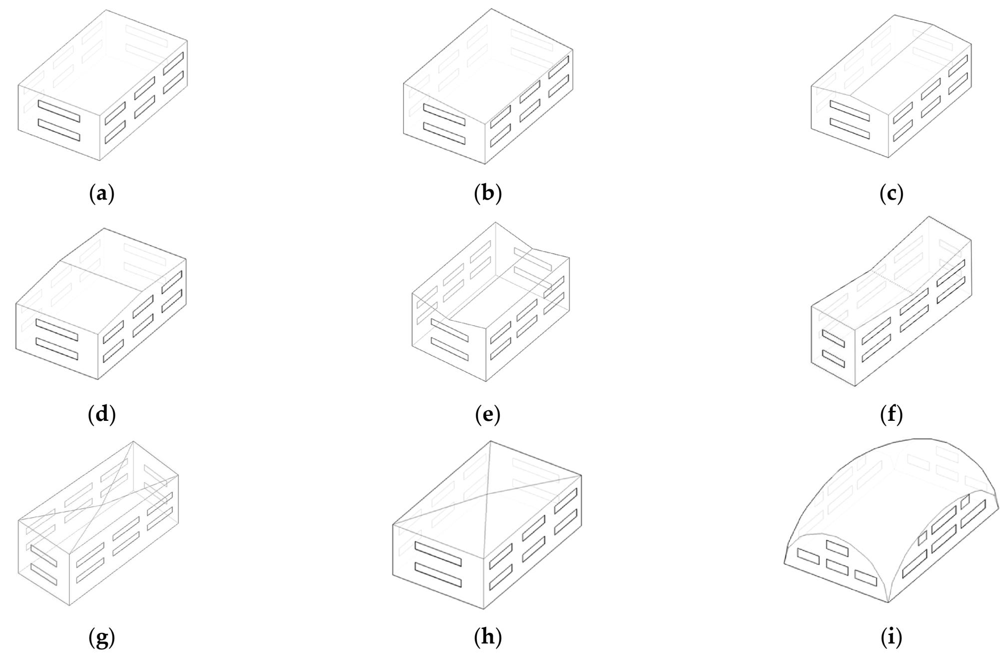
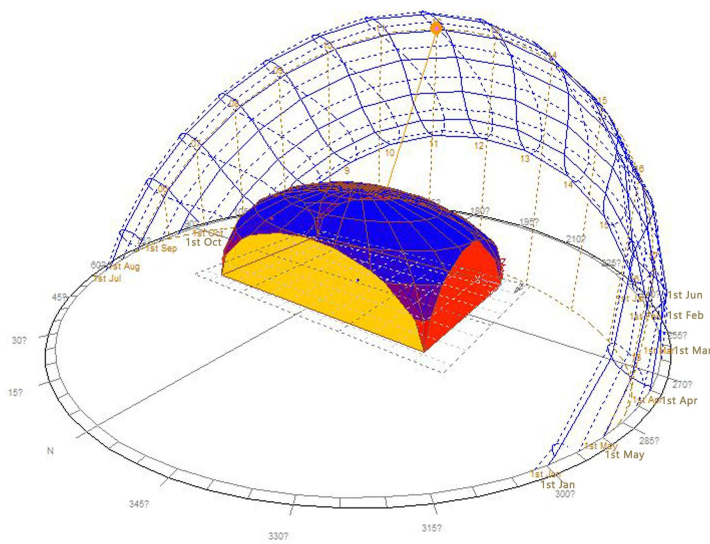


Figure 11. Different types of abstract architectural form models. (**a**) Flat slope. (**b**) Single slope. (**c**) Short-sided double slope. (**d**) Long-sided double slope. (**e**) Short-sided concave. (**f**) Long-sided concave. (**g**) Double-sided concave. (**h**) Double side double slope. (**i**) Dome.

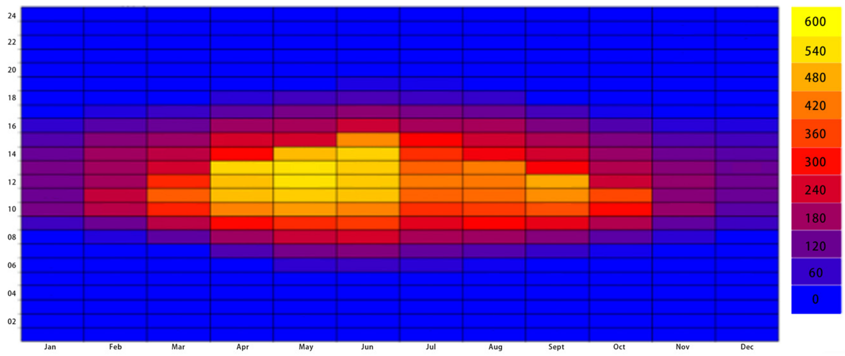
4.2.2. Simulation Condition Setting of Shape Abstract Model

Ecotect 2011 analysis software is used to simulate the heat gain of building shapes in different roof forms. In the specific simulation process, the same Nanjing meteorological data is selected and a flat roof form of 65 × 40 × 22 m is used as the basic form, based on the nine types of gymnasiums being unified in terms of internal volume and unified in terms of the conditions of unshaded areas. The dome is taken as an example to calculate the heat increment of the external surface area. The amount of heat increment can better measure the relationship between solar radiation on the outer surface of the gymnasium (Figure 12). For areas with hot summers and cold winters, the smaller the heat increment of the outer surface in summer, the lower the indoor temperature rises and the easier it is to maintain the indoor environment at a better level.



(**a**)

Figure 12. *Cont*.



(**b**)

Figure 12. 24 h heating simulation analysis of the dome in Nanjing area in each month of the year. (**a**) Average daily radiation analysis. (**b**) Radiant heat map of the façade.

4.2.3. Simulation Results of Shape Abstract Model

As shown in Table 3, after simulation and comparison of each form, it is found that there is an overall positive correlation between the area of the external surface form and the amount of solar radiation.

Table 3. Thermal radiation analysis of building forms.

Type	The Radiant Surface Area (m^2)	Total Radiation Value (wh/m^2)	Mean Radiation Value (wh/m^2)
Flat slope	7900	53,983,330.7	6833.333
Single slope	7918.678	47,542,246.08	6003.811
Short-sided double slope	7673.863	73,880,238.81	9627.516
Long-sided double slope	7733.105	75,141,923.97	9716.915
Short-sided concave	8237.863	136,742,413.3	16,599.258
Long-sided concave	8133.105	95,773,630.8	11,775.777
Double-sided concave	8758.484	116,453,232.4	13,296.049
Double side double slope	7453.484	89,399,211.34	11,994.285
Dome	2063.476	27,436,078.01	13,296.049

According to the results revealed in Table 3, we find that: (1) Compared with the other eight types, the heat increment of the outer interface of the dome (27,436,078.01 wh) obviously has the advantage of the lowest radiant heat increment, among which, compared with the short-sided concave type with the highest heat increment (136,742,413.30 wh), the radiant heat increment can even be reduced (79.93%), mainly because the dome is a spherical curved surface change and the heating surface area is smaller. The dome shape has the lowest radiant heat increment, so the dome has a significantly better radiant heat increment ability than other roof forms; it is widely used as the roof form of sports stadia. (2) Compared with the flat roof (53,983,330.70 wh), the radiant heat increment of a single slope roof (47,542,246.08 wh) increases (13.55%) and the radiation amount does not change significantly. (3) Compared with the average number of double slopes (74,511,081.39 wh), there is also a certain radiation reduction phenomenon (38.03%) in the flat roof form (53,983,330.70 wh), mainly because the double slope roof increases the roof surface area, which to a certain extent causes the increase of radiant heat increment. (4) The difference in radiation between the short-sided (73,880,238.81 wh) and the long-sided (75,141,923.97 wh) concave in the double slope form is not obvious. (5) The average heat increment of the concave roof is the highest and, after analysis, it is found that this is due to the fact that on the one hand, the concave part accumulates more energy and is not easy to volatilize and, on the other hand, the surface area of the concave building is the largest. Therefore, according to the amount of heat gained by the building shape, it can be sorted from largest to smallest: concave roof–sloped roof–flat roof–dome.

4.3. Simulation Analysis of Building Structure

4.3.1. Construction of Structure Abstract Model

The construction form of sports stadia takes a more microscopic approach to the external form and physical properties of the stadium, with the characteristics of being highly selective, influential, and acceptable. This study adopts the stadium canopy as a structural form because, on the one hand, the wind environment in the inner field defined by the stadium canopy is an important factor affecting the quality of exercise and competition use in the field and, on the other hand, because the canopy form has a more obvious and intuitive impact on the form of the stadium and is one of the forms explored to unify the design form and physical performance. Based on the previous case study, most of the stadiums are rounded flat and the impact of the canopy on the indoor wind environment is more direct. The permeability model of the canopy connection can be divided into three types: fully enclosed connection, semi-closed connection, and fully open connection, with the same floor plan using four-sided through canopy, with the size the same as the three models in the canopy profile form. Among them, the fully enclosed connection model is the gap between the canopy and the agent is completely shielded by the baffle. The semi-closed connection model is not set at the corner of the open connection model without occlusion. This study simulates the three forms and, from the results of the study, the internal wind environment has little relationship with the canopy connection form. In order to study readability, the semi-closed connection type is used here as an example to discuss the research results. This study uses the square inverted rounded building plan form in the site and the canopy profile form is divided into three kinds of upward tilt, flat and downward tilt, upward tilt canopy, and downward tilt canopy, respectively, on the basis of flat and straight canopy upward and downward tilt of 15°. The final abstract model is shown in Figure 13.

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

Figure 13. Building structure abstract models. (**a**) Upward canopy. (**b**) Flat canopy. (**c**) Downward canopy.

4.3.2. Simulation Condition Setting of Structure Abstract Model

For the building construction analysis, three initial wind speed conditions are selected (5 m/s, 10 m/s, and 15 m/s) at a height of 10 m and urban gradient wind parameters are chosen for the air inlet. The specific expression for the gradient wind is as follows:

$$\frac{U_{(y)}}{U_0} = \left(\frac{y}{\delta}\right)^n \tag{1}$$

where $U_{(y)}$ represents the wind speed at height y, m/s; U_0 is initial wind speed (in this experiment, three wind speeds of 5 m/s, 10 m/s, and 15 m/s are taken); y is height, m; δ represents reference height, taken as 10 m; n is roughness coefficient, taken as 0.15.

The model selected in this paper is an abstract model and the research content is the influence of canopy morphology on the infield wind environment. In the course of the study, each wind direction is simulated. The data results show little to do with the wind direction, considering that the composite variables would greatly increase the complexity of the study and weaken the accuracy of the single variable. Therefore, this paper ignores the influence of different wind directions and only discusses the influence of professional stadium canopy morphology on the infield wind environment from the perspective of an abstract model and selects a single wind direction as the initial condition.

4.3.3. Simulation Results of Structure Abstract Model

After simulation analysis, the following observations are noted under the same wind speed and direction in the external environment. (1) When the canopy is an upward canopy, a vortex is formed in the northeast and southwest areas, the average wind speed in the audience area on the west side is significantly higher than that in the east side, a small area of vortex circle appears locally on the northeast side, and the static wind area is actively small and has poor stability. (2) The average wind speed of the sports area is the smallest under the three canopy profile forms when the canopy is a flat canopy and there are many areas with sudden wind speed changes in the entire audience area, e.g., when the wind speed at the entrance is 15 m/s, the wind speed difference is about 7 m/s. (3) When the canopy is a downward canopy, the average wind speed in the field is large and a large area of low wind speed circle appears locally on the southeast side and the area of the quiet wind area is small. (4) In general, the whirlpool area in the field of the upward canopy and downward canopy is more obvious and less stable, especially in the sports area, and will have a certain impact on sports, while the flat canopy has the best stability and is the best for competitive sports. The wind speed difference between the inside and outside of the downward canopy is obvious and the speed reduction is the best. The speed reduction of the flat canopy is moderate and the area with sudden wind speed change in many places only appears in the audience area. The wind speed difference inside and outside the field of the upward canopy is not obvious and the speed reduction is poor (Figure 14).

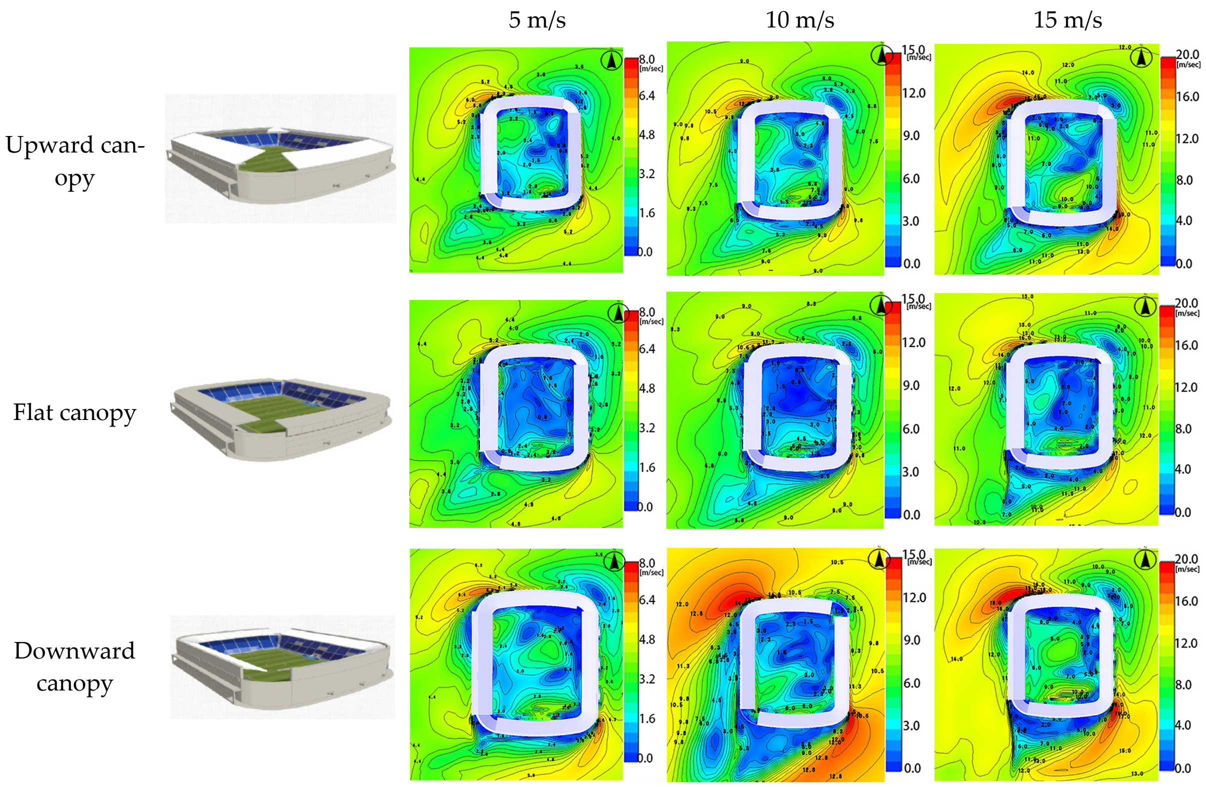


Figure 14. Wind speed maps in stadiums in different canopy forms.

5. Discussion

The unique wind and heat environment in the hot summer and cold winter zone has a great impact on sports stadia and the climate adaptation strategy of stadia is also more complicated. According to the simulation analysis above, climate adaptation strategies are proposed from three aspects: building layout, building shape, and building structure, as shown in Table 4.

Table 4. Climate adaptation strategy.

Dimension	Type	Simulation Result	Cause	Strategy
Layout	One-line	When the axis is east west, the maximum wind speed of the site is 4.0338 m/s; when the axis is northeast and northwest, the wind speed of the site is the smallest and the induced wind effect is significantly lower than that of other directions.	Since the prevailing wind direction crosses the axis at 45° in summer, the wind speed is highest when the dominant wind direction runs diagonally through the site; the axis of the stadia runs parallel to the field and the walls of the gymnasiums block most of the wind.	Under the demand for induced wind, the orientation of the layout needs to cross the site axis with the prevailing wind direction at 45° to achieve the highest wind speed of the site.
	Triangle	The wind speed in the field is the largest in the southwest orientation, about 4.7980 m/s; the second is the northeast orientation, with a wind speed of about 4.6715 m/s; the wind speed in the due north direction is the lowest at only 1.8963 m/s.	When the axis of the stadia intersects diagonally with the dominant wind direction, the wind can better penetrate the square space formed by the two gymnasiums; the average wind speed in the north direction is the smallest and, after analysis, it is found that this is due to the fact that the air inlets and outlets are blocked by the gymnasiums, so the wind speed is the smallest.	From the perspective of the demand for ventilation in the field, the wind environment of the oblique layout is better than the positive layout. Wind blowing through the sides of the square can maximize wind speed in the square space. At the same time, it is necessary to try to make the square space as little as possible on the windward side.
Shape	Flat slope	Radiant surface area: 7900.00 m^2. Radiant heat increment: 53,983,330.70 wh.	Because of the uniform solar radiation, the flat slope is not greatly affected by the orientation of the building.	Follow-up measures include reducing the body size factor and improving natural ventilation and
	Single slope	Radiant surface area: 7918.678 m^2. Radiant heat increment: 47,542,246.08 wh.	The orientation of the single slope has a critical effect on heat increment.	adjusting the orientation and shape of the building to achieve a good relationship between solar radiation and radiant heat increment, while also considering synergy with natural ventilation technology.
	Short-sided double slope	Radiant surface area: 7673.863 m^2. Radiant heat increment: 73,880,238.81 wh	There is a positive correlation between the external surface area of the roof slope and the amount of solar radiation.	The change of the roof shape of the building itself is used to form an effective shading surface and create a suitable thermal environment for the interior and exterior space of the building.
	Long-sided double slope	Radiant surface area: 7733.105 m^2. Radiant heat increment: 75,141,923.97 wh.	The surface area and orientation of the long slope determine the amount of solar radiation.	Adjust the orientation of the outer surface of the long slope, increase the effective shading surface, and effectively reduce solar radiation.
	Short-sided concave	Radiant surface area: 8237.863 m^2. Radiant heat increment: 136,742,413.30 wh.	Because the short side is concave and the long side is completely exposed to solar radiation, the surface area exposed to solar radiation is larger than that of other roofs. At the same time, the concave part of the roof is easy to accumulate large energy and is not easy to volatilize.	Adjust the orientation of the building, reduce the solar radiation on the long side, rationally use the wind pressure above and below the roof, increase the wind pressure on the welcoming and leeward sides of the gymnasium, strengthen the power of natural ventilation, and accelerate the rapid dissipation of accumulated energy.

Table 4. *Cont.*

Dimension	Type	Simulation Result	Cause	Strategy
Shape	Long-sided concave	Radiant surface area: 8133.105 m^2. Radiant heat increment: 95,773,630.80 wh.	The concave part of the roof is easy to accumulate large energy and is not easy to evaporate. At the same time, the roof is concave, resulting in a larger surface area than other roofs.	The formation of area changes at different interfaces in the wind direction strengthens the power of natural ventilation, accelerates the rapid dissipation of the accumulated energy of the roof, and then aggravates the contrast between the wind pressure of the stadium and the leeward side.
	Double-sided concave	Radiant surface area: 8758.484 m^2. Radiant heat increment: 116,453,232.40 wh.	Because there are two concave parts, it is easier to accumulate more energy than the single concave, it is not easy to volatilize, and the surface area of the double-concave building is also larger.	On the basis of the area change of different interfaces in the wind direction, measures such as reducing the body size coefficient, reducing the total daily average solar radiation of the building, and effectively reducing the external surface area of external heat radiation can be taken.
	Double side double slope	Radiant surface area: 7453.484 m^2. Radiant heat increment: 89,399,211.34 wh.	All four slopes are likely to have a positive correlation with the amount of solar radiation as a whole.	A more desirable body size factor of a building can be studied to form an effective shading surface and an external surface area that reduces heat source radiation.
	Dome	Radiant surface area: 2063.476 m^2. Radiant heat increment: 27,436,078.01 wh.	Because the dome is a spherical curved surface, the heating surface area is smaller and the dome has the lowest radiant heat increment, so the dome has a significantly better ability to reduce radiant heat increment than other roof forms.	Shading components can be added to block the direct radiation of sunlight to the building interface and improve natural ventilation and other follow-up measures.
Structure	Upward canopy	The wind speed stability is not good and the speed reduction is poor.	Whirlpools are formed in the northeast and southwest areas, the average wind speed in the audience area on the west side is significantly higher than that on the east side, and a small area of vortex circles appear locally on the northeast side. The static wind area is actively small, the wind speed difference inside and outside the field is not obvious, and the speed reduction is poor.	Pay attention to the upward tilt angle of the upward canopy, as a roof with too high an upward tilt angle will cause external airflow to pass above the site and prevent access to the interior space.
	Flat canopy	The wind speed stability is good and the speed reduction is moderate.	The average wind speed in the sports area is the smallest under the three canopy profiles; there are many areas with sudden wind speed changes in the entire audience area, such as when the wind speed at the entrance is 15 m/s, the wind speed difference is about 7 m/s, and the area with multiple sudden wind speed changes only appears in the audience area.	Reasonable setting of openings in the grandstand area can make the wind environment in the field more uniform and, when selecting unilateral openings, it should be set on the inlet side. When setting up bilateral openings, try to stagger the settings to avoid alignment.

Table 4. *Cont.*

Dimension	Type	Simulation Result	Cause	Strategy
Structure	Downward canopy	The wind speed reduction is the best, but the stability is poor.	The average wind speed inside the field is large and a large area of low wind speed circle appears locally on the southeast side. The area of static wind is small, the wind speed difference between inside and outside the field is obvious, and the speed reduction is the best.	Try to keep a gap height of more than 3 m between the canopy and the stand so that the stability of the wind environment in the field can be improved.

First of all, in the layout of the building, it is necessary to strengthen the air-induced air capacity of the sports stadia and balance the internal thermal environment of the gymnasium through ventilation and heat dissipation. After simulation studies, climate response can be summarized as follows: in the one-line layout, the axis is east-west and the wind speed of the site is the largest; when the axis is northeast and northwest, the wind speed of the site is the smallest and the induced wind effect is significantly lower than that of other directions. Therefore, under the demand of induced wind, the one-line layout is subject to wider changes in the ratio of external wind speed and site-affected area and whether the layout is reasonable or not has a greater impact on it. Through this simulation, the orientation of the one-line layout needs to cross the site axis with the prevailing wind direction at 45° to achieve the highest wind speed in the site. In the triangular layout, the southwest orientation has the largest wind speed in the field, followed by the northeast orientation, and the wind speed in the due north direction is the lowest. Regarding the need for ventilation, the wind environment of the oblique layout is better than the positive layout, that is, the wind blowing from the side of the square can make the square space obtain the maximum wind speed. At the same time, the square space needs to be made as little as possible on the windward side.

Secondly, due to its large surface area and the most direct form of external contact, the roof of the gymnasium has huge radiant heat, which directly affects the thermal environment inside the gymnasium. Through simulation studies, it is found that there is a positive correlation between the external surface area of the roof and the amount of solar radiation as a whole. The dome is a spherical surface change, the heating surface area is smaller, and the dome has the lowest radiant heat increment, so the dome ability to reduce radiant heat increment is significantly better than that of other roof forms. The concave roof increases the external surface area of the building because the concave part increases; the concave part is easy to accumulate energy and is not easy to volatilize, resulting in the highest average radiant heat increment of such roofs. In the form of sloped roofs and flat roofs, the amount of radiant heat increment is directly related to its own shape system number and slope orientation. Therefore, according to the size of the heat gained by the roof shape of the building, it can be sorted from largest to smallest: concave roof–sloped roof–flat roof–dome. Therefore, the priority use of the dome can greatly reduce the radiant heat increment of the roof interface of the gymnasium and, in specific engineering practice, it should also be combined with subsequent measures such as reducing the building size coefficient, increasing external shading, and improving natural ventilation to effectively improve the thermal environment quality of indoor space.

Finally, because of its semi-open form, the stadium has a direct connection between the internal environment and the external environment. The wind speed in the hot summer and cold winter zone is generally large; how to reduce the wind speed and stabilize the wind field in the field is one of the main concerns of stadia in this area. According to simulation results, it is found that the stability of the upward canopy and the downward canopy are poor, especially the whirlpool formed in the sports area, which will have a certain impact on sports, while the flat canopy has the best stability and is the best for competitive sports. The downward canopy has the best speed reduction. The flat canopy has moderate speed reduction and many areas with sudden wind speed change only appear in the audience area. The upward canopy has poor speed reduction, forming a vortex in the northeast and southwest areas. Therefore, compared with the upward canopy and the downward canopy, the flat canopy has more low wind speed areas and better wind resistance, which can effectively avoid the impact of windy weather on the training and competition of personnel in the stadium, improve the quality of use of the sports stadia, and improve the comfort of the overall environment.

6. Conclusions

This study uses Phoenics 2016, and Ecotect 2011 software as simulation tools and explores the general layout, building form, and canopy form of sports stadia in terms of wind and sunlight environment simulation, in response to the above-mentioned usage requirements and spatial characteristics. The findings of the study are summarized in a "simulation-quantification-comparison" approach and the rules and design strategies that are useful for climate design are summarized to propose a more comprehensive climate adaptation design strategy. According to the simulation results, when the triangular layout is made, the axis of the sports stadia is parallel to the dominant wind direction and the wind can better penetrate the square space formed by the two gymnasiums. In the one-line layout, due to the difference in layout, there is no enclosure space, so the wind speed is highest when the dominant wind direction runs diagonally through the site. For building shape, in the selection of roof form, it is better to choose the form with the smallest external surface area, such as a dome, because the external interface has the least contact and the external heat radiation also has the least interference with the indoor environment. When choosing the structure of the building, it is necessary to pay attention to the initial interference of the ground wind and choose a flat canopy with better wind resistance, more low wind speed areas, and better wind resistance, which will improve the comfort of the overall environment in the sports stadia.

This study provides a reference and basis for the climatic design practice of sports stadia in hot summer and cold winter zones in a theoretical sense, thereby accelerating the pace of greening sports stadia. At the same time, at the practical level, the climate adaptation design strategies proposed in this paper provide a system of ideas and methods for contemporary sports stadia design with mutual perspectives and appropriate strategies, which enhance the green, healthy, and economic value of sports stadia.

Although the results of the study are more instructive, there are still some shortcomings in this study. First of all, the simulation setting conditions in this study are relatively single, ignoring the influence of site greening, terrain, and other factors. At the same time, the abstract model of this study is also subject to the research methods, only considering the influence effect of the main aspects, and does not study the role of various details on the experimental results from the perspective of the fine model.

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

Funding: This research was funded by the Major project of philosophy and social sciences in colleges and universities of Jiangsu, grant number 2020SJZDA095.

Data Availability Statement: The data presented in this research are available upon request from the corresponding author. The data are not publicly available due to privacy.

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

References

1. Zhao, X.; Ma, X.; Chen, B.; Shang, Y.; Song, M. Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resour. Conserv. Recycl.* **2022**, *176*, 105959. [CrossRef]
2. Bazazzadeh, H.; Nadolny, A.; Safaei, S.S.H. Climate Change and Building Energy Consumption: A Review of the Impact of Weather Parameters Influenced by Climate Change on Household Heating and Cooling Demands of Buildings. *Eur. J. Sustain. Dev.* **2021**, *10*, 1–12. [CrossRef]
3. Liu, X.; Liu, X.; Luo, X.; Wang, M.; Fu, H.; Wang, B.; Sun, Y.; Hu, W. Analysis on the influencing mechanism of informational policy instrument on adopting energy consumption monitoring technology in public buildings. *Energy Effic.* **2020**, *13*, 1485–1503. [CrossRef]
4. Wang, L.; Huang, Q.; Zhang, Q.; Xu, H.; Yuen, R.K. Role of atrium geometry in building energy consumption: The case of a fully air-conditioned enclosed atrium in cold climates, China. *Energy Build.* **2017**, *151*, 228–241. [CrossRef]
5. Xu, P.; Huang, J.; Shen, P.; Ma, X.; Gao, X.; Xu, Q.; Jiang, H.; Xiang, Y. Commercial building energy use in six cities in Southern China. *Energy Policy* **2013**, *53*, 76–89. [CrossRef]
6. Yuce, B.; Li, H.; Rezgui, Y.; Petri, I.; Jayan, B.; Yang, C. Utilizing artificial neural network to predict energy consumption and thermal comfort level: An indoor swimming pool case study. *Energy Build.* **2014**, *80*, 45–56. [CrossRef]
7. Wang, K.; Wang, X. Providing Sports Venues on Mainland China: Implications for Promoting Leisure-Time Physical Activity and National Fitness Policies. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5136. [CrossRef] [PubMed]
8. Vogeler, C.S.; van den Dool, A.; Chen, M. Programmatic action in Chinese health policy—The making and design of "Healthy China 2030". *Rev. Policy Res.* **2023**, *40*, 534–552. [CrossRef]
9. Stagrum, A.E.; Andenæs, E.; Kvande, T.; Lohne, J. Climate Change Adaptation Measures for Buildings—A Scoping Review. *Sustainability* **2020**, *12*, 1721–1738. [CrossRef]
10. Oropeza-Perez, I.; Østergaard, P.A. Potential of natural ventilation in temperate countries—A case study of Denmark. *Appl. Energy* **2014**, *114*, 520–530. [CrossRef]
11. Cerra, J. Inland Adaptation: Developing a Studio Model for Climate-adaptive Design as a Framework for Design Practice. *Landsc. J.* **2016**, *35*, 37–55. [CrossRef]
12. Liu, Y.; Wang, J.; Ren, J.; Xiao, Q.; Zhao, J. A Preliminary Study on the Climate Adaptive Design of Green Rural Houses in west China. *Procedia Eng.* **2017**, *180*, 735–740. [CrossRef]
13. Shen, J.; Copertaro, B.; Sangelantoni, L.; Zhang, X.; Suo, H.; Guan, X. An early-stage analysis of climate-adaptive designs for multi-family buildings under future climate scenario: Case studies in Rome, Italy and Stockholm, Sweden. *J. Build. Eng.* **2020**, *27*, 100972. [CrossRef]
14. Liu, L.; Liu, J.; Jin, L.; Liu, L.; Gao, Y.; Pan, X. Climate-conscious spatial morphology optimization strategy using a method combining local climate zone parameterization concept and urban canopy layer model. *Build. Environ.* **2020**, *185*, 107301. [CrossRef]
15. Teshnehdel, S.; Akbari, H.; Di Giuseppe, E.; Brown, R.D. Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran. *Build. Environ.* **2020**, *178*, 106899. [CrossRef]
16. Aboulnaga, M.; Alwan, A.; Elsharouny, M.R. Climate Change Adaptation: Assessment and Simulation for Hot-Arid Urban Settlements—The Case Study of the Asmarat Housing Project in Cairo, Egypt. In *Sustainable Building for a Cleaner Environment: Selected Papers from the World Renewable Energy Network's Med Green Forum 2017*; Sayigh, A., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 437–449.
17. Mughal, M.O.; Li, X.-X.; Norford, L.K. Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones. *Urban Clim.* **2020**, *34*, 100714. [CrossRef]
18. Mabon, L.; Kondo, K.; Kanekiyo, H.; Hayabuchi, Y.; Yamaguchi, A. Fukuoka: Adapting to climate change through urban green space and the built environment? *Cities* **2019**, *93*, 273–285. [CrossRef]
19. Mauree, D.; Naboni, E.; Coccolo, S.; Perera, A.; Nik, V.M.; Scartezzini, J.-L. A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renew. Sustain. Energy Rev.* **2019**, *112*, 733–746. [CrossRef]
20. Kim, H.; Clayton, M.J. A multi-objective optimization approach for climate-adaptive building envelope design using parametric behavior maps. *Build. Environ.* **2020**, *185*, 107292. [CrossRef]
21. Yang, L.; Fu, R.; He, W.; He, Q.; Liu, Y. Adaptive thermal comfort and climate responsive building design strategies in dry-hot and dry-cold areas: Case study in Turpan, China. *Energy Build.* **2019**, *209*, 109678. [CrossRef]
22. Zhou, Y.; Zheng, S.; Liu, Z.; Wen, T.; Ding, Z.; Yan, J.; Zhang, G. Passive and active phase change materials integrated building energy systems with advanced machine-learning based climate-adaptive designs, intelligent operations, uncertainty-based analysis and optimisations: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109889. [CrossRef]
23. Wilson, K.L.; Tittensor, D.P.; Worm, B.; Lotze, H.K. Incorporating climate change adaptation into marine protected area planning. *Glob. Chang. Biol.* **2020**, *26*, 3251–3267. [CrossRef] [PubMed]
24. Juan, X.; Ziliang, L.; Weijun, G.; Mengsheng, Y.; Menglong, S. The comparative study on the climate adaptability based on indoor physical environment of traditional dwelling in Qinba mountainous areas, China. *Energy Build.* **2019**, *197*, 140–155. [CrossRef]
25. Izadyar, N.; Miller, W.; Rismanchi, B.; Garcia-Hansen, V. Impacts of façade openings' geometry on natural ventilation and occupants' perception: A review. *Build. Environ.* **2020**, *170*, 106613. [CrossRef]

26. Ghosh, A.; Norton, B. Advances in switchable and highly insulating autonomous (self-powered) glazing systems for adaptive low energy buildings. *Renew. Energy* **2018**, *126*, 1003–1031. [CrossRef]
27. Qi, J.; Wei, C. Performance evaluation of climate-adaptive natural ventilation design: A case study of semi-open public cultural building. *Indoor Built Environ.* **2020**, *30*, 1714–1724. [CrossRef]
28. Li, Y.; Tong, Z. Development of real-time adaptive model-free extremum seeking control for CFD-simulated thermal environment. *Sustain. Cities Soc.* **2021**, *74*, 103166. [CrossRef]
29. Javad, K.; Navid, G. Thermal comfort investigation of stratified indoor environment in displacement ventilation: Climate-adaptive building with smart windows. *Sustain. Cities Soc.* **2019**, *46*, 101354. [CrossRef]
30. Hu, J.; Yu, X. Adaptive building roof by coupling thermochromic material and phase change material: Energy performance under different climate conditions. *Constr. Build. Mater.* **2020**, *262*, 120481. [CrossRef]
31. Gaspari, J.; Emanuele, N.; Caterina, P.; Adele, R. A Study on the Impact of Climate Adaptive Building Shells on Indoor Comfort. *J. Facade Des. Eng.* **2019**, *7*, 27–40. [CrossRef]
32. Vasigh, B.; Shiri, T. Climatic Adaptation of the Dome Body Based on Solar Radiation Received; Case Study: The Domes of Shah Mosque, Sheikh Lotfollah Mosque, Al-Nabi Mosque of Qazvin and Jameh Mosque of Urmia. *Arman. Archit. Urban Dev.* **2021**, *13*, 211–225. [CrossRef]
33. Sakiyama, N.; Carlo, J.; Frick, J.; Garrecht, H. Perspectives of naturally ventilated buildings: A review. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109933. [CrossRef]
34. Bensafi, M.; Ameur, H.; Kaid, N.; Hoseinzadeh, S.; Memon, S.; Garcia, D.A. Thermophysics Analysis of Office Buildings with a Temperature–Humidity Coupling Strategy Under Hot-Arid Climatic Conditions. *Int. J. Thermophys.* **2021**, *42*, 118. [CrossRef]
35. Kuru, A.; Oldfield, P.; Bonser, S.; Fiorito, F. Performance prediction of biomimetic adaptive building skins: Integrating multifunctionality through a novel simulation framework. *Sol. Energy* **2021**, *224*, 253–270. [CrossRef]
36. Fosas, D.; Coley, D.A.; Natarajan, S.; Herrera, M.; de Pando, M.F.; Ramallo-Gonzalez, A. Mitigation versus adaptation: Does insulating dwellings increase overheating risk? *Build. Environ.* **2018**, *143*, 740–759. [CrossRef]
37. Xu, W. Environmental Performance Optimization Design of Marine Climate Adaptive Green Public Buildings. *J. Coast. Res.* **2020**, *106*, 342–346. [CrossRef]
38. Xue, F.; Gou, Z.; Lau, S.S. Human Factors in Green Office Building Design: The Impact of Workplace Green Features on Health Perceptions in High-Rise High-Density Asian Cities. *Sustainability* **2016**, *8*, 1095. [CrossRef]
39. Jing, Q.; Li, J.; Li, L.; Jia, M.; Zhou, Y.; Zhao, X. Passive design of green public buildings adapted to cold climate: A case study of China pavilion of the international horticultural exhibition 2019 Beijing China. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *768*, 012130. [CrossRef]
40. Hong, Y.; Ezeh, C.; Deng, W.; Lu, J.; Ma, Y.; Jin, Y. Climate adaptation of design scheme for energy-conserving high-rise buildings—Comparative study of achieving building sustainability in different climate scenarios. *Energy Rep.* **2022**, *8*, 13735–13752. [CrossRef]
41. Manni, M.; Nicolini, A. Multi-Objective Optimization Models to Design a Responsive Built Environment: A Synthetic Review. *Energies* **2022**, *15*, 486. [CrossRef]
42. Upadhyay, A.K.; Yoshida, H.; Rijal, H.B. Climate Responsive Building Design in the Kathmandu Valley. *J. Asian Archit. Build. Eng.* **2006**, *5*, 169–176. [CrossRef]
43. Huang, Z.; Cheng, B.; Gou, Z.; Zhang, F. Outdoor thermal comfort and adaptive behaviors in a university campus in China's hot summer-cold winter climate region. *Build. Environ.* **2019**, *165*, 106414. [CrossRef]
44. Guo, Y.; Bart, D. Optimization of Design Parameters for Office Buildings with Climatic Adaptability Based on Energy Demand and Thermal Comfort. *Sustainability* **2020**, *12*, 3540. [CrossRef]
45. Lee, J.; Lee, K.S.; Lim, J. Passive Design Techniques Aplied to Green Buildings As An Aesthetic and Spatial Design Concept. *J. Green Build.* **2015**, *10*, 79–109. [CrossRef]
46. Cheng, Z.; Lei, N.; Bu, Z.; Sun, H.; Li, B.; Lin, B. Investigations of indoor air quality for office buildings in different climate zones of China by subjective survey and field measurement. *Build. Environ.* **2022**, *214*, 108899. [CrossRef]
47. Pan, L.; Xu, Q.; Nie, Y.; Qiu, T. Analysis of climate adaptive energy-saving technology approaches to residential building envelope in Shanghai. *J. Build. Eng.* **2018**, *19*, 266–272. [CrossRef]
48. Wu, H.; Zhang, T. Multi-objective optimization of energy, visual, and thermal performance for building envelopes in China's hot summer and cold winter climate zone. *J. Build. Eng.* **2022**, *59*, 105034. [CrossRef]

buildings

MDPI

Article

Green Building Consumption Perception and Its Impact on Fitness Service Purchasing Intentions: An Extended Institutional Analysis and Development Decision-Making Model Analysis

Yuyang Hou [1,†], Sen Chen [1,†], Zhenning Yao [1,†], Qian Huang [2,*], Xinyi Shen [1], Luning Cao [1], Junyang Cheng [1], Fuwei Gui [1], Yujie Zhang [1] and Xinbo Wang [1]

[1] Graduate Department, Xi'an Physical Education University, Xi'an 710068, China; yuyanghou2424@163.com (Y.H.); rockychensen@126.com (S.C.); countship3@gmail.com (Z.Y.); sxy1997713@163.com (X.S.); cln1999@126.com (L.C.); cjy109917@163.com (J.C.); gfw0305@126.com (F.G.); 19909453720@163.com (Y.Z.); 18392557108@163.com (X.W.)
[2] Department of Sports Training, Xi'an Physical Education University, Xi'an 710068, China
* Correspondence: huangqian168@126.com
† These authors contributed equally to this work.

Abstract: Green buildings play a pivotal role in advancing ecological civilization and promoting green, low-carbon development. Numerous studies have delved into the construction techniques, process attributes, economic benefits, risk management, and benefit assessments associated with green buildings. Concurrently, research on the profitability models, marketing strategies, and public purchasing intentions of commercial fitness clubs has also yielded extensive findings. Yet, there is a noticeable gap: limited research has investigated the nexus between green building development and consumers' propensity to purchase fitness services from these commercial establishments. Building upon the foundation set by previous scholars and employing the Extended IAD Decision-Making Model, this study utilizes the PLS-SEM method to analyze collected questionnaire data. Through path analysis, we examine the relationships between variables. Our findings indicate that: (1) Positive perceptions of green building consumption bolster the purchasing intentions toward fitness services in commercial fitness clubs. (2) Perceived risk mediates the relationship between green building consumption perceptions and consumers' fitness service purchasing intentions in commercial fitness clubs. (3) Environmental awareness enhances the correlation between green building consumption perceptions and the propensity to purchase services in these clubs. The goal of this research is to underscore the importance of green buildings both in environmental and economic contexts and to offer insights that can elevate the profitability of commercial fitness clubs.

Keywords: green building; commercial fitness clubs; PLS-SEM method; perceived risk; environmental awareness

1. Introduction

According to economic data, the contribution rate of consumption expenditure in China's GDP growth in 2016 was as high as 64.6%, which is close to the average level of developed countries [1]. Thus, along with the fundamental transformation of China's economic structure and growth mechanism, consumption has replaced investment as the most important driving force for economic growth [2]. In recent decades, the world fitness service industry has undergone revolutionary changes in terms of scale and business management concepts, and more and more people have regarded sports and fitness consumption as a way of life, rather than as an experimental consumption in the past [3]. As a whole, the development of China's fitness service industry now presents three main features: First, China's fitness service industry is still in the stage of survival of the fittest and internal competition; second, the fitness industry is still in the continuous "reshuffle", meaning that the fitness industry in the business strategy and marketing strategy is still based on conservative management; third, the fitness industry needs of the consumer. More and more diversified consumer enthusiasm for fitness consumption continues to rise. Therefore, it is worth thinking about and exploring how the fitness and leisure service industry can respond to the new changes and demands of consumers in fitness and leisure consumption under the background of consumption upgrading, how to accurately locate the value orientation of the new generation, how to reconstruct the organizational structure of the fitness and leisure service, and how to create a change in the content system. From a macroscopic perspective, economy is the basis of sustainability, environment is the condition of sustainability, and society is the purpose of sustainability. Consequently, the fitness and leisure service industry must refine its industrial system, champion ecological civilization, and emphasize the harmonization of economic, environmental, and societal factors to foster the industry's ecological advancement [4].

Commercial health clubs, as specific places where people provide exercise and fitness services, are an important component of the fitness service industry. Commercial clubs and their related business activities offer strength exercise equipment, aerobics classes, or other sports and programs as their main service content, encompassed by the goal of providing fitness services for people's fitness businesses. With the 2020 pneumonia epidemic, the topic of physical health research has attracted renewed interest [5]. Reviewing the domestic and international research results on physical fitness, they are mainly reflected in the six major aspects of physical fitness engineering, physical fitness clubs, physical fitness services, physical fitness market, physical fitness consumption, and physical fitness management [6]. The existing research on fitness consumption mainly focuses on fitness consumption demand, fitness consumption ability, fitness consumption experience effect, fitness consumption subjective sense of well-being, and consumer behavior driving force [7–9]. Among them, the research on consumers' willingness to purchase fitness services mainly focuses on two aspects, namely the demand side of commercial fitness consumption and the supply side of commercial fitness consumption [10,11]. This study encompasses four primary dimensions on the demand side: the service quality and awareness of commercial clubs, satisfaction with equipment and facilities, service variability, and the expression of class culture. On the supply side, it focuses on three aspects: the business strategies and revenue streams of commercial clubs, the ability to retain customer resources, and the adaptability in integrating Internet technology. These considerations are grounded in the subsequent research findings.

From an anthropological perspective, the primary unit of the social ecosystem is the individual. While natural conditions provide the essential material foundation for system functionality, it is through environmental interactions that individuals enhance their living conditions, fostering a harmonious relationship between humanity and nature. In practice, humans leverage advancements in science and technology to enhance the efficiency of production tools, thereby progressively minimizing resource expenditure [12]. The green building is one of the outstanding products of the harmony between man and nature. Since the Chinese government officially released the green building evaluation standard in 2007, the development of green buildings in China has ushered in a brand new stage. By the end of 2020, a total of 930 million square meters of buildings in China have been certified as green buildings, and the development of green buildings in China has gradually come into a mature stage from the initial start-up stage. A green building adheres to the concept of sustainable and healthy development, and its connotation lies in the safety and environmental protection of the whole life cycle from program design to later operation [13]. The green building is an inevitable trend in the development of the construction industry, which helps to ease the pressure imparted on environmental resources brought by high energy consumption, high pollution, and rough management, while achieving green development [14]. Under the premise of ensuring health, comfort, and safety, the green building integrates the concept of energy-saving design, the use of pollution-free materials, a construction process that is green and environmentally friendly, a green and sustainable mode of operation (so as to maximize the protection of the environment), and the successful implementation of the concept of green building design, which can enable major cities to ensure a healthy road to sustainable development. Consumers choose to go to commercial fitness clubs to participate in fitness consumption, partly in order to receive more scientific fitness guidance, but mainly to enhance their physical and mental health. The concept of sustainable and healthy development of green buildings is precisely unified with the concept of people's fitness consumption, so an in-depth exploration of the internal role of the relationship between the two to stimulates the enthusiasm of the fitness service consumers, promotes the healthy development of fitness services, and enhances the necessary profitability of commercial fitness clubs.

Green buildings prioritize health, comfort, and safety by integrating energy-efficient design, utilizing non-polluting materials, and adopting environmentally friendly construction processes. Their operational mode is sustainable, aiming to minimize environmental impact. Implementing green building concepts can guide major cities toward sustainable and healthy development pathways. Consumers attend commercial fitness clubs primarily for expert fitness guidance and overall well-being. The principles of green building, emphasizing sustainable and healthy development, align with the motivations behind fitness consumption. Therefore, examining the interplay between these concepts can invigorate public enthusiasm for fitness, bolster the growth of fitness services, and enhance the profitability of commercial fitness clubs. In essence, green buildings offer spaces that are health-centric, comfortable, energy-efficient, and environmentally benign. They embody the principles of sustainable development, harmoniously blending innovative designs with features like natural ventilation, daylighting, energy-efficient structures, solar energy utilization, eco-friendly materials, and smart controls. This synergy showcases the balance between humanistic values, architectural design, and technological advancements. The pertinent questions are: Does a green building enhance the appeal of commercial health clubs? Can green architectural designs boost people's inclination toward fitness services? What strategies can amplify this inclination? This research employs the extended IAD model, drawing from the theory of perceived risk, to develop a conceptual framework. This framework explores the mediating effects of perceived risk between green building design and the willingness to purchase fitness services in commercial clubs. Such insights can stimulate fitness participation and identify the key drivers of fitness consumption.

2. Literature Review and Research Hypotheses

2.1. Green Building Consumption Perceptions and Willingness to Purchase Fitness Services

Cognitive theory suggests that the degree of cognition plays an important role in the formation of behavioral willingness. A certain choice made by the consumer begins with a grasp of the relevant information about the product and the formation of a preliminary understanding of the product, added to a continuous accumulation of knowledge and information to perceive the overall value of the product, to finally end with the choice to consume [15].

Scholars in the academic world do not define green consumption perception in the same way, and most scholars define the connotation of green consumption perception based on the following two aspects: first, the consumer's perception of environmental issues, including mastery of environmental knowledge, environmental awareness, etc. For example, Biswas [16] defined green consumption perception as the value of the consumer's favorable impact on the environment through the adoption of green consumption behavior and the degree of understanding of green product information. Second, the consumer's awareness and understanding of green products, including the degree of understanding of specific product information such as the concept of green product design or green certification. The second is the degree of the consumer's knowledge and understanding of green products, including the degree of knowledge of green product design concepts or green certification and other product-specific information. For example, Rauchow [17] defines green consumption perception as the degree of the consumer's understanding of the benefits of participating in green consumption and their knowledge of green labels such as eco-labels. Based on this, this study combines the concepts related to green consumption perception and defines consumer green building consumption perception as the degree of consumer understanding of green concepts such as the functions and connotations of green buildings in health clubs.

As scholars in various fields continue to explore the research related to green consumption perception, different scholars classify green consumption perception into different dimensions from different research perspectives, and thus the way of classifying and measuring green consumption perception by scholars is also different. For example, Sivek et al. [18] divided green consumption perception into general environmental perception and specialized environmental perception. General environmental perception can prompt consumers to pay more attention to the environmental value of consumption objects, while specialized environmental perception can enhance consumers' awareness of the environmental crisis and make them more actively participate in environmental consumption. Hirsh et al. [19] divided green consumption perception into environmental perception and green product perception based on the green product consumption market, and the study showed that both environmental perception and green product perception can predict consumers' willingness to engage in green behaviors. Kwon et al. [20] measured green consumption perception based on the perspective of environmental cognition and divided green consumption perception into two categories, namely environmental knowledge and environmental awareness, from the point of view of the environmental knowledge and environmental awareness that consumers have learned and worked on in the process of study and work. In summary, the way scholars divide and measure green consumption knowledge in the existing studies differs from each other, such as some scholars divide and measure green consumption perception from a single perspective, and some scholars carry out related studies from multiple perspectives, but regardless of these differences, scholars essentially explore green consumption perception around the two aspects of green environmental protection perception and green product cognition. Therefore, combining the previous scholars' research, this study coalesces the connotation of green building consumption perception into green building value perception, i.e., the consumer's accumulated knowledge that a green building is beneficial to environmental protection; and green building function perception, i.e., the consumer's understanding of a green building as a consumption object and their degree of functional cognition.

At the same time, existing studies on the specific links between green consumption perception and consumers' purchase intention are almost always explored from four perspectives: functional value, emotional value, social value, and environmental value. (1) Green consumption functional value perception and purchase intention. The functional value perspective focuses on consumers' perceptions of the price, quality, safety, and durability of the products they choose. For example, the findings of Biswas et al. [16] and Goncalves et al. [21] show that the perception of functional value positively affects the willingness to buy of consumers in India and Portugal. (2) Green consumption emotional value perception and purchase intention. Emotional value perspective focuses on consumers' emotional feelings of satisfaction when choosing, purchasing, and using products or services; therefore, emotional value can play a crucial role in promoting green product purchase intention. For example, the research of Nalchy et al. [22] shows that, when consumers have positive emotional attitudes toward a product or brand, such emotions can lead consumers to repeat a purchase of the same product or brand. (3) Green consumption social value perception and purchase intention. As exemplified in ref. [23], social value refers to the social benefits that consumers reap from the products or services they buy, specifically including the relationship between consumers and nature and the relationship between consumers and others; the relationship between consumers and nature refers to the impact that consumers have on nature through their consumption behaviors, while the relationship between customers and others refers to the impact that purchasing behaviors have on the customers' personal image. The study of Finch pointed out that the characteristic of improving self-image by purchasing green products may have a significant impact on consumers' green consumption behavior. (4) Perceived environmental value of green consumption and purchase intention. Purchasing green products represents the consumers' active pursuit of ecological value, and environmental value is the consumers' own assessment of the value and benefits of green products' environmental protection function. As Chen [24] and others have pointed out, green value is the value that consumers constantly weigh from the perceived environmental utility of green products and the costs they pay to judge the green value of the product, which in turn generates the willingness to consume and influences consumption behavior.

Scholarly research shows that the consumers' systematic cognition of environmental issues and specific cognitive ability regarding green products are the prerequisite and foundation for generating green consumption perceptions and the starting point for generating purchase intentions. Based on this, consumers with high green building consumption perception can enhance their own sense of acquisition, participation, and other subjective efficacy perceptions through information collection, peer influence, or personal participation, so that consumers perceive that they have a greater sense of responsibility and influence, and that participation in consumption can have more benefits, which will help to form the willingness to consume and generate consumption behavior. Therefore, the following hypothesis is proposed:

Hypothesis 1. *Green building consumption perceptions positively contribute to the willingness to purchase fitness services in commercial health clubs.*

2.2. Green Building Perceived Risk and Willingness to Purchase Fitness Services

The application of the term risk in the field of scientific research first originated in the economics research in the 1920s, and then this concept was gradually extended to finance, sociology, marketing, and so on. At that time, the term risk was used in the research to represent the subjective feelings based on the objective unknowability in the process of consumption. Perceived risk was firstly applied to the marketing field by marketing scholar Bauer [25] from the field of psychology who, based on the theory of limited rationality and satisfaction theory, organically combined the concept of perceived risk with the research related to consumer behavior, and defined the perceived risk so that it gained wide attention. Bauer's understanding of perceived risk reflects two characteristics of perceived risk: first, the uncertainty of the outcome of the behavior, i.e., consumers do not know in advance whether the outcome of the decision is in line with their expectations, and second, the severity of the outcome, i.e., consumers do not know in advance whether the outcome of the decision is in line with their expectations. Bauer's "uncertainty theory" has been widely recognized and used by academics, but unlike his "uncertainty theory", some scholars have adopted the "loss theory" as the basis for their understanding of perceived risk. For example, Mauricio et al. [26] argue that perceived risk is some type of loss that consumers may suffer when they expect the outcome of their purchasing behavior.

At the same time, with the continuous development of marketing, scholars have gradually reached a relative consensus on the dimensional division of perceived risk, and the current research on perceived risk is mostly based on the dimensions contained in the perceived risk. For example, Cox [27] specifies the concept of perceived risk, and he points out that, when the consequences of consumers' purchasing behavior do not meet their goals or when the consequences of consumption have adverse effects, perceived risk arises, so he focuses on consumers' pre-consumption goals, and divides the perceived risk into two dimensions: on the one hand, it is the risk that is predicted before the purchasing behavior occurs, and on the other hand, it is the adverse effects that are generated after the purchasing behavior occurs. With the development of marketing, scholars have further subdivided the dimensions of perceived risk, for example, Cunningham [28] believes that perceived risk includes product performance, physical damage, financial damage, loss of time, or social consequences, etc.; Stone et al.'s study [29] will divide perceived risk into six constructs of risk such as physical, performance, financial, temporal, social, and psychological. On the basis of their predecessors, contemporary scholars have been condensing the different dimensions of perceived risk, and the dimensional division of perceived risk and the measurement angle have gradually become more consistent, for example, Woodside [30] divides the perceived risk into social, functional, and economic dimensions. Some other scholars have subdivided perceived risk according to different research contexts, but most of the studies generally agree that perceived risk includes financial risk, physical risk, and psychological risk [31].

Numerous research results have shown that there are a large number of risk factors which will have an impact on the consumer's willingness to buy or their purchase behavior. Among the many risk factors, there is the fact that the consumer's decision to buy a product or service will inevitably take into account the elements of the risk to be borne. One viewpoint in the field of marketing suggests that the trade-off between perceived value and perceived risk is the key to the consumer's decision of whether to make a purchase; another viewpoint suggests that the level of perceived risk is an important psychological evaluation criterion in the consumer's decision of whether to make a purchase. This study focuses on the second point of view, and although scholars have not reached a unified conclusion on the relationship between willingness to buy and perceived risk, most scholars believe that willingness to buy is significantly negatively correlated with perceived risk. For example, Murray [32], in his study on the purchase process of service products, clearly points out that there is a significant negative correlation between user-perceived risk and user willingness to buy, i.e., the higher the degree of user-perceived risk, the lower the user's willingness to buy service products. In terms of the perceived risk of green products and consumers' willingness to buy, previous scholars have also obtained similar conclusions, such as Mandal et al.'s [33] study, which suggested that the psychological risk perceived by consumers when purchasing green products is different from that of purchasing traditional products, and the reason for such risk is that the health or environmental protection function of the green product fails to meet the psychological expectations of the consumers, which is partly the mental pursuit generated by the independent thoughts and positive expectations of individual consumers. This part of the psychological expectation is the consumers' personal independent thoughts and positive expectations generated by the spiritual pursuit, so the negative impact on the consumer's willingness to consume is also greater. ODonovan et al.'s [34] research also found that, in the context of consumer's purchase of green brands or green consumption, often the green product purchase is not a decision that is easy to influence.The higher cost of green products compared to ordinary products and the limited access to green products, among other disadvantages, make consumers prone to negative evaluations and thus negative attitudes. For example, Kasterine [35] points out that part of the reasons why consumers choose to buy green products may be due to the pressure of ethical norms on environmental protection or the pressure of their roles in the social network, etc. A considerable portion of consumers will pay some attention to green products out of ethical considerations, that is to say, the perceived ethical risk affects the purchasing behavior of consumers to a certain extent. The research of Priester et al. [36] also shows that consumers may have ambivalent attitudes when they have low evaluations of the price factor, perceived value, availability, access to information, and credibility of green products. After the ambivalence, consumers may experience significant psychological discomfort and conflict, making them hesitant.

In summary, green building design represents a new environmental endeavor favorable to public health. As such, the "double health" effect of commercial fitness clubs adhering to green building criteria, as well as offering sport and fitness services, becomes a key marketing selling point. However, the green building, as a novel entity, triggers in consumers curiosity as well as doubts about its function or utility and other aspects, which can be summarized as follows: (1) Consumers have psychological uncertainty about whether the green building of the fitness club is damaged, due to the fact that green buildings may exhibit design, manufacturing, or decoration defects. (2) Compared with other traditional fitness clubs, the consumer price of green building fitness clubs may be higher than the price of other traditional fitness clubs. Green building fitness clubs may therefore bring greater economic losses to consumers. (3) Green buildings adopt new technologies, new techniques, or use new raw materials, so green buildings have some green performance characteristics that distinguish them from non-green buildings. Before consumption, consumers will take the initiative to understand the functional characteristics of green buildings for reasons such as curiosity, etc., and will have certain psychological expectations for the future consumption experience, which will cause greater harm if the special functions or service quality of the green building fitness clubs fail to meet the consumers' expected results. Therefore, the following hypothesis is proposed:

Hypothesis 2. *The consumers' perceived risk of green buildings in commercial health clubs has a negative inhibitory effect on their willingness to purchase fitness services.*

2.3. Perceived Green Building Consumption in Commercial Health Clubs and Perceived Risk to the Public

Environmental stimuli can stimulate and influence consumers' internal thoughts and perceptual states, making them engage in positive or avoidance behaviors in the purchasing process [37]. In contemporary society, merely relying on product or service quality is insufficient for providers to secure a competitive edge. To effectively capture consumer attention, it is imperative to understand and cater to their preferences. Continuous communication is essential to foster strong relationships. Furthermore, pinpointing the primary determinants of consumer value and monitoring real-time dynamics are crucial for sustained consumer attraction and enhanced business efficiency. A review of the existing research on the correlation between green consumer perception and perceived risk reveals three primary dimensions: the green value perspective, the personal perception perspective, and the information acquisition perspective.

Almost all scholars who conducted research centered on green perception believe that the more green knowledge consumers have, the more they can enhance the perceived value of green products, which in turn reduces consumers' worries and enhances their willingness to buy. For example, Sun Jian et al. [38] found that the consumers' knowledge of green products has a greater impact on their willingness to buy, and that the more knowledge or experience consumers accumulate about green products, the deeper their perception of green products and the more positive their willingness to buy. Sun [39] also pointed out that, after consumers have accumulated a certain degree of knowledge about environmental protection, they will form a deeper perception of environmental protection, which will motivate them to rationally choose consumer products, and thus be willing to pay more for green products. Sun also pointed out that, after accumulating a certain degree of environmental knowledge, consumers will form a deeper level of environmental perception, which will encourage them to rationally choose consumer products, and thus be willing to pay more for green products. Yadav et al. [40], based on the Indian green product consumer market, show from their research results that environmental awareness and knowledge have an impact on consumer attitudes, subjective norms, and cognitive control, which in turn drive consumers' green purchasing intentions.

Scholars who have conducted research centered on individual perception have focused on monitoring the changes in consumers' consumption psychology in response to changes in the external environment or the transaction process, such as RAMBALAK et al. [41] who observed that environmental knowledge is a key factor influencing consumers' consumption psychology and consumption behavior, and that this factor will affect the entire process of consumers making purchases. And Mitchell et al. [42] argued that perceived risk varies at different stages of the consumer's buying process. In the initial awareness stage, the perceived risk level gradually increases; after searching for information and deepening their understanding, the perceived risk level gradually decreases; in the stage of making purchase decisions, the perceived risk level slightly increases; in the stage of post-purchase evaluation, if they are satisfied with the shopping process, the perceived risk level will decrease rapidly. ZOU et al. [43] also showed that most consumers believe that they have the obligation to protect the environment, and therefore need to contribute to environmental protection, i.e., consumers' own green cognition will transform their concern for the environment into actual green consumption behavior; therefore, once consumers have a sense of ethical identity, it will have a direct effect on their willingness to consume in a green way, and thus generate the willingness to purchase to complete the purchasing behavior.

Scholars who conduct research centered on the perspective of information acquisition argue that the link between consumers' consumption cognition and their perceived risk is based on the perspective of information transmission and information collection. For example, Paul [44] argues that information asymmetry is an important reason for consumers to feel risky and indecisive when choosing, and that continuously garnering product information and deepening their understanding of the product by searching for other people's evaluations can reduce uncertainty and perceived risk. Another study by Nepomuceno [45] and others also pointed out that, when consumers want to buy a certain product, they will search for information about the product through various methods to reduce the occurrence of consumption risk.

Green building fitness services, characterized as experiential products, fall within a unique category. The dual nature of these services, both tangible and intangible, intensifies consumers' concerns regarding the perceived value of fitness services offered by green building fitness clubs and the associated risk of not meeting consumer expectations. A comprehensive service description, detailed information, and a holistic service display can enhance the perceived value for consumers considering fitness services in green buildings, subsequently reducing their perceived risk.

The stimuli related to green building information act as catalysts for consumers' cognitive and emotional responses. These stimuli encompass various elements, including the fitness club's environmental design, the distinctive features of the green building, environmental protection principles, service quality, user evaluations, and more. Together, these elements shape the consumer's perception of green building consumption. The perception of green building consumption can be viewed as a balance between perceived gains and losses. Losses encompass all costs borne by consumers when purchasing fitness services in green building fitness clubs. Gains, on the other hand, include tangible assets, fitness service attributes, technical support, pricing, and other elements that contribute to the perceived value of the products or services. This study posits that consumer attitudes toward green building fitness clubs influence their risk perception. However, due to varying information sources, either online or offline, a herd effect may emerge. This effect can alter consumers' value perception of the fitness club's green building attributes, subsequently influencing their risk perception related to green buildings and ultimately affecting their purchase intentions. Based on this, we propose the following hypotheses:

Hypothesis 3. *Consumers' perceptions of green building consumption in commercial health clubs have a negative inhibitory effect on their perceived risk.*

Hypothesis 4. *Perceived risk mediates the relationship between consumers' perceptions of green building consumption in commercial health clubs and their willingness to purchase fitness services.*

2.4. The Moderating Role of Environmental Awareness

Environmental awareness is an individual's incorporation of green concepts into his/her self-consciousness, which reflects his/her concern for the environment [46]. Relevant studies have shown that environmental awareness can motivate individuals to change their own behavior and habits, so as to show their own sense of environmental responsibility and achieve environmental protection purposes. This is because environmental awareness, as a kind of green coordinating value, can make consumers with strong environmental awareness have a greater sense of green responsibility, which is more likely to motivate individuals to implement green behaviors to achieve environmental protection purposes. For example, the study by Balderjahn [47] directly points out that good environmental awareness and attitudes motivate consumers to purchase and use eco-friendly products.

Consumers will produce corresponding consumption feelings after consumption, and such consumption feelings can be roughly divided into two levels, namely the material level and the spiritual level. The material level is the consumption feelings about the use value of the purchased goods, such as function, quality, etc., which is the most basic level in the composition; the spiritual level pays attention to the extensiveness of the consumption process, which specifically refers to the degree of contribution to the social development that the consumers experience in the process of purchasing the products or services. The spiritual level is concerned with the extensiveness of the consumption process, specifically the degree of their own contribution to social development experienced by consumers in the process of purchasing products or services, such as the moral value and ecological value of products or services. At the same time, the occurrence of consumers' green consumption behavior is influenced by the internal thoughts of individuals, and environmental awareness makes human behavior have a series of characteristics such as directionality, purposefulness, regulation, and constraints, which prompts consumers to select product or service information in a directional way from a green perspective, selectively choose the target products or services, and regulate and control their own consumption behavior in a purposeful way.

The self-determination theory was proposed by American psychologists Deci and Ryan in the 1980s, emphasizing the dynamic role of self-consciousness in the individual's action process. The self-determination theory suggests that an individual's internal drive, intrinsic needs, and self-emotions are the sources of motivation for self-determined behavior. Therefore, when consumers' environmental awareness is high, consumers will better appreciate the favorable impacts of green buildings, and the more the degree of self-identification is elevated, the more they will participate in green building fitness consumption; when consumers' environmental awareness is low, consumers are likely to ignore the environmentally friendly features of green buildings, and their self-identification is low, resulting in their willingness to purchase green building fitness services also being low. Therefore, the following hypotheses are proposed:

Hypothesis 5. *Environmental awareness has a positive moderating effect between consumers' commercial health club green building consumption perceptions and fitness service purchase intentions.*

In summary, this study uses the IAD extended decision model as the modeling logic, wherein the consumer's green building consumption perceptions serve to represent the conditional control, the consumer's perceived risk of green building fitness clubs serves to represent the external environment and the participant's judgment of the net benefit, and the hypothetical model, which is shown in Figure 1, is proposed.

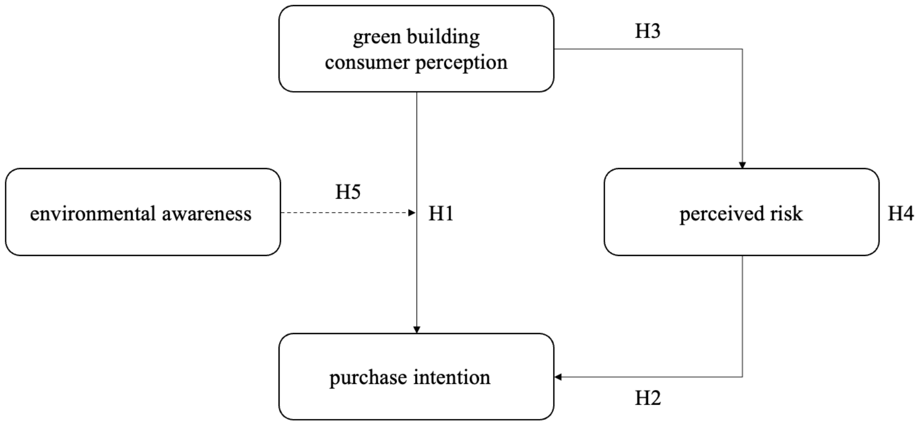


Figure 1. Diagram of the hypothetical model.

3. Study Design

3.1. IAD Extended Decision Model

The extended IAD (Institutional Analysis and Development framework) model proposed by Elinor Ostrom [48,49] (Figure 2), which is the core of the IAD model, is centered on the participant's intellectual decision-making model, and its core connotations are as follows: In addition to the external environment and cultural influences, on the one hand, the participant's decision-making is influenced by information about the participant's situation, condition control, net benefits, and the participant's perception of these conditions. In addition to external environmental and cultural influences, on the one hand, the participants' decisions are influenced by information about the participants' situation, the control of the conditions, the net benefits, and the participants' perception of these conditions, and on the other hand, by the extent to which the participants know the actual final outcome before they act.

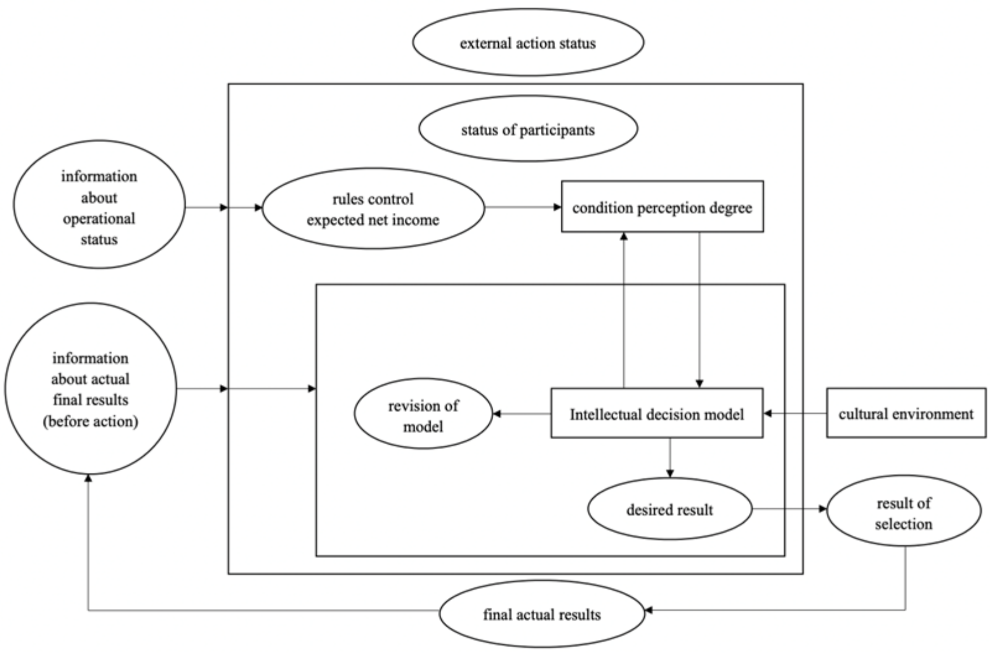


Figure 2. Diagram of the IAD extended decision model.

This research aims to examine consumers' inclination to engage with fitness services offered by green building fitness clubs. It seeks to contextualize the elements of the extended IAD model by considering various factors present in the green building consumption process. The subsequent analyses will utilize the basic consumer profile to depict the participant's status, the consumer's perception of green building consumption as a measure of condition control, and the consumer's perceived risk associated with green building fitness clubs to represent both the external and cultural environments, as well as the participant's assessment of the net benefits.

3.2. Data Sources

This study mainly takes the form of online distribution of electronic questionnaires. The electronic questionnaires are mainly distributed and recovered through WeChat APP, and in order to ensure the representativeness of the research samples, this study adopts the quota sampling method to carry out the research work. The specific questionnaire distribution time is April 2023, during which a total of 400 questionnaires were distributed, of which 392 questionnaires were retrieved, and after excluding invalid questionnaires, a total of 363 valid samples were obtained, so the validity rate of the questionnaire was 90.75%.

In terms of scales and questionnaire items, the dependent variable of this study refers to the well-established research scales of Fishbein et al. [50] and Sheng Guanghua et al. [51] for fitness service purchase intention. The independent variable of green building consumption perception refers to the well-established research scales of Jaiswal et al. [52] and Chan et al. [53]. The mediator variable of perceived risk refers to the well-established research scales of Séquier [54] et al. and Stone et al. [55]. The moderator variable of environmental awareness refers to the well-established research scales of Ballantyne et al. [56] and Schill et al. [57]. The scales in this study are all based on the mature scales of previous scholars, adjusted and modified to the format of the questions according to the characteristics of green building clubs and fitness services. The scales in this study all adopt the Likert-5 point scoring method.

3.3. Analytic Strategy and Reliability Tests

3.3.1. Analytical Strategies

In this study, we employed the Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS 4.0 software for model validation. PLS-SEM is an iterative estimation technique that integrates principal component analysis, canonical correlation analysis, and multiple regression for causal modeling. This method extracts principal components for specific variables associated with different latent variables, incorporates them into the model, and then refines the principal component weights to optimize the model's predictive capability. Given its superior ability to handle multivariate complex structural models, PLS-SEM was chosen over the covariance-based CB-SEM approach.

3.3.2. Reliability Test

The evaluation of the measurement model includes reliability analysis and validity analysis. The reliability analysis of this study uses Cronbach's Alpha reliability coefficient to verify the degree of consistency of the questionnaire research variables on each measurement item. Academic research has shown that variables have good reliability when Cronbach's Alpha coefficient is greater than 0.7 [58]. As shown in Table 1, the reliability of Cronbach's Alpha coefficient of each variable in this study is greater than 0.7, which indicates that the reliability of each variable in this study is good.

Table 1. Structural reliability and validity analysis.

Variable	Item	Questions	Factor Loading	Cronbach's Alpha	CR	AVE
Environmental Awareness (EA)	EA11	You will take the initiative to understand or learn something about environmental protection in your life and improve your environmental protection ability.	0.829	0.890	0.919	0.649
	EA12	You will spontaneously adopt environmentally friendly behaviors in your life and work.	0.854			
	EA13	You encourage your family, friends, and colleagues to adopt more environmentally conscious behaviors.	0.834			
	EA14	You are aware of the environmental initiatives promoted by the media.	0.810			
	EA15	You maintain a positive attitude toward environmental protection or green efforts.	0.836			
Green Building Consumer Perception (GBCP)	GBCP31	You think participating in green building commercial fitness club is good for the environment.	0.890	0.925	0.944	0.770
	GBCP32	You are more concerned about the green value, and you believe that consuming fitness services in green building commercial fitness clubs is beneficial to the ecological environment.	0.891			
	GBCP33	You think you have a responsibility to choose green building commercial fitness clubs to experience fitness services over ordinary fitness clubs.	0.843			
	GBCP34	Participating in fitness in green building commercial fitness clubs is consistent with your fitness program and you will be immersed in it.	0.909			
	GBCP35	You believe that participating in green building commercial fitness clubs helps you to improve your personal image and receive more recognition from others.	0.853			
Perceived Economic Risk (PER)	PER21	You will be concerned about excessive financial loss if the green building commercial fitness club service experience does not meet your requirements.	0.878	0.870	0.911	0.720
	PER22	You may be concerned that the green building commercial fitness club is not value for money.	0.870			
	PER23	You will be concerned about the possibility of discounts or price reductions that may occur soon after the purchase of the green building commercial fitness club fitness service.	0.834			
	PER24	You will be concerned about the true value for money of the green building commercial fitness club.	0.811			
Purchase Intention (PI)	PI21	You will be willing to buy the services of green building commercial fitness clubs if you have the need to buy fitness services.	0.875	0.825	0.895	0.740
	PI22	You would recommend green building commercial fitness clubs to your friends when they need fitness services.	0.847			
	PI23	Green building commercial fitness clubs are an ideal place for you to spend your money on fitness services.	0.859			

Table 1. *Cont.*

Variable	Item	Questions	Factor Loading	Cronbach's Alpha	CR	AVE
Perceived Safety Risk (PSR)	PSR11	You may be concerned that the technology associated with green building commercial fitness clubs is immature, flawed, or defective.	0.881	0.860	0.905	0.704
	PSR12	You may be concerned about potential safety issues associated with green building commercial fitness clubs.	0.802			
	PSR13	You may be concerned that participation in a green building commercial fitness club is closely related to your health.	0.809			
	PSR14	You are concerned about whether a green building as a selling point for a fitness club is beneficial to your physical and mental health.	0.862			
Perceived Utility Risk (PUR)	PUR21	You may be concerned that the specific features or functionality of the green building commercial fitness clubs do not match what is being advertised by the business.	0.869	0.845	0.906	0.763
	PUR22	You may worry that the unique green features of green building commercial fitness clubs cannot meet your expectations.	0.883			
	PUR23	Green building is a new thing, you may worry that its function is not stable.	0.868			

3.3.3. Validity Tests

Validity analysis is assessed on the basis of convergent validity and discriminant validity. Convergent validity refers to the degree of similarity of measurement results when different measures are applied to determine the same characteristic, i.e., different measures should converge in the determination of the same characteristic. AVE is a reliability evaluation index of the ability to comprehensively account for the variable. The magnitude of the AVE value is able to reflect whether the latent variable is able to account for the ability of the measurement variable it corresponds to at the same time. When the average extracted variance (AVE) of a research variable is higher than 0.5, it means that this variable can explain more than 50% of the variance and has good convergent validity. CR is a measure of the consistency of the effects between the variables, and well-known scholars such as Nunnally believe that the value of CR should be greater than the criterion of 0.7. Therefore, this paper combines the experience of previous researchers, and in order to be able to successfully carry out the subsequent testing and analysis, the AVE is not less than 0.5 and the CR is not less than 0.7 as a measure of whether the latent variables designed in the present study have a good degree of convergence. As shown in Table 1, the factor loading of the various measurement topics is greater than 0.7, the CR value of the dimensions is greater than 0.7, and the AVE values are greater than 0.5, indicating that each dimension has good convergent validity.

The test of the discriminant validity of the measurement model can be conducted by applying the Fomell–Larcker criterion, which serves to test the discriminant validity by looking at the magnitude of the square root of the average variance extracted (AVE) and the correlation coefficients of the latent variables; if the square root of the AVE is greater than the correlation coefficients of the latent variables (i.e., the values on the diagonal are greater than the values on the non-diagonal), then it indicates that the latent variables in the measurement model have a good discriminant validity. As shown in Table 2, the square root value of the AVE of each variable is greater than the correlation coefficient between the variables, which indicates that there is discriminant validity between the variables.

Table 2. Distinctive validity test table.

	EA	GBCP	PER	PI	PSR	PUR
EA	**0.833**					
GBCP	0.372	**0.878**				
PER	−0.450	−0.591	**0.848**			
PI	0.440	0.712	−0.456	**0.861**		
P SR	−0.189	−0.537	0.321	−0.641	**0.839**	
PUR	−0.293	−0.622	0.380	−0.693	0.484	**0.873**

From the cross-loading coefficient results show in Table 3, we can find that the factor loadings of the variables of this study with large values fall on the measurement question items of the corresponding latent variables, thus meeting the cross-loading criterion, which further indicates that the variables have differential validity.

Table 3. Table of cross-loading factors.

	EA	GBCP	PER	PI	PSR	PUR
EA11	**0.829**	0.291	−0.374	0.316	−0.095	−0.208
EA12	**0.854**	0.292	−0.382	0.345	−0.107	−0.270
EA13	**0.835**	0.363	−0.383	0.386	−0.166	−0.232
EA14	**0.810**	0.257	−0.329	0.348	−0.185	−0.225
EA15	**0.836**	0.334	−0.401	0.420	−0.216	−0.277
GBCP31	0.366	**0.890**	−0.493	0.641	−0.481	−0.566
GBCP32	0.367	**0.891**	−0.552	0.653	−0.510	−0.582
GBCP33	0.256	**0.843**	−0.515	0.599	−0.448	−0.502
GBCP34	0.335	**0.909**	−0.539	0.650	−0.488	−0.577
GBCP35	0.302	**0.853**	−0.493	0.575	−0.424	−0.495
PER21	−0.407	−0.504	**0.878**	−0.393	0.256	0.330
PER22	−0.376	−0.558	**0.870**	−0.438	0.324	0.367
PER23	−0.382	−0.480	**0.834**	−0.389	0.295	0.306
PER24	−0.363	−0.454	**0.811**	−0.317	0.204	0.275
PI21	0.415	0.651	−0.417	**0.875**	−0.539	−0.616
PI22	0.356	0.582	−0.401	**0.847**	−0.580	−0.601
PI23	0.363	0.603	−0.359	**0.859**	−0.536	−0.570
PSR11	−0.169	−0.444	0.280	−0.581	**0.881**	0.427
PSR12	−0.116	−0.389	0.275	−0.475	**0.802**	0.376
PSR13	−0.142	−0.455	0.238	−0.518	**0.809**	0.397
PSR14	−0.200	−0.506	0.285	−0.570	**0.862**	0.420
PUR21	−0.261	−0.524	0.338	−0.598	0.361	**0.869**
PUR22	−0.273	−0.573	0.399	−0.622	0.471	**0.883**
PUR23	−0.233	−0.531	0.253	−0.594	0.432	**0.868**

In addition to the Fomell–Larcker criterion and the cross-loading approach to testing validity, recent studies have suggested the use of a newer test of discriminant validity proposed by Henseler. Traditional tests have the disadvantage of overestimating factor loadings and underestimating the relationship between variables, resulting in discriminant validity being more likely to pass the test, so Henseler proposed a superior test, the heterogeneity–monomorphism ratio (HTMT), which is the ratio of the means of the correlation of the indicators between different variables relative to the means of the correlation of the indicators between the same variables, and it is generally recommended that the HTMT between two variables be less than 0.85. As shown in Table 4, the values of HTMT between the variables in this study are less than 0.85. Therefore, it is again proved that the present measurement model has good discriminant validity.

Table 4. HTMT table.

	EA	GBCP	PER	PI	PSR	PUR
EA						
GBCP	0.405					
PER	0.510	0.655				
PI	0.508	0.813	0.534			
PSR	0.208	0.598	0.367	0.759		
PUR	0.335	0.701	0.438	0.829	0.565	

4. Findings

4.1. Descriptive Statistical Analysis

Table 5 shows the descriptive statistical results of the research samples of this study. First of all, from the basic information of the sample reflected by the control variables, with 363 valid samples in the gender composition, of which 172 men, accounting for 47.4%, and 191 women, accounting for 52.6%, the proportion of male and female samples is relatively balanced; in the age distribution, the majority is represented by 19–30 year olds, for a total of 163 people, accounting for 44.9%, and 31–40 year olds, for a total of 102 people, accounting for 28.1%. Although most of the samples were selected from young adults, all age groups were involved; in terms of marital status, 196 people were married, accounting for 54%, and 167 people were unmarried, accounting for 46%; in terms of self-assessment of health status, 197 people, accounting for 54.3%, thought that their own health was at a good level, and 166, accounting for 45.7%, thought that their own health was average or poor; in terms of the type of hukou, 137 people, accounting for 37.7%, came from the urban areas, and 137 people, accounting for 37.1%, came from the rural areas; in terms of education level, 280 people, accounting for 77.1%, had high school education or above, and 83 people, accounting for 22.9%, had less than high school education; in the research sample, 60.9% of the people had fitness habits or physical exercise habits, and 71.6% of the people had heard of green building. From the perspective of the overall descriptive statistical distribution of the sample demographic characteristics, the proportionate distribution of the sample data in this study is more reasonable and has a certain degree of data representativeness.

Table 5. Descriptive analysis of basic information.

Name (of a Thing)	Options (as in Computer Software Settings)	N Sample Size	Percentage
Distinguishing between the sexes	male	172	47.4
	female	191	52.6
(A person's) age	16–18	33	9.1
	19–30	163	44.9
	31–40	102	28.1
	41–50	52	14.3
	51–60	13	3.6
Marital status	married	196	54
	Unmarried	167	46
Self-assessed health status	favorable	197	54.3
	Fair or poor	166	45.7
Account type	municipalities	137	37.7
	Countryside	226	62.3
Educational attainment	Bachelor's degree or higher	280	77.1
	Less than high school education	83	22.9
Have a fitness habit or physical activity habit	yes	221	60.9
	no	142	39.1
Ever heard of green building	yes	260	71.6
	no	103	28.4

4.2. Structural Equation Modeling Analysis

4.2.1. Modeling

In this study, the PLS-SEM model was constructed on the basis of previous related studies, and the collected data were examined by the partial least squares method using SmartPLS 4.0 statistical analysis software. The partial least squares method belongs to the multivariate statistical data analysis method, which finds the best function match for a set of data by minimizing the square of the error, and is able to regressively model multiple dependent variables on multiple independent variables, and the test of the structural model includes the estimation of path coefficients and the value of R Square in PLS analysis. The path coefficients reflect the direction and degree of influence between the latent variables. The value of R Square reflects the degree to which the endogenous latent variables can be explained by the exogenous latent variables in the structural model, and also the explanatory power of the model. In the theoretical model constructed in this chapter, in order to verify the model and hypotheses proposed in this study, this study used the visualization Smart PLS 4.0 software to perform data analysis and calculated the significance of the path coefficients in the constructed model using the Bootstrapping = 5000 sampling method.

PLS-SEM, as a kind of structural equation modeling, has more relaxed requirements for data and higher practicality, and has a greater advantage in addressing complex causal relationships. In general, PLS-SEM can address general linear structural relationships as well as reactive and formative relational models, and in the face of interfering data and missing values, it can also carry out the interpretation of model relationships that provide better predictions. In this study, a model was constructed to test the hypotheses in accordance with the research hypotheses, and the specific model setup is shown in Figure 3.

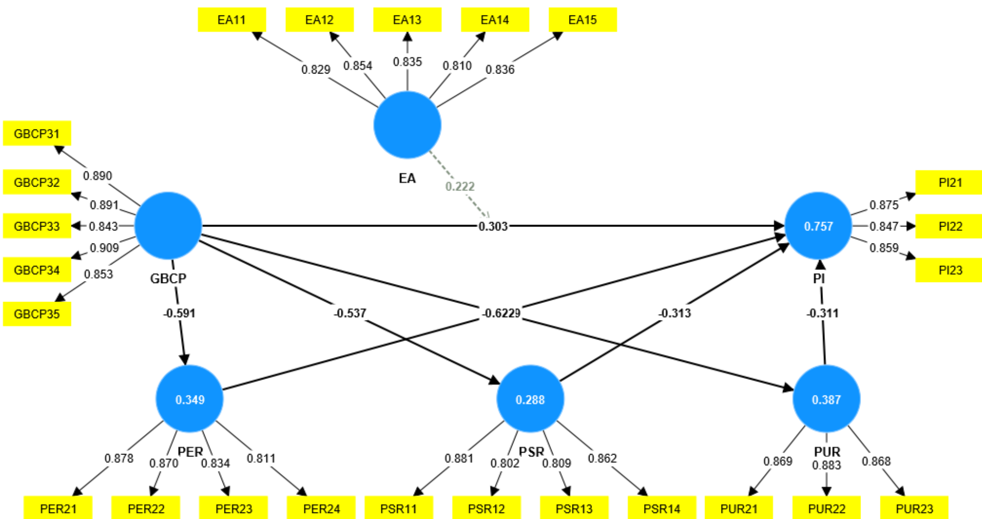


Figure 3. Model setup diagram.

4.2.2. Multicollinearity Test

Higher multicollinearity increases the parameter estimates and reduces the accuracy of the proposed model. To determine whether this indicator meets the requirements of the study, the variance inflation factor (VIF) is usually used for testing. As shown in Table 6, the variance inflation factor values of the variables designed in this study are less than 5, indicating that there is no serious multicollinearity among the variables.

Table 6. Multiple covariance test table.

	PER	PI	PSR	PUR
EA		1.328		
GBCP	1	2.386	1	1
PER		1.712		
PI				
PSR		1.486		
PUR		1.734		
EA × GBCP		1.085		

4.2.3. Model Evaluation

In order to visualize the fitness of the proposed model, SmartPLS 4.0 provides R Square, Q Square, and SRMR as reference indicators. Among them, R Square represents the proportion of variation in the dependent variable that can be explained by the independent variable, Q Square is to predict the correlation between the explicit variables, and SRMR is an important indicator of model fitness. In this study, Bootstrapping sampling 5000 times and the Blindfolding algorithm were used to derive the correlation evaluation indices of the structural model, and the results of the data analysis showed the following: the R Square of each variable in this study was in the range of 0.288–0.757, which indicated that the variables had a better explanatory power; the Q Square was in the range of 0.2–0.542, all exceeding the 0 limit level; the SRMR value is 0.048, which is lower than the limiting level of 0.08. The results of the above analysis indicate that the proposed model in this study has good explanatory power and predictive power (as shown in Table 7).

Table 7. Structural model evaluation form.

	R-Square	Q-Square	SRMR
PER	0.349	0.247	0.048
PI	0.757	0.542	
PSR	0.288	0.200	
PUR	0.387	0.291	

4.3. Hypothesis Testing

4.3.1. Overall Path Factor

According to the results of data analysis in Table 8, the hypotheses H1, H2, H3, H4, and H5 are valid in the preliminary stage of this study. Specific exhaustive path analysis and hypothesis testing results are as follows:

H1: *There is a significant positive effect of green building consumption perception on consumers' willingness to purchase fitness services in commercial health clubs ($\beta = 0.591$, $p < 0.05$), and the hypothesis is valid.*

H2: *Perceived economic risk does not have a significant negative effect on consumers' willingness to purchase commercial health club fitness services ($\beta = -0.009, p > 0.05$), and the path is not valid; perceived security risk has a significant negative effect on consumers' willingness to purchase commercial health club fitness services ($\beta = -0.313, p < 0.05$); perceived utility risk has a significant negative effect on consumers' commercial health club fitness service purchase intention ($\beta = -0.311, p < 0.05$), which has a significant negative effect, and the hypothesis is valid.*

H3: *Green building consumption perception has a significant negative effect on consumer perceived economic risk ($\beta = -0.591, p < 0.05$), and the hypothesis is valid; green building consumption perception has a significant negative effect on consumer perceived safety risk ($\beta = -0.537$, $p < 0.05$), and the hypothesis is valid; and green building consumption perception has a significant negative effect on consumer perceived utility risk ($\beta = -0.311, p < 0.05$), which has a significant negative effect, and the hypothesis is valid.*

Table 8. Table of path coefficients.

Path	β	STDEV	T	p Values
GBCP -> PER	−0.591	0.042	14.132	0.000
GBCP -> PI	0.303	0.052	5.811	0.000
GBCP -> PSR	−0.537	0.046	11.597	0.000
GBCP -> PUR	−0.622	0.037	16.969	0.000
PER -> PI	−0.009	0.033	0.281	0.778
PSR -> PI	−0.313	0.024	12.816	0.000
PUR -> PI	−0.311	0.026	12.141	0.000
EA -> PI	0.236	0.042	5.637	0.000

4.3.2. Tests for Mediating Effects

In this study, in order to prove the mediating effect, the Bootstrap mediation effect test is used to test whether the mediation effect is significant, and the number of repetitive samples is 5000 times to test the mediation effect results. As shown in Table 9, (1) the point estimate of the total effect in this study is positive, and the absolute value of the T-statistic is greater than 1.96 while the confidence interval does not include 0, indicating the existence of the total effect of the latent variable. (2) The indirect effect of perceived security risk in this study is 0.168, $p < 0.05$, and the corresponding confidence interval does not include 0, indicating a significant mediation effect; the indirect effect of perceived utility risk is 0.193, $p < 0.05$, and the corresponding confidence interval does not include 0, indicating a significant mediation effect; the indirect effect of perceived economic risk is 0.006, $p > 0.05$ and the corresponding confidence interval includes 0, indicating that the mediation effect is not significant. (3) The point estimate of the direct effect in this study is positive, the absolute value of the t-statistic is more than 1.96, and the confidence interval does not include 0, indicating the existence of direct effects of latent variables.

It can be concluded that H4: Perceived safety risk and perceived utility risk, have a mediating role between consumers' commercial fitness club green building consumption perceptions and fitness service purchase intentions, and the hypothesis is valid. Meanwhile, the perceived economic risk does not have a mediating role between consumers' green building consumption perceptions and fitness service purchase intentions.

Table 9. Intermediation test table.

Path	Effect	STDEV	T	P	2.5%	97.5%
		aggregate effect				
GBCP -> PI	0.670	0.048	13.876	0.000	0.565	0.753
		indirect effect				
GBCP -> PSR -> PI	0.168	0.019	8.956	0.000	0.131	0.206
GBCP -> PUR -> PI	0.193	0.018	10.969	0.000	0.158	0.227
GBCP -> PER -> PI	0.006	0.020	0.279	0.780	−0.031	0.047
		direct effect				
GBCP -> PI	0.303	0.052	5.811	0.000	0.191	0.395

4.3.3. Moderating Effects Test

As can be seen from Table 10, environmental awareness has a significant positive effect between consumers' perception of green building consumption in commercial fitness clubs and their willingness to purchase fitness services ($\beta = 0.222$, $p < 0.05$), i.e., environmental awareness has a positive moderating effect, and the hypothesis is valid. And it can be seen from Figure 4 that the moderating effect is increasing as the environmental awareness becomes greater.

Table 10. Reconciliation effect test table.

Path	β	STDEV	T	p Values
EA × GBCP ->PI	0.222	0.040	5.611	0.000

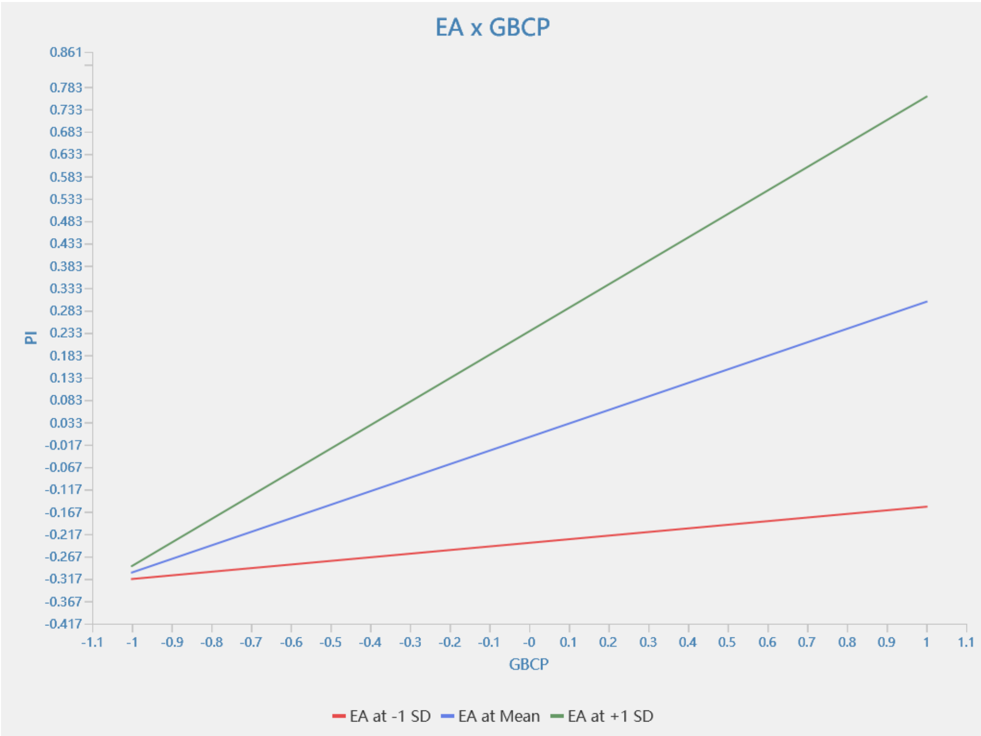


Figure 4. Diagram of moderating effects.

5. Discussion and Analysis

Before analyzing the specifics, let us first discuss a real-life practical example: the Marina Bay Sands Hotel, one of Singapore's landmarks. Not only has its unique design style aroused extensive curiosity among a large number of consumers, it has also attracted a large number of consumers to participate in experiential consumption due to its green architectural design. On the one hand, a sense of environmental responsibility has prompted some consumers to choose to stay in "environmentally friendly" hotels, and green building hotels reduce environmental pollution to a certain extent, which is in line with the consumers' environmental values. On the other hand, out of social identity considerations, some consumers believe that participation in green building hotel consumption has the important function of showing their social identity. In order to show their environmental responsibility to their friends or others, and to emphasize their sense of environmental responsibility, they are eager to participate in green building consumption.

5.1. Positive Contribution of Green Building Consumption Perceptions on Consumers' Willingness to Purchase Fitness Services in Commercial Health Clubs

Green building is central to the sustainable evolution of the construction industry, marking its anticipated trajectory. For sports and fitness facilities, embracing green building principles offers multifaceted benefits throughout their life cycle. These include resource conservation, environmental protection, pollution reduction, and delivering a healthful, efficient space for users. Such an approach accentuates the harmonious coexistence of humans with nature. The choice of green building design for fitness clubs can largely influence consumers' willingness to buy fitness services. Based on the combination of previous research, this paper divides the influence of green building consumption perception on fitness service purchase willingness into three aspects. First, green building consumption social value perception. On the one hand, due to the influence of symbolic stimuli, consumers learn about the performance, attributes, quality, and other information related to green building fitness venues through a variety of media, such as the government's green evaluation, etc., which affects fitness users' willingness to purchase fitness services. On the other hand, people will be affected by external stimuli when choosing green building fitness clubs to participate in fitness services, such as family recommendations, friends' evaluations, and social calls. Second, green building consumer environmental value perception. For consumers who are deeply influenced by environmentalism, the concept of green consumption has been deeply integrated into their minds and influences their consumption methods, so when they choose fitness services, they will naturally choose fitness venues that embody their green philosophy. Thirdly, green building consumption function value perception. Consumers who often exercise will pay attention to the professionalism, quality, and comfort of the services provided by the fitness clubs, and the green building fitness clubs happen to provide a satisfactory place for them. Consumers will only generate green consumption intention if they feel enough value can be retrieved from green buildings. A high green building consumption perception of consumers around the concept of sustainable development relates to the hopes of the consumer that certain places can provide a comfortable and healthy fitness environment on the basis of the use of green technology, minimize the damage to the surrounding environment, and further highlight the concept of health, so as to meet the needs of consumers, and thus affect the consumer's willingness to buy.

5.2. The Mediating Role of Perceived Risk between Consumers' Green Building Consumption Perceptions and Fitness Service Purchase Intentions in Commercial Health Clubs

The level of perceived risk is an important psychological assessment criterion for consumers in deciding whether to execute the purchase. Before analyzing the specific impact of the various dimensions of perceived risk, we will first discuss the impact of "brand marketing", which is the largest element of consumer-perceived risk. Here, we say "brand" to refer to the consumer of green building fitness clubs as a consumer object of the overall cognitive process and the processing of relevant information, and at the same time, the brand effect is also accompanied by the gradual occurrence of the brand cognitive process. Regarding green buildings, this can be considered a "marketing gimmick"; even if the perceived risk is high, for consumers in the process of making purchasing decisions, it is often difficult to be in a state of absolute rationality, and coupled with the brand effect of the depth of the impact of the consumer, it is difficult not to be "flocked" to participate in the consumption.Before making a purchase decision related to green building consumption, consumers can rely on their own high degree of consumer perception to identify whether a green building fitness club brand is "real material", or whether the health advantages are exaggerated to cover up the real disadvantages of a series of marketing scams. This "skepticism" enables consumers with a high degree of green building consumer perception to avoid the influence of brand concepts in a rational manner, gradually reducing the perceived risk, and then participating in the experience of consumption.

And from the dimensions of perceived risk, perceived security risk is significantly influenced by the integration of green principles into health club services. The association with a "green label" conveys notions of environmental responsibility, cleanliness, and health. This reduces the consumers' perceived risks, fostering greater trust and subsequently bolstering their purchasing intentions. As consumers gather information about green fitness facilities, they develop a perception of these establishments as both environmentally friendly and safe. This eco-conscious and safety-oriented image substantially diminishes the perceived security risks. Furthermore, the perception of green fitness clubs as safer and more dependable elicits positive emotional responses in the consumers. This heightened sense of security and environmental responsibility enhances the emotional value consumers associate with these establishments.

Perceived utility risk refers to the fact that, when consumers make consumption choices, they prejudge the functional value of the product in advance and compare it with the expectations in their minds, and the level of expected risk affects the consumption decision. In the perceived utility risk, consumers pursue the maximization of benefits, and purchase products not only to pursue the use value, but also to pursue the maximization of emotional value and social value. When consumers make fitness service choices, traditional fitness venues are dominated by use efficiency, and provide little benefit to consumers in terms of emotional and social value, so the perceived risk borne by consumers in terms of social value is higher. When consumers choose green building fitness clubs for consumption services, they not only satisfy the interests of consumers, but also contribute to environmental protection. One of the purposes of green consumption for customers is to show their own environmental attitude, so as to obtain social acceptance and improve the opinions of others of themselves, thus enhancing their social value, so the functional characteristics of green building fitness clubs reduce the perceived risk of consumers in the emotional and social utility, which in turn affects the willingness to buy.

In terms of perceived economic risk, on the one hand, the purchase price of green building health clubs in the current market is relatively high, which makes it difficult for some consumers to accept them. Although the maintenance costs of green building health clubs are lower than those of ordinary clubs, operators will still invest a large amount of money in green upgrading of health clubs, and the costs borne by consumers who choose the services of green building health clubs will be correspondingly higher. On the other hand, although the government has introduced tax incentives to encourage producers and consumers to choose green venues, consumers still have a wait-and-see attitude in the face of new things, and do not dare to take the risk to bear the economic risks of new fitness venues. For consumers, price is still an important influence on whether or not to choose green building health clubs for fitness exercise.

5.3. The Moderating Role of Environmental Awareness between Consumers' Perceptions of Green Building Consumption and Fitness Service Purchase Intentions in Commercial Fitness Clubs

Environmental awareness reflects the degree of individual awareness of the environmental situation, which in practice represents the participation of people in environmental protection activities, the adjustments of their economic activities and social behavior, regulating the relationship between man and nature consciously. For consumers, the stronger the environmental awareness, the more they can feel the harm caused by environmental damage, and the more they are willing to adhere to the concept of green consumption in all aspects of life, and therefore will be more willing to choose green building fitness clubs in the consumption of fitness services, and further encourage friends and family members to choose green building fitness clubs. In addition, if consumers perceive the outstanding value of green buildings on the basis of their environmental awareness also being strong, in the fitness service consumption choice, they are more likely to experience the benefits of green building fitness places, but also more willing to buy green building fitness club fitness services. If consumers' environmental awareness is weak, they are more likely to ignore the green features of green buildings, and their willingness to purchase green building fitness services will be reduced.

6. Concluding Remarks

This study statistically analyzes the screened 363 samples through questionnaires, uses the IAD extension model to analyze the influence effect between green building consumption perception on consumers' willingness to purchase fitness services for commercial health clubs based on perceived risk theory and other related theories, and further explores the role that perceived risk and environmental awareness play in it on this basis. The following conclusions are drawn: (1) Green building consumption perception has a positive promotion effect on the purchase intention of commercial health club fitness services. (2) Perceived risk mediates the relationship between green building consumption perceptions and commercial health club fitness service purchase intentions. (3) Environmental awareness plays a positive moderating role between green building consumption perception and commercial health club fitness service purchase intention.

Green building integration within commercial health clubs offers distinct advantages for fitness enthusiasts. Primarily, green structures prioritize internal conditions such as lighting, humidity, and temperature more than conventional edifices. For instance, the incorporation of green roofs reduces the reliance on air conditioning, fostering a more organic and agreeable exercise ambiance. Furthermore, numerous sociological and anthropological investigations have elucidated the psychological rewards of pro-social behavior, encompassing feelings of gratification and well-being. Pro-social actions align with societal expectations and benefit individuals, groups, and the broader community. Engaging in green building consumption can be viewed as an eco-friendly act and a nod to societal environmental advocacies, classifying it as pro-social behavior. Such engagement not only carries profound "significance" but also addresses the public's self-actualization aspirations.

Author Contributions: Conceptualization: Y.H. Writing—review and editing: Y.H.; Formal analysis: S.C., Z.Y., X.S, L.C. and Y.Z.; Data curation: S.C., Z.Y., X.S. and Y.Z.; Methodology: Q.H., J.C., F.G. and X.W.; Writing—original draft: Q.H.; Investigation: L.C., F.G. and J.C.; Resources: S.C.; Software: S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data available on request from the authors.

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

References

1. Ma, G. The golden decade of the rise of consumption. *Contemp. Guizhou* **2017**, *22*, 64.
2. Shi, Y.; Shi, C.; Wu, C. The road to create changes in China's fitness and leisure service industry under consumption upgrading. *Res. Phys. Educ.* **2018**, *1*, 63–71.
3. Ying, L.; Chen, Q. Meaning of customer satisfaction in sports and fitness service industry and its development path. *Contemp. Sports Sci. Technol.* **2013**, *3*, 113, 115.
4. Li, Y.; Zhan, M.; Shi, Z. Model construction and development strategy of fitness and leisure service industry under the view of industrial ecology. *Shandong Sports Sci. Technol.* **2021**, *43*, 1–5.
5. Tian, Y.; Zou, S.; Zheng, Y. Analysis of Consumer Behavior in Commercial Fitness Clubs. *Sports Cult. Guide* **2009**, 29–34.
6. Park, Z.Z.; Qian, T. Exploration of Sports and Fitness Service Mode in the Context of IOT Era. In *Chinese Society of Sports Science, China Sporting Goods Industry Federation. 2015 Anthology of China Sports Industry and Sporting Goods Industry Development Forum*; Atlantis Press: Dordrecht, The Netherlands, 2015; pp. 132–133.
7. Yun, Z.; Rongri, L. Research on the impact of brand image on brand loyalty in professional tennis tournaments: The mediating effect of perceived value and trust. *J. Shenyang Sports Inst.* **2019**, *38*, 62–70.
8. Li, J. Research on national fitness consumption supply in China in the new era. *J. Shenyang Sport. Inst.* **2018**, *37*, 8–13.
9. Li, C.; Wang, Q. Mimetic myth:The paradigm of sports star making in the context of consumer society. *J. Shandong Sports Inst.* **2018**, *34*, 39–43.
10. Zhu, Z.; Cheng, J.; Liu, F. Review and Prospect of Consumer Uniqueness Demand Research. *East China Econ. Manag.* **2017**, *31*, 151–158.
11. Economist, T.F. Traditional Business Models Put to the Test as Gyms Transition to 'Small and Beautiful'. Available online: http://www.qianzhan.com/analyst/detail/220/180802-493ee957.html (accessed on 26 August 2023).
12. Zhang, J.; Sun, H.; Zhang, J. Influencing factors and development countermeasures of physical fitness service for disabled people in Gansu Province. *Sports Cult. Guide* **2018**, 48–52, 84.
13. Wang, J.; Qin, X.; Wan, X. Identification of Risk Factors and Risk Path Analysis of Green Building Projects. *Constr. Technol.* **2012**, 30–34.
14. Jian, S. Construction industry must face the challenge of "industrial ecology". *Low Temp. Build. Technol.* **2021**, *43*, 116.
15. Ellen, P.S.; Wiener, J.L.; Cobb-Walgren, C. The role of perceived consumer effectiveness in motivating environmentally conscious behaviors. *J. Public Policy Mark.* **1991**, *10*, 102–117. [CrossRef]
16. Biswas, A.; Roy, M. Leveraging factors for sustained green consumption behavior based on consumption value perceptions: Testing the structural model. *J. Clean. Prod.* **2015**, *95*, 332–340. [CrossRef]
17. Laukov. Research on the influence mechanism of consumer innovativeness on green consumption behavior. *Nankai Manag. Rev.* **2013**, *16*, 106–113.
18. Sivek, D.J.; Hungerford, H. *Predictors of Responsible Behavior and Human Decision Process*; ResearchGate: Berlin, Germany, 1991.

19. Hirsh, J.B. Personality and environmental concern. *J. Environ. Psychol.* **2010**, *30*, 245–248. [CrossRef]
20. Kwon, W.S.; Englis, B.; Mann, M. Are third-party green–brown ratings believed?: The role of prior brand loyalty and environmental concern. *J. Bus. Res.* **2016**, *69*, 815–822. [CrossRef]
21. Gonçalves, H.M.; Lourenço, T.F.; Silva, G.M. Green buying behavior and the theory of consumption values: A fuzzy-set approach. *J. Bus. Res.* **2016**, *69*, 1484–1491. [CrossRef]
22. Nalchy, A.; Rasoulian, M.; Boojari, H. Consumer Purchasing Behavior towards Foreign Brands in the Domestic Brands. *Dev. Manag. J.* **2012**, *8*, 47–56.
23. Finch, J.E. The impact of personal consumption values and beliefs on organic food purchase behavior. *J. Food Prod. Mark.* **2006**, *11*, 63–76. [CrossRef]
24. Chen, Y.S.; Chang, C.H. Enhance green purchase intentions: The roles of green perceived value, green perceived risk, and green trust. *Manag. Decis.* **2012**, *50*, 502–520. [CrossRef]
25. Bauer, R.A. A consumer behavior as risk taking in dynamic marketing for a changing world. In Proceedings of the 43rd Conference of the American Marketing Association, Chicago, IL, USA, 15–17 June 1960; pp. 89–398.
26. Featherman, M.S.; Pavlou, P.A. Predicting e-services adoption: A perceived risk facets perspective. *Int. J.-Hum.-Comput. Stud.* **2003**, *59*, 451–474. [CrossRef]
27. Engel, J.F. Risk taking and information handling in consumer behavior. *J. Mark.* **1968**, *32*, 111.
28. Cunningham, M.S. The major dimensions of perceived risk. *Risk Tak. Inf. Handl. Consum. Behav.* **1967**, *48*, 917–923.
29. Keller, K.L. Conceptualizing, measuring, and managing customer-based brand equity. *J. Mark.* **1993**, *57*, 1–22. [CrossRef]
30. Woodside, A.G. Constructing business-to-business marketing models that overcome the limitations in variable-based and case-based research paradigms. *J.-Bus.-Bus. Mark.* **2015**, *22*, 95–110. [CrossRef]
31. Jacoby, J.; Kaplan, L.B. The components of perceived risk. *Proc. Annu. Conf. Assoc. Consum. Res.* **1972**, *10*, 382–393.
32. Murray, K.B. A test of services marketing theory: Consumer information acquisition activities. *J. Mark.* **1991**, *55*, 10–25. [CrossRef]
33. Mandal, S.; Paul, R. Consumer perception of genetically modified food: Empirical evidence from India. *J. Int. Food Agribus. Mark.* **2012**, *24*, 169–183. [CrossRef]
34. O'Donovan, P.; McCarthy, M. Irish consumer preference for organic meat. *Br. Food J.* **2002**, *104*, 353–370. [CrossRef]
35. Kasterine, A.; Vanzetti, D. The Effectiveness, Efficiency and Equity of Market Based and Voluntary Measures to Mitigate Greenhouse Gas Emissions from the Agri-Food Sector. *UNCTAD Trade Environ. Rev.* **2010**. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1768948 (accessed on 26 August 2023).
36. Priester, J.R.; Petty, R.E.; Park, K. Whence univalent ambivalence? From the anticipation of conflicting reactions. *J. Consum. Res.* **2007**, *34*, 11–21. [CrossRef]
37. Eroglu, S.A.; Machleit, K.A.; Davis, L.M. Atmospheric qualities of online retailing: A conceptual model and implications. *J. Bus. Res.* **2001**, *54*, 177–184. [CrossRef]
38. SUN Jian, L.C.; Zonghuang, H. An empirical study on the influence of green food information and value attributes on green purchasing behavior. *J. Manag.* **2010**, *7*, 57–63.
39. Sun, Y.; Liu, N.; Zhao, M. Factors and mechanisms affecting green consumption in China: A multilevel analysis. *J. Clean. Prod.* **2019**, *209*, 481–493. [CrossRef]
40. Yadav, R.; Pathak, G.S. Young consumers' intention towards buying green products in a developing nation: Extending the theory of planned behavior. *J. Clean. Prod.* **2016**, *135*, 732–739. [CrossRef]
41. Yadav, R.; Pathak, G.S. Determinants of consumers' green purchase behavior in a developing nation: Applying and extending the theory of planned behavior. *Ecol. Econ.* **2017**, *134*, 114–122. [CrossRef]
42. Mitchell, V.W.; Boustani, P. A Preliminary Investigation into Pre-and Post-Purchase Risk Perceptionand Reduction. *Eur. J. Mark.* **1994**, *28*, 56–71. [CrossRef]
43. Zou, J.; Tang, Y.; Qing, P.; Li, H.; Razzaq, A. Donation or discount: Effect of promotion mode on green consumption behavior. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1912. [CrossRef]
44. Pavlou, P.A.; Liang, H.; Xue, Y. Understanding and mitigating uncertainty in online exchange relationships: A principal-agent perspective. *MIS Q.* **2007**, *31*, 105–136. [CrossRef]
45. Nepomuceno, M.V.; Laroche, M.; Richard, M.O. How to reduce perceived risk when buying online: The interactions between intangibility, product knowledge, brand familiarity, privacy and security concerns. *J. Retail. Consum. Serv.* **2014**, *21*, 619–629. [CrossRef]
46. Lin, Y.C.; Chang, C.c.A. Double standard: The role of environmental consciousness in green product usage. *J. Mark.* **2012**, *76*, 125–134. [CrossRef]
47. Balderjahn, I. Personality variables and environmental attitudes as predictors of ecologically responsible consumption patterns. *J. Bus. Res.* **1988**, *17*, 51–56. [CrossRef]
48. Ostrom, E.; Gardner, R. Coping with asymmetries in the commons: Self-governing irrigation systems can work. *J. Econ. Perspect.* **1993**, *7*, 93–112. [CrossRef]
49. Ostrom, E. Collective action and the evolution of social norms. *J. Econ. Perspect.* **2000**, *14*, 137–158. [CrossRef]
50. Fishbein, M.; Ajzen, I. *Behavior: An Introduction to Theory and Research Reading*; Addison-Wesley: Reading, MA, USA, 1975.
51. Sheng Guanghua, G.S.; Fang, X. Theoretical basis and empirical test for the formation of Chinese consumers' green purchase intention-TPB extension model based on ecological values, personal perception relevance. *J. Soc. Sci. Jilin Univ.* **2019**, *59*, 134–142.

52. Jaiswal, D.; Kant, R. Green purchasing behaviour: A conceptual framework and empirical investigation of Indian consumers. *J. Retail. Consum. Serv.* **2018**, *41*, 60–69. [CrossRef]
53. Chan, R.Y.; Lau, L.B. Antecedents of green purchases: A survey in China. *J. Consum. Mark.* **2000**, *17*, 338–357. [CrossRef]
54. Séquier, A.; Stoebner, A.; Gourgou, S.; Lence, J.J.; Bonifaci, C.; Sancho-Garnier, H. Métodos educativos en la prevención del tabaquismo, en escolares del Departamento del Herault, Francia. *Salud Pública de México* **2002**, *44*, s93–s100. [CrossRef]
55. Stone, R.N.; Grønhaug, K. Perceived risk: Further considerations for the marketing discipline. *Eur. J. Mark.* **1993**, *27*, 39–50. [CrossRef]
56. Ballantyne, R.; Packer, J.; Hughes, K. Environmental awareness, interests and motives of botanic gardens visitors: Implications for interpretive practice. *Tour. Manag.* **2008**, *29*, 439–444. [CrossRef]
57. Schill, M.; Godefroit-Winkel, D.; Diallo, M.F.; Barbarossa, C. Consumers' intentions to purchase smart home objects: Do environmental issues matter? *Ecol. Econ.* **2019**, *161*, 176–185. [CrossRef]
58. Nunnally, J.C. *Psychometric Theory*, 3rd ed.; McGraw-Hill: New York, NY, USA, 1994.

buildings

MDPI

Article

The Spatiotemporal Distribution Characteristics and Driving Factors of Carbon Emissions in the Chinese Construction Industry

Jun Yang [1,*] and Xiaodan Zheng [2]

[1] College of Civil Engineering, Sanjiang University, Nanjing 210012, China
[2] College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China; zhengxiaodan90@163.com
* Correspondence: yang_jun2094@sju.edu.cn; Tel.: +86-153-4518-3492

Abstract: As a pillar industry of the national economy, the construction industry not only promotes urban development and social prosperity but also has an irreversible impact on the environment with the trend of high carbon emissions. Therefore, it is of great significance for the construction industry to take the lead in achieving carbon emissions reduction. This paper attempts to explore the spatiotemporal distribution characteristics and specific driving factors of carbon emissions in the construction industry in 30 provinces of China from 2011 to 2020 based on the spatial econometric analysis, so as to clarify the development trajectory and formation mechanism. The key findings are (1) there are obvious differences in carbon emissions across Chinese provinces, culminating in a distinct "Belt–Ring–Dot" spatial distribution; (2) the carbon emissions in the construction industry follow an inverted U-shaped pattern from south to north, with lower emissions in the west and higher emissions in the east, which means the pressure and potential of carbon emissions reduction coexist; (3) the Moran's *I* index values from 2011 to 2020 were all greater than 0, with a maximum value of 0.284, indicating that there is a notable positive spatial correlation in carbon emissions in the construction industry between provinces; and (4) among the five factors, the number of employees displays the most pronounced spatial correlation, passing the test a total of eight times, and the mean test coefficient is the largest at 0.552. This factor positively influences carbon emissions alongside the gross product. On the other hand, the patents granted factor significantly inhibits carbon emissions with all test coefficients being negative with a maximum absolute value of 0.166. The impact of the technical equipment rate shows a characteristic of initial positive stimulation followed by later negative inhibition. In contrast, the urbanization rate exhibits the weakest spatial correlation with the minimum test coefficient being only 0.001.

Keywords: carbon emissions; construction industry; spatial econometric analysis; spatiotemporal distribution; driving factors

1. Introduction

On 15 November 2022, the World Meteorological Organization (WMO) released an interim report on "Global Climate Conditions 2022", which stated that the global average temperature in 2022 was about 1.15 °C higher than the pre-industrial period (1850–1900), and the last eight years may have been the hottest years on record. Since most of the greenhouse gases that cause climate warming are carbon dioxide, reducing carbon emissions can mitigate the severe risks and adverse effects of climate change to the greatest extent [1]. The UK was the world's largest carbon emitter from the Industrial Revolution until it was replaced by the US in 1888. Since then, developing countries have relied on fossil energy to accelerate urban development, resulting in a rapid increase in carbon emissions. By 2006, China had surpassed the US to become the country with the largest carbon emissions in the world [2]. The Chinese government put forward the "Dual Carbon

Targets" at the 75th session of the United Nations General Assembly in this grim situation, aiming to solve the dilemma of resource and environmental constraints and achieve green sustainable development [3].

Recent studies suggest that the construction industry globally is responsible for approximately one-quarter of carbon emissions [4]. The reason is that compared to other sectors, the construction industry is a resource-intensive industry that consumes a large amount of fossil energy, thereby increasing carbon emissions while promoting the rapid development of urbanization, and improving people's livelihoods [5]. Therefore, it is of great significance for the construction industry to take the lead in achieving carbon emissions reduction. However, the achievement of emission reduction targets depends not only on national policies but also on provincial actions [6]. In particular, China is in the development stage, and the development level of the construction industry varies between different regions, as well as between resource endowment and technological levels. Meanwhile, the existing research predominantly concentrates on carbon emissions within a specific region, or explores them from a single perspective of time or space, ignoring the evolution characteristics across different regions. How to clarify the different characteristics of carbon emissions in the construction industry for the implementation of differentiated carbon reduction measures is worth careful consideration.

It has also been found that there may be significant carbon emission interactions between provinces, which means the mechanisms affect both local and neighboring regions [7]. Therefore, by using the carbon emissions data of the construction industry in 30 provinces from 2011 to 2020, this paper attempts to explore the spatiotemporal distribution characteristics and formation mechanisms of carbon emissions from the construction industry at the provincial level in China, based on spatial econometric analysis. And it exhibits innovation in three aspects. Firstly, it delves into the dynamic evolution characteristics of carbon emissions in the construction industry by integrating a dual perspective of time and space, presenting them visually. Secondly, it validates the spatial correlation of carbon emissions in the construction industry and unveils new distribution patterns through the Moran's index. Finally, the inclusion of technological innovation factors in the spatial econometric model adds a crucial dimension and has significantly enriched the research findings. It is expected to provide a scientific basis for the relevant government departments to formulate differentiated carbon emission reduction measures and the overall linkage governance program in the construction industry.

This paper is structured as follows. Section 2 reviews the existing literature on the carbon emission. Section 3 presents the data sources and research methods. Section 4 presents the results of the spatial econometric analysis. Section 5 discusses the results. Finally, the conclusions are presented in Section 6.

2. Literature Review

2.1. Carbon Emissions Distribution

According to the existing literature collection, the distribution characteristics of carbon emissions are analyzed in different countries and regions or different industrial sectors. For example, Yang et al. (2018) observed that the spatial distribution of total carbon emissions in China primarily exhibits a pattern of higher levels in the east and lower levels in the west [8]. Building upon this observation, Liu et al. (2021) identified a specific trend characterized by the central agglomeration in the northeast–southwest direction and spatial divergence in the northeast–southeast direction [9]. Gregg et al. (2009) explored that the characteristics of fossil-fuel-based carbon emissions on a monthly scale have greater temporal and spatial variability than the flux aggregated to the national annual level in North America [10]. At the global level, some scholars have found that there is cross-country convergence in carbon emissions [11], while with the passage of time and economic development, other scholars hold the opposite view [12]. These viewpoints collectively indicate spatial variations in the distribution of carbon emissions. From the perspective of different industrial sectors, the aforementioned studies on carbon emissions have broadly encompassed various sectors, including industry, transportation, and construction [13]. Some scholars have also focused their attention on agriculture, aviation, logistics, and so on [14]. For instance, Zhou et al. (2022) found that the carbon emissions of agriculture are basically characterized by rapid growth in the early stage and gradual stabilization in the later stage [15]. Liu et al. (2019), focusing on local carbon emissions from civil airports, discovered that the emission intensity in the central and eastern regions of China is significantly higher than that in the northeast and western regions [16]. At present, the construction industry is known as a representative industry for its high energy consumption and pollution where the spatial distribution of emission efficiency is unbalanced [17], contributing to regional disparities with an increasing trend of international linkage effects [18]. Meanwhile, some scholars have attempted to explore the variation characteristics of carbon emissions during the operational phase of buildings from a life cycle perspective [19].

2.2. Influencing Factors

On account of the complex system formed by the interaction of various factors [8], it is necessary to correctly identify the impact mechanism of carbon emissions in order to establish an effective reduction strategy as soon as possible. Generally speaking, the driving force behind carbon emissions cannot be separated from overall factors such as economic level, scientific and technological capabilities, population, and policy guidance of a country or region [20]. Among them, industrial structure, per capita income, population, and urbanization level have a positive driving effect on carbon emissions [21], while scientific and technological capabilities and policy releases have a negative inhibitory effect [22]. However, it is worth noting that the impact of economic level and industrial structure is not simple, as studies have found variations in their influence [23]. For instance, there is no consensus on whether trade openness has a positive impact on decoupling carbon emissions from economic growth in high-income countries [24], while there is consensus that it has a more negative impact on low-income countries [25]. As for industrial agglomeration, Gong et al. (2022) found that the agglomeration of primary and secondary industries in China promotes carbon emissions while the agglomeration of tertiary industries has a significant effect on reduction [26]. Despite the varying characteristics of carbon emission factors in different industrial sectors and regions, the construction industry is resource-intensive and involves all aspects of urban production, consumption, and circulation, which are necessary to clarify the individual factors consistent with its characteristics [27]. Some studies have been conducted to investigate whether the structure of the construction industry, output scale effect [28], land expansion, and building materials are the main factors of carbon emissions [29]. Conversely, energy intensity, green building, low-carbon construction patents, and policies have negative effects [30]. For example, Hou (2021) argues that mechanisms to reform supply-side incentives could offer immediate benefits [31].

2.3. Relevant Research Methods

For the measurement of carbon emissions data, the most widely accepted and used by countries around the world is the Intergovernmental Panel on Climate Change (IPCC) Sectoral Approach, which provides a standardized approach for countries to estimate their greenhouse gas emissions and removal [32]. Regarding the distribution of carbon emissions, Liu et al. (2022) conducted a comparative analysis of the basic data of industrial carbon emissions to explore its development trend in Jiangsu Province [33]. In addition, some researchers predicted carbon emissions by modifying the Moon–Sonn model or using the gray model GM (1, 1) [34]. Liu et al. (2022) conducted a peak analysis of agricultural carbon emissions in Shandong Province using the Moon–Sonn model [35]. Recently, more researchers have discovered that the spatial relationships between cities are becoming stronger, making the connections of carbon emissions more intricate and extensive. To better analyze these spatial effects, scholars have started using methods such as social network analysis and spatial econometrics [36]. For example, Zheng et al. (2022) combined Social Network Analysis (SNA) with Quadratic Assignment Procedure (QAP) to measure the spatial correlation network characteristics of carbon emissions in the Pearl River Delta urban agglomeration in China [37]. Wang et al. (2022) calculated the Moran's I index of carbon emissions from the construction industry by spatial exploration methods at both global and Chinese scales, revealing a significant positive autocorrelation across diverse urban areas [38]. In the realm of carbon emissions impact analysis, a rich array of existing methods has been employed. Most researchers have collected panel data and employed the Kaya Identity to decompose the driving factors of carbon emissions. Subsequently, they use the Logarithmic Mean Divisia Index (LMDI) model to disaggregate the contributions of each factor [26]. Additionally, some scholars have utilized various methods including Panel Vector Auto-Regressive (PVAR) models [39], Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) models [40], Random Forest models [41], Granger causality tests [42], and system dynamics to identify and analyze the influencing factors of carbon emissions [43]. In contrast, a minority of scholars have adopted a spatial econometrics perspective by incorporating spatial weight matrices into their analyses [44]. They have employed Spatial Error, Lag, and Durbin models to investigate the factors while accounting for spatial dependencies [45].

2.4. Literature Summary

In summary, extant literature exhibits diversities in research perspectives, content, and methodologies concerning carbon emissions. Nevertheless, it predominantly concentrates on the assessment of carbon emissions distribution within individual national or provincial regions, thereby disregarding potential spatial interactions with adjacent areas. Furthermore, prevalent approaches primarily encompass measurements conducted along either temporal or spatial dimensions, thus failing to capture the nuanced spatiotemporal dynamics inherent in simultaneous processes influencing carbon emissions distribution. Therefore, to address the deficiencies in the existing research, this study utilizes exploratory spatial statistical analysis to examine the spatiotemporal trends of carbon emissions in the construction industry across Chinese provinces from 2010 to 2020. Additionally, spatial econometric models are employed to investigate the driving factors contributing to regional disparities. The objective is to furnish a theoretical foundation and policy implications for China's carbon reduction initiatives, facilitating the realization of environmentally friendly and low-carbon development within the construction industry.

3. Data and Methods

This study integrates the IPCC Sectoral Approach, provincial greenhouse gas inventory guidelines, and the Chinese carbon accounting database to calculate carbon emissions from the construction industry in 30 provinces of China from 2010 to 2020, so as to conduct descriptive statistical analyses [46]. Subsequently, we attribute spatial characteristics to the dataset, exploring its spatiotemporal distribution patterns and developmental trends. Conclusively, the approach involves the meticulous selection of influential factors from multifaceted vantage points encompassing economic, social, demographic, technological, and innovation dimensions. These selected factors form the basis for the construction of a spatial econometric model, employed to probe the intricate causal mechanisms that underlie the observed phenomena.

3.1. Data Definition and Source

3.1.1. Vector Data of Carbon Emissions

The research subject of this study is the carbon dioxide emissions from the construction industry in 30 provinces across China (excluding Hong Kong, Taiwan, Tibet, and Macao) from 2011 to 2020. This dataset not only includes the specific annual emissions values for the construction industry but also encompasses the geographical coordinates of these 30 provinces, representing a vector dataset that combines both economic and spatial attributes. The spatial attribute data consist of coordinates for administrative regions of 30 provinces in China and originate from the Resource and Environment Science and Data

Center. The economic attribute data represent the carbon emissions for each province in the construction industry. To derive carbon emissions data, this study combines the IPCC Sectoral Approach, provincial greenhouse gas inventory guidelines, and the Chinese carbon accounting database. Specifically, based on the physical quantity data extracted from the provincial energy balance tables found in the China Energy Statistical Yearbook, we consider 17 categories of fossil fuel energy consumption within the construction industry including raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, petroleum asphalt, liquefied petroleum gas, natural gas, and others. Then Equation (1) is used to measure the carbon emissions:

$$C = \sum_{n=1}^{17} E_n \times J_n \times F_n \tag{1}$$

where E_n is the consumption of the nth fossil energy, J_n is average low calorific value of the nth fossil energy, and F_n is carbon content per unit calorific value of the nth fossil energy.

3.1.2. Factors Selection

The relationship between economic activities and the environment can be decomposed into scale, structure, and technological effects [47]. Considering that previous literature has extensively explored mature factors affecting carbon emissions, such as economic levels, industrial structure, energy intensity, and material consumption [21], and recognizing that decarbonization in the construction industry is closely tied to the development of green building and technological innovation, this paper endeavors to select factors related to carbon emissions from the perspectives of machinery utilization and technological innovation. In view of the availability of data, the rate of technical equipment and the number of granted patents in the construction industry are characterized. The rate of technological equipment refers to the ratio of the net value of self-owned mechanical equipment to the total number of workers of construction industry enterprises at the end of the year, reflecting the level of mechanization and technological investment. The number of granted patents represents the count of invention patents authorized by the intellectual property administrative department, indicating the level of scientific development and innovation capability in each province. Given the diversity and comprehensiveness of influencing factors, this study incorporates three influencing factors from the perspectives of economic, social, and population development, including gross product of construction industry, provincial urbanization rates, and the number of employees in the construction industry. The definitions of the variables are shown in Table 1. The aforementioned original data are sourced from annual publications such as China Statistical Yearbook, China Construction Industry Statistical Yearbook, China Energy Statistical Yearbook, and China Science and Technology Statistical Yearbook.

Table 1. Variables and data definitions.

Variables	Definition	Unit
CE	Carbon emissions in the construction industry	MT
GP	Gross product of the construction industry	10^{10} Yuan
NE	Number of employees in the construction industry	10^{6} Person
UR	Urbanization rates	%
TR	Technological equipment rates	10^{4} Yuan/Person
PG	Domestic Patents Granted	10^{4} Item

3.2. Spatial Econometric Analysis

3.2.1. Spatial Correlation Analysis

American geographer W.R. Tobler proposed that everything is related to everything else, but near things are more related than distant things in 1970 [48]. This principle is known as the First Law of Geography, which means that different phenomena are more similar when they are closer in space, indicating the presence of spatial correlation. If the opposite is observed, meaning that closer objects are less similar, it indicates spatial heterogeneity. When there is no relationship between the attributes of objects and their spatial positions, it suggests that the attribute lacks spatial correlation [49]. Therefore, whether there exists spatial correlation among various economic variables at different distances in different regions needs to be statistically measured. The Moran's *I* index, proposed by Australian statistician Patrick Alfred Pierce Moran in 1950, is a widely used metric in global spatial autocorrelation analysis of economic variables to measure the degree of spatial correlation and regional homogeneity. Its definition is as follows:

$$Moran's\ I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(c_i - \bar{c})}{W_0\sum_{i=1}^{n}(c_i - \bar{c})^2} \tag{2}$$

$$W_o = \sum\nolimits_{i=1}^{n}\sum\nolimits_{j\neq i}^{n} W_{ij} \tag{3}$$

where n represents the number of provinces in China, c_i and c_j represent carbon emissions in provinces i and j, c is the average carbon emissions in all provinces, and W_{ij} is the spatial weight matrix and represents the spatial disparity between regions i and j.

W_{ij} is a binary spatial weight matrix, which can be categorized into two types. One is based on adjacency, where regions share common boundaries, and the other is based on distance, where the distance between the centroids of regions is less than a given critical value. The selection of the spatial weight matrix can affect the calculation of the ratio. In this paper, since the regions are represented by provincial surface data and provinces share common boundaries with each other, we have chosen the spatial weight matrix based on adjacency. Its form is as follows:

$$W_{ij} = \begin{cases} 1\ Region\ i\ and\ j\ share\ a\ common\ boundary \\ \qquad\qquad 0\ else \end{cases} \tag{4}$$

The Moran's *I* index typically ranges between [−1 and 1]. When Moran's $I > 0$, it indicates a positive spatial correlation in the carbon emissions from the construction industry among different regions, meaning that neighboring regions have similar emissions. When Moran's $I < 0$, it indicates a negative spatial correlation, signifying those emissions are heterogeneous among neighboring regions. When Moran's $I = 0$, it suggests that there is no spatial correlation, implying that emissions are independent of each region [50].

3.2.2. Spatial Econometric Models

The two fundamental types of spatial econometric models can be classified based on the way spatial dependencies are introduced. One is the introduction of spatial lag correlation, known as the Spatial Lag Model (SLM); the other introduces spatial error dependence, referred to as the Spatial Error Model (SEM). The former involves correlation in the dependent variable, while the latter involves correlation in the error terms. These models are used in spatial econometrics to handle spatial dependencies and better capture the relationships between observations in spatial datasets [51].

- Spatial Lag Model (SLM)

The SLM examines whether various variables in a particular region exhibit diffusion or spillover effects. The dependent variable is influenced not only by the independent variables within the same region but also by the dependent variables in neighboring regions. The expression for this model is as follows:

$$y = \rho W_y + X\beta + \varepsilon \tag{5}$$

where y is the dependent variable, X is the matrix of explanatory variables, W is the spatial weight matrix, ρ is the spatial autoregressive coefficient, β is the parameter vector, and ε is the error term. This relationship reflects the spatial dependency in the sample observations, indicating how the observations in neighboring regions influence the observations in the focal region, including both the direction and magnitude of the influence.

- Spatial Error Model (SEM)

The SEM is used to capture the spatial interactions between individual units by considering spatial correlations within the error term. This model is applicable when there are variations in the spatial interactions among units due to differences in their relative positions. The expression for SEM is as follows:

$$y = \lambda W_{\varepsilon} + X\beta + \eta \quad (6)$$

where λ is the spatial error term in the cross-sectional dependent variable vector, η denotes independently distributed random error terms that measure the spatial dependency effects present in the error disturbances and also quantify the extent to which neighboring areas affect the observed values in the local area due to errors in the dependent variable.

4. Results

4.1. Initial Exploration of Carbon Emissions

4.1.1. Statistics of the Carbon Emissions

From the Table 2, the annual carbon emission values are valid and there are no default data. It can be observed that although the average carbon emissions from the construction industry in each province generally exhibit an upward trend, the median values exhibit a fluctuating decline. They reach their troughs in 2011, 2015, and 2018, and peak in 2013, 2016, and 2019. Simultaneously, the peak values are decreasing, indicating a declining trend in carbon emissions for provinces located around the dataset's median values. It reflects that these provinces have implemented carbon emission reduction measures and achieved certain results during this period. The increase in the average, on the other hand, may be attributed to the influence of extreme values in certain provinces. Especially when examining the percentile values, half of the provinces have carbon emissions of only 2 million tons, significantly lower than the maximum value of 6 million tons. Additionally, the carbon emissions of three-quarters of the provinces are also around 3 million tons, with only half of the maximum value. The difference between the minimum and maximum values is significant. By this token, the carbon emissions of most provinces are relatively close to each other, while a small number of provinces exhibit significant differences in carbon emissions, indicating a greater pressure for emissions reduction in those areas.

Table 2. Descriptive statistics of carbon emissions in 30 provinces from 2011 to 2020.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Valid (n)	30	30	30	30	30	30	30	30	30	30
Null (n)	0	0	0	0	0	0	0	0	0	0
Mean	2.080	2.044	2.170	2.204	2.261	2.242	2.305	2.263	2.308	2.334
Median	1.760	1.786	2.117	1.974	1.929	2.063	2.000	1.858	1.962	1.874
Standard Deviation	1.505	1.421	1.528	1.588	1.635	1.534	1.578	1.610	1.649	1.680
Minimum	0.127	0.148	0.048	0.058	0.144	0.068	0.075	0.049	0.187	0.186
Maximum	5.850	5.549	5.942	6.033	6.103	5.921	5.925	6.139	6.326	6.532
25%	0.893	0.953	1.111	1.129	1.026	1.047	1.062	0.988	0.996	1.072
75%	2.828	2.710	2.577	2.747	3.011	3.101	3.331	3.353	3.411	3.616

4.1.2. Carbon Emissions Trends

According to Figure 1, on the one hand, there are 4 provinces out of the 30 provinces in China that have cumulatively emitted more than 40 million tons of carbon in the construction industry from 2011 to 2020. These provinces are Jiangsu, Zhejiang, Hubei, and Hunan, with Zhejiang having the highest emissions at 53.80 million tons. On the other hand, there are three provinces with emissions totaling less than 5 million tons, which are Guangxi, Hainan, and Heilongjiang. Among them, Heilongjiang has the lowest carbon emissions, amounting to only 2.74 million tons, approximately 4% of Zhejiang's emissions. Over the course of a decade, the carbon emissions in several provinces exhibit different trends. Shanghai, Beijing, Shandong, Hubei, Liaoning, and Shanxi, consistently witness year-to-year reductions in carbon emissions. Conversely, provinces like Jilin, Hebei, and Shaanxi initially experienced an increase in emissions followed by a subsequent decrease. Anhui, Jiangxi, Ningxia, Henan, Guizhou, and Hunan register slight increases in emissions. Meanwhile, areas like Yunnan, Tianjin, Jiangsu, Fujian, and Chongqing maintain relatively stable emission levels.

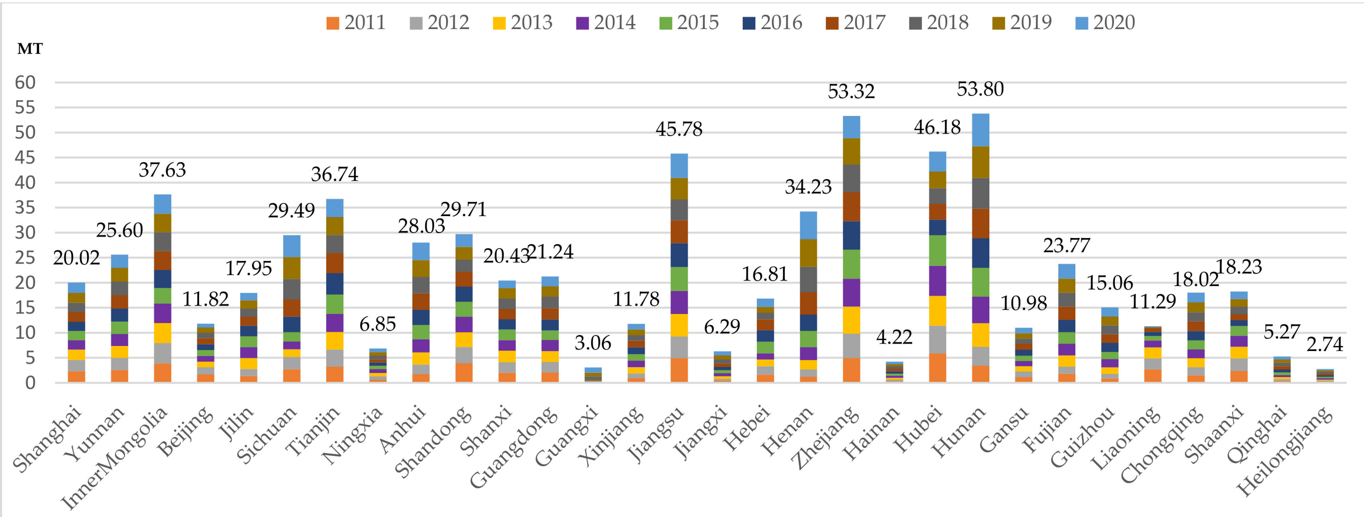


Figure 1. Carbon emissions in 30 provinces of China's construction industry from 2011 to 2020.

From this perspective, carbon emissions in the 30 provinces of China vary significantly. Although the construction industry has made some progress in reducing carbon emissions since the introduction of energy-saving and emission reduction targets during the "Eleventh Five-Year Plan" and the subsequent issuance of several guiding documents, the carbon emissions in some provinces remain high. This is due to the crucial role of the construction industry in the economic development and urbanization of developing countries. Hence, high carbon emission areas must simultaneously address the challenges and capitalize on opportunities for further carbon reduction. This also indirectly shows that there are regional disparities in the management of carbon emissions, which will help us gain an in-depth understanding of the diverse performances and challenges in carbon reduction across different areas.

4.2. Spatiotemporal Distribution Characteristics of Carbon Emissions

4.2.1. Spatiotemporal Distribution Pattern

From Figure 2, it is evident that there is a significant regional disparity in carbon emissions. Beginning in 2010, the northern region, including Inner Mongolia, the central region, with Hubei, and the eastern coastal areas such as Shandong and Zhejiang, exhibited the highest emissions. In contrast, the northeastern province of Heilongjiang, northwestern Qinghai, and southern Guangxi had the lowest carbon emissions during this period. However, emissions in Inner Mongolia and Sichuan began to decrease annually, while, from 2012, the central region's emissions gradually increased and formed a central cluster. This cluster encompassed provinces such as Hunan, Hubei, Henan, Anhui, Zhejiang, Jiangsu, and Guangdong, forming a roughly circular distribution around the lower-emission area of Jiangxi. By 2015, the circular distribution pattern became more pronounced, along with southwestern Sichuan, collectively radiating toward the central region. Emissions began to decrease in most areas to the north along the line from the westernmost Xinjiang to the easternmost Heilongjiang. In contrast, emissions in the central regions of Henan and Hunan, as well as in the western regions of Sichuan and Yunnan, showed a gradual increase. Meanwhile, the eastern coastal areas, including Shandong, Zhejiang, and Jiangsu, consistently remained in the high emissions zone. By 2020, it had developed into a transverse low-value distribution belt spanning from east to west (referred to as the "Belt"). This belt separated the high-value regions of northern Inner Mongolia from the eastern coastal areas, including Zhejiang, Jiangsu, and Shandong, in addition to the central regions of Henan, Hunan, and Sichuan (referred to as the "Ring" and the "Dot"). Ultimately, this pattern evolved into the "Belt–Ring–Dot" spatial distribution, exhibiting a noticeable spatial clustering characteristic.

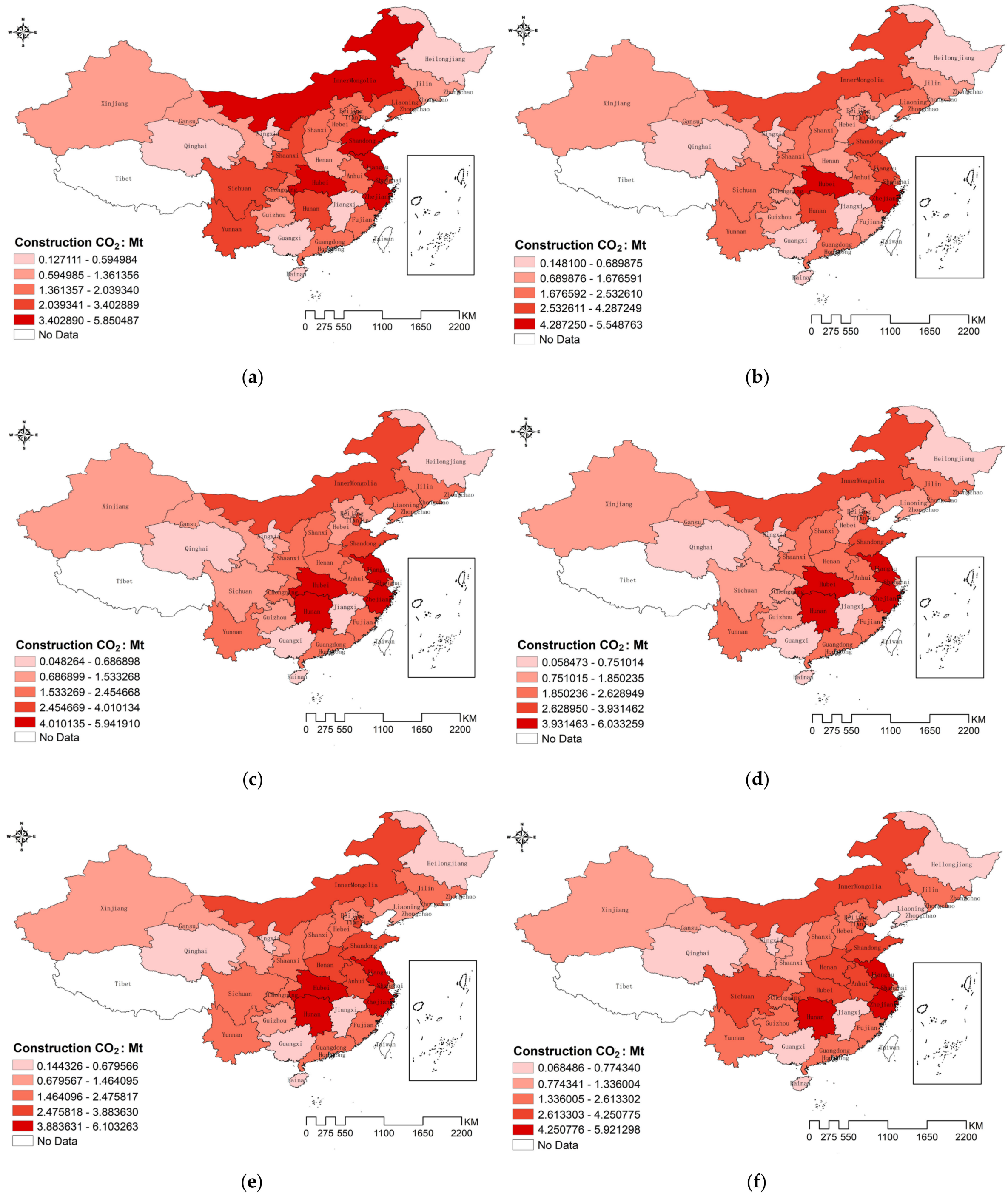
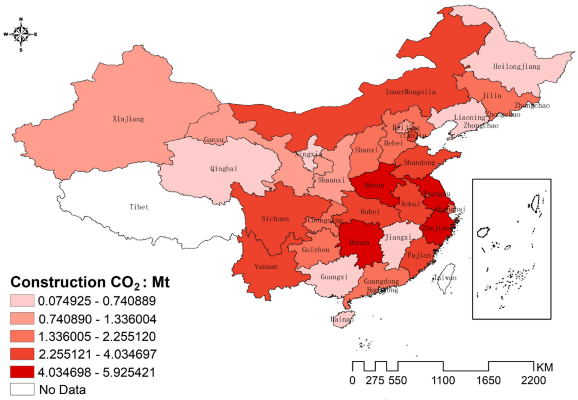
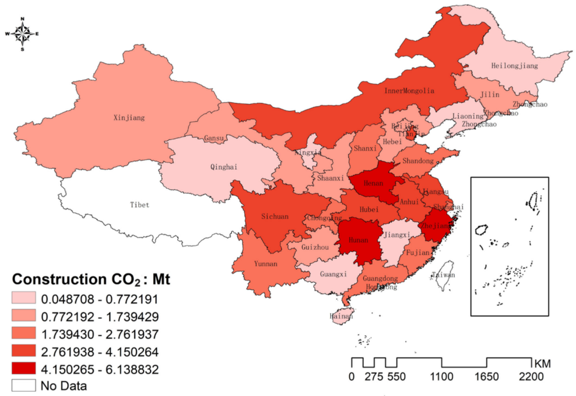


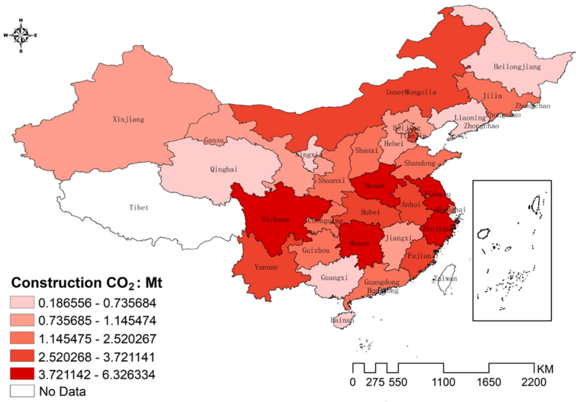
Figure 2. *Cont.*



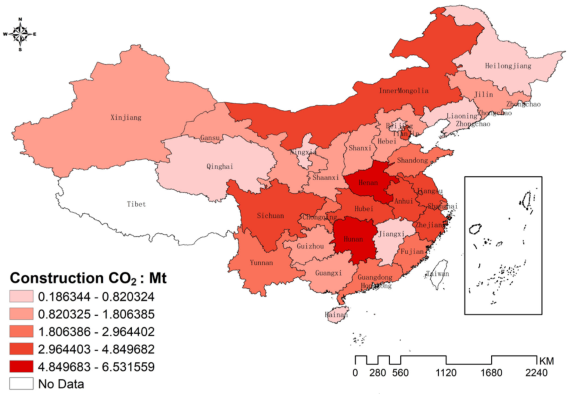
(**g**)



(**h**)



(**i**)



(**j**)

Figure 2. Spatial distribution characteristics of carbon emissions from 2011 to 2020: (**a**) represents the year 2011, (**b**) represents the year 2012, (**c**) represents the year 2013, (**d**) represents the year 2014, (**e**) represents the year 2015, (**f**) represents the year 2016, (**g**) represents the year 2017, (**h**) represents the year 2018, (**i**) represents the year 2019, (**j**) represents the year 2020.

This distribution pattern indicates that, on a national scale, carbon emissions from the construction industry exhibit a specific clustering pattern in space, which is differentiated and uneven. The "Belt" represents a low-value aggregation area of carbon emissions horizontally, while the "Ring" and the "Dot" are high-value aggregation areas. This spatial clustering property suggests that carbon emissions from the construction industry are not only influenced by local factors such as economic development, industrial structure, and energy consumption, but also by the influence of neighboring regions. Therefore, in the study of influencing factors on carbon emissions from the construction industry, it is necessary to consider the existence of spatial clustering effects.

The Y-axis in the trend analysis graph represents the north–south direction, the X-axis represents the east–west direction, and the Z-axis represents carbon emissions. The blue line connects the projected points of carbon emissions in the north–south direction, while the green line represents the east–west direction. This line signifies the simulated optimal trend direction for carbon emissions in the construction industry. Connecting the projected points with lines allows us to simulate the most suitable trend direction. Upon examination, it becomes apparent that the spatial trends in carbon emissions in the construction industry are relatively consistent across provinces, thus warranting our focus on presenting the trend analysis only for 2011 and 2020. Figure 3 illustrates that there is a clear inverted U-shaped trend in the north–south direction, while in the east–west direction, emissions are lower in the west and higher in the east. This suggests that the central regions of China exhibit higher carbon emissions, gradually decreasing toward the north and south, while the western regions demonstrate lower emissions compared to the eastern regions. This aligns with the spatial distribution of carbon emissions in Figure 2. Furthermore, the trend analysis graph also indicates that as carbon emissions move eastward, the rate of increase in carbon emissions slows down, and after reaching a peak, there is a slight decreasing trend. From this observation, it becomes evident that there exists a substantial spatial disparity in carbon emissions from the construction industry among provinces in China.

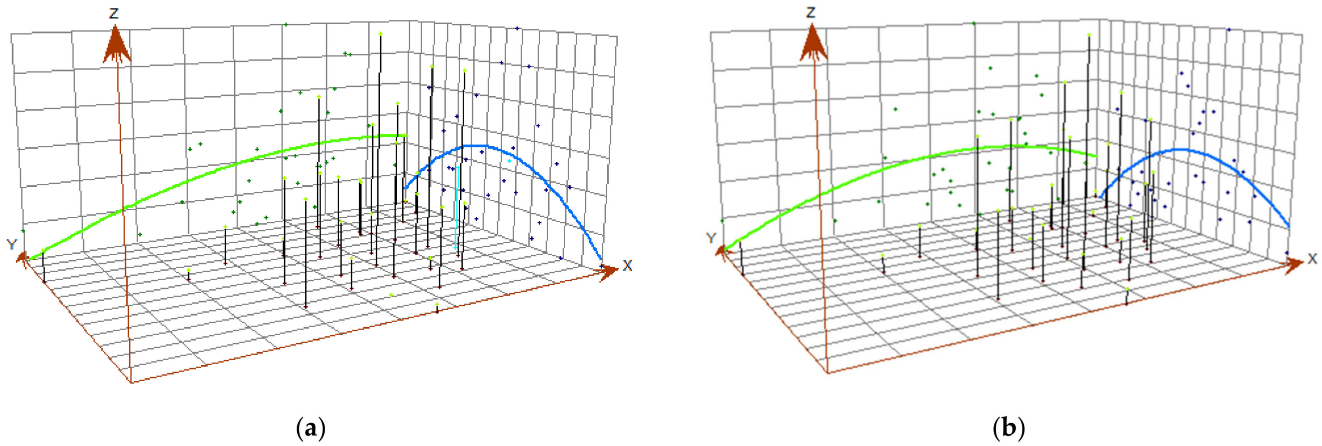


Figure 3. Trend Analysis of carbon emissions in 2011 and 2020: (**a**) represents the year 2011; (**b**) represents the year 2020.

4.2.2. Global Spatial Autocorrelation Analysis

To verify the spatial effects of carbon emissions in the provincial-level construction industry in China, a spatial weight matrix based on adjacency relationships is constructed. Since Hainan Province is an independent island and does not share a land border with other provinces and cities, the calculation index will be excluded. Therefore, for the sake of data completeness and accuracy, we adjusted the adjacency of Hainan Province with Guangdong Province and Guangxi Province. The final calculation results are as Table 3.

Table 3. Moran's *I* index from 2011 to 2020.

Year	Moran's *I*	*p*-Value	*z*-Value
2011	0.151	0.015	2.1739
2012	0.142	0.011	2.1638
2013	0.162	0.004	2.4164
2014	0.194	0.001	2.8491
2015	0.225	0.001	3.2964
2016	0.245	0.001	3.3674
2017	0.279	0.001	3.8362
2018	0.284	0.001	3.8130
2019	0.281	0.001	3.8397
2020	0.269	0.001	3.5399

From 2011 to 2020, the Moran's *I* index values of carbon emissions were all greater than 0, with a minimum value of 0.124 in 2010 and increasing fluctuation thereafter, reaching a maximum of 0.284 in 2018. Additionally, the *p*-value passed the 5% significance test in the first two years, while the *p*-value consistently passed the 1% significance test in the last eight years. This demonstrates that there is a certain positive spatial correlation in carbon emissions in the construction industry. Specifically, when the carbon emissions in one region's construction industry are high, the surrounding or adjacent regions also tend to exhibit elevated carbon emissions in a spatially consistent pattern. Meanwhile, the Moran's *I* index being greater than zero validates that an econometric model neglecting spatial correlation would lead to biases.

4.3. Spatial Driving Factors

4.3.1. Construction of Spatial Econometric Models

As mentioned earlier, there is spatial autocorrelation in carbon emissions at the provincial level, so it is appropriate to apply spatial econometric models to examine the influencing factors. Spatial econometric models are divided into two fundamental types: SLM and SEM. To determine which model offers a superior fit, it is essential to conduct parameter estimation. After spatially comparing the influencing factors of carbon emissions in the construction industry from 2011 to 2020, it is found that the spatial error model consistently outperformed the spatial lag model in terms of assessment over the years. The model estimation results from 2019 are used as an example for analysis.

R^2 represents the degree of fit for the regression, ranging between 0 and 1. The closer the value is to one, the higher the degree of model fit. Both Sigma^2 and S.E of regression indicate the stability of the data; a smaller value suggests more stability, while a larger value indicates greater dispersion. The Log likelihood (LogL), Akaike Information Criterion (AIC), and Schwarz Criterion (SC) are diagnostic metrics for the goodness of fit in multivariate regression models. An augmented LogL, coupled with diminished AIC and SC values, denotes an optimal model fit. From the Table 4, the R^2 and LogL values for the SEM are higher than those of the SLM, while the AIC and SC values for the former are lower than the latter [52]. This implies the SEM more effectively captures the dynamics of provincial construction carbon emissions compared to the SLM model. Additionally, the Sigma^2 and S.E of regression for the SEM model are also smaller, indicating a more stable dataset. Given these considerations, this study has chosen the SEM model for further research.

Table 4. Comparison of model results.

Index	Spatial Error Model	Spatial Lag Model
R^2	0.700504	0.602019
Sigma^2	0.787003	1.0458
S.E of regression	0.887132	1.02264
LogL	−41.209947	−43.9397
AIC	94.4199	101.879
SC	102.827	111.688

4.3.2. Model Results Analysis

The selection of the SEM model indicates that the spatial dependence of influencing factors for carbon emissions in the construction industry exists within the error term. In the Table 5, LAMBDA stands for the spatial autoregressive coefficient (λ) in the error term. The significance test of the coefficient only failed in 2014 and 2015, proving that for the remaining years, the null hypothesis that there is no spatial correlation effect in carbon emissions from the Chinese construction industry should be rejected under a significance level of 1–10%. This suggests that carbon emissions in China's construction industry exhibit a certain degree of spatial dependence, being easily influenced by the emissions from neighboring regions.

Following 10 simulations, in terms of spatial correlation, both the number of employees (NE) and patents granted (PG) pass the significance test eight times while the mean test coefficient for NE (0.552) is greater than that of PG (−0.085), showing that NE has the highest spatial correlation. This is trailed by the technical equipment rate (TR) and the construction industry's gross production (GP). Conversely, the urbanization rate (UR) exhibits the weakest spatial correlation, only meeting significance thresholds three times. With regard to influence directionality, NE, GP, and UR all indicate a positive association with carbon emissions, underscoring their role in amplifying emissions. Contrastingly, PG, representing technological innovation capabilities, demonstrates a negative correlation with carbon emissions, indicating its efficacy in mitigating emissions. Specifically, the correlation of TR transitioned from a positive stance before 2018 to a negative one post that year, signifying an evolution in its impact on carbon emissions from an initial boost to subsequent restraint.

Table 5. Estimation results of Spatial Error Model.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
GP	0.0825 (1.68) *	0.0464 (1.10)	0.0438 (1.04)	0.0414 (0.86)	0.0319 (0.81)	0.0481 (1.93) *	0.0579 (2.36) **	0.0499 (2.24) **	0.0532 (3.08) ***	0.0673 (3.65) ***
NE	0.5959 (2.40) **	0.7659 (2.64) ***	0.8008 (2.78) ***	0.5143 (1.79) *	0.7875 (3.22) ***	0.6436 (4.45) ***	0.4638 (3.30) ***	0.3972 (2.26) **	0.2748 (1.58)	0.2763 (1.55)
UR	0.0065 (0.46)	0.0083 (0.50)	0.0333 (2.25) **	−0.0063 (−2.89)	0.0154 (0.68)	0.0011 (0.06)	0.0183 (1.07)	0.0200 (0.99)	0.0396 (2.14) **	0.0469 (1.97) **
TR	0.4492 (2.35) **	0.2619 (1.85) *	0.0276 (0.33)	0.5544 (2.10) **	1.0375 (2.15) **	0.6840 (2.62) ***	0.4232 (1.52)	−0.2591 (−0.20)	−0.1624 (−1.68) *	−0.1170 (−1.98) **
PG	−0.0618 (−0.94)	−0.1197 (−1.85) *	−0.1658 (−2.22) **	−0.0242 (−0.30)	−0.1287 (−2.01) **	−0.0717 (−1.73) *	−0.0710 (−2.05) **	−0.0623 (−2.40) **	−0.0760 (−3.38) ***	−0.0640 (−3.48) ***
LAMBDA	−0.4461 (−1.66) *	−0.5210 (−1.96) *	0.6602 (−2.56) **	−0.1840 (−0.53)	0.4394 (1.61)	−0.8849 (−3.75) ***	−0.9191 (−3.97) ***	−0.9783 (−4.38) ***	0.8722 (−3.67) ***	−0.9980 (−4.53) ***

Note: The data in parentheses are the *z*-value. *, **, and *** represent the significant level of 10%, 5%, and 1%, respectively.

5. Discussion

This study conducts a spatial econometric analysis of the carbon emissions in the construction industry across 30 provinces in China from 2011 to 2020. The findings suggest that over the decade, regions with high carbon emissions have progressively shifted from the northern, central, and eastern coastal areas, consolidating into a circular pattern in the central region, characterized by a "Belt–Ring–Dot" spatial distribution. Concurrently, the central region exhibits a gradual decrease in carbon emissions from south to north. Moreover, the western provinces have lower carbon emissions compared to the eastern ones, with the rate of increase in emissions slowing as one moves eastward. This indicates substantial disparities in carbon emissions across provinces and displays inconsistent reduction trajectories. While many provinces have made commendable strides in reducing emissions, a select few grapple with considerable emission challenges.

Global spatial autocorrelation results further affirm a discernible positive correlation in carbon emissions of the construction industry. Drawing from economic, societal, population, technological, and innovative lenses, we employed five key indicators: the gross product of the construction industry (GP), the number of employees (NE), urbanization rates (UR), technical equipment rate (TR), and patents granted (PG). These factors informed the formulation of a spatial error model to reveal three distinct directional impacts: stimulatory effect, inhibitory effect, and special effect. In light of the results, we propose specific recommendations for differentiated carbon emissions reduction, aiming to promote the green, healthy, and sustainable development of the construction industry and achieve "Dual Carbon Targets".

5.1. Aggravating Effect

5.1.1. The Gross Product (GP)

The construction industry, recognized as a foundational pillar of the national economy, has experienced a continuous expansion in its operational and production capacities. This expansion is consistently reflected in the industry's increasing total output value over time. Such a trend underscores a direct correlation between the industry's developmental progress and its economic contribution. Data from the table show that since 2016, higher construction output has escalated carbon emissions. Essentially, the more advanced the industry becomes, the greater the energy consumption and carbon output, with the impact growing progressively. This is consistent with the research findings of Shi et al. (2023) [53]. Owing to the aggravating effect of surrounding areas, it also indirectly affects the local carbon emissions. Therefore, while adjusting the industry structure for the development of the construction sector, it is essential to accelerate the enhancement of its energy efficiency.

5.1.2. The Number of employees (NE)

NE in construction activities has shown a proportional relationship with carbon emissions in the construction industry for eight consecutive years since 2010. That is, the more people involved in construction activities, the higher the carbon emissions. Given that value creation in the construction industry is reliant on labor, the strength of the labor force directly influences the industry's economic growth, subsequently affecting the volume of carbon emissions [54]. Construction workers, often relocating to align with the location of their projects, inherently exhibit a notable degree of mobility. This increased mobility can subsequently escalate demands for housing, transportation, food, and infrastructure, indirectly leading to an uptick in carbon emissions [55].

However, the impact coefficient has been gradually decreasing since 2013, indicating that the influence of NE is progressively diminishing. Moreover, starting from 2019, this factor does not pass significance testing. A possible explanation might be that, with the continuous advancement of technological levels and rising mechanization, even with fewer laborers, there is an elevation in productivity. This increased efficiency in creating more industrial value might, in turn, lead to a rise in carbon emissions. As a result of the cumulative impacts of various factors, its inherent influence begins to wane. This decline became particularly pronounced at the end of 2019 due to the emergence of the novel coronavirus in Wuhan. The subsequent nationwide outbreak in 2020 resulted in widespread shutdowns, gravely affecting construction projects. With construction workers ceasing their movement, the spatial interactivity was lost, leading to the complete loss of their spatial influence. Liu et al. (2022) also believe that the novel coronavirus had a certain impact on the reduction in carbon emissions [56].

5.2. Inhibitory Effect

Only the patents granted (PG) factor has an inhibiting effect on carbon emissions. PG allows technological innovations to be directly transformed into production factors. Safeguarding and enhancing the adoption of digital, modular, information-driven, and eco-friendly technologies in construction serves as a pivotal catalyst, driving the industry's evolution and modernization. According to the table, with few exceptions, there is an inverse relationship between PG and carbon emissions in the construction industry. That is, the greater the number of patents granted, the less the carbon emissions. This underscores the significant role of technological innovation, as represented by PG, in curbing carbon emissions. By obtaining PG, construction companies can continuously develop and apply new energy-saving and emission-reduction technologies, processes, equipment, and materials, enhancing energy utilization efficiency and reducing carbon emissions. However, Zhang et al. (2020) consider that once energy consumption exceeds a critical level, the promoting effect of technological innovation on carbon emissions reduction will turn into an inhibiting effect [57]. Additionally, this indicator possesses a certain spatial spillover effect, signifying that innovative collaboration in the construction industry across neighboring provinces can pool more intelligence and resources. They can collaboratively develop advanced carbon emission reduction technologies, engage in technology sharing, and accelerate technological exchanges, achieving the goal of energy savings and emission reductions at the source. This is consistent with the view of Dong et al. [58].

5.3. Special Effect

5.3.1. The Urbanization Rate (UR)

It is widely believed that urbanization primarily manifests as an expansion of construction land and frequent building activities. Such progression often triggers deforestation, a reduction in arable land, shifts in land cover, and, consequentially, climatic changes and elevated carbon emissions. However, some studies argue that the impact of different stages of urbanization on carbon emissions varies. Zhou et al. (2021) believe that the relationship between urbanization and land-use change emissions (LUCEs) can be summarized into three modes; however, the findings of this study differ from that perspective [59]. According to the data, only in specific years does UR directly correlate with carbon emissions, indicating that heightened urbanization levels lead to an uptick in carbon emissions within the construction industry. However, in the remaining years, UR did not pass the hypothesis test, indicating a weak association between UR and carbon emissions across various provinces and their neighbors. Given China's vast territorial extent and stark regional differences, the urbanization pace is not uniform across the country.

For instance, while Shanghai leads with an urbanization rate of 89.3%, Yunnan stands at the lower end with a mere 50.5%. Regions with higher urbanization levels usually boast advanced infrastructure, leading to fewer new construction initiatives. Moreover, construction projects in these regions often employ eco-friendly methodologies and materials, minimizing their carbon emissions. Conversely, regions with lower urbanization rates often intensify measures like land expansion and infrastructure development to accelerate urbanization. This tends to sustain high energy consumption in the construction industry, consequently exacerbating carbon emissions. Hence, the influence of UR on construction carbon emissions might be bidirectional, which cannot be simply understood as a direct cause-and-effect relationship between them. Their interrelation remains influenced by multiple factors, aligning with the research perspectives of Wang et al. [60].

5.3.2. Technical Equipment Rate (TR)

The level of TR signifies the degree of mechanization and technological investment within the construction industry. This, in turn, affects the efficiency of construction production, indirectly determining the volume of carbon emissions. Although technological progress is widely recognized as a method of reducing carbon emissions, some scholars believe that technological progress can also have the opposite effect [61]. The results of this study, however, demonstrate both positive and negative impacts. The data indicate that TR passes the significance test in more than six times, demonstrating a certain spatial correlation between TR and carbon emissions. However, it is noteworthy that the relationship was positive prior to 2018 but turned negative afterward. While construction firms have steadily acknowledged the value of mechanization and technological advancement, ramping up their machinery investments, or the use of information and communication technology (ICT), such shifts bring challenges [62]. The high energy demands of the newly introduced machinery can lead to an increase in fossil fuel consumption, boosting carbon emissions. Moreover, there is an inherent learning curve when introducing new technologies. Workers initially might not fully grasp the optimal methods of operation, which can hinder the machinery's efficiency and inadvertently escalate energy wastage and carbon emissions. With the accumulation of practical experience, the widespread application of information technology, the introduction of newer low-energy construction machinery, guidance from green building policies, and the sharing and emulation of successful practices from neighboring provinces' construction industries, the rise in TR has simultaneously led to reduced resource consumption and lower carbon emissions, ultimately exhibiting a negative correlation [63].

5.4. Policy Recommendations

According to the research results, NE has the highest degree of influence. Therefore, in high carbon-emission areas, the first step is to strengthen publicity and education, improve construction workers' awareness of clean energy and green buildings, and form a social consensus. Secondly, considering the significant role of technological innovation and machinery investment in suppressing carbon emissions, government departments can provide policy support or tax incentives to encourage construction companies to adopt clean energy, green low-carbon technologies, and low-energy machinery, fostering structural adjustments within the industry [64]. Simultaneously, corresponding restrictions and emission reduction targets should be imposed on carbon emissions, with rewards for those achieving the targets and penalties for excessive emissions.

In low carbon-emission areas, establishing low-carbon demonstration projects could be considered. Through skill training or academic seminars, the successful experiences of emission reduction and advanced technologies could be exchanged and shared externally, facilitating the transfer of low-carbon knowledge. Alternatively, the implementation of technology assistance programs could provide technical support to high carbon-emission areas, fostering collaborative efforts to promote the transformation and upgrading of the construction industry. Taking into account the spatial correlation of carbon emissions, regional cooperation could be explored, such as establishing a carbon emission information platform for tracking construction-related carbon emissions, bolstered by data-sharing mechanisms, which would enhance monitoring, auditing, and oversight processes. These initiatives aim to promote the healthy and sustainable development of the construction industry, ultimately achieving the "dual-carbon" goals.

6. Conclusions

This research analyzed the carbon emissions from the construction industry of 30 provinces in China over a decade, from 2011 to 2020. From a spatiotemporal perspective, after 10 years of evolution, the carbon emissions of the construction industry have gradually formed a "Belt–Ring–Dot" distribution characteristic. The "Belt" represents a low-value aggregation area of carbon emissions horizontally, while the "Ring" and the "Dot" are high-value aggregation areas. Analysis of the trend indicates a U-shaped pattern in carbon emissions from north to south, with higher emissions in the central region gradually decreasing toward the north and south. In the east–west direction, emissions are lower in the west and higher in the east, with a deceleration in the rate of increase. This suggests significant regional disparities in carbon emissions from the construction industry, while many provinces have made strides in carbon reduction, a select few continue to grapple with heightened emission challenges.

Based on the global spatial autocorrelation analysis from 2011 to 2020, the Moran's I index of carbon emissions in the construction industry consistently surpassed 0, with a maximum value of 0.284 in 2018. Every value met the criteria for statistical significance, highlighting a clear spatial correlation in construction carbon emissions throughout the 30 provinces. To address the limitations of traditional economic models that neglect spatial correlations, this study employs a spatial error model to analyze the influencing factors of carbon emissions. Evaluating from economic, social, demographic, technological, and innovative perspectives, five indicative variables are incorporated: the gross product (GP), number of employees (NE), urbanization rates (UR), technological equipment rate (TR), and patents granted (PG). Among the five variables, the spatial correlation of UR is the weakest, failing the test a total of seven times, with the minimum test coefficient being only 0.001. While the spatial correlation of NE is the highest, passing the test eight times, and the mean test coefficient is the largest, at 0.552. Simultaneously, NE and GP show a positive correlation with carbon emissions, indicating an aggravating effect on the emissions, whereas NE tops the list in spatial correlation, followed by PG, TR, and GP. On the other hand, due to the consistently negative test coefficients, with the maximum absolute value of 0.166, PG demonstrates an inverse relationship with carbon emissions. This underscores the significant role that technological innovation, as represented by PG, plays in curbing carbon emissions. TR, however, has shown a shift from a positive correlation to a negative one, with 2018 as the turning point.

This study still has some research limitations. For instance, given sufficient data, extending the study timeframe beyond the current 10 years could reveal a more comprehensive pattern of evolution. Additionally, future research could consider expanding the categories of influencing factors of carbon emissions in the construction industry to broaden the research findings. Furthermore, in terms of regional segmentation, it might be beneficial to shift the study focus from provincial to municipal levels for a more detailed conclusion.

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

Funding: This research received no external funding.

Data Availability Statement: The data presented in this research are available upon request from the corresponding author. The data are not publicly available due to privacy.

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

References

1. Gu, C.; Tan, Z.; Liu, W.; Yu, F.; Han, Q.; Liu, H.; Dai, Y.; Liu, Z.; Zheng, S. A study on climate change, carbon emissions and low-carbon city planning. *Urban Plan. Forum* **2009**, *3*, 38–45.
2. CO_2 Emissions. Available online: https://ourworldindata.org/co2-emissions (accessed on 24 September 2023).
3. Qi, Y.; Stern, N.; He, J.; Lu, J.; Liu, T.; King, D.; Wu, T. The policy-driven peak and reduction of China's carbon emissions. *Adv. Clim. Chang. Res.* **2020**, *11*, 65–71. [CrossRef]
4. Karlsson, I.; Rootzén, J.; Johnsson, F. Reaching net-zero carbon emissions in construction supply chains—Analysis of a Swedish road construction project. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109651. [CrossRef]
5. Shi, Q.; Chen, J.; Shen, L. Driving factors of the changes in the carbon emissions in the Chinese construction industry. *J. Clean. Prod.* **2017**, *166*, 615–627. [CrossRef]
6. Liu, Y.; Yang, C.; Cai, H. Inter-provincial diversity and factor decomposition of the totality and intensity of carbon emissions in China. *J. Hunan Univ. Technol.* **2022**, *36*, 1–9. [CrossRef]
7. Shen, N.; Peng, H.; Wang, Q. Spatial dependence, agglomeration externalities and the convergence of carbon productivity. *Socio Econ. Plan. Sci.* **2021**, *78*, 101060. [CrossRef]
8. Yang, Q.; Zhao, R.; Ding, M.; Man, Z.; Wang, S.; Yu, J.; Yang, W. Spatial pattern and influencing mechanism of urban carbon emissions in China based on cross—Section data of 285 cities. *Resour. Dev. Mark.* **2018**, *34*, 1243–1249. [CrossRef]
9. Liu, H.; Shao, M.; Ji, Y. The spatial pattern and distribution dynamic evolution of carbon emissions in China: Empirical study based on county carbon emission data. *Sci. Geogr. Sin.* **2021**, *41*, 1917–1924. [CrossRef]
10. Gregg, J.S.; Losey, L.M.; Andres, R.J.; Blasing, T.J.; Marland, G. The temporal and spatial distribution of carbon dioxide emissions from fossil-fuel use in North America. *J. Appl. Meteorol. Climatol.* **2009**, *48*, 2528–2542. [CrossRef]
11. Ezcurra, R. Is there cross-country convergence in carbon dioxide emissions? *Energy Policy* **2007**, *35*, 1363–1372. [CrossRef]
12. Nazlioglu, S.; Payne, J.E.; Lee, J.; Rayos-Velazquez, M.; Karul, C. Convergence in OPEC carbon dioxide emissions: Evidence from new panel stationarity tests with factors and breaks. *Econ. Model.* **2021**, *100*, 105498. [CrossRef]
13. Li, L.; Han, R.; Zhang, X. Spatial-temporal evolution of carbon emission and its efficiency in Chinese aviation. *Acta Ecol. Sin.* **2022**, *42*, 3919–3932. [CrossRef]
14. Wang, L.; Liu, M. Carbon emission measurement for China's logistics industry and its influence factors based on input-output method. *Resour. Sci.* **2018**, *40*, 195–206. [CrossRef]
15. Zhou, Y.; Li, B.; Zhang, R. Spatiotemporal evolution and influencing factors of agricultural carbon emissions in Hebei Province at the county scale. *Chin. J. Eco-Agric.* **2022**, *30*, 570–581. [CrossRef]
16. Liu, H.; Tian, H.; Hao, Y.; Liu, S.; Liu, X.; Zhu, C.; Wu, Y.; Liu, W.; Bai, X.; Wu, B. Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis. *Sci. Total Environ.* **2019**, *648*, 871–879. [CrossRef] [PubMed]
17. Du, Q.; Deng, Y.; Zhou, J.; Wu, J.; Pang, Q. Spatial spillover effect of carbon emission efficiency in the construction industry of China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 2466–2479. [CrossRef] [PubMed]
18. Zhang, L.; Liu, B.; Du, J.; Liu, C.; Li, H.; Wang, S. Internationalization trends of carbon emission linkages: A case study on the construction sector. *J. Clean. Prod.* **2020**, *270*, 122433. [CrossRef]
19. Wang, J.; Wei, J. The temporal variation characteristics and scenario analysis of operation carbon emissions of buildings in Beijing. *J. Beijing Univ. Technol.* **2022**, *48*, 220–238. [CrossRef]
20. Wei, D.; Huang, W.; Cao, Z. Influencing factors and reduction mechanism of carbon emissions in the provincial range: A case study of Zhejiang province. *Ecol. Econ.* **2017**, *33*, 14–18.

21. O'neill, B.C.; Dalton, M.; Fuchs, R.; Jiang, L.; Pachauri, S.; Zigova, K. Global demographic trends and future carbon emissions. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 17521–17526. [CrossRef]
22. Du, Q.; Shao, L.; Zhou, J.; Huang, N.; Bao, T.; Hao, C. Dynamics and scenarios of carbon emissions in China's construction industry. *Sustain. Cities Soc.* **2019**, *48*, 101556. [CrossRef]
23. Kohler, M. CO_2 emissions, energy consumption, income and foreign trade: A South African perspective. *Energy Policy* **2013**, *63*, 1042–1050. [CrossRef]
24. Wang, Q.; Zhang, F. The effects of trade openness on decoupling carbon emissions from economic growth–evidence from 182 countries. *J. Clean. Prod.* **2021**, *279*, 123838. [CrossRef] [PubMed]
25. Shahbaz, M.; Nasreen, S.; Ahmed, K.; Hammoudeh, S. Trade openness–carbon emissions nexus: The importance of turning points of trade openness for country panels. *Energy Econ.* **2017**, *61*, 221–232. [CrossRef]
26. Gong, X.; Xia, Y.; Hou, J.; Li, D. Industrial agglomeration and carbon emissions: Boost or inhibition?—Based on empirical evidence of the provincial level in China. *Xinjiang State Farms Econ.* **2022**, *3*, 71–78.
27. Du, Q.; Lu, X.; Li, Y.; Wu, M.; Bai, L.; Yu, M. Carbon Emissions in China's Construction Industry: Calculations, Factors and Regions. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1220. [CrossRef] [PubMed]
28. Chuai, X.; Huang, X.; Zhang, M.; Zhao, R.; Lu, J. Spatiotemporal Changes of Built-Up Land Expansion and Carbon Emissions Caused by the Chinese Construction Industry. *Environ. Sci. Technol.* **2015**, *49*, 13021–13030. [CrossRef] [PubMed]
29. Wu, P.; Song, Y.; Zhu, J.; Chang, R. Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015. *J. Clean. Prod.* **2019**, *221*, 552–566. [CrossRef]
30. Huang, L.; Krigsvoll, G.; Johansen, F.; Liu, Y.; Zhang, X. Carbon emission of global construction sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
31. Hou, H.; Feng, X.; Zhang, Y.; Bai, H.; Ji, Y.; Xu, H. Energy-related carbon emissions mitigation potential for the construction sector in China. *Environ. Impact Assess. Rev.* **2021**, *89*, 106599. [CrossRef]
32. Lu, N.; Feng, S.; Liu, Z.; Wang, W.; Lu, H.; Wang, M. The Determinants of Carbon Emissions in the Chinese Construction Industry: A Spatial Analysis. *Sustainability* **2020**, *12*, 1428. [CrossRef]
33. Liu, T.; Dong, H.; Gao, L.; Luo, T. Research on identification of evolution characteristics and influencing factors of industrial carbon emission in Jiangsu province. *J. Xi'an Univ.* **2022**, *25*, 105–111.
34. Zhu, Y.; Wang, Z.; Pang, L.; Wang, L.; Zou, X. Simulation on China's economy and prediction on energy consumption and carbon emission under optimal growth path. *Acta Grograph. Sin.* **2009**, *64*, 935–944.
35. Liu, Y.; Liu, H. Characteristics, influence factors, and prediction of agricultural carbon emissions in Shandong Province. *Chin. J. Eco-Agric.* **2022**, *30*, 558–569. [CrossRef]
36. Wang, Y.; Chen, W.; Liu, B. Manufacturing/remanufacturing decisions for a capital-constrained manufacturer considering carbon emission cap and trade. *J. Clean. Prod.* **2017**, *140*, 1118–1128. [CrossRef]
37. Zheng, H.; Ye, A. Spatial correlation network structure and influencing factors of carbon emission in urban agglomeration. *China Environ. Sci.* **2022**, *45*, 2413–2422. [CrossRef]
38. Wang, Z.; Li, Z.; Wu, W. Spatio-temporal evolution and influencing factors of carbon emissions in different grade cities in the Yangtze River Economic Belt. *Res. Environ. Sci.* **2022**, *35*, 2273–2281. [CrossRef]
39. Liu, Z.; Xu, J.; Zhang, C. Technological innovation, industrial structure upgrading and carbon emissions efficiency: An analysis based on PVAR model of panel data at provincial level. *J. Nat. Resour.* **2022**, *37*, 508–520. [CrossRef]
40. Chen, K.; Hua, J.; Li, Y. Are there regional differences in the impact of the fossil energy market on the carbon emission rights market? *Syst. Eng.* **2022**, *40*, 18–32.
41. Soytas, U.; Sari, R.; Ewing, B.T. Energy consumption, income, and carbon emissions in the United States. *Ecol. Econ.* **2007**, *62*, 482–489. [CrossRef]
42. Zhang, X.; Cheng, X. Energy consumption, carbon emissions, and economic growth in China. *Ecol. Econ.* **2009**, *68*, 2706–2712. [CrossRef]
43. Li, D.; Huang, G.; Zhu, S.; Chen, L.; Wang, J. How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu Province. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110953. [CrossRef]
44. Hong, H.; Hu, R.; Huang, M.; Zhang, J. Spatial-temporal Characteristics and Driving Factors of Aircraft Carbon Emissions in Airports. *J. Wuhan Univ. Technol.* **2022**, *46*, 953–958. [CrossRef]
45. Wu, Y.; Zheng, H.; Dong, S.; Qian, J. Study on the spatial effects of industrial development and carbon emission in central and western regions of China. *Ecol. Econ.* **2022**, *38*, 21–29+59.
46. Shan, Y.; Liu, J.; Liu, Z.; Xu, X.; Shao, S.; Wang, P.; Guan, D. New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. *Appl. Energy* **2016**, *184*, 742–750. [CrossRef]
47. Grossman, G.; Krueger, A.B. Environmental Impacts of a North American Free Trade Agreement. *Natl. Bur. Econ. Res.* **1991**, *3914*, 1–57. [CrossRef]
48. Tobler, W.R. A computer movie simulating urban growth in the Detroit region. *Econ. Geogr.* **1970**, *46*, 234–240. [CrossRef]
49. Wang, J.; Fischer, M.M.; Liu, T. *Spatial Analysis of Economic and Social Sciences*; Science Press: Beijing, China, 2012; pp. 6–20.
50. Moran, P.A.P. Notes on continuous stochastic phenomena. *Biometrika* **1950**, *37*, 17–23. [CrossRef]
51. Lesage, J.P.; Fischer, M.M. Spatial growth regressions: Model specification, estimation and interpretation. *Spat. Econ. Anal.* **2008**, *3*, 275–304. [CrossRef]

52. Lesage, J.; Pace, R.K. *Introduction to Spatial Econometrics*; Chapman and Hall/CRC Press: New York, NY, USA, 2009.
53. Shi, Z.; Bi, A. Spatiotemporal pattern and influencing factors of carbon emissions from construction sector in the Yangtze River Delta urban agglomeration. *J. Xi'an Univ. Technol.* **2023**, 1–10.
54. Ke, Y. Analysis of the influence of construction labor quality on economic growth. *Wuhan Univ. Technol.* **2019**, *32*, 130–137. [CrossRef]
55. Liu, H.; Tan, Y.; Li, N.; Cui, P.; Mao, P. How will rural houses go green? exploring influencing factors of villagers' participation in green housing construction in rural communities. *J. Green Build.* **2023**, *18*, 159–190. [CrossRef]
56. Liu, Z.; Deng, Z.; Davis, S.; Giron, C.; Ciais, P. Monitoring global carbon emissions in 2021. *Nat. Rev. Earth Environ.* **2022**, *3*, 217–229. [CrossRef] [PubMed]
57. Zhang, M.; Li, B.; Yin, S. Is technological innovation effective for energy saving and carbon emissions reduction? Evidence from China. *IEEE Access* **2020**, *8*, 83524–83537. [CrossRef]
58. Dong, F.; Zhu, J.; Li, Y.; Chen, Y.; Gao, Y.; Hu, M.; Qin, C.; Sun, J. How green technology innovation affects carbon emission efficiency: Evidence from developed countries proposing carbon neutrality targets. *Environ. Sci. Pollut. Res.* **2022**, *29*, 35780–35799. [CrossRef] [PubMed]
59. Zhou, Y.; Chen, M.; Tang, Z.; Mei, Z. Urbanization, land use change, and carbon emissions: Quantitative assessments for city-level carbon emissions in Beijing-Tianjin-Hebei region. *Sustain. Cities Soc.* **2021**, *66*, 102701. [CrossRef]
60. Wang, Y.; Shi, H.; Yan, H.; Huang, W.; Hao, Z. Analysis of carbon emission intensity distribution and spatial effect of China's construction industry based on the Spatial Durbin Model. *J. Eng. Manag.* **2021**, *35*, 1–6. [CrossRef]
61. Chen, J.; Gao, M.; Mangla, S.; Song, M.; Wen, J. Effects of technological changes on China's carbon emissions. *Technol. Forecast. Soc. Chang.* **2020**, *153*, 119938. [CrossRef]
62. Moyer, J.D.; Hughes, B.B. ICTs: Do they contribute to increased carbon emissions? *Technol. Forecast. Soc. Chang.* **2012**, *79*, 919–931. [CrossRef]
63. Qian, Y.; Liu, H.; Mao, P.; Zheng, X. Evaluation of safety management of smart construction sites from the perspective of resilience. *Buildings* **2023**, *13*, 2205. [CrossRef]
64. Elkins, P.; Baker, T. Carbon taxes and carbon emissions trading. *J. Econ. Surv.* **2001**, *15*, 325–376. [CrossRef]

buildings

MDPI

Article

A BIM-FDS Based Evacuation Assessment of Complex Rail Transit Stations under Post-Earthquake Fires for Sustainable Buildings

Hui Xu [1,2], Yuxi Wei [1], Yongtao Tan [3,*] and Qilin Zhou [4]

[1] School of Economics and Management, Chongqing University of Posts and Telecommunications, Chongqing 400065, China; xuhui@cqupt.edu.cn (H.X.); s220701033@stu.cqupt.edu.cn (Y.W.)
[2] Chongqing Innovation Center of Industrial Big-Data Co., Ltd., National Engineering Laboratory for Industrial Big-Data Application Technology, Chongqing 400707, China
[3] School of Engineering, Royal Melbourne Institute of Technology, Melbourne, VIC 3001, Australia
[4] Chongqing Major Projects Service, Chongqing 401120, China; qilindd@163.com
* Correspondence: yongtao.tan@rmit.edu.au

Abstract: Post-earthquake fire is considered as a catastrophic secondary disaster to personal and property safety, especially in complex rail transit station. This is primarily attributed to intricate infrastructure, densely populated floors, and the unrestricted layout of these areas. The aim of this study is to evaluate the evacuation capacity of complex railway stations under post-earthquake fires, and provide sustainable recommendations for building design. In this article, an evacuation assessment of a complex rail transit station under the post-earthquake fire for sustainable buildings was conducted from the internal environment and external rescue based on Building Information Modeling (BIM) and Fire Dynamic Simulation (FDS). The internal environment evacuation assessment simulation experiments were conducted in six hypothetical high-risk scenarios. In addition, the external rescue assessment was based on investigation of the route and the required rescue time during different periods of holidays and workdays. The results show that (1) The influence caused by different sizes of fire area in the power distribution room is smaller than those in the train at the platform floor. (2) In fire scenarios with the same fire area but different fire locations, the temperature is more affected than the CO concentration in the power distribution room. (3) It shows slight differences between single-floor fire and double-floor fire on evacuation of small area fire in power distribution room. Meanwhile, optimized design recommendations are proposed to reduce the risk of emergency evacuation in both internal and external environments of rail transit stations for sustainable future buildings, which include strategically locating the power distribution room away from public areas, installing fire-resistant doors around the room, increasing the quantity of smoke detectors and alarms with regular maintenance, minimizing the size of the power distribution room, developing specific emergency plans for train fires, and incorporating small fire stations in urban planning near complex public buildings to mitigate post-earthquake road obstruction challenges.

Keywords: evacuation assessment; post-earthquake fire; BIM; complex rail transit station; sustainable buildings

1. Introduction

Earthquakes are recognized as one of the most powerful and impactful natural disasters [1]. According to the statistics of the China Earthquake Networks, 12 *Ms* 8.0 earthquakes occurred around the world from 2012 to 2022, resulting in lots of casualties and economic losses [2]. In addition to direct losses, numerous secondary disasters after an earthquake, such as post-earthquake fire, also cause serious destructive consequences, including people injured, infrastructure damage, etc. [3]. The post-earthquake fires can be ignited due to various factors, such as broken gas pipes, open-flame sources, electrical short-circuits, leakage of flammable liquids, etc. [4]. Post-earthquake fires have been historically frequent, and each occurrence has resulted in catastrophic damage to the cities and buildings. For instance, on 17 January 1994, the *Mw* 6.7 Northridge earthquake in California caused ground cracks and approximately 110 fires directly attributed to its effects [5]. The Japan Kobe *Ms* 7.3 earthquake caused 269 fires due to natural gas leaking and 7036 buildings were destroyed in the post-earthquake fires in 1995 [6]. On 6 February 2023, Turkey was struck by two earthquakes, measuring *Mw* 7.8 and *Mw* 7.5, respectively, resulting in an estimated death toll of around 50,000 people. At the Port of Iskenderun, the earthquake caused a collapse of a part of containers, resulting in a fire that severely disrupted port operations. Post-earthquake fires can cause extensive damage to buildings, so it is essential to conduct evacuation assessments for providing sustainable improvements to buildings.

Nowadays, complex public spaces with multi-layer structures and high population density, such as rail transit stations, integrated railway transportation hubs, and airport terminals, have become increasingly prevalent [7]. The complex rail transit station facilitates people's transportation and meets the needs of various commercial functions [8]. However, the complex structure, high population density on each floor, and the open nature of these spaces, pose significant challenge for evacuation in the post-earthquake fire [9]. According to statistics of the Ministry of Emergency Management of China's Fire and Rescue Department, electrical fires have increased by 42.7% in the past 10 years [10]. Short circuit, poor electrical contacts, aging electrical equipment and overload are the main causes of electrical fires [11]. Due to lots of circuits and electrical equipment, complex urban public spaces are vulnerable to post-earthquake fires [9]. Emergency evacuation in complex urban public spaces, especially complex rail transit stations, has become a hot topic in recent years. Recently, targeted studies have been conducted on complex rail transit stations in some cities in China, such as Guangzhou, Xiamen, Chongqing, etc. The rail transit stations in these cities are relatively well-developed, with high traffic flow and complex infrastructure, which presents certain difficulties and challenges in emergency evacuation. To address these challenges, researchers have employed various methods including fluid dynamics, agent simulation, numerical simulation, and theoretical frameworks to conduct studies on emergency evacuation simulations [12–14]. Many studies have explored fire simulation in rail transit stations, but few have considered evacuation assessment in complex rail transit stations under post-earthquake fires. Post-earthquake fire rescue is usually more difficult than normal fire. The assessment of evacuation from post-earthquake fires is important for several reasons. Firstly, post-earthquake fires damage tends to be concentrated, and multiple fires can occur simultaneously. This poses unique challenges compared to other evacuation studies where fires may be more localized or isolated. Secondly, post-earthquake fires have the potential to cause large fire areas, which can quickly spread and pose a significant threat to human lives and property. Lastly, external rescue during post-earthquake fires can be particularly difficult due to the disruption of infrastructure and potential hazards present after an earthquake. Therefore, it becomes crucial to evaluate the response capabilities of complex rail transit stations to ensure effective evacuation procedures and facilitate sustainable design improvements for rail transit stations.

In recent years, many research have emerged in the field of fire research using different methods, including an emergency decision-making approach [15], crowd flow modeling [16], BIM-based simulation framework [17], systematic hybrid approach [18], etc. Researchers also have conducted a series of related studies regarding fires in rail transit stations from different perspectives, such as the emergency ventilation strategies [19], emergency response [20], the impact of the escalators and automatic ticket checkers [21], flow rate [22], and different door statuses (open and closed) [23]. However, post-earthquake fires have received relatively limited attention and in-depth research in the literature; thus, the need for more attention and in-depth research is obvious. Post-earthquake fires have been explored in various aspects, including the identification of fire-prone buildings using a risk matrix [24], the quantification of post-earthquake fire risks in densely populated urban areas [25], the exploration of simulation frameworks using BIM and VR [26], the finite element numerical analyses [4], and the framework for performance-based evaluation of fire engineering after earthquakes [27]. In addition, the development of a comprehensive method for the seismic damage assessment of sprinkler systems based on the combination of BIM, computational fluid dynamics (CFD) models, and fire dynamics simulator (FDS) programs has also been conducted [28]. According to the existing studies, BIM has been widely employed in post-earthquake fire simulation research. To analyze the virtual fire scenario, a more intuitive model could be built in BIM, allowing for the adjustment of various parameters.

The aim of this study is to address three critical research gaps in the field of fire simulation and emergency evacuation in complex rail transit stations. Firstly, there is a lack of research on evacuations ability assessment in these stations, resulting in a gap in sustainable building recommendations. Secondly, complex rail transit stations, which are characterized by multiple lines, intricate spatial structures, and high traffic flow, have received little attention in current research on fire simulations. Thirdly, post-earthquake fires have been relatively less considered in existing studies. Accordingly, comprehensive research on evacuations ability assessment of complex rail transit stations for post-earthquake fires is essential. By addressing these research objectives, this study aims to contribute to the development of safer and more resilient rail transit stations, ensuring the well-being and safety of passengers during post-earthquake fires. Accordingly, this research focuses on the evacuation assessment within the internal environment and external rescue of a complex rail transit station under the post-earthquake fire for sustainable. This research aims to (1) establish a fire simulation model based on BIM and Fire Dynamic Simulation (FDS) application, (2) conduct a case demonstration to verify the feasibility of the established model and assess the evacuation ability of the complex rail transit station, and (3) supply optimization design suggestions for the internal and external environment of the rail transit station to reduce risks in emergency evacuation.

2. Methodology

The research methodology consists of five modules: (1) Building Information Modeling (BIM), (2) Fire Dynamic Simulation (FDS), (3) assumptions in Revit and Pyrosim, (4) fire scenarios, and (5) fire simulation. The framework is shown in Figure 1, where the green background blocks represent specific research content and the purple graphics represent hypothesized fire scenarios.

2.1. BIM

BIM it is an important technology in the construction digitalization world, which can be used by adopting computer visualization technology and simulation method [29]. Based on BIM, buildings can be simulated by BIM to provide valuable management suggestions for subsequent operation and maintenance measures, such as emergency evacuation simulation in earthquake, fire, etc. [30]. It is crucial to gather information about the geometric characteristics of buildings for fire simulation and assessment. This includes accurately representing the following components:

(1) Building structure, such as platform floors, concourse floors, entrances/exits, stairs, elevators, fire-resistant, as well as their quantity, dimensions, height, geometric shapes, position and orientation. This level of detail was particularly crucial for complex structures like a complex rail transit station.
(2) BIM elements association. The relationships between different elements, such as the connection between the platform floor and stairs, elevators, and entrances/exits, should be considered in BIM elements association.
(3) Ventilation and fire protection system. Determine the positioning and layout of ventilation and fire protection systems to ensure the safety of the railway transit station during fires. This involves factors such as smoke control devices, fire-extinguishing

systems, fire doors, etc. Generally, non-graphical information is not required to be included in fire scenarios.

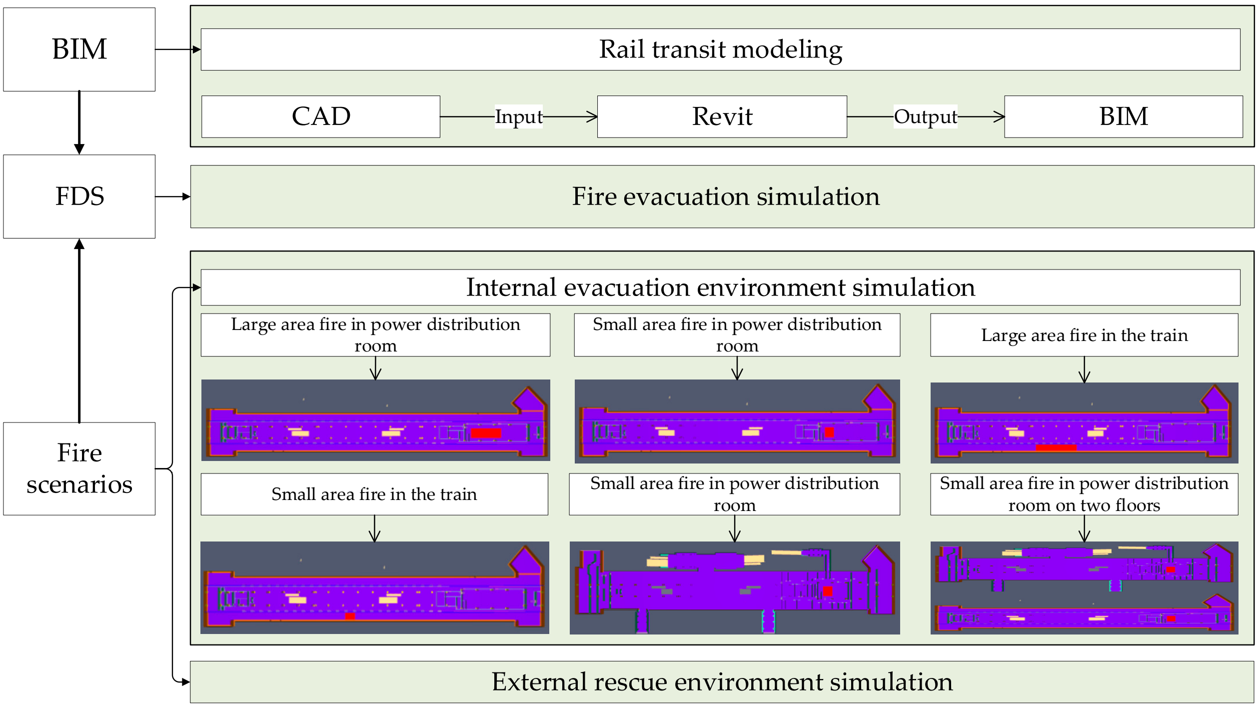


Figure 1. Simulation framework.

2.2. FDS

The Pyrosim software, developed by the American Institute of Standard Technology based on FDS, enables fire dynamic simulation. The stage of fire development involves a complex dynamic field generated by the interaction of coupled physical and chemical reactions, hydrodynamics, and heat transfer. It mainly follows the conservation equations, which are shown in Equations (1)–(4).

(1) Mass conservation law:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \tag{1}$$

where ρ is the density of the combustion gas, t is the combustion time, ∇ is the divergence magnitude, and $\vec{u}$ is the smoke gas velocity.

(2) Energy conservation law:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \vec{u}) = \frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p - \nabla \vec{q}_r + \nabla \cdot (k \nabla T) + \sum_i \nabla (h_i \rho D_i \nabla Y_i) \tag{2}$$

where h is the enthalpy, p is the ambient pressure, $\nabla \vec{q}_r$ is the radiative heat flux, k is the thermal conductivity, T is the temperature, D is the diffusion coefficient, and Y is the component mass fraction.

(3) Momentum conservation law:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \frac{1}{2}\nabla\left|\vec{u}\right|^2\right) + \nabla p - \rho g = \vec{f}_b + \nabla \cdot \tau_{ij} \tag{3}$$

where $\vec{f}_b$ is the external force vector, and τ_{ij} is the viscous stress tensor.

(4) Gas component conservation law:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \vec{u}) = \nabla(\rho D_i \nabla Y_i) + \dot{m}_i^m \tag{4}$$

where $\dot{m}_i^m$ is the formation rate.

2.3. Assumptions in Revit and Pyrosim

It is assumed that the building structures suffer no considerable damage and the escape routes are not disrupted after the earthquake, at least for the first minutes of the a fire event [31]. In addition, the worst-case scenarios of non-structural damage such as elevator or fire-extinguishing system damage are considered. In addition, people evacuate rooms without closing fire-resistant doors, and non-fire-resistant doors are excluded from the model to focus on simulating critical fire and smoke emissions.

2.4. Fire Scenarios

The different locations of fire points in the complex rail transit station have different impacts on emergency evacuation. In order to better respond to emergencies and achieve sustainable future buildings, the most unfavorable principle should be applied in the fire site design. Combustible materials in rail transit station include various components, such as the trains bodies and some circuits [11]. Therefore, this paper mainly considers the locations that are most susceptible to fires: the train and the power distribution room. To provide a more comprehensive understanding of the fire risk in rail transit stations, the specific hypothetical ignition points are illustrated in the case study section. The fire simulation is divided into two parts: internal environment evacuation simulation and external environment rescue simulation.

2.4.1. Internal Evacuation Environment Simulation

The standard atmospheric pressure is 101,325 Pa and the relative humidity before the disaster was 50% without considering the influence of internal wind speed. To improve the detection of the temperature and CO concentration in the populated rail transit station after an earthquake, thermocouples and gas-phase devices are set at the populated area. According to Report on the Nutrition and Chronic Disease Status of Chinese Residents (2020), the average height of a male adult is stated to be 170.6 cm and for adult females is 158.7 cm [32]. Considering that the height of the human mouth and nose is lower than the height, the height of the thermocouple and gas-phase device are set lower than 170.6 cm on each floor. The two important parameters to consider are temperature and CO concentration.

(1) Temperature

Human endurance to high temperatures is limited, particularly when it can cause irreversible damage to the skin and respiratory tract. To ensure the safety of the evacuees, the temperature must be maintained within a certain range. Research reveals that thermal burns to the respiratory tract can occur when individuals inhale air above 60 °C saturated with water vapor and the maximum exposure time is 10.1 min [33]. In this research, 60 °C is considered as a threshold value. Additionally, research indicates that humans can endure a maximum exposure time of 6 min at a temperature of 70 °C, and 3.8 min at 80 °C, which provide a reference for the following research [33].

(2) CO Concentration

The primary threat to people's life safety in a fire is the CO produced during the combustion process [31]. Furthermore, the proportion of hemoglobin (HB) in the form of carboxyhemoglobin (COHb) increases steadily as CO is inhaled causing HB to lose its ability to provide oxygen. Thus, the acute toxicity of CO depends mainly on the percentage of COHb [34]. Survival is rare in subjects with blood levels exceeding 50–60% COHb and 50% COHb is usually considered as an average lethal level [34]. According to research, when the CO concentration reaches 1600 ppm, the COHb concentration can reach 40–50%. Evacuees will exhibit symptoms of poisoning, including headache, tachycardia, dizziness, and nausea within 20 min. In severe cases, death can occur in less than 2 h [31,35]. Thus, 1600 ppm (1.6×10^{-3} mol/mol) is considered as a threshold value.

2.4.2. External Rescue Environment Simulation

External rescue, such as fire rescue and medical services, is necessary for all escapees [36]. Rail transit stations usually connect to the major urban roads with strong accessibility. This research investigates the route and the time required from the fire station to the complex rail transit station through the map during different periods of holidays and workdays for the evacuation assessment of the sustainable rail transit station in terms of external rescue.

3. Case Study

At present, there are many underground rail transit stations in China, and these stations are basically consistent in design principles. For instance, power distribution rooms, which are essential facilities, can be found in every rail transit station. It indicates that the design principles of rail transit stations are universally applicable. Trains and power distribution rooms may experience malfunctions or equipment failures during earthquakes, which can increase the risk of fire. Valuable insights and guidance can be obtained by considering similarities, consistency in design principles, and similarity in fire risk factors. Based on the above principles, a complex rail transit station with an underground two-floor structure was selected as the case study to provide research results that have reference value. The selected station is located at the intersection of two rail transit lines, which presents large area, high density passenger flow, and large numbers of power lines. Thus, the station shows applicability for fire simulation and evacuation assessment. The heights of the platform floor and concourse floor are 6.05 m and 5.15 m, respectively. In addition, the two floors are 181.2 m long and 20.7 m wide. Through field investigation, the station was found to have 37 fire-resistant doors and 9 wooden doors, which is shown in Table 1.

Table 1. Types and location of doors.

Types	Number	Size		Quantity	Location
		Width	Height		
Fire-resistant doors	FM−1	1000	2400	7	Power distribution room, control room and cable room, etc.
	FM−2	1000	2400	11	
	FM−3	1200	2700	6	
	FM−4	1200	2700	12	
	FM−5	1800	2700	1	
Wooden doors	M−1	1000	2400	7	Public works room, meeting and reception room, sewage pump room, toilet, etc.
	M−2	800	2400	2	
	M−3	1200	2700	3	

Two staircases are available for the escaping from the platform floor to the concourse floor. In addition, four exits are available for escaping from the concourse floor to the outside. The plan of the two floors of the station is shown in Figure 2.

3.1. BIM Modeling and Pyrosim Software

In this research, the Revit 2016 was used for BIM modeling. The BIM model of the rail transit station case is shown in Figure 3. The building structure of the station include platform floors, concourse floors, entrances/exits, stairs, elevators, etc. In the case study of a complex rail transit station with an underground two-floor structure, the selected station is situated at the intersection of two rail transit lines. The platform floor of the rail transit station has a height of 6.05 m, while the concourse floor stands at 5.15 m. These floors span a length of 181.2 m and a width of 20.7 m. This configuration presents a large area, high density of passenger flow, and significant numbers of power lines, making it a suitable candidate for fire simulation and evacuation assessment.

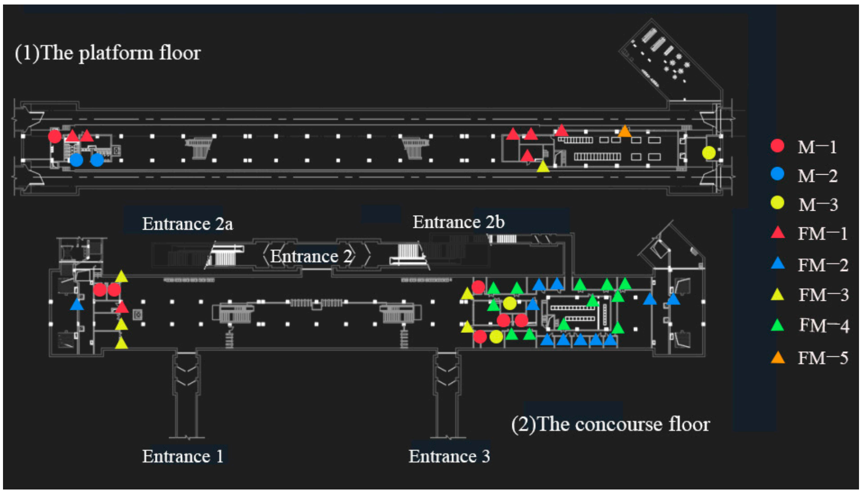


Figure 2. Plan of a complex rail transit station in Beijing.

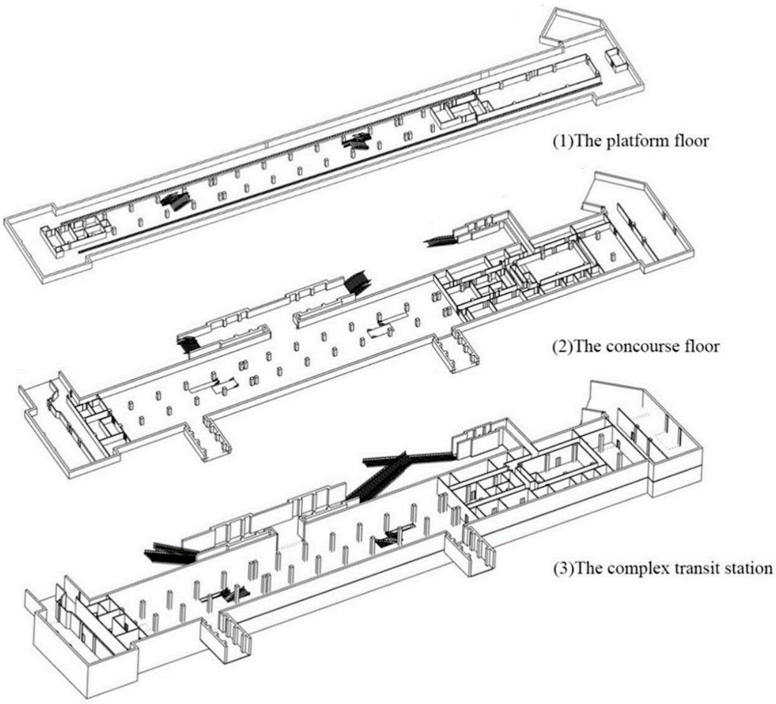


Figure 3. BIM model of the rail transit station case.

Rail transit stations encompass a multitude of interconnected elements. The rail transit station has two sets of stairs and escalators to facilitate movement between the platform floor and the concourse floor. Additionally, there is one elevator available on the platform floor to ensure accessibility for passengers with mobility needs. On the concourse floor, there are four entrances/exits to ensure convenient access and egress for passengers. Accurately documenting the associations between elements, such as the platform floor, stairs, elevator, and entrances/exits, within the BIM model is essential for maintaining consistency.

Ventilation systems are installed in public areas within the rail transit station case. The air intake in the public area of underground stations is directly taken from the atmosphere, and the exhaust is directly discharged from the ground. There are two stairs in the platform floor, several train doors on both sides, and four exits on the concourse floor, which are directly considered as natural ventilation openings. Fire hydrants are installed indoors at various locations within the station, including the concourse floor, the platform floor, the equipment areas, and pedestrian walkways. A Type II fire box is installed at the stairwell entrance of the public area on the platform floor, the equipment area on the platform floor. Fire hydrant pump start buttons are installed on each fire box, and an alarm button is installed outside the box. Type I fire boxes are used on the concourse floor, with staggered arrangements on both sides of the public area on the concourse floor.

The Pyrosim 2019 was used for building a FDS model, conducting simulation, and analyzing simulation results. The BIM model is exported in DWG format, and then imported into the Pyrosim software to transform the BIM model into a FDS model. The temperature and CO concentration are two main monitoring parameters in FDS.

3.1.1. Combustion Calculation Method

In the fire simulation, the actual fire combustion process can be more closely approximated by defining the combustion reactions and setting the relevant parameters such as products of fire combustion and heat release rate. The common way to determine the pyrolysis reaction in FDS is to determine the heat release rate (HRR) on a surface [31]. In this study, the heat release rate in per unit area (HRRPUA) are specified as the combustion calculation method in Pyrosim simulation.

3.1.2. "Surfaces" Parameters

The "Surface" parameters are used to define the properties of the solid objects and vents in FDS. For example, the "Burner" in the Surface parameter is used to define a fire, the "Layered" in the Surface parameter is to represent a solid and thermally conductive wall, and the "OPEN" in the Surfaces parameter is to represent a vent that is passively open to the outside and is often used to simulate an open door or window.

3.1.3. Detection Equipment Settings

Considering the damage of non-structural components such as fire extinguishing facilities, the locations of different fires in the complex rail transit station were determined. The detection devices include temperature detectors and CO detectors, both of which are set on the necessary escape routes, such as stairways, entrances, etc. The device numbers and locations are shown in Table 2 and Figure 4.

Table 2. Devices number and location.

The Layer of the Devices	Devices Number	Devices	Devices Location
The platform floor	1−01	(1) Temperature detector (2) CO detector	Left stairway of the platform floor
	1−02	(1) Temperature detector (2) CO detector	Right stairway of the platform floor
	1−03	(1) Temperature detector (2) CO detector	In the middle of the platform floor
The concourse floor	2−01	(1) Temperature detector (2) CO detector	Left stairway of the concourse floor
	2−02	(1) Temperature detector (2) CO detector	Right stairway of the concourse floor
	2−03	(1) Temperature detector (2) CO detector	Entrance 2
	2−04	(1) Temperature detector (2) CO detector	Entrance 1
	2−05	(1) Temperature detector (2) CO detector	Entrance 3

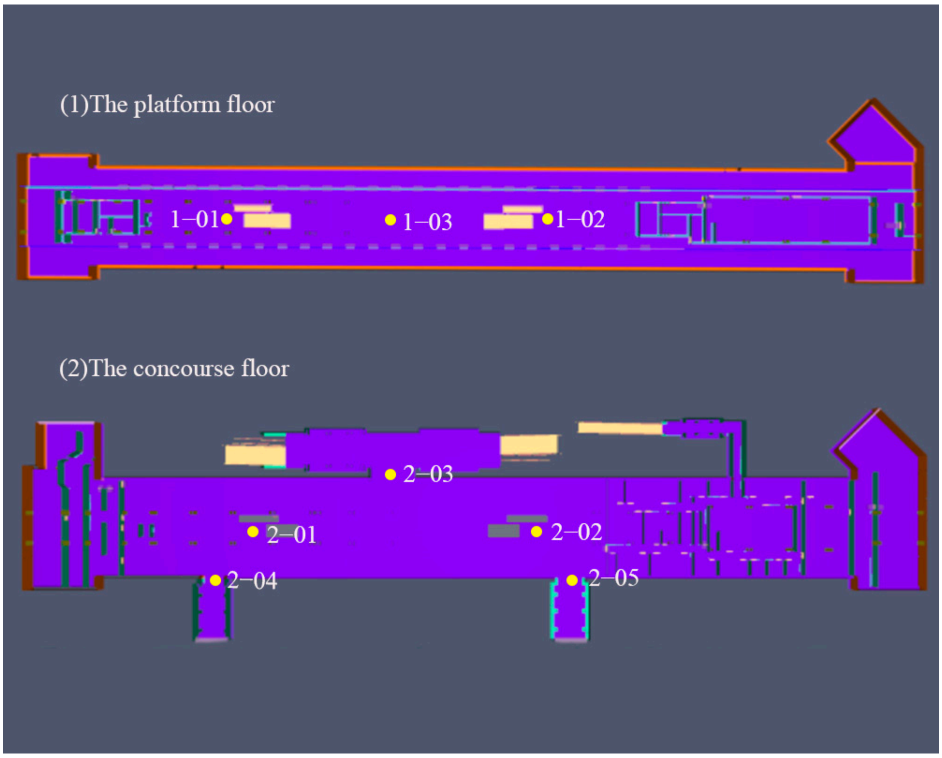


Figure 4. The detectors location.

3.2. Fire Scenarios

When a fire occurs in an underground station, the smoke flow usually coincides with that of the normal passenger's evacuation routes that will cause fatalities by asphyxiation [37]. In this research, two situations, the single-floor fire and the double-floor fire were considered. The six fire scenarios based on the size of the fire area are shown in Table 3.

Table 3. Fire scenarios.

Situation	Floor	Fire Scenario	Fire Size	Consideration
Single-floor fire (one fire point)	The platform floor	1. Large area fire in power distribution room	16.3 m × 5.3 m	Switchgear operating equipment and transformers in the power distribution room are on the right side of the platform floor, which are prone to cause a circuit fire.
		2. Small area fire in power distribution room	5.3 m × 5.3 m	
		3. Large area fire in the train	25.3 m × 3 m	Assuming the train enters the station and the platform doors are all opening, while the middle of the train catches fire.
		4. Small area fire in the train	5.3 m × 3 m	
	The concourse floor	5. Small area fire in power distribution room	5.3 m × 5.3 m	The power distribution rooms and control rooms on the right side of the concourse floor are prone to cause fires.
Double-floor fire (two fire points)	The platform floor and The concourse floor	6. Small area fire in power distribution room on two floors	The platform floor 5.3 m × 5.3 m The concourse floor 5.3 m × 5.3 m	Scenario 2 and Scenario 5 occur simultaneously.

3.3. Internal Evacuation Environment Simulation Results

The time required for reaching the maximum CO concentration and the maximum temperature under the six fire scenarios are shown in Tables 4 and 5, respectively. The simulation diagram of temperatures under different fire scenarios is shown in Figure 5.

Table 4. The time required for reaching the maximum CO concentration.

Fire Scenario	Maximum CO Concentration at the Platform Floor (mol/mol)	The Time Required for the Platform Floor to Reach the Maximum CO Concentration (s)	Maximum CO Concentration at the Concourse Floor (mol/mol)	The Time Required for the Concourse Floor to Reach the Maximum CO Concentration (s)	The Fire Point with the Maximum CO Concentration
Scenario 1	3.48×10^{-4}	175	3.89×10^{-4}	81.3	2−02
Scenario 2	2.52×10^{-4}	605	3.35×10^{-4}	598	2−02
Scenario 3	1.65×10^{-3}	288	7.18×10^{-4}	595	1−03
Scenario 4	7.17×10^{-4}	622	6.15×10^{-5}	611	1−01
Scenario 5	4.02×10^{-6}	619	2.15×10^{-4}	606	2−01
Scenario 6	2.65×10^{-4}	607	2.32×10^{-4}	614	1−03

Table 5. The time required for reaching the maximum temperature.

Fire Scenario	Maximum Temperature at the Platform Floor (°C)	The Time Required for the Platform Floor to Reach the Maximum Temperature (s)	Maximum Temperature at the Concourse Floor (°C)	The Time Required for the Concourse Floor to Reach the Maximum Temperature (s)	The Fire Point with the Maximum Temperature
Scenario 1	68.1	175	84	81.3	2−03
Scenario 2	43.2	609	63.8	598	2−02
Scenario 3	418	282	65	620	1−03
Scenario 4	104	622	31.4	616	1−01
Scenario 5	20.3	567	69	605	2−01
Scenario 6	47.4	614	57.5	619	2−03

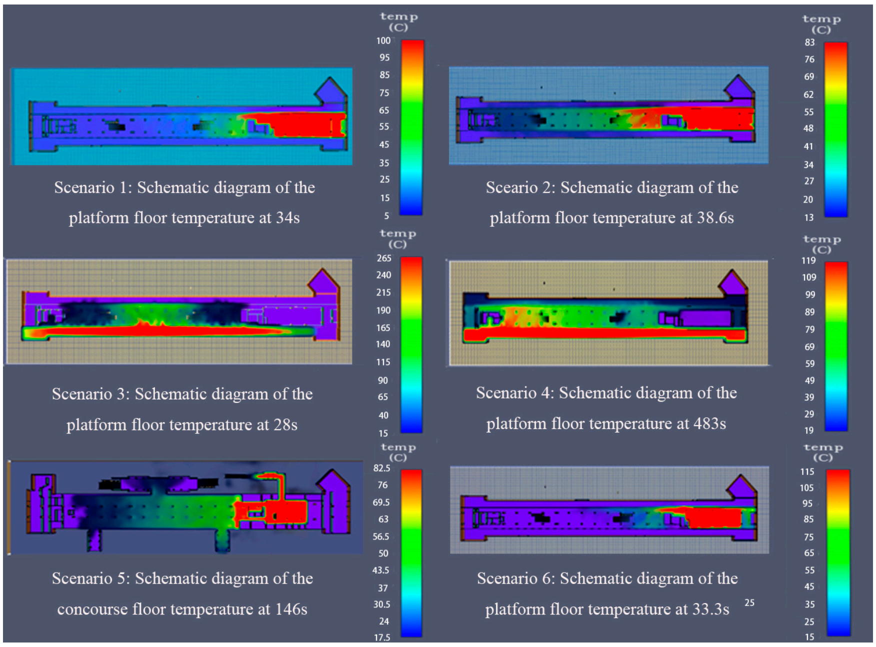


Figure 5. Simulation diagram of temperatures under different fire scenarios.

3.3.1. Large Area Fire in Power Distribution Room at the Platform Floor

In the Scenario 1, both the CO concentrations at the platform floor and the concourse floor are below the threshold values (1.6×10^{-3} mol/mol), as shown in Figure 6. The CO concentrations and temperatures of the detected points increased from the initial values and eventually fluctuated around some values.

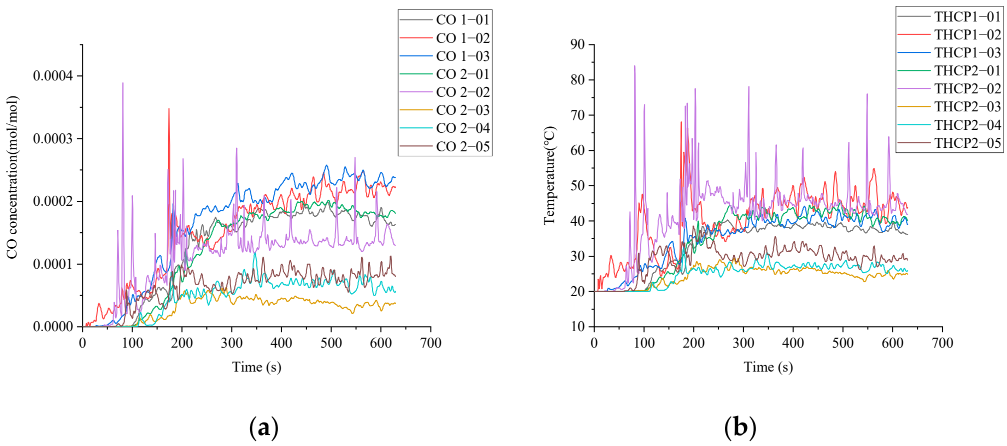


Figure 6. CO concentrations and temperatures fluctuation trend under Scenario 1. (**a**) CO concentrations; (**b**) Temperature.

The platform floor:

(1−02): When the large area fire started in the power distribution room on the platform floor, the nearest stairway (1−02) firstly reaches the maximum CO concentration of 3.75×10^{-5} mol/mol and the maximum temperature of 30.2 °C at 34 s.

Then, the smoke continued to spread and reached the temperature of 68.1 °C, which lasted only 1 s and the highest CO concentration was 3.48×10^{-4} mol/mol at 175 s at the right stairway entrance (1−02).

The concourse floor:

(2−02): The smoke and fire spread rapidly to the upper floor through the stairway. The gap in the stairway makes the smoke gather rapidly at the right stairway (2−02). Thus, the time of reaching the peak at the right stairway of the concourse floor is shorter than that of the platform floor.

The highest CO concentration of 3.89×10^{-4} mol/mol and the highest temperature of 84 °C at the concourse floor were both reached at 81.3 s. In addition, the time above 60 °C lasted for only 3 s between 81 s and 83 s.

According to "2.4.1. Internal evacuation environment simulation", the maximum exposure time is 3.8 min when the exposure temperature is 80 °C. The short duration of exceeding the threshold value means that the two stairway entrances (1−02) (2−02) near the distribution room have little impact on the escapees.

Therefore, it is escapable for the escapees in the Scenario1.

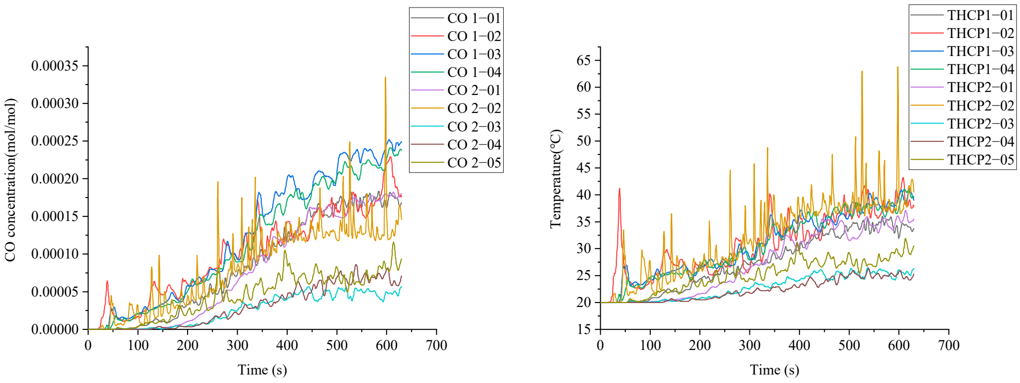
3.3.2. Small Area Fire in Power Distribution Room at the Platform Floor

In the Scenario 2, the CO concentrations and temperatures at the platform floor and concourse floor showed a gradual increase when small area fire in the power distribution room at the platform floor, as shown in Figure 7. The figures show that the CO concentrations at both the two floors did not exceed the threshold values.

The platform floor:

(1−02): When the power distribution room were on fire, the nearest stairway (1−02) was the first reaching to the highest CO concentration of 6.44×10^{-5} mol/mol and the highest temperature of 41.2 °C at 38.6 s.

With the continuous diffusion of smoke, the platform floor reached its maximum CO concentration of 2.52×10^{-4} mol/mol and the maximum temperature of 43.20 °C at 609 s, both of which were lower than the threshold values.



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

Figure 7. CO concentrations and temperatures fluctuation trend under Scenario 2. (**a**) CO concentrations; (**b**) Temperature.

The concourse floor:

(2−02): Smoke and fire spread rapidly to the upper floor through the stairway gap, resulting in the rapid accumulation of smoke at the right stairway (2−02). Therefore, the time to reach to the peak at the right stairway of the concourse floor was shorter than the platform floor.

In addition, the maximum CO concentration of 3.89×10^{-4} mol/mol at the concourse floor was reached at 81.32 s. And then, the second maximum CO concentration of 3.35×10^{-4} mol/mol at the concourse floor was reached at 595 s.

Later, the maximum temperature of 63.8 °C at the concourse floor was reached at 598 s, but only last for 2 s, which is lower than the maximum human endurance time of 10.1 min.

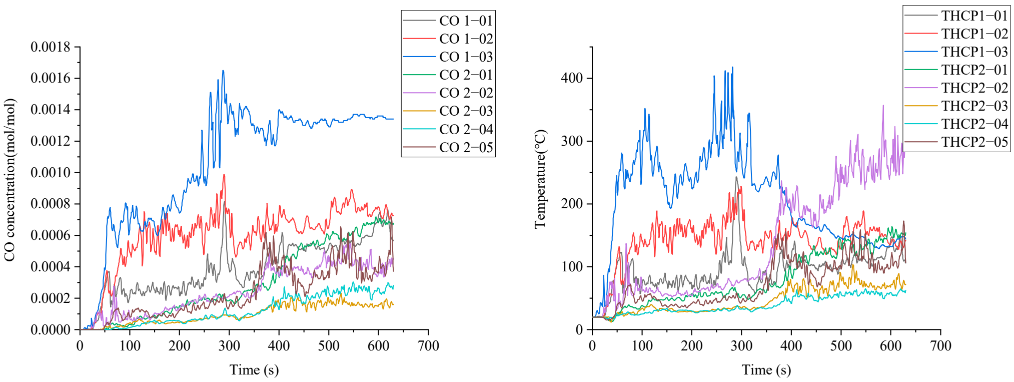
Thus, it is escapable for the escapees in the Scenario 2.

3.3.3. Large Area Fire in the Train

Large area fire in the train is considered the worst situation.

The platform floor:

As shown in Figure 8, the CO concentration and temperature of the detection points at the platform floor rapidly increased from 28 s to 59 s, and then gradually presented stable trend.



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

Figure 8. CO concentrations and temperatures fluctuation trend under Scenario 3. (**a**) CO concentrations; (**b**) Temperature.

(1−03): In this scenario, the temperature in the middle of the platform floor (1−03) has reached 60 °C at 23 s, and then continued to rise over 200 °C. Additionally, CO concentration in the middle of the platform floor (1−03) has exceed 1600 ppm from 286 s to 289 s.

Under this condition, the escape presents high difficulties. The possibility that the escapees can escape smoothly under this condition is very small.

3.3.4. Small Area Fire in the Train

The platform floor:

As shown in Figure 9, the CO concentrations did not exceed the threshold value of 1600 ppm in the platform floor.

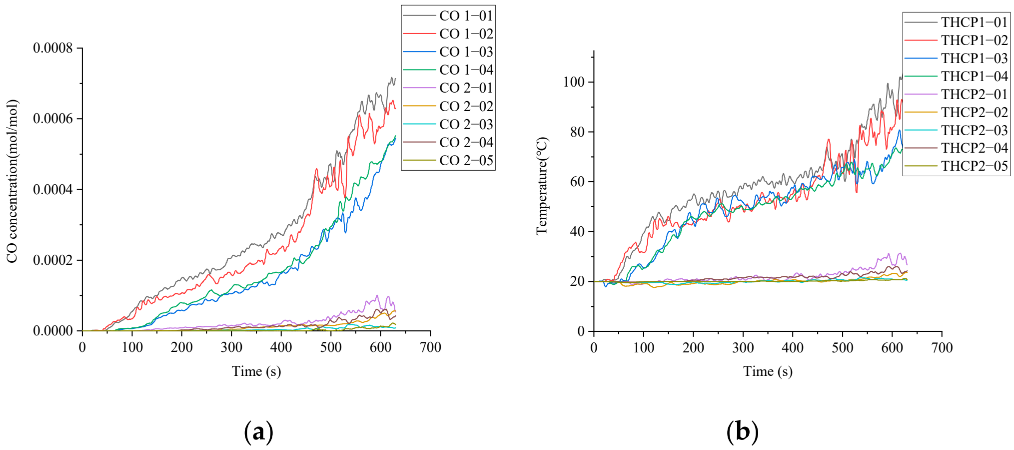


Figure 9. CO concentrations and temperatures fluctuation trend under Scenario 4. (**a**) CO concentrations; (**b**) Temperatures.

(1−01): The highest CO concentration reached 7.17×10^{-4} mol/mol at 622 s, and the temperature of the stairway (1−01) reached to 60 °C at 330 s. Subsequently, the temperature of the platform floor gradually increased and the temperatures of every detector on the platform floor reached more than 60 °C from 330 s to 630 s. The maximum temperature of 104 °C at (1−01) was reached at 622 s.

The concourse floor:

As shown in Figure 9, both of the CO concentration and temperature at the concourse floor increased slowly and did not exceed the threshold value. The small area fire in the train has little impact on the concourse floor.

Thus, escaping in this situation is very difficult.

3.3.5. Small Area Fire in Power Distribution Room at the Concourse Floor

As shown in Figure 10, the CO concentration and temperature at multiple detection points at the platform floor present stable trend under Scenario 5. The fire had little impact on the platform floor, revealing a continuous increase in CO concentration and temperature at the detection points on the concourse floor.

The concourse floor:

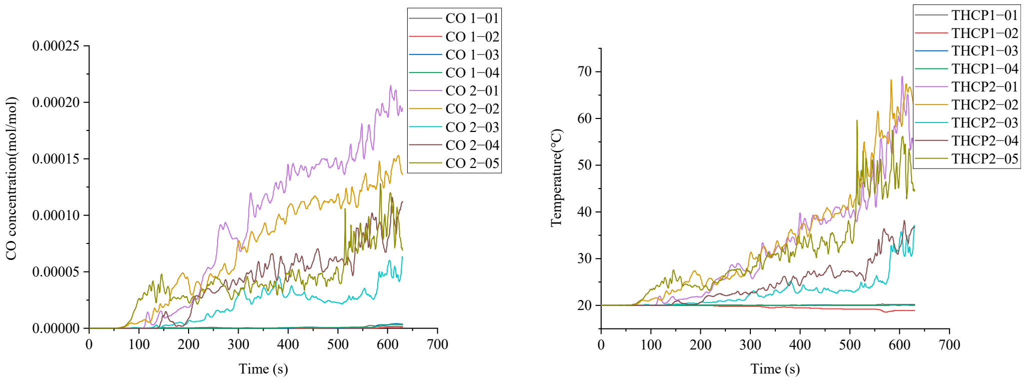
(2−05): The concourse floor entrance nearest to the fire starting point (2−05) firstly reached to the highest temperature of 27.6 °C and the highest CO concentration of 4.80×10^{-5} mol/mol at 146 s.

(2−02): With the continuous diffusion of smoke, the stairway nearest to the fire point (2−02) reached the maximum temperature of 27.4 °C and the maximum CO concentration of 4.90×10^{-5} mol/mol at 189 s.

(2−01) and (2−02): Later, the stairway (2−01) (2−02) reached 60 °C at the time of 597 s and 594 s, respectively. However, the duration that the temperature exceed 60 °C was very short, lasting only 21 s for stairway (2−01) and 34 s for stairway (2−02), respectively, and the maximum temperature at the concourse floor was 69 °C. According to "2.4.1.

Internal evacuation environment simulation", the human endurance time is 6 min when the temperature reaches 70 °C.

Therefore, it is escapable for the escapees in this scenario.

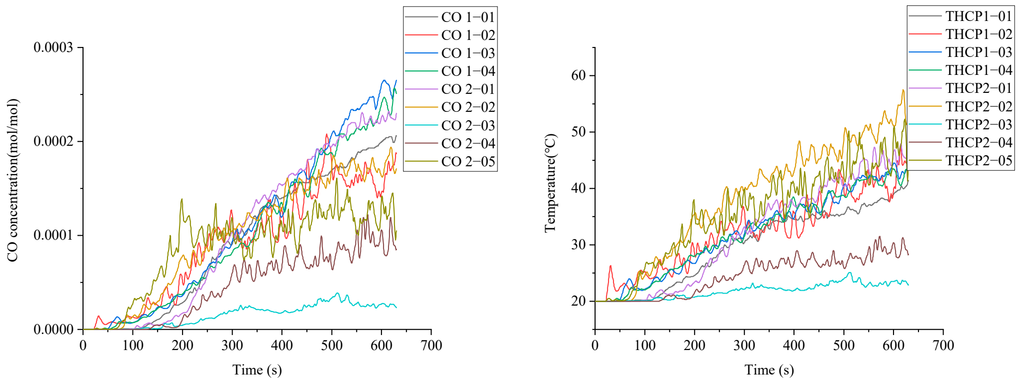


(**a**) (**b**)

Figure 10. CO concentrations and temperatures fluctuation trend under Scenario 5. (**a**) CO concentrations; (**b**) Temperature.

3.3.6. Simultaneous Small Area Fire in Power Distribution Room on the Two Floors

As shown in Figure 11, when a small area of the power distribution room on two floors catches fire simultaneously, the CO concentration and temperature at the detection points on both floors exhibit a gradual increase over time.



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

Figure 11. CO concentrations and temperatures fluctuation trend under Scenario 6. (**a**) CO concentrations; (**b**) Temperature.

The platform floor:

(1−02): The stairway (1−02) nearest to the power distribution room on platform floor reached the highest temperature of 32.9 °C and the highest CO concentration of 9.85×10^{-5} mol/mol at 33.3 s.

(1−03): With the continuous diffusion of smoke, the middle position of the platform floor (1−03) reached the maximum temperature of 24 °C and the maximum CO concentration of 1.34×10^{-5} mol/mol at 69.3 s.

In addition, the maximum CO concentration of 2.65×10^{-4} mol/mol at the platform floor was reached at 607 s, and the maximum temperature of 47.4 °C at the platform floor was reached at 614 s.

The concourse floor:

(2−05): The nearest entrance to the fire starting location (2−05) reached the maximum temperature of 38 °C and the maximum CO concentration of 1.39×10^{-4} mol/mol at 199 s.

Additionally, the maximum CO concentration of 2.32×10^{-4} mol/mol at the concourse floor was reached at 614 s, and the maximum temperature of 57.5 °C at the concourse floor was reached at 619 s. It has been confirmed that both the maximum CO concentration and the maximum temperature were lower than the threshold value.

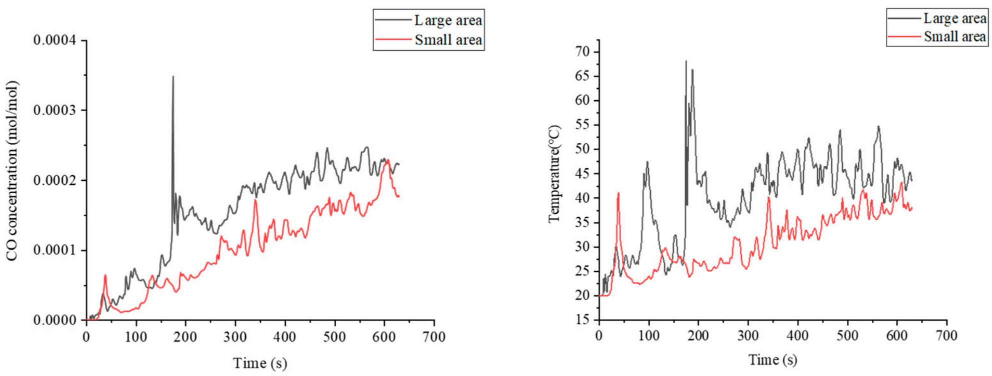
Thus, it is safe to escape in this scenario.

In summary, it becomes difficult to escape when large area fire or small area fire occurs in the train, which are Scenario 3 and Scenario 4. Comparatively, it is possible to escape in the Scenario 1, Scenario 2, Scenario 5 and Scenario 6 when the fire occurs in the power distribution room.

3.4. Influence of Fire Areas and Location

3.4.1. The Influence of Different Fire Areas

According to Section 3.3, the assessment results indicate that evacuation is feasible when a fire occurs in the power distribution room. However, evacuating becomes challenging when a fire breaks out on the platform floor of a train. Scenario 1, Scenario 2, Scenario 3, and Scenario 4 were selected for analyzing the influence of different fire areas on CO concentration and temperature. The stairway (1−02) nearest to the power distribution room on platform floor in Scenario 1 and Scenario 2 and the middle position of the platform floor (1−03) in Scenario 3 and Scenario 4 are considered for the analysis. The results of the CO concentrations and temperatures fluctuation trend are shown in Figures 12 and 13. The difference of temperature and CO concentration in Scenario 1 and Scenario 2 are smaller than those in Scenario 3 and Scenario 4. Taking the example of 300 s, in Figure 12, the CO concentration is 1.53×10^{-4} mol/mol and the temperature is 37.3 °C under a large area fire, while under the small area fire is 9.3×10^{-5} mol/mol and 26.2 °C, respectively. As shown in Figure 13, the CO concentration is 7.59×10^{-4} mol/mol and the temperature is 225 °C under the large area fire, while the CO concentration is 1.59×10^{-4} mol/mol and the temperature is 48.7 °C under a small area fire. In this case, there is a difference of 6×10^{-4} mol/mol in CO concentration and 176.3 °C in temperature between the large area fire and the small area fire.



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

Figure 12. CO concentrations and temperatures fluctuation trend of (1−02) under Scenario 1 and Scenario 2. (**a**) CO concentrations; (**b**) Temperature.

It can be seen that the CO concentration and temperature generated by large area fires are generally higher than those of small area fires. In addition, the influence caused by different size of the post-earthquake fire area in the power distribution room at the platform floor is smaller than those in the train at the platform floor. For a fire in the power distribution room, smoke can only flow through open doors, while for a fire in the train, smoke could enter the open space through all doors on the train.

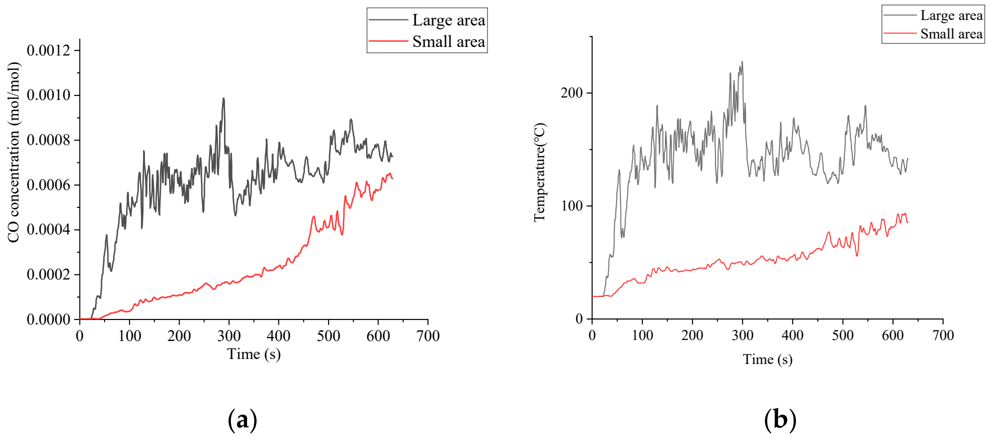


Figure 13. CO concentrations and temperatures fluctuation trend of (1−03) under Scenario 3 and Scenario 4. (**a**) CO concentrations; (**b**) Temperature.

3.4.2. The Influence of Different Fire Locations

In Scenario 2 and Scenario 5, although the fire areas are the same, the fire locations differ. In these two scenarios, the stairways nearest to the fire point (1−02) and (2−02) are chosen for analyzing. As shown in Figure 14, the CO concentration in (2−02) is lower than that in (1−02), and the difference in CO concentration between the two scenarios is 0.4×10^{-4} mol/mol at 630 s. As for temperature, the temperature in (1−02) is initially higher than that in (2−02), but the temperature increase rate in (2−02) is significantly greater than that in (1−02). Subsequently, the temperature becomes consistent at 177 s, and the final temperature in (2−02) is 23.6 °C higher than that in (1−02).

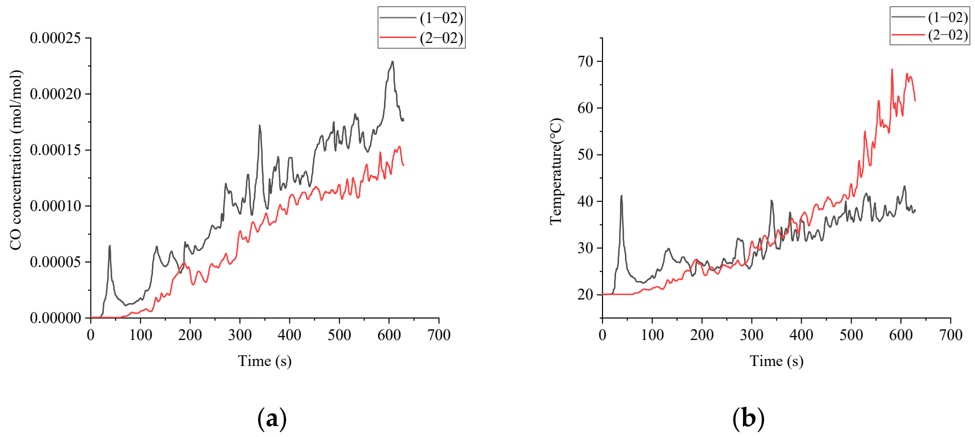


Figure 14. CO concentrations and temperatures fluctuation trend of (1−03) under Scenario 2 and Scenario 5. (**a**) CO concentrations; (**b**) Temperature.

According to the results, the CO concentration presents consistent fluctuation trend for the small area fire in power distribution room in different floors of the station, while the temperature fluctuation show more obvious differences.

3.4.3. The Influence of Single-Floor Fire and Double-Floor Fire

To compare the different impact of single-floor fire and double-floor fire on evacuation, Scenario 2, Scenario 5, and Scenario 6 were selected with the same fire area for analysis. In this paper, (1−02) was selected as the analysis area to explore the difference between single-floor fire in Scenarios 2 and double-floor fire in Scenario 6. In addition, (2−02) was selected as the analysis area for Scenario 5 and Scenario 6.

The analysis results are shown in Figure 15. Regarding CO concentration, the increase rate in Scenario 2 and Scenario 6 is relatively consistent. At 630 s, the difference in CO concentration between the two scenarios is only 0.11×10^{-4} mol/mol. Regarding temperature, the temperatures show gradually increasing trend, and the temperature becomes consistent at 602 s. At 630 s, the temperature difference between Scenario 2 and Scenario 6 is only 9 °C. As shown in Figure 16, the CO concentrations in the two scenarios become the same at 83 s. Subsequently, the CO concentration in Scenario 6 is generally higher than that in Scenario 5. Finally, the CO concentration difference between Scenario 5 and Scenario 6 is 0.35×10^{-4} mol/mol at 630 s. In addition, the temperature in Scenario 6 is initially higher than that in Scenario 5, but the temperature increase in Scenario 5 is faster than that in Scenario 6. The temperatures become consistent at 542 s, and at 630 s, the temperature in Scenario 5 is 8.1 °C higher than that in Scenario 6.

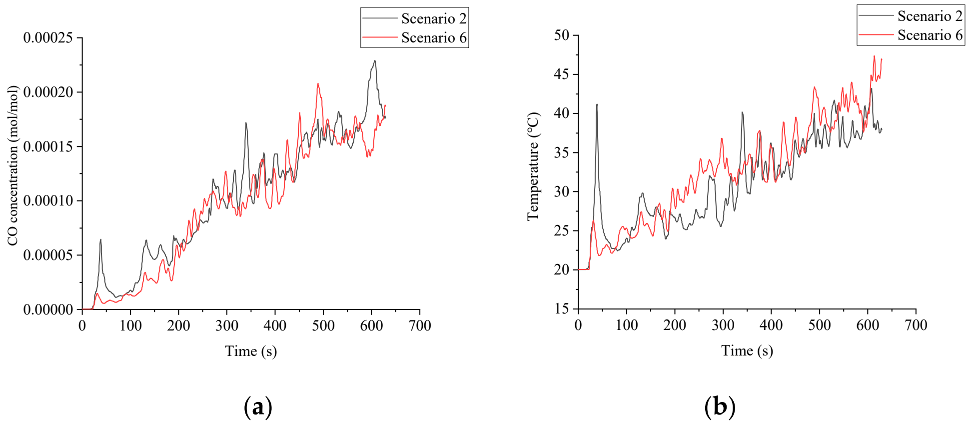


Figure 15. CO concentrations and temperatures fluctuation trend of (1−02) under Scenario 2 and Scenario 6. (**a**) CO concentrations; (**b**) Temperature.

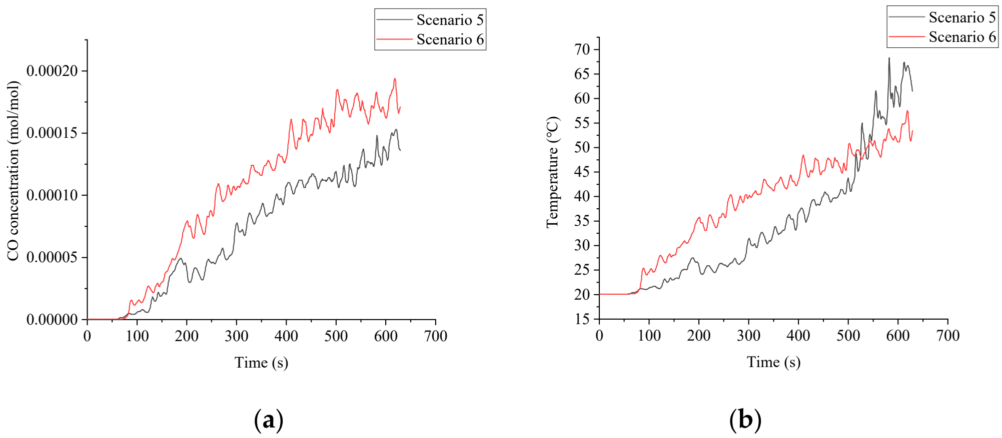


Figure 16. CO concentrations and temperatures fluctuation trend of (2−02) under Scenario 5 and Scenario 6. (**a**) CO concentrations; (**b**) Temperature.

According to the above results, it shows slight differences of the influence on evacuation for small area fire in power distribution room on single-floor or double-floor.

3.5. External Rescue Environment Simulation Results

Through investigating the surrounding environment, two fire stations are 6.2 km and 4.2 km away from the complex rail transit station, as shown in Figure 17. The road condition from fire station A and fire station B to the complex rail transit station are observed though electronic map in all time of a day from "0:00" to "24:00". It was found that the roads were consistently smooth on both workdays and holidays. Thus, the fire engine can smoothly travel from fire station A and fire station B to the complex rail transit station.

(**a**)

(**b**)

Figure 17. Routes from two fire stations to the complex rail transit station. (**a**) Route from fire station A to the station; (**b**) Route from fire station B to the station.

In China, the planning and construction of urban fire stations are regulated by the "Code for Planning of Urban Fire Control GB 51080-2015" and "Construction Standards for Urban Fire Station 152-2017". The "Construction Standards for Urban Fire Station 152-2017" indicates that the rescuers should arrive at the fire scene within 5 min after receiving the dispatch command. It is assumed that no surrounding collapsed houses and no traffic congestion on the roads after the earthquake. According to the real-time road condition analysis by the electronic map, a fire vehicle takes approximately 4 min and 3 min to reach the complex rail transit station from the fire station A and the fire station B, respectively. However, uncertainties such as weather and road conditions may arise during the firefighting vehicles moving from the fire station to the complex rail transit station. Due to the potential for damage to surrounding buildings, blocked access, and additional rescue tasks that fire stations must attend to after an earthquake, ensuring timely rescue is a considerable challenge.

4. Discussion

According to the research results, optimized design recommendations are proposed for reducing the risk of emergency evacuation in both internal and external environments of rail transit stations to achieve sustainable buildings.

4.1. Designing Power Distribution Room for Safety

The power distribution room in a complex rail transit station should be designed to be located away from public areas, such as stairwells or heavily trafficked corridors. It is recommended to set up the power distribution room in a relatively independent area, preferably on the concourse floor. This separation can help minimize the risk of fire spreading to public areas and provide easier access for maintenance personnel in case of emergencies.

To further quantify the risk reduction, this article takes the example of a small area fire in distribution room and demonstrates the effect of redesign the distribution room, which moves 8 m to the right based on the original design, as shown in Figure 18. The temperature and CO concentration at (2−02) have been measured. The results show that from 0 s to 630 s, the CO concentrations in the relocated power distribution room are lower than 1600 ppm (1.6×10^{-3} mol/mol), and the temperatures are below 60 °C. The highest CO concentration is 1.38×10^{-4} mol/mol at 589 s, and the highest temperature is only 45.2 °C at 620 s. Compare the (2−02) before and after the relocation, as shown in Figure 19. The difference in temperature is significantly greater than the difference in CO concentration.

In order to further explore the reduced risk of relocating the power distribution room away from public areas, this article compared the time required for the (2−02) to start heating up, reach the highest CO concentration, reach the highest Temperature before and after relocation, as shown in Table 6. According to the results, it can be seen that relocating the power distribution room 8 m away from the public areas reduces the risk by 23.23%, 9.8%, and 34.49%, respectively.

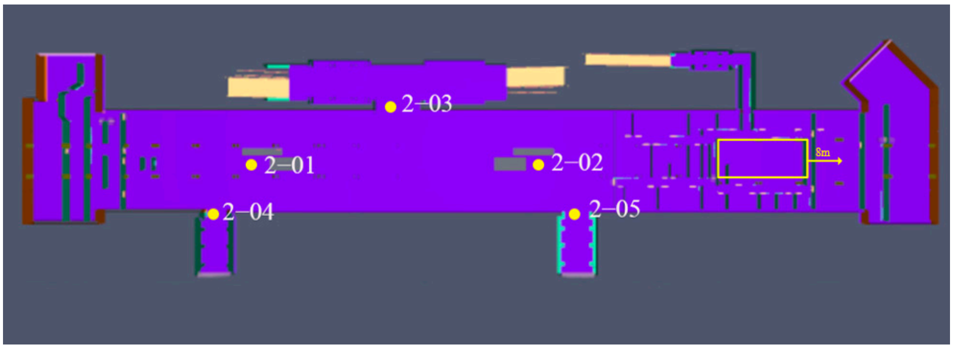
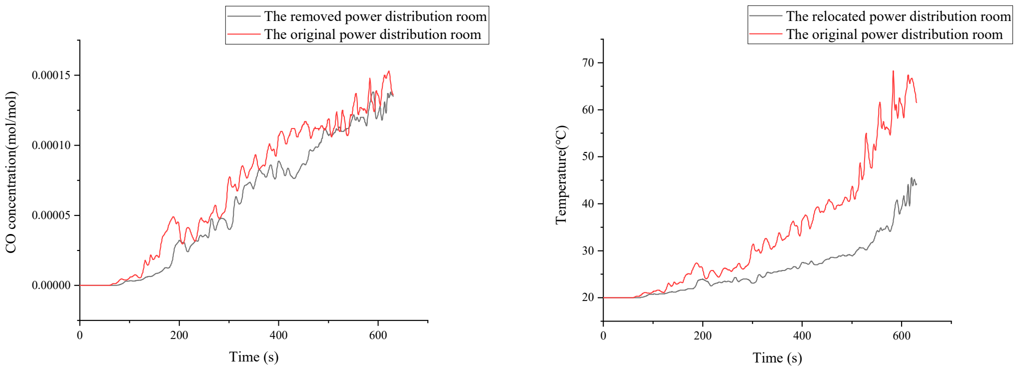


Figure 18. The original and relocated power distribution room of Scenario 5.



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

Figure 19. CO concentrations and temperatures fluctuation trend of (2−02) under Scenario 5 before and after relocating power distribution room. (**a**) CO concentrations; (**b**) Temperatures.

Table 6. Risk reduction calculation.

Analysis	The Original Power Distribution Room	The Relocated Power Distribution Room	The Percentage of Risk Reduction
Comparison of starting time of heating up at (2−02)	99 s	76 s	$\frac{99-76}{99} = 23.23\%$
Comparison of reaching the highest CO concentration	1.53×10^{-4} mol/mol	1.38×10^{-4} mol/mol	$\frac{(1.53 \times 10^{-4}) - (1.38 \times 10^{-4})}{1.53 \times 10^{-4}} = 9.8\%$
Comparison of reaching the highest Temperature	69 °C	45.2 °C	$\frac{69-45.2}{69} = 34.49\%$

4.2. Installing Fire-Resistant Doors

It is advisable to consider installing fire-resistant doors around the power distribution rooms. According to the "Fire Protection Design Standard for Subways" (GB51298−2018) in China, Class A fire-resistant doors should be installed at the entrances of firewalls, smoke-proof stairwells, refuge walkways, and connecting passages. Class B fire-resistant doors are recommended for the entrances of fire barriers, inspection doors in pipeline shafts, and evacuation doors in other areas. According to "Fire Doors" (GB 12955−2023) in China, Class A fire-resistant doors are required to have a minimum fire resistance and thermal insulation of 90 min, while Class B fire-resistant doors should have a minimum fire resistance and thermal insulation of 60 min.

While important position doors are replaced with fire-resistant doors, it can effectively prevent the spread of fire and reduce the risk of fire. These fire-resistant doors can act as barriers to prevent the spread of fire and smoke, ensuring that the impact of a fire accident remains localized and does not compromise the safety of passengers or critical infrastructure. Therefore, replacing the doors with fire-resistant doors may greatly reduce the risk of a post-earthquake fire.

4.3. Improving Fire Detection Systems

Enhancing the safety of complex rail transit stations requires an increased quantity of smoke detectors and alarms, especially in high-risk areas like power distribution rooms and trains. Regular maintenance and testing of these detection systems are crucial to ensure their effectiveness at detecting and alerting occupants to potential fire accidents promptly. It is recommended to apply the latest digital technologies to establish intelligent protection systems, such as fire detection and alarm system based on image processing. Real-time monitoring of the detection environment through cameras and regular collection of image information is suggested to be implemented. Combining with computer information processing and automatic image recognition technology, the implementation of a fire alarm system could achieve automation and intelligence of fire detection and alarm.

4.4. Optimizing Power Distribution Room Design

When considering the design and layout of the power distribution room, it is important to recognize that a large area fire can have a more significant impact than a small area fire. As shown in Figure 12, a comparison is made between Scenario 1 and Scenario 2. The large area fire has the highest CO concentration and temperature at 187 s. Specifically, the CO concentration in the large area fire is 1.72×10^{-4} mol/mol with a temperature of 66.4 °C, whereas the CO concentration in the small area fire is 4.58×10^{-5} mol/mol with a temperature of 24.7 °C. It can be seen that the temperature and CO concentration of a large area fire are obviously higher than those of a small area fire. In addition, the time to exceed the threshold of 60 °C is 10.1 min. Therefore, if the area of the power distribution room is reduced as much as possible, it can effectively slow down the speed of fire spread and reduce the risk of fire. A smaller distribution room area means fewer combustibles and combustion products, which can reduce the possibility of fire spreading. In addition, reducing the area of the power distribution room can also reduce the impact of fires on important facilities and public safety with-in the station. Therefore, efforts should be made to minimize the area of the power distribution room wherever possible.

4.5. Developing Emergency Plans for Train Fires

It has shown that the consequences of a fire occurring within a train are typically more severe than those originating in a power distribution room. As shown in Figures 12 and 13, the temperature and CO concentration differences between Scenario 1 and Scenario 2 are smaller than those between Scenario 3 and Scenario 4. The results show that it is often difficult for people to escape during train fires. In order to avoid train fire accidents, it is crucial to develop specific emergency plans and response strategies tailored to train fires. This may involve specialized evacuation procedures, the installation of fire suppression systems, and training programs for staff to effectively manage such accidents and ensure the safety of passengers.

4.6. Establishing Additional Small Fire Stations

In urban planning considerations, it is recommended to incorporate the establishment of additional small fire stations around complex public buildings in different areas within the city. This proactive measure helps to ensure that there are sufficient fire-fighting resources readily available in an earthquake or other emergencies. By strategically locating these fire stations, potential road obstruction issues can be mitigated, enabling quicker response times and reducing the overall impact of fires on critical infrastructure and public safety.

5. Conclusions

Post-earthquake fires have a significant impact on personal and property safety. This research conducted an evacuation assessment of complex rail transit station under post-earthquake fires for sustainable buildings based on BIM and FDS. By establishing a fire simulation model based on BIM and FDS, this paper assessed the feasibility of evacuation in a complex rail transit station under post-earthquake fires through monitoring temperature and CO concentration. In addition, this paper considered external factors related to disaster relief to determine whether external rescue forces can promptly arrive at the complex rail transit station to provide rescue coverage. According to the research, six optimized design recommendations were discussed to reduce the risk of emergency evacuation in both internal and external environments of rail transit stations for sustainable future buildings.

However, the study did not discuss the optimal evacuation routes for passengers. Chaotic conditions can hinder a safe and efficient evacuation, thereby increasing the risk of injuries or casualties. Therefore, as a future research direction, it is crucial to develop reasonable passenger escape route plans specifically tailored for complex rail transit stations under a post-earthquake fire. This would help address the limitations of the current study and enhance the overall emergency preparedness and response strategies in such critical scenarios. Moreover, examining the effectiveness of evacuation strategies through simulations or conducting field studies to analyze real-world evacuation scenarios could provide valuable insights for improving the safety and resilience of urban buildings facing post-earthquake fires.

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

Funding: This research was funded by The General Project of Chongqing Natural Science Foundation (Grant No. cstc2021jcyj-msxmX0951); The Western Project of the National Social Science Fund of China (Grant No. 22XGL013); The China Postdoctoral Science Foundation (Grant No. 2021M700617); and The Innovative Project of Chongqing Oversea Study Innovation Program (Grant No. cx2020035).

Data Availability Statement: The data presented in this research are available upon request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: Author Hui Xu was employed by the company Chongqing Innovation Center of Industrial Big-Data Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Lou, T.; Wang, W.; Li, J. Post-earthquake fire behaviour of a self-centring connection with buckling-restrained plates and pre-stressed bars: An experimental investigation. *J. Build. Eng.* **2022**, *56*, 104733. [CrossRef]
2. Historical Query of China Earthquake Networks Center. China Earthquake Networks Center. Available online: http://www.ceic.ac.cn/history (accessed on 24 November 2023).
3. Ni, S.; Birely, A.C. A simplified model for the post-fire earthquake flexural response of reinforced concrete walls with boundary elements. *Eng. Struct.* **2018**, *175*, 721–730. [CrossRef]
4. Risco, G.V.; Zania, V.; Giuliani, L. Numerical assessm3.ent of post-earthquake fire response of steel buildings. *Saf. Sci.* **2023**, *157*, 105921. [CrossRef]
5. Trifunac, M.D.; Todorovska, M.I. The Northridge, California, earthquake of 1994: Fire ignition by strong shaking. *Soil Dyn. Earthquake Eng.* **1998**, *17*, 165–175. [CrossRef]
6. Nishino, T. Probabilistic analysis of the vulnerability of fire departments to ignitions following megathrust earthquakes in the Nankai Trough subduction zone, Japan. *Fire Saf. J.* **2021**, *120*, 103038. [CrossRef]
7. Xu, H.; Li, Y.; Wang, L. Resilience Assessment of Complex Urban Public Spaces. *Int. J. Environ. Res. Public Health* **2020**, *17*, 524. [CrossRef]
8. Li, M.; Wang, Y.H.; Jia, L.M. On operation safety assessment model for urban rail transit station. *Adv. Transp. Stud.* **2015**, *1*, 13–22.
9. Xu, H.; Xue, B. Key indicators for the resilience of complex urban public spaces. *J. Build. Eng.* **2017**, *12*, 306–313. [CrossRef]

10. Zhang, J.; Chen, T.; Su, G.; Li, C.; Zhao, F.; Mi, F. Microstructure and component analysis of glowing contacts in electrical fire investigation. *Eng. Fail. Anal.* **2022**, *140*, 106539. [CrossRef]
11. Sarreshtehdari, A.; Khorasani, N.E. Integrating the fire department response within a fire following earthquake framework for application in urban areas. *Fire Saf. J.* **2021**, *124*, 103397. [CrossRef]
12. Feng, J.; Gai, W.; Yan, Y. Emergency evacuation risk assessment and mitigation strategy for a toxic gas leak in an underground space: The case of a subway station in Guangzhou, China. *Saf. Sci.* **2021**, *134*, 105039. [CrossRef]
13. Chen, Y.; Wang, C.; Yap, J.B.H.; Li, H.; Zhang, S. Emergency evacuation simulation at starting connection of cross-sea bridge: Case study on Haicang Avenue Subway Station in Xiamen Rail Transit Line. *J. Build. Eng.* **2020**, *29*, 101163. [CrossRef]
14. Xu, H.; Tian, C.; Li, Y. Emergency Evacuation Simulation and Optimization for a Complex Rail Transit Station: A Perspective of Promoting Transportation Safety. *J. Adv. Transp.* **2020**, *2020*, 8791503. [CrossRef]
15. Wang, Y.; Liang, Y.; Sun, H.; Yang, Y. Decision-making for fire emergency of urban rail transit based on prospect theory. *Math. Probl. Eng.* **2021**, *2021*, 3414589. [CrossRef]
16. Huang, D.; Lo, S.; Chen, J.; Fu, Z.; Zheng, Y.; Luo, L.; Zhuang, Y.; Cheng, H.; Yang, L. Mapping fire risk of passenger-carried fire load in metro system via floor field cellular automaton. *Autom. Constr.* **2019**, *100*, 61–72. [CrossRef]
17. Sun, Q.; Turkan, Y. A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance. *Adv. Eng. Inf.* **2020**, *44*, 101093. [CrossRef]
18. Zhang, L.; Wu, X.; Liu, M.; Liu, W.; Ashuri, B. Discovering worst fire scenarios in subway stations: A simulation approach. *Autom. Constr.* **2019**, *99*, 183–196. [CrossRef]
19. Long, Z.; Zhong, M.; Chen, J.; Cheng, H. Study on emergency ventilation strategies for various fire scenarios in a double-island subway station. *J. Wind Eng. Ind. Aerodyn.* **2023**, *235*, 105364. [CrossRef]
20. Liu, Q.; He, R.; Zhang, L. Simulation-based multi-objective optimization for enhanced safety of fire emergency response in metro stations. *Reliab. Eng. Syst. Saf.* **2022**, *228*, 108820. [CrossRef]
21. Wang, C.; Song, Y. Fire evacuation in metro stations: Modeling research on the effects of two key parameters. *Sustainability* **2020**, *12*, 684. [CrossRef]
22. Qin, J.; Liu, C.; Huang, Q. Simulation on fire emergency evacuation in special subway station based on Pathfinder. *Case Stud. Therm. Eng.* **2020**, *21*, 100677. [CrossRef]
23. Peng, M.; Shi, L.; He, K.; Yang, H.; Cong, W.; Cheng, X.; Richard, Y. Experimental study on fire plume characteristics in a subway carriage with doors. *Fire Technol.* **2020**, *56*, 401–423. [CrossRef]
24. Juliá, P.B.; Ferreira, T.M.; Rodrigues, H. Post-earthquake fire risk assessment of historic urban areas: A scenariobased analysis applied to the Historic City Centre of Leiria, Portugal. *Int. J. Disaster Risk Reduct.* **2021**, *60*, 102287. [CrossRef]
25. Sarreshtehdari, A. The Impact of Fire Following Earthquake on Urban Environment considering the Seismic Performance of Infrastructure Networks. Ph.D. Thesis, State University of New York at Buffalo, Buffalo, NY, USA, 2021.
26. Lu, X.; Yang, Z.; Xu, Z.; Xiong, C. Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality. *Adv. Eng. Softw.* **2020**, *143*, 102792. [CrossRef]
27. Lou, T.; Wang, W.; Izzuddin, B.A. A framework for performance-based assessment in post-earthquake fire: Methodology and case study. *Eng. Struct.* **2023**, *294*, 116766. [CrossRef]
28. Xu, Z.; Zhang, Z.; Lu, X.; Zeng, X.; Guan, H. Post-earthquake fire simulation considering overall seismic damage of sprinkler systems based on BIM and FEMA P-58. *Autom. Constr.* **2018**, *90*, 9–22. [CrossRef]
29. Zhang, W.; Liu, Y.; Yu, S.; Zhang, Y.; Yang, L.; Qi, L. The Application Research of BIM Technology in the Construction Process of Yancheng Nanyang Airport. *Buildings* **2023**, *13*, 2846. [CrossRef]
30. Deng, H.; Wei, X.; Deng, Y.; Pan, H.; Deng, Q. Can information sharing among evacuees improve indoor emergency evacuation? An exploration study based on BIM and agent-based simulation. *J. Build. Eng.* **2022**, *62*, 105418. [CrossRef]
31. Lotfi, N.; Behnam, B.; Peyman, F. A BIM-based framework for evacuation assessment of high-rise buildings under post-earthquake fires. *J. Build. Eng.* **2021**, *43*, 102559. [CrossRef]
32. *Report on the Nutrition and Chronic Disease Status of Chinese Residents*; The State Council Information Office of the People's Republic of China: Beijing, China, 2022.
33. *NFPA13*; Standard for the Fixed Guideway Transit and Passenger Rail Systems. National Fire Protection Association: Quincy, MA, USA, 2020.
34. Purser, D.A.; McAllister, J.L. Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In *SFPE Handbook of Fire Protection Engineering*, 5th ed.; Springer: New York, NY, USA, 2016; pp. 2308–2428.
35. Goldstein, M. Carbon monoxide poisoning. *J. Emerg. Nurs.* **2008**, *34*, 538–542. [CrossRef] [PubMed]
36. Hahne, D.; Rehm, S. Full-scale tests of external rescue with firefighters in underground stations. *Fire Saf. J.* **2022**, *128*, 103538. [CrossRef]
37. Yang, H.; Li, S. Numerical Investigation on the Effect of Mobile Smoke Ventilator on Fire-induced Smoke Extraction for Underground Platform in a High-speed Railway Station. *Procedia Eng.* **2018**, *211*, 871–880. [CrossRef]

buildings

MDPI

Article

Social Media's Influence on Eco-Friendly Choices in Fitness Services: A Mediation Moderation Approach

Samira Hafyana and Ahmad Alzubi *

Institute of Social Sciences, University of Mediterranean Karpasia, TRNC, Mersin 33000, Turkey; 210634074@std.akun.edu.tr
* Correspondence: ahmad.alzaubi@akun.edu.tr

Abstract: In the evolving landscape of the building sector, the digital sphere is reshaping consumer engagement and purchase behaviors, especially in the sustainability-focused niche of fitness facilities. Utilizing the theory of planned behavior (TPB) and elaboration likelihood model (ELM), this study examines the impact of social media influence (SMI) on purchasing intentions for sustainable fitness services (PISFS) through the mediating role of green building consumption perceptions (GBCPs) and the moderating effect of environmental awareness (EA). To examine the proposed relationships and achieve the objectives of the study, 672 valid responses were collected from professionals and customers in fitness services in Turkey and analyzed using Smart PLS 4. The results of the data analysis revealed that SMI positively impacts PISFS, SMI positively impacts GBCP, GBCP positively impacts PISFS, GBCP plays an effective mediation role between SMI and PISFS, the influence of social media on purchasing intentions for sustainable fitness services is further enhanced at high levels of environmental awareness, and the impact of social media on green building consumption perceptions is further strengthened at higher levels of environmental awareness. This study's insights call for the building sector, particularly in sustainable fitness facilities, to actively integrate social media strategies and environmental awareness into their marketing and design. Emphasizing green building attributes on digital platforms can significantly influence consumer choices, steering the industry toward a more environmentally conscious and digitally engaged future.

Keywords: green building consumption; fitness services; environmental awareness; social media influence; SmartPLS; purchase intention

1. Introduction

The fitness industry has undergone a transformative shift in recent years, with an increasing emphasis on sustainability. As society becomes more environmentally conscious, consumers are seeking fitness services that align with their values of eco-friendliness and social responsibility. Concurrently, the pervasive influence of social media has become a driving force in shaping consumer decisions across various industries. The global sport and fitness industry is experiencing exponential growth, commanding attention as one of the most rapidly expanding sectors. The 2018 Global Wellness Institute report states that the global health and wellness sector, which includes fitness, boasts a substantial value of EUR 3.83 trillion, representing 5.3% of the world's economic production. Particularly, the fitness sector, constituting 21% of the global health and wellness industry, achieved a remarkable growth rate of 12.8% between 2015 and 2017, culminating in a total market value of EUR 83.4 billion [1–3].

Turkey has emerged as a key player in the European fitness market, experiencing substantial growth with 2555 fitness centers and generating a revenue of approximately EUR 823 million [4]. Despite having the lowest penetration rate, Turkey leads in membership growth at around 8%, signifying significant potential for sustained growth in the medium- and long-term [5,6]. In this increasingly competitive landscape, businesses providing fitness services must adopt customer-centric approaches and strategies to thrive, necessitating a keen understanding of consumer expectations [7,8]. Effective management in the fitness industry is crucial for both the success of the company and the well-being of its clientele. The failure to adapt to market changes may result in business obsolescence or necessitate a shift to new markets. Consequently, long-term sustainability is imperative in the dynamically evolving global landscape [9]. The emergence of green products, designed to minimize environmental impact, introduces a new dimension to consumer choices. Consumers' environmental consciousness significantly influences their purchasing decisions, making it imperative for marketers to understand and cater to these preferences. Studies indicate that factors such as green trust and subjective norms positively affect consumers' green purchase intentions [10–16].

This shift toward sustainability in the fitness domain reflects broader societal trends. With climate change, resource depletion, and pollution becoming increasingly prominent global concerns, individuals are scrutinizing their lifestyle choices with a discerning eye. The fitness industry, as a significant contributor to consumer habits, is not exempt from this scrutiny. Consumers are now, more than ever, cognizant of the environmental impact of their choices and are actively seeking ways to integrate sustainability into their fitness routines. The pervasive influence of social media has emerged as a potent force shaping consumer decisions across various industries. However, despite the wealth of research on social media and consumer behavior, there exists a significant gap in understanding how this influence specifically translates to the fitness sector, particularly in the field of sustainable fitness services.

One pivotal theoretical framework that guides this study is the theory of planned behavior (TPB) [17]. The TPB posits that an individual's intention to perform a behavior is influenced by their attitude toward the behavior, subjective norm, perceived social pressure to perform or not perform the behavior, perceived behavioral control, and perceived ease or difficulty of performing the behavior [18]. In this study, applying the TPB to understand how individuals' attitudes toward sustainable fitness services, the influence of social norms, and their perceived control over choosing such services collectively shape their intentions to purchase. Social media has become a powerful platform for influencing consumer behavior and preferences. Many fitness service providers use social media to promote their products and services, as well as to communicate their environmental and social values. However, the impact of social media influence on purchasing intentions for sustainable fitness services is not well understood. This paper aims to explore this topic by examining the mediator role of green building consumption perceptions and the moderator role of environmental awareness. The research questions are as follows:

1. How does social media influence individuals' attitudes toward sustainable fitness services as per the TPB?
2. To what extent do subjective norms, particularly those propagated through social media, affect individuals' intentions to choose sustainable fitness services?
3. How does perceived behavioral control, influenced by social media, impact individuals' intentions to opt for sustainable fitness services?
4. Do green building consumption perceptions mediate the relationship between social media influence and the components of the TPB in sustainable fitness service choices?
5. Does environmental awareness play a moderation role in the relationship between social media influence and green building consumption perceptions and the subsequent impact on purchasing intentions for sustainable fitness services?

By addressing these research questions, the study seeks to provide a comprehensive understanding of the factors influencing individuals' intentions to choose sustainable fitness services. While the TPB provides a valuable framework for understanding the factors influencing purchasing intentions, its application within the fitness industry and, more specifically, within sustainable fitness services, is underexplored. This gap makes it even more important to look into how attitudes, subjective norms, and perceived behavioral control, as described in the TPB, affect people's choices about sustainable fitness services, with a focus on how perceptions of green building consumption play a role.

Social media, particularly influential among younger generations, plays a pivotal role in shaping consumer behaviors and opinions. The pervasive influence of social media in daily life, coupled with its role in encouraging environmentally friendly consumption, highlights its significance for businesses promoting sustainable products. The rapid growth of social media platforms, currently engaging 3.6 billion users, is anticipated to reach 4.41 billion by 2025, providing businesses with direct engagement opportunities and a platform to promote green products [19–23]. The intersection of consumer behavior and environmental consciousness has led to an increased demand for green products. Environmental sustainability has become a key consideration for consumers, influencing not only their product choices but also their lifestyle habits, including dietary preferences. Social networking, deeply embedded in consumers' lives, serves as a powerful marketing tool, altering communication dynamics between buyers and marketers [24–31]. To elucidate the underlying cognitive processes driving the influence of social media on consumer behavior, this study employs the elaboration likelihood model (ELM) [32]. ELM posits that individuals engage in two distinct routes of information processing: the central route and the peripheral route. In situations where individuals are motivated and capable of engaging in detailed cognitive processing, such as when making significant purchasing decisions, they are likely to take the central route [33]. This involves thoroughly evaluating the information and considering the merits and relevance of the message. In sustainable fitness services, consumers engaging the central route may critically assess information from social media, evaluating its alignment with their values and the environmental impact of the services. When individuals lack the motivation or cognitive resources for in-depth processing, they may take the peripheral route. This involves relying on cues such as celebrity endorsements, visual appeal, or social media trends. Understanding the role of the peripheral route is crucial, especially in social media, where influencers and visual content often play a significant role in shaping consumer perceptions. By applying the ELM, this research aims to decipher whether the influence of social media on sustainable fitness service purchasing intentions operates primarily through the central route, where consumers critically evaluate information, or through the peripheral route, where cues and influencers play a more dominant role.

Green consumption aligns closely with concepts of sustainable development and consumer behavior, prompting global manufacturing firms to focus on green marketing and innovate constantly to satisfy the needs of eco-friendly customers. Green inventions have a key role in forming consumer buying habits and contribute to the overall competitiveness of firms [34]. While environmental awareness is recognized as a potential moderator in this dynamic relationship, there is limited research on how varying levels of environmental awareness might impact the interplay between social media, green building consumption perceptions, and the TPB components. Investigating this interaction is crucial for uncovering the conditions under which social media has a more pronounced effect on individuals' intentions to choose sustainable fitness services, considering their environmental consciousness. Within the fitness industry, the adoption of green building practices emphasizes environmental sustainability. Green building consumption in fitness services involves integrating energy-efficient technologies, sustainable materials, and water conservation measures. This approach not only contributes to environmental conservation but also aligns with the preferences of eco-conscious consumers, fostering a positive impact on both the environment and individual well-being. Environmental concerns significantly influence people's behavior, prompting companies to focus on environmental issues in their outputs. Earlier research, frequently using the theory of planned behavior (TPB), has explored the motivations behind green purchasing, emphasizing the importance of consumer green values in shaping attitudes and intentions toward green consumption [35–38]. Customers select professional fitness centers not only for skilled fitness advice but also to improve their physical and mental well-being. The principles of green building, emphasizing eco-friendly and healthy growth, align with the rationale behind fitness spending [10]. Furthermore, the trend of green building consumption perceptions introduces a layer of complexity to the sustainable fitness landscape. Existing research has not fully explored how these perceptions act as a mediator between social media influence and the components of the TPB, leaving a critical research gap. Understanding the relationship between social media, green building consumption perceptions, and the elements of the TPB is vital for comprehending the decision-making processes driving individuals toward sustainable fitness choices. Yet, despite the significance of sustainable practices and social media influence in the fitness industry, there is a notable gap in understanding their collective impact on purchasing intentions for sustainable fitness services. This research aims to address this gap by investigating the interplay between purchase intention, social media influence, green building consumption, and environmental awareness in fitness services.

2. Underpinning Theory

2.1. Theory of Planned Behavior (TPB)

Ajzen introduced the TPB [18], positing that an individual's behavioral intentions are shaped by the interplay of attitude (AT), subjective norm (SN), and perceived behavioral control (PBC) [17]. Within this framework, attitude reflects an individual's approval or disapproval of a specific behavior, while subjective norm relates to the social pressures associated with performing or abstaining from a particular behavior. Perceived behavioral control involves assessing the ease or difficulty of executing a specific behavior [39]. The TPB is versatile and applicable across diverse research domains. It can be utilized to ascertain consumers' intentions when considering a product or service, as well as their brand preferences. This theory accommodates adaptation and extension by incorporating additional behavioral constructs, thereby acquiring meanings based on the specific focus of research. In the TPB, an individual's attitude toward a behavior signifies the extent to which the individual perceives that behavior as either favorable or unfavorable. According to the TPB, a more favorable attitude increases the likelihood of an individual replicating that behavior. Positive attitudes are often displayed when individuals positively evaluate the outcomes associated with certain behaviors, influencing their likelihood of engagement. Subjective norms within the TPB encompass perceptions of social expectations regarding participation or nonparticipation in a particular behavior [38]. The opinions of people who are important to the person shape these norms, influencing their decision-making process. If an individual believes that those important to them either approve or disapprove of a behavior, it may impact the decision to engage in that behavior. Conversely, perceived behavioral control within the TPB gauges the ease or difficulty a person associates with performing a specific behavior. The TPB has proven instrumental in predicting intention and behavior across various disciplines, including applications in predicting behavior related to green buildings, energy-efficient products, and environmentally friendly products. Exposure to social media content promoting the advantages of sustainable fitness practices, including environmentally friendly initiatives and wellness benefits, shapes attitudes that reflect people's approval or disapproval. Subjective norms extend to perceptions of social expectations, wherein social media becomes a key influencer, potentially framing sustainable fitness services as socially desirable. Perceived behavioral control, assessing the ease or difficulty of adopting a behavior, involves individuals' perceptions of access to and engagement with sustainable fitness services and is influenced by the availability of information on social media platforms. This direct application of TPB underscores the integral role of social media in shaping attitudes, norms, and control perceptions, thereby influencing individuals' purchasing intentions for sustainable fitness services. The study's enhanced structured understanding provided by TPB offers a comprehensive lens to analyze the intricate relationships between social media, green building consumption perceptions, environmental awareness, and the decision-making process regarding sustainable fitness service consumption.

2.2. Elaboration Likelihood Model (ELM)

ELM is a theoretical framework that becomes particularly pertinent in the context of the new economic era and the prevalence of digitalization, which overwhelms consumers with an abundance of information, especially through social media channels. In understanding the impact of social media on purchasing intentions for sustainable fitness services, ELM serves as a valuable tool, explaining how individuals process persuasive messages in an information-rich environment. The beginning of a new economic era and the rise of digitalization have overwhelmed consumers, with an abundance of information affecting products, services, and various brands through social media channels [32]. Given constraints such as limited time, individuals may struggle to process the numerous persuasive messages originating from sources such as companies or friends [33]. The ELM serves as a theoretical framework explaining how individuals process information, particularly in terms of its influence. It encompasses persuasive messages disseminated through social media and endeavors to anticipate how consumers will react, identifying instances of persuasion and nonpersuasion. ELM provides a valuable tool for comprehending the appropriateness of persuasive communication capable of influencing consumers [40]. Numerous studies suggest that the key determinant in ELM affecting enduring persuasiveness is linked to consumers' ability to elaborate on and comprehend the conveyed persuasion. ELM posits two potential routes for persuasion, influencing consumers' behavioral changes: the central route and the peripheral route. The central route involves a focused and thoughtful understanding process, while the peripheral route involves focusing on things other than the content of the message while it is being processed [40]. The rise of user-generated content makes the quality and credibility of persuasive messages even more important, warranting close attention.

3. Literature Review and Research Hypotheses

3.1. Social Media Influence and Purchasing Intentions for Sustainable Fitness Services

Sustainable fitness services refer to fitness offerings that prioritize ecological responsibility, minimizing environmental impact in areas such as facility operations, equipment production, and waste management. Social media influence is understood as the impact that content, recommendations, and advertisements encountered on social media platforms have on individuals' perceptions and decisions regarding sustainable fitness services. According to TPB [18], attitudes, subjective norms, and perceived behavioral control are the three main factors that affect people's behavioral intentions. In this hypothesis, social media is expected to influence individuals' attitudes and subjective norms regarding sustainable fitness services, ultimately shaping their purchasing intentions. ELM proposes two processing routes, central and peripheral, through which individuals engage with information. In the central route, individuals critically evaluate information, while the peripheral route relies on cues such as influencers and visual appeal. Social media content, as a primary source of information, may trigger either route depending on the individuals' motivation and ability to process information, thus influencing their purchasing intentions [32]. The main purpose of this study is to understand how social media affects people's decision to buy sustainable fitness services. Sustainable fitness services are those that prioritize being environmentally friendly, such as using eco-friendly equipment and reducing waste. The hypothesis holds that social media can positively influence what people think about these services and how likely they are to buy them.

The incorporation of TPB and ELM provides a comprehensive understanding of the psychological mechanisms at play. Social media, acting as a persuasive tool, is expected to influence individuals' attitudes and subjective norms (TPB) while triggering either central or peripheral processing routes (ELM), ultimately impacting their intentions to purchase sustainable fitness services. There is believed to be a relationship between the use of social media and individuals' intentions to purchase sustainable fitness services, with the expectation that this influence is positive. In exploring the impact of social media on purchasing intentions for sustainable fitness services, several key studies have contributed valuable insights. Exposure to social media content is anticipated to contribute positively to the likelihood that individuals will express an intention to purchase fitness services that are characterized by sustainability. Some studies highlight the role of social media content in shaping people's decisions about sustainable fitness services. However, there is a gap in understanding regarding how people think when they see this content. This study proposes a more in-depth examination using surveys or experiments to explore how individuals engage with social media content, considering their attitudes, what others think, and their perceived control over their behavior. Additionally, this study suggests looking into how environmental advertising on social media influences people's attitudes and intentions to buy eco-friendly products. It emphasizes the need for a more detailed exploration of the cognitive processes involved in understanding how advertising on social media shapes people's thoughts about sustainable fitness services.

According to Erwin Halim and Rizal Haqo Karami [41], purchasing intentions for sustainable fitness services suggest that individuals, under the influence of social media, are expected to express a higher intention to purchase fitness services that are deemed sustainable. Social media platforms are expected to have a constructive impact on individuals' intentions to purchase fitness services that align with sustainability principles. The hypothesis could be tested through empirical research, perhaps using surveys, experiments, or other research methods to gather and analyze data on social media usage and purchasing intentions for sustainable fitness services. Environmental advertising, especially on social media, has been shown to have a substantial influence on shaping consumer attitudes and intentions. While existing studies highlight the positive influence of social media on sustainable fitness service intentions, there is a gap in understanding regarding the cognitive processes involved. A more comprehensive exploration of how individuals cognitively engage with social media content, considering factors such as attitudes, subjective norms, and perceived behavioral control, would contribute to a more comprehensive understanding. While the importance of environmental advertising is acknowledged, there is a gap in understanding regarding the specific dynamics through which environmental advertising on social media shapes consumer attitudes and fortifies the intention to purchase green products. A more in-depth exploration of these dynamics would contribute to a more holistic understanding of the role of advertising in influencing sustainable fitness service intentions. The study underscores the importance of environmental advertising in encouraging positive environmental actions and strengthening the intention to purchase green products [35]. Fitness brands are increasingly leveraging data analytics and artificial intelligence (AI) to personalize marketing messages, workout plans, and promotions to individual preferences, through which companies enhance user experiences and drive engagement. In a study of [42], the effectiveness of personalization strategies in fitness marketing is emphasized. Influencers, fitness bloggers, and user-generated content contribute significantly to brand visibility and consumer engagement. In [43,44] the impact of social media marketing on fitness brand equity is explored. Fitness apps have become indispensable for consumers seeking convenient solutions. These apps offer features such as workout tracking, nutrition guidance, and community support. Brands that invest in user-friendly mobile experiences gain a competitive edge.

The studies examines two psychological theories, one concerning people's planned behavior and the other about how they process information. Together, these theories suggest that social media, as a persuasive tool, can shape people's attitudes and what others around them think (subjective norms). Moreover, social media can affect how individuals process information, either by critically evaluating it or relying on cues such as influencers and visuals. In simpler terms, the study aims to determine out how social media makes people want to buy eco-friendly fitness services. It brings together two psychological theories and suggests a need to understand how people think when they see social media content and ads about these services. One study demonstrated that the attractiveness, expertise, and trustworthiness of branded material associated with fitness products shared by social media influencers have a significant impact on followers' purchase intentions [45].

Another study found that social media usage, social influence, drive for environmental responsibility, and perceived trust in social media are major antecedents of consumers' sustainable purchasing attitudes [46]. The sample should ideally represent a diverse range of individuals who engage with social media and have an interest in fitness services. Potential biases could arise from self-selection, as individuals who are more active on social media and more interested in sustainable fitness might be more likely to participate in the study. In essence, this study aims to understand how social media affects people's decision to buy sustainable fitness services. Sustainable fitness services are those that prioritize being environmentally friendly, which may include using eco-friendly equipment and reducing waste. The hypothesis holds that social media can positively influence what people think about these services and how likely they are to buy them [47]. Based on a literature review and the research question, this paper proposes the following hypothesis to test the relationships among the variables of interest:

H1: *Social media influence has a positive impact on purchasing intentions for sustainable fitness services.*

3.2. Social Media Influence and Green Building Consumption Perceptions

The hypothesis under consideration investigates the relationship between social media influence and individuals' perceptions of green building consumption. Green building consumption perceptions encompass attitudes, beliefs, and views related to environmentally friendly building practices and how individuals positively perceive and engage in consumption behaviors aligned with green building principles. Social media influence is defined as the transformative effect of social media on consumer behavior. Research has specifically focused on how exposure to information, content, or discussions related to green building practices on platforms like Facebook, Instagram, Twitter, etc., shapes individuals' attitudes and perceptions regarding green building consumption [20]. The theoretical foundation for understanding this relationship is based on the TPB and the ELM. TPB helps explain how attitudes, subjective norms, and perceived behavioral control shape individuals' perceptions, while ELM aids in understanding the cognitive processes involved in the influence of social media on these perceptions.

Si Xie and Ghulam Rasool Madni [19] explored the transformative impact of social media on green consumption patterns, offering insights into how social media shapes consumer psychology and attitudes toward green practices. Their study surveyed 303 young people in China and applied multiple statistical techniques to determine the reliability and validity of the data. However, potential biases could have arisen from self-selection, as individuals who are more active on social media and more interested in sustainable fitness might have been more likely to participate in the study. Similarly, Karina Sokolova and Charles Perez [48] investigated the reasons why users follow fitness celebrities on YouTube, examining the connection between parasocial communication, intentions to view fitness content, and intentions to work out. Their paper acknowledges consumers as significant actors in fostering a green lifestyle, using social media as a platform for exchanging opinions about green products, influencing others, and promoting a collective commitment to environmental preservation. Erwin Halim and Rizal Haqo Karami [41] highlight how social media influence encompasses the information, messages, and discussions about sustainable and environmentally friendly building practices that individuals are exposed to on platforms such as Facebook, Instagram, Twitter, etc. Their hypothesis is that a higher level of exposure to information and discussions about green buildings on social media is expected to result in more favorable attitudes and perceptions toward green building consumption. Social media influence is anticipated to have a positive impact on green building consumption perceptions, suggesting that exposure to information, content, or discussions related to green building practices on social media platforms leads individuals to form more favorable attitudes and perceptions toward consuming products or services associated with green buildings [23]. This aligns with the transformative influence of social media on consumer behavior and the expected positive link between social media impact and individuals' views on green building consumption. Based on the literature review and the research question, this paper proposes the following hypothesis to test the relationships among the variables of interest:

H2: *Social media influence has a positive impact on green building consumption perceptions.*

3.3. Green Building Consumption Perceptions and Purchasing Intentions for Sustainable Fitness Services

The provided hypothesis focuses on the positive impact of green building consumption perceptions on purchasing intentions for sustainable fitness services. It draws on the TPB to understand how attitudes, subjective norms, and perceived behavioral control influence individuals' intentions. Additionally, the ELM is used to comprehend the cognitive processes involved in the influence of green building consumption perceptions on purchasing intentions [38]. The existing literature, as exemplified by Yuyang Hou et al. [49], indicates that positive perceptions of green building usage can increase motivations to buy fitness services in business health clubs. This suggests a positive relationship between consumers' perceptions of green building practices in fitness services and their intentions to purchase sustainable fitness services. The focus here is on how individuals perceive environmentally friendly features associated with fitness service buildings, such as energy efficiency, sustainable materials, or overall environmental consciousness.

The hypothesis holds that as green building consumption perceptions improve, there is a corresponding increase in purchasing intentions for sustainable fitness services. It anticipates that individuals who perceive fitness facilities as environmentally conscious, perhaps due to features such as eco-friendly architecture or energy-saving practices, are more likely to express an intention to choose and use these services. In essence, the hypothesis implies a positive connection between the perceived green aspects of the building and consumers' inclination to choose sustainable fitness services. To contribute significantly to this research area, a potential research gap is identified. While the hypothesis provides a general expectation of a positive connection, it acknowledges the need for a more nuanced exploration of the intricate dynamics of green building consumption perceptions. Ying-Kai Liao et al. [35] integrated signaling theory and the attitude-behavior-context (ABC) theory to explore the multifaceted nature of green purchasing behavior. The study suggests that green building consumption perceptions involve various aspects, including energy efficiency, the use of sustainable materials, and overall environmental consciousness. A potential area for significant contribution could involve a detailed examination of how each of these specific aspects influences purchasing intentions. Consumers are actively seeking fitness centers that prioritize sustainability. Eco-friendly gyms incorporate energy-efficient equipment, implement recycling programs, and embrace green building practices. These initiatives resonate with environmentally aware members who appreciate the commitment to reducing the environmental footprint [50]. Fitness facilities are increasingly pursuing certifications such as LEED (leadership in energy and environmental design). These certifications are tangible evidence of a facility's dedication to sustainable practices. When consumers see the LEED certification, it positively influences their perceptions and reinforces the facility's commitment to environmental responsibility [51]. Research indicates that consumers prefer workout clothing made from eco-friendly materials. Brands that offer sustainable activewear gain favor among environmentally conscious fitness enthusiasts. Whether it is recycled fabrics, organic cotton, or low-impact dyes, sustainable apparel aligns with the values of health-conscious consumers [52]. Exploring the specific factors within the theoretical frameworks that may have varying impacts on consumers' willingness to engage in environmentally friendly transactions would deepen the understanding of this topic. In essence, a more comprehensive exploration of the multifaceted nature of green building consumption perceptions and their distinct influences on purchasing intentions could enhance the understanding of this relationship. Based on the literature review and the research question, this paper proposes the following hypothesis to test the relationships among the variables of interest:

H3: *Green building consumption perceptions have a positive impact on purchasing intentions for sustainable fitness services.*

3.4. Green Building Consumption, Social Media Influence, and Purchasing Intentions for Sustainable Fitness Services

The provided hypothesis explores the influence of green building consumption perceptions and social media on individuals' purchasing intentions, utilizing the TPB to understand how attitudes, subjective norms, and perceived behavioral control shape these intentions. Additionally, the ELM provides insights into the cognitive processes related to how individuals process information regarding green building consumption and social media influence.

Arun Kumar and Mrinalini Pandey [53] conducted research on the intersection of social media, consumer motivations, and subjective norms, focusing on their impact on green consumption habits. Their study highlighted the roles of altruistic and egoistic motivations, as well as social norms, in influencing young consumers' intentions to buy green or organic products. The findings revealed that both environmental and health motivations significantly influenced youth's green purchasing intentions, with a particular emphasis on health concerns affecting green product choices. The study acknowledged the role of social media as a powerful communication tool that can contribute to environmental and health awareness, positively influencing green consumption behavior. It emphasized the importance of businesses leveraging social media platforms to enhance customer motivation, buying intentions, and behavior toward green products. A potential research gap in this context could involve a more comprehensive exploration of the specific mechanisms through which social media contributes to environmental and health awareness, ultimately influencing green consumption behavior. While the study recognized the positive impact of social media, it did not delve into the intricacies of how different aspects of social media content, interaction, or platform features may differently shape consumers' perceptions and intentions. A potential area for significant contribution could involve conducting research that delves deeper into the nuances of social media's influence on green consumption behavior. This could include examining specific types of content, engagement strategies, or platform features that have varying effects on individuals' attitudes and purchasing intentions. Understanding these specific mechanisms can provide businesses with actionable insights into how to optimize their use of social media to positively impact consumer behavior related to green products. Consumers who exhibit high environmental awareness tend to make choices aligned with their values. When it comes to fitness services, this translates into preferences for environmentally friendly options. Green gyms that prioritize energy efficiency, recycling, and sustainable practices attract individuals who value eco-consciousness. Additionally, organic food options and eco-friendly fitness gear resonate with this segment [54]. Trust in fitness brands is closely linked to their commitment to sustainability. Consumers appreciate transparency regarding eco-friendly initiatives. Brands that communicate their green practices whether through certifications, clear messaging, or visible efforts build trust with environmentally conscious consumers [55]. Subjective norms play a significant role in shaping consumer behavior. When friends, family, or social circles endorse sustainable fitness practices, individuals are more likely to adopt them. Social influence acts as a powerful motivator, reinforcing the importance of eco-friendly choices within fitness contexts [56]. While the existing literature acknowledges the positive influence of social media on green consumption behavior, there is a potential research gap in understanding the specific mechanisms at play. A significant contribution could involve a more detailed exploration of how different aspects of social media contribute to environmental and health awareness, providing businesses with practical insights for enhancing customer motivations and intentions to purchase green products. Based on the literature review and the research question, this paper proposes the following hypothesis to test the relationships among the variables of interest:

H4: *Green building consumption perceptions play a mediation role between social media influence and purchasing intentions for sustainable fitness services.*

3.5. Environmental Awareness as a Moderator

In TPB, attitudes, subjective norms, and perceived behavioral control collectively influence behavioral intentions. Here, environmental awareness acts as a moderator, influencing the strength of these components. For instance, individuals with higher environmental awareness may exhibit more positive attitudes, stronger subjective norms, and greater perceived behavioral control toward sustainable fitness services. Within the ELM framework, central and peripheral information processing routes are relevant. Environmental awareness can impact the central route, where individuals contemplate information, and the peripheral route, where cues and heuristics influence perceptions. In hypotheses H5 and H6, individuals with high environmental awareness may be more inclined to engage in central processing, leading to a deeper consideration of information related to social media influence, purchasing intentions, and green building consumption perceptions. Yuyang Hou et al. [40] investigated environmental awareness identified as a positive moderator and established a link between green building usage views and the tendency to buy fitness services in business fitness centers. This emphasizes the importance of environmental consciousness in influencing consumer behavior. Their study surveyed 303 young people in China and applied multiple statistical techniques to determine the reliability and validity of the data [19]. However, potential biases could have arisen from self-selection, as individuals who are more active on social media and more interested in sustainable fitness might have been more likely to participate in the study. Vijay Kumar Jain et al. [34] underscore the importance of shaping policies that encourage the acceptance of green products, contribute to environmental sustainability, and reduce the environmental impact through informed consumer choices. This study anticipates that the inclination of consumers, particularly that of millennials, toward green products will stimulate companies to innovate in this space. Such green innovations are expected to not only improve environmental performance but also enhance firm performance and productivity. Deepak Jaiswal and Rishi Kant [57] showed that green buying intention may be notably and directly influenced by environmental consciousness. Environmental consciousness is one of the strongest predictors of holding a positive attitude toward green products and green buying intention and is compatible with the field of green consumer behavior [58]. Environmental awareness can either enhance or reduce the link between social media impact and buying intentions for eco-friendly fitness services depending on the level of awareness and the direction of influence. This hypothesis holds that environmental awareness, which is the degree of concern or interest that people have for the natural environment and its protection, influences how social media, purchasing intentions, and green building perceptions are related to each other. Based on the literature review and the research question, this paper proposes the following hypotheses to test the relationships among the variables of interest:

H5: *Environmental awareness plays a moderator role in the relationship between social media influence and purchasing intentions for sustainable fitness services.*

H6: *Environmental awareness plays a moderator role in the relationship between social media influence and green building consumption perceptions.*

4. Research Design and Methodology

4.1. Research Framework and Variable Measures

This study examined the impact of social media on consumers' perceptions of green buildings in fitness services and the factors influencing their purchasing intentions for sustainable fitness services. The key components of the framework included the independent variable, social media influence (SMI), which was measured using a composite index that considered the frequency of interaction with fitness-related content, types of content engaged with sustainability, fitness routines, and the depth of engagement, such as likes, shares, and comments. Meanwhile, the dependent variable was purchasing intentions for sustainable fitness services (PISFS), which was examined through Likert-scale questions related to the likelihood and willingness to subscribe to or purchase sustainable fitness services. Green building consumption perceptions (GBCPs) were considered to be a mediator and were measured through dimensions such as perceived eco-friendliness, energy efficiency, and sustainable materials. Environmental awareness (EA) was used to assess how individuals' environmental awareness moderates the impact of social media on perceptions of green buildings and purchasing intentions. The framework in Figure 1 provides a structured approach to understanding the complex relationships among social media influence, green building perceptions, environmental awareness, and consumers' intentions to purchase sustainable fitness services.

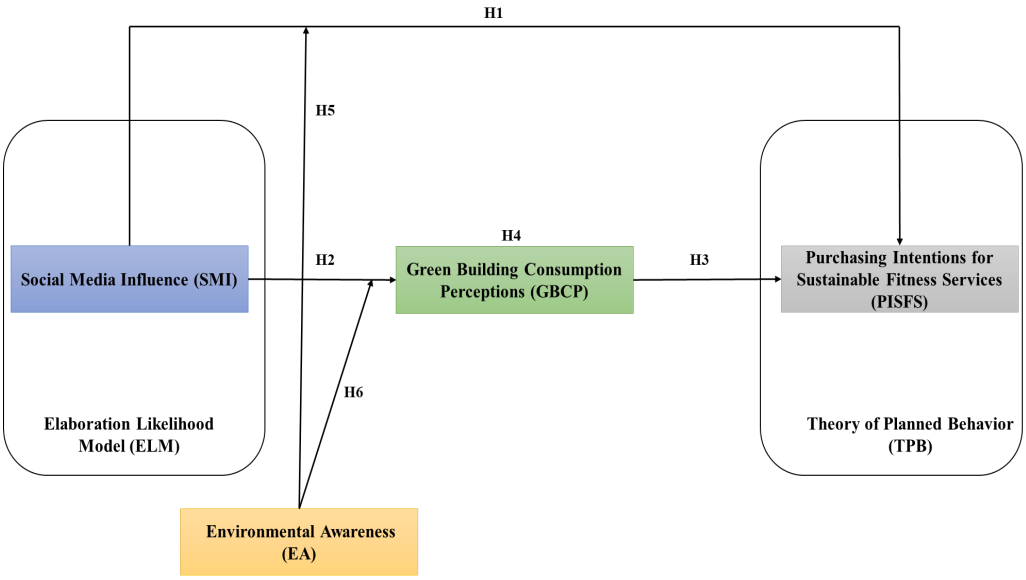


Figure 1. Conceptual research framework.

4.2. Design of the Study

This study adopted an online survey-based questionnaire approach to gather data on consumer perceptions, social media habits, and purchasing intentions regarding sustainable fitness services. Respondents rated various elements on a Likert scale ranging from 1 to 5, where 5 indicated strong agreement and 1 denoted strong disagreement. PISFS was assessed using items selected based on their relevance to the fitness industry and their alignment with sustainable practices, ensuring face validity [1,7,49]. SMI was chosen to capture the multifaceted nature of social media engagement in the fitness context [5,24]. GBCPs were recognized for their applicability in assessing perceptions related to green building features [1,19,24]. EA was evaluated using items derived from [1,2,13] to measure individual environmental awareness comprehensively. For a detailed list of the survey items used to measure Social Media Influence (SM), Green Building Consumer Perception (GBCP), Purchase Intention (PI), and Environmental Awareness (EA), see Appendix A. The process of selecting the sample for this research study was conducted meticulously to align with the study's goals and contextual framework. A purposive sampling technique was employed, which involved purposely targeting professionals and customers within Turkey's fitness industry. This strategic selection aimed to capture individuals who have a genuine interest in sustainability within the fitness sector, ensuring that the collected data would accurately reflect the attitudes and behaviors relevant to the study's objectives.

In this research study, it was crucial to recognize and mitigate potential biases that could influence the results. One such bias that was carefully considered was self-selection bias. This bias occurs when individuals who already have a strong interest in the subject being studied are more likely to participate, potentially skewing the findings. To address self-selection bias, the research team employed a strategic approach known as stratified sampling. This method involves dividing the population into distinct subgroups, or strata, based on relevant characteristics, and then selecting samples from each subgroup. In this study, the stratification focused on different consumer segments within the fitness industry. Using stratified sampling ensured that participants were drawn from various segments of the fitness industry and represented a diverse range of backgrounds, preferences, and levels of environmental awareness. This approach helped to minimize the impact of self-selection bias by providing a more balanced and representative sample. Furthermore, the study meticulously collected demographic data from the participants. These data included information such as age, gender, fitness level, and environmental awareness. By collecting and analyzing these demographic factors, the study sought to provide a comprehensive understanding of the sample's diversity and its relevance to the research goals. In essence, this detailed approach to sample selection aimed to ensure that the findings derived from the study would be applicable and reflective of a wide spectrum of perspectives within Turkey's fitness industry, thereby enhancing the validity and robustness of the research outcomes.

The data were collected over six weeks through online surveys, resulting in a robust sample of 672 participants. Descriptive statistical techniques, including measures of central tendency and variability, were applied for data summarization. Confirmatory factor analysis (CFA) within structural equation modeling (SEM) was utilized to assess the interrelationships among latent variables, thereby validating the measurement model and facilitating hypothesis testing. This methodology enhances the statistical validity of the study.

5. Results and Interpretation

5.1. Measurement Model

(i) Demographics

Demographic analysis involves the systematic examination and interpretation of various demographic characteristics within a population or sample. Demographics encompass a range of socioeconomic and personal attributes that provide insights into the composition and diversity of a group. These characteristics commonly include age, gender, marital status, education, ethnicity, income, occupation, and other relevant factors. The purpose of demographic analysis is to understand the composition of a population and identify patterns, trends, or associations that may exist among different demographic groups. Table 1 provides demographic information via a detailed list of the study participants, revealing a diverse and representative sample. The majority of respondents were female (70%), reflecting a gender distribution that is crucial for understanding the broader impact of social media on purchasing intentions for sustainable fitness services. Age-wise, the study captured a significant segment of individuals between 21 and 30 years old (55%), while also including representation across other age groups. The educational spectrum was broad, ranging from participants with no formal education to those holding PhDs, with the majority possessing at least a bachelor's degree (51%). Social media use duration varied, with the majority having used it for 1–2 years (52%). This demographic representation enhances the generalizability of findings, allowing for an advanced exploration of the impact of social media on purchasing intentions among varied participants.

(ii) Descriptive Test

Descriptive statistics involves summarizing and describing the main features of data, providing its central tendencies, variability, and distributional characteristics. These statistics are essential to gaining a preliminary understanding of the data and communicating the key features to others. Table 2 presents key statistical measures for four variables in the study: SMI, GBCP, EA, and PISFS. For SMI, the mean score of 3.76 indicates a moderate level of influence, with a slightly leftward skew in the distribution. GBCP shows a generally positive perception (mean of 4.001) with a symmetric distribution. EA reflects a moderate level of awareness (mean of 3.648), exhibiting a leftward skew in participants' responses. PISFS has a moderately positive inclination (mean of 3.997), with a slightly leftward-skewed distribution. These findings characterize the participants' sentiments and preferences regarding sustainable fitness services, highlighting the variability and distributional patterns within the sample of 672 participants. The data contributes valuable information for understanding the interplay of SMI, GBCP, PISFS, and EA in sustainable fitness services.

Table 1. Demographic analysis.

Name	Options	N Sample Size		Percentage	
Gender	Male	202	672	30	100
	Female	470		70	
Age	Below 20 years	18	672	3	100
	21–30 years	375		55	
	31–40 years	192		29	
	41–50 years	56		8	
	51–60 years	28		4	
	Above 60 years	3		1	
Education	No formal education	2	672	1	100
	Primary school	8		2	
	High school	68		10	
	Diploma	137		20	
	Bachelor's degree	348		51	
	Master's degree	95		13	
	PhD	14		3	
Social media use	Less than 1 year	135	672	20	100
	1–2 years	358		52	
	3–4 years	159		24	
	5–6 years	17		3	
	More than 6 years	3		1	

Table 2. Descriptive test.

	Mean	Median	Min	Max	Standard Deviation	Kurtosis	Skewness	Number of Observations Used
SMI	3.76	3.75	1.75	5	0.625	0.433	−0.305	672
GBCP	4.001	4	2.4	5	0.544	−0.131	0.054	672
EA	3.648	3.8	1.6	5	0.729	0.106	−0.543	672
PISFS	3.997	4	2	5	0.67	0.578	−0.548	672

(iii) Reliability and validity test

Reliability refers to the consistency and stability of measurement instruments. In this study, reliability was assessed through Cronbach's alpha and composite reliability (CR). Table 3 provides Cronbach's alpha values for PISFS, SMI, GBCP, and EA, which are all above the commonly accepted threshold of 0.7. This indicates a high level of internal consistency within each construct, suggesting that the selected items reliably measure the intended concepts. Additionally, composite reliability values for each construct exceed the recommended threshold of 0.7, further supporting the reliability of the measurement model. Validity assesses whether the measurement items truly measure the intended constructs. Factor loadings represent the strength of the relationship between the items and their respective constructs. In this study, factor loadings for all items within each construct are high, indicating a strong connection between the items and their latent constructs.

Specifically, factor loadings for items related to PISFS, SMI, GBCP, and EA are consistently strong, ranging from 0.712 to 0.873. These high factor loadings provide evidence supporting the construct validity of the measurement items, suggesting that they effectively capture the underlying concepts they are intended to measure.

Table 3. Reliability and validity test.

Variable	Item	Factor Loading	Cronbach's Alpha	CR	AVE
Purchasing intentions for sustainable fitness services (PISFS)	PISFS1 PISFS2 PISFS3	0.868 0.873 0.831	0.823	0.836	0.735
Social media influence (SMI)	SMI1 SMI2 SMI3 SMI4	0.788 0.827 0.828 0.793	0.824	0.826	0.655
Green building consumer perception (GBCP)	GBCP1 GBCP2 GBCP3 GBCP4 GBCP5	0.712 0.759 0.836 0.827 0.763	0.828	0.835	0.595
Environmental awareness (EA)	EA1 EA2 EA3 EA4 EA5	0.701 0.733 0.821 0.864 0.863	0.851	0.849	0.631

(iv) Discriminant validity test

The Table 4 outlines the outcomes of the Fornell–Larcker criterion, a commonly used method in structural equation modeling to measure discriminant validity. The logic is that a construct's AVE should be higher than its associations with other constructs, implying that the variance explained by the construct's items is greater than the shared variance with other constructs. In this study, the square root of AVE values for EA, GBCP, PISFS, and SMI are approximately 0.794, 0.77, 0.857, and 0.809, respectively. These values surpass the corresponding associations between constructs, confirming that each construct is more closely related to itself than to others. This supports the measurement model's ability to efficiently differentiate between the constructs, providing evidence of discriminant validity.

Table 4. Discriminant validity test—Fornell–Larcker criterion.

Variable	EA	GBCP	PISFS	SMI
EA	**0.794**			
GBCP	0.381	**0.77**		
PISFS	0.502	0.32	**0.857**	
SMI	0.394	0.43	0.256	**0.809**

The heterotrait–monotrait (HTMT) ratio test results, as presented in Table 5, demonstrate discriminant validity among the key constructs in the research study. The HTMT ratios were calculated by comparing the correlations between different constructs (heterotrait correlations) with the average correlations within the same construct (monotrait correlations). For discriminant validity, the HTMT ratios should be considerably below 1.0, signifying that the correlations between distinct constructs are markedly lower than the average correlations within each construct. In this study, the HTMT ratios of 0.444 (EA-GBCP), 0.37 (PISFS-GBCP), and 0.303 (SMI-PISFS) are all below the important level, which means there is strong evidence for discriminant validity. These results imply that the correlations between different constructs are smaller than the average correlations within each construct, strengthening the measurement model and effectively distinguishing between EA, GBCP, PISFS, and SMI.

Table 5. Discriminant validity test—heterotrait–monotrait ratio.

Variable	EA	GBCP	PISFS	SMI
EA				
GBCP	0.444			
PISFS	0.571	0.37		
SMI	0.46	0.51	0.303	

Table 6 presents the cross-loading values, which represent the strength of relationships between individual items and their intended constructs, as well as potential associations with other constructs. The interpretation involves examining the pattern of these cross-loadings to assess their discriminant validity. Each item should exhibit a higher correlation with its intended construct than with other constructs. In this study, the results indicate that items related to EA, GBCP, PISFS, and SMI normally align with their intended constructs. This pattern supports the discriminant validity of the constructs, suggesting that the measurement items effectively capture the distinct aspects of each construct.

Table 6. Cross loadings.

Code	EA	GBCP	PISFS	SMI
EA1	**0.701**	0.29	0.512	0.293
EA2	**0.733**	0.3	0.372	0.359
EA3	**0.821**	0.3	0.366	0.32
EA4	**0.864**	0.33	0.363	0.319
EA5	**0.863**	0.27	0.321	0.248
GBCP1	0.186	**0.71**	0.233	0.271
GBCP2	0.234	**0.76**	0.271	0.363
GBCP3	0.345	**0.84**	0.23	0.288
GBCP4	0.379	**0.83**	0.223	0.313
GBCP5	0.306	**0.76**	0.261	0.393
PISFS1	0.386	0.23	**0.868**	0.216
PISFS2	0.384	0.22	**0.873**	0.174
PISFS3	0.496	0.34	**0.831**	0.255
SMI1	0.266	0.32	0.205	**0.788**
SMI2	0.263	0.33	0.19	**0.827**
SMI3	0.37	0.38	0.189	**0.828**
SMI4	0.365	0.35	0.244	**0.793**

5.2. Structural Model

(i) Modelling

This study used partial least squares structural equation modeling (PLS-SEM) method via SmartPLS 4.0 to build and analyze a model based on insights from previous studies. This involved evaluating path coefficients, significance levels, and the coefficient of determination (R^2) for each dependent construct. The significance of path coefficients was highlighted, along with their orientation and statistical relevance, with 5000-sample bootstrapping being used for stability evaluation. Path coefficients indicate the intensity and direction of relationships between constructs. A positive path coefficient implies a positive relationship, while a negative coefficient indicates a negative relationship. The size of the coefficient shows the intensity of the relationship. The t-values associated with path coefficients show their statistical significance. Bootstrapping with 5000 samples is frequently used to produce t-values and assess the stability of outcomes. The coefficient of determination (R^2) quantifies how well the model accounts for the variation in dependent constructs. A higher R^2 implies a better-fitting model. It is essential to assess both the overall model and individual construct R^2 values. High R^2 values imply that the model efficiently explains the variation in dependent constructs based on the given independent variables. Figure 2 displays the structural model setup for testing the research hypotheses.

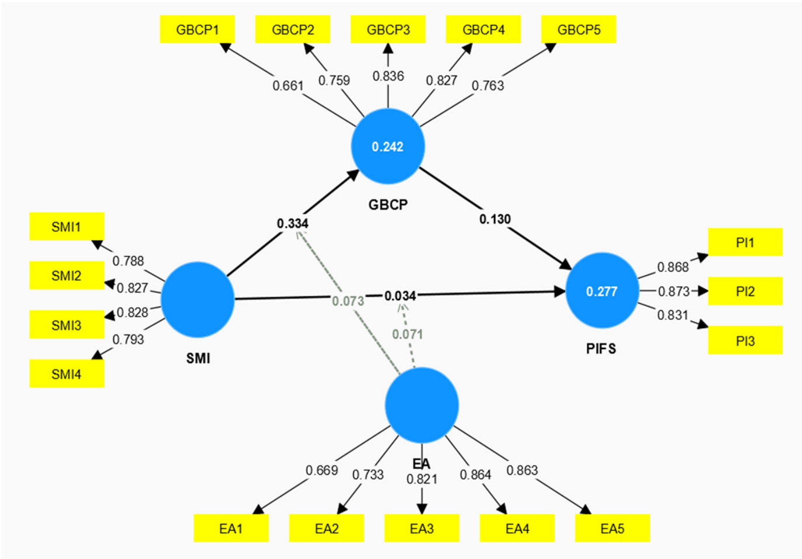


Figure 2. Structural model.

(ii) Collinearity test

The Table 7 shows the variance inflation factor (VIF) values for collinearity assessment between the latent constructs. The VIF values were calculated to evaluate the degree of multicollinearity between variables, with higher values indicating a greater level of collinearity. Generally, VIF values below 5 are considered acceptable, and values exceeding this threshold may suggest potential collinearity issues. The absence of extremely high VIF values in this table suggests that the latent constructs are relatively independent of each other in the analysis.

Table 7. Collinearity test.

Variable	EA	GBCP	PISFS	SMI
EA		1.202	1.294	
GBCP			1.319	
PISFS				
SMI		1.192	1.34	

(iii) Model fit

Table 8 shows the several model fit indices for the latent constructs GBCP and PISFS. For GBCP, the Q^2 value is 0.232, indicating the predictive significance of the model for this construct. Q^2 assesses the model's ability to predict the endogenous latent variable, with higher values suggesting better predictive accuracy. In this study, a Q^2 of 0.232 for GBCP implies that the model has a moderate level of predictive relevance for green building consumer perception. For PISFS, the Q^2 value is 0.253, suggesting a moderate predictive relevance for purchasing intentions for sustainable fitness services. The R^2 values measure the proportion of variation in the dependent constructs accounted for by the independent variables. For GBCP, the R^2 is 0.242, implying that approximately 24.2% of the variance in green building consumer perception is accounted for by the predictors, reflecting a moderate level of explanatory power. For PISFS, the R^2 is 0.277, indicating that around 27.7% of the variance in purchasing intentions for sustainable fitness services is explained by the model. SRMR (standardized root mean square residual) is a measure of the discrepancy between observed and predicted covariances. A lower SRMR value suggests a better fit, with values below 0.08 generally considered acceptable. The SRMR value of this study is 0.078.

Table 8. Model fit test.

Variable	Q^2	R^2	SRMR
GBCP	0.232	0.242	0.078
PISFS	0.253	0.277	

(iv) Hypotheses Test

(a) Path coefficient

Table 9 explains the relationships between latent constructs and the strength and statistical significance of these connections. The path from EA to GBCP is positively significant, with a path coefficient (β) of 0.264 and a highly strong T statistic of 6.928, and the p value is 0.000 ($p < 0.001$). Moreover, the path from EA to PISFS is even stronger, with a β of 0.487, a highly significant T statistic of 14.522, and a p value of 0.000 ($p < 0.001$), suggesting an extensive influence of EA on PISFS. The path from GBCP to PISFS, while positive, is comparatively weaker, with a β of 0.13 and a significant T statistic of 3.455, and the p value is 0.001 ($p = 0.001$). Also, SMI appears to have a positive effect on both GBCP and PISFS. The path coefficient for SMI to GBCP is 0.334 (T statistic = 9.999, $p < 0.001$), while the path coefficient for SMI to PISFS is 0.078 (T statistic = 2.139, $p = 0.033$), which shows that PISFS is affected less strongly by SMI. Standard deviations for each path represent variability in observed scores. The varying strengths of these relationships underscore the strong relationship between the latent constructs in the structural model.

Table 9. Path coefficient test.

Path	β	Standard Deviation (STDEV)	T-Statistic	p-Value
EA -> GBCP	0.264	0.038	6.928	0.000
EA -> PISFS	0.487	0.034	14.522	0.000
GBCP -> PISFS	0.13	0.038	3.455	0.001
SMI -> GBCP	0.334	0.033	9.999	0.000
SMI -> PISFS	0.078	0.036	2.139	0.033

(b) Mediator test

Table 10 shows the results of tests that looked at the mediating effect of GBCP in the relationships between EA and PISFS and between SMI and PISFS. The tests were run along two sequential paths in the structural equation model. For the EA -> GBCP -> PISFS path, the path coefficient (β) of 0.034 signifies a positive mediating effect of GBCP between EA and PISFS. The significant T statistic of 2.929 ($p = 0.003$) indicates the strength of this mediation effect, and the confidence interval (2.50% to 97.50%) spans from 0.014 to 0.174. Similarly, for the SMI -> GBCP -> PISFS path, the path coefficient is 0.043, signifying a positive mediation effect of GBCP between SMI and PISFS. The highly significant T statistic of 3.315 ($p = 0.001$) underscores the strength of this mediation effect, with a confidence interval ranging from 0.019 to 0.198. Overall, these findings suggest that GBCP serves as a significant mediator, explaining how both EA and SMI contribute to influencing individuals' intentions to purchase sustainable fitness services.

Table 10. Mediating effect test.

Path	β	STDEV	T-Statistic	*p*-Value	2.50%	97.50%
EA -> GBCP -> PISFS	0.034	0.035	0.012	2.929	0.003	0.014
SMI -> GBCP -> PISFS	0.043	0.043	0.013	3.315	0.001	0.019

(c) Moderator test

The results of the moderating effect test, as represented in Table 11, clarify the relationship between EA and SMI and its impact on GBCP and PISFS. The significant path coefficient of 0.073 demonstrates a positive moderating effect for EA × SMI -> GBCP. This suggests that the influence of EA and SMI has a distinct impact on shaping consumers' perceptions of green building fitness services. Similarly, EA × SMI -> PISFS exhibits a positive moderating effect on PI, with a significant path coefficient of 0.071. This implies that the influence of EA and SMI significantly affects consumers' intentions to purchase sustainable fitness services. The T statistics of 0.029 and 0.035 for GBCP and PISFS, respectively, show that both interactions are statistically significant. These results highlight the moderating role of SMI in influencing the link between EA and consumers' perceptions and intentions, providing advanced knowledge of EA and SMI in sustainable fitness services. Figure 3 depicts the correlation between EA at various levels of standard deviations (SD) and SMI on GBCP. The lines depict the values of EA at −1 standard deviation (below average), EA at the mean (average), and EA at +1 standard deviation (above average). As the SMI increases, the GBCP also increases across all levels of EA. Nevertheless, the gradient is most pronounced for individuals with higher environmental awareness, specifically those at +1 standard deviation. This indicates that as their social media influence increases, their perceptions of green building consumption experience a more significant rise. Conversely, for those with lower environmental awareness (EA at −1 SD), the increase in GBCP is less significant.

Table 11. Moderating effect test.

Path	β	STDEV	T-Value	*p*-Value
EA × SMI -> GBCP	0.073	0.072	0.029	2.486
EA × SMI -> PISFS	0.071	0.07	0.035	2.002

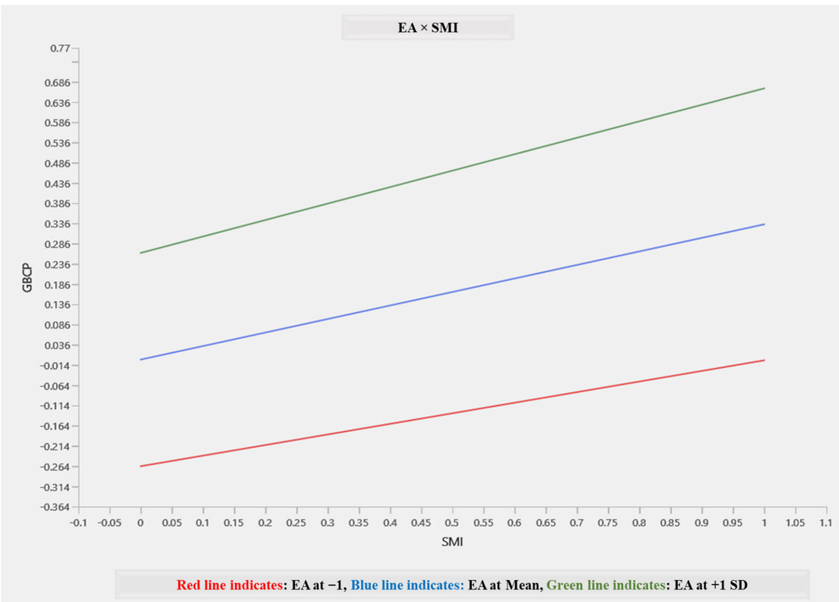


Figure 3. Moderating effect.

6. Discussion

6.1. Interpretation of Findings

In examining the relationship between SMI and PISFS, the findings underscore the significant impact of SMI on consumer decisions within the sustainable fitness sector. The positive correlation observed suggests that social media plays a pivotal role in shaping consumers' intentions to engage with eco-friendly fitness services. Moreover, the exploration of GBCP reveals that it serves as a mediator in this relationship. This implies that consumers' perceptions of sustainable infrastructure directly influence their purchasing intentions and provide a relationship between environmental consciousness and consumer choices.

6.2. Role of Green Building Consumption Perceptions

The mediating role of GBCP illuminates the significance of perceived environmental sustainability in consumer decision-making processes. The study contributes to the understanding of consumer behavior within the context of sustainable services by emphasizing the pivotal role of GBCP. Consumers' perceptions of green building practices emerged as influential factors that shaped their intentions to adopt sustainable fitness services. Fitness service providers must invest in sustainable infrastructure and communicate these efforts effectively, as positive GBCP enhances consumers' likelihood to engage with eco-friendly fitness options. These findings attest to a deep relationship between consumer perceptions and sustainable service adoption and provide practical implications for businesses seeking to align with environmental values.

6.3. Importance of Environmental Awareness

In this study, the moderating role of environmental awareness (EA) on the relationship between SMI and both PISFS and GBCP underscores the importance of fostering environmental consciousness in targeted marketing strategies. The results suggest that consumers with heightened environmental awareness exhibit an amplified response to social media influence, further influencing their purchasing intentions and perceptions of green building practices. This finding underscores the need for fitness service providers to tailor marketing efforts to enhance environmental awareness, thereby leveraging social media as a powerful tool to resonate with ecologically conscious consumers. This implication aligns with current trends in sustainability marketing and emphasizes the potential for businesses to amplify the impact of social media campaigns by strategically targeting and engaging environmentally aware consumer segments.

7. Implications for Practice and Policymakers

7.1. Theoretical Implication

The TPB and the ELM provide a strong theoretical framework for understanding consumer behavior in sustainable fitness services influenced by social media. The TPB theory underscores the importance of attitudes, subjective norms, and perceived behavioral control in determining consumers' intentions to engage with sustainable fitness services. The findings align with the TPB, as they demonstrate the influence of attitudes, subjective norms, and perceived control on purchasing intentions for sustainable fitness services. The study extends TPB by incorporating social media as a significant external factor impacting these psychological constructs. Additionally, ELM is supported by illustrating how social media serves as a peripheral cue, influencing consumer attitudes and intentions through heuristic processing. The study underscores the importance of attitudes, subjective norms, and perceived control in shaping purchasing intentions. In particular, favorable attitudes toward sustainable fitness services, subjective norms influenced by social media, and a sense of perceived control over decision-making play a significant role in consumers' intentions to adopt sustainable fitness practices. Green building consumption perceptions act as a crucial mediator within the TPB framework. The study reveals that individuals form positive attitudes toward sustainable fitness services through their perceptions of environmentally friendly facilities. This mediator role emphasizes the interconnectedness of environmental considerations and purchasing intentions within the TPB model. Social media, in sustainable fitness services, functions as a peripheral cue in the ELM. Consumers exposed to sustainability-related content on social media platforms undergo heuristic processing, impacting their attitudes and intentions. The study demonstrates how social media serves as a source of information that influences consumers' mental shortcuts in decision-making.

7.2. Practical Implications

Fitness service providers can leverage social media by creating content that emphasizes the sustainability aspects of their services. Strategies may include showcasing eco-friendly facilities, sharing success stories of sustainable fitness transformations, and collaborating with influencers who align with environmental values. To influence consumer perceptions and intentions, providers should focus on visually appealing content. This could involve sharing videos or images depicting sustainable practices, virtual tours of green facilities, and infographics illustrating the positive environmental impact of choosing their services. Recognizing the varying levels of environmental awareness among consumers, social media campaigns should be customized to different segments. For instance, content targeting environmentally conscious consumers may emphasize detailed sustainability practices, while content for less-aware segments may serve as educational material to raise awareness gradually. Creating interactive content, such as polls, challenges, or virtual events, fosters community building and brand loyalty. This not only enhances the overall consumer experience but also strengthens the connection between the brand and environmentally conscious consumers who seek a sense of community. These practical recommendations directly align with the study's findings. For instance, the results show that exposure to perceptions of green building consumption on social media influences positive attitudes toward sustainable fitness services, reinforcing the need for providers to incorporate these elements into their strategies. The study's implications extend beyond individual providers, suggesting industry-wide implications. Policymakers can consider incentivizing sustainability initiatives in fitness services, and industry associations may develop certification programs that recognize and promote environmentally friendly practices, creating a collective push toward sustainable fitness.

8. Conclusions and Future Research

This study employed SmartPLS 4 software to conduct a comprehensive analysis of the measurement model and structural model using a sample of 672 participants, providing robust evidence supporting the relationships between social media impact, green building consumption perceptions, environmental awareness, and purchasing intentions for sustainable fitness services. The results of the measurement model analysis show a high degree of internal coherence within each construct, implying that the chosen items accurately assess the expected concepts. Factor analysis for all items within each construct is high, showing a strong link between the items and their hidden constructs. In the discriminant validity test, the values surpass the corresponding associations between constructs, confirming that each construct is more closely related to itself than to others. This supports the measurement model by effectively distinguishing between the constructs and providing evidence of discriminant validity. The results imply that the correlations between different constructs are smaller than the average correlations within each construct, strengthening support for the measurement model in effectively distinguishing between EA, GBCP, PISFS, and SMI. In addition, the structural model analysis revealed the associations among the variables being studied. Path coefficients indicate the magnitude and orientation of relationships between constructs. The model fit test suggests a better fit for the latent constructs, GBCP, and PISFS. Furthermore, the mediating role of green building consumption perceptions was evident, emphasizing the importance of environmentally conscious facilities in influencing consumers' preferences for sustainable fitness services. Furthermore, the moderation analysis in this study highlights the significance of environmental awareness in shaping the intensity of the correlation between social media impact and the intention to make purchases. This study contributes to the understanding of the TPB and the ELM, elucidating the intricate dynamics between social media, green building consumption perceptions, and environmental awareness in shaping consumer behavior. Industry professionals can leverage the findings to enhance the design and promotion of sustainable fitness services, emphasizing the importance of environmentally conscious facilities and strategic social media engagement. The study's robust methodology strengthens its validity, and the findings provide a foundation for future research improvements. Qualitative approaches such as interviews or focus groups can be further employed to gain deeper insights into the subjective experiences influencing consumer perceptions and behaviors related to sustainable fitness services. Moreover, future research should investigate other potential mediators such as consumer knowledge of sustainability, the brand image of sustainable practices, the perceived value of sustainability in fitness services, or trust in green claims made on social media, as well as moderators such as personal health consciousness, public commitment to sustainability, frequency of social media usage, or cultural attitudes toward sustainability with regards to the relationship between social media and purchasing intentions to reveal different dimensions shaping consumer behavior.

Author Contributions: Spearheaded by S.H., this research illuminates the effect of social media influence on purchasing intentions within the context of sustainable fitness services, integrating the roles of green building consumption perceptions and environmental awareness. Under A.A.'s supervision, it addresses literature gaps in the sustainability of service industries, particularly fitness. Through empirical analysis, S.H.'s work, enriched by A.A.'s seasoned perspective, proposes practical strategies for the industry's sustainable advancement. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available on request from the authors.

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

Appendix A

Social Media Influence (SM)
SM1: Your social media engagement significantly influences your decision to purchase products from green building commercial fitness clubs.
SM2: You use social media to seek information about products offered by green building commercial fitness clubs.
SM3: You consider information related to green building commercial fitness clubs on social media to be reliable.
SM4: You deem the content regarding green building commercial fitness clubs on social media to be credible.
Green Building Consumer Perception (GBCP)
GBCP1: You believe that engaging in green building commercial fitness clubs is environmentally beneficial.
GBCP2: Prioritizing environmental concerns, you affirm that choosing fitness services in green building commercial fitness clubs contributes positively to the ecological environment.
GBCP3: You feel a responsibility to prefer green building commercial fitness clubs for fitness experiences over conventional fitness clubs.
GBCP4: Aligning with your fitness program, participation in fitness activities at green building commercial fitness clubs is integral to your immersion.
GBCP5: You perceive engaging in green-building commercial fitness clubs as a means to enhance your image and garner recognition from others.

Purchase Intention (PI)
PI1: If you require fitness services, you are open to purchasing them from green building commercial fitness clubs.
PI2: When friends seek fitness services, you would suggest green building commercial fitness clubs.
PI3: Green building commercial fitness clubs serve as an optimal choice for investing in fitness services.
Environmental Awareness (EA)
EA1: Taking the initiative, you seek to understand environmental protection in your life and enhance your ability to protect the environment.
EA2: Adopting environmentally friendly behaviors in your personal and professional life is a spontaneous choice.
EA3: You actively encourage your family, friends, and colleagues to embrace more environmentally conscious behaviors.
EA4: You stay informed about environmental initiatives promoted through social media.
EA5: Your attitude toward environmental protection and green initiatives remains consistently positive.

References

1. Eskiler, E.; Altunışık, R. The Moderating Effect of Involvement in the Relationship Between Customer Behavioral Intentions and Its Antecedents. *SAGE Open* **2021**, *11*, 21582440211014495. [CrossRef]
2. Deloitte, E. *European Health & Fitness Market Report (EHFMR)*; Deloitte: Krakow, Poland, 2019.
3. Enstitute, G.W. Global Wellness economy monitor. *Erişim Adresi* **2018**, *11*, 2021.
4. Deloitte. European Health & Fitness Market Report 2022. Available online: https://www2.deloitte.com/content/dam/Deloitte/de/Documents/consumer-business/European%20Health%20and%20Fitness%20Market_Reportauszug%202021.pdf (accessed on 22 November 2023).
5. Sevilmiş, A.; Özdemir, I.; García-Fernández, J.; Zhang, J.J. Examining the Relationships Among Perceived Quality, Perceived Value, Customer Satisfaction, and Behavioral Intention in Turkish Fitness Centers. *Phys. Cult. Sport. Stud. Res.* **2022**, *96*, 40–54. [CrossRef]
6. Yildiz, K.; Polat, E.; Yildiz, S.M. The fitness industry in Turkey. In *The Global Private Health & Fitness Business: A Marketing Perspective*; Emerald Publishing Limited: Leeds, UK, 2021; pp. 51–57.
7. Altinişik, N.S.A.L.; Çelik, A.K.I.N. Investigation of Service Quality Perceived by Fitness Center Consumers. *Pak. J. Med Heal. Sci.* **2021**, *15*, 3225–3229. [CrossRef]
8. Roof, K.; Murat, C.; Gallipoli, L. The relationship between customer expectations and customer loyalty: An example of a five-star hotel. *Cukurova Univ. J. Inst. Soc. Sci.* **2010**, *19*, 429–446.
9. León-Quismondo, J.; García-Unanue, J.; Burillo, P. Best practices for fitness center business sustainability: A qualitative vision. *Sustainability* **2020**, *12*, 5067. [CrossRef]
10. Zhuang, W.; Luo, X.; Riaz, M.U. On the Factors Influencing Green Purchase Intention: A Meta-Analysis Approach. *Front. Psychol.* **2021**, *12*, 644020. [CrossRef]
11. Ottman, J.A.; Stafford, E.R.; Hartman, C.L. Avoiding Green Marketing Myopia: Ways to Improve Consumer Appeal for Environmentally Preferable Products. *Environ. Sci. Policy Sustain. Dev.* **2006**, *48*, 22–36. [CrossRef]
12. Dangelico, R.M.; Pontrandolfo, P. From green product definitions and classifications to the Green Option Matrix. *J. Clean. Prod.* **2010**, *18*, 1608–1628. [CrossRef]
13. Cherrier, H.; Black, I.R.; Lee, M. Intentional non-consumption for sustainability: Consumer resistance and/or anti-consumption? *Eur. J. Mark.* **2011**, *45*, 1757–1767. [CrossRef]
14. Gil, M.T.; Jacob, J. The relationship between green perceived quality and green purchase intention: A three-path mediation approach using green satisfaction and green trust. *Int. J. Bus. Innov. Res.* **2018**, *15*, 301–319. [CrossRef]
15. Konuk, F.A.; Rahman, S.U.; Salo, J. Antecedents of green behavioral intentions: A cross-country study of Turkey, Finland and Pakistan. *Int. J. Consum. Stud.* **2015**, *39*, 586–596. [CrossRef]
16. Sreen, N.; Purbey, S.; Sadarangani, P. Impact of culture, behavior and gender on green purchase intention. *J. Retail. Consum. Serv.* **2018**, *41*, 177–189. [CrossRef]
17. Amoako, G.K.; Dzogbenuku, R.K.; Abubakari, A. Do green knowledge and attitude influence the youth's green purchasing? Theory of planned behavior. *Int. J. Product. Perform. Manag.* **2020**, *69*, 1609–1626. [CrossRef]
18. Ajzen, I. The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. [CrossRef]
19. Xie, S.; Madni, G.R. Impact of Social Media on Young Generation's Green Consumption Behavior through Subjective Norms and Perceived Green Value. *Sustainability* **2023**, *15*, 3739. [CrossRef]
20. Wang, C.; Cardon, P.W.; Liu, J.; Madni, G.R. Social and economic factors responsible for environmental performance: A global analysis. *PLoS ONE* **2020**, *15*, e0237597. [CrossRef]

21. Huang Minxue, Z.H. The frontier practice of news feed advertising and its theoretical interpretation. *Bus. Manag. J.* **2019**, *41*, 193–208.
22. Zhao, J.; Madni, G.R. The impact of economic and political reforms on environmental performance in developing countries. *PLoS ONE* **2021**, *16*, e0257631. [CrossRef] [PubMed]
23. Pop, R.-A.; Săplăcan, Z.; Alt, M.-A. Social Media Goes Green—The Impact of Social Media on Green Cosmetics Purchase Mo-tivation and Intention. *Information* **2020**, *11*, 447. [CrossRef]
24. Kumar, A.; Pandey, M. Social Media and Impact of Altruistic Motivation, Egoistic Motivation, Subjective Norms, and EWOM toward Green Consumption Behavior: An Empirical Investigation. *Sustainability* **2023**, *15*, 4222. [CrossRef]
25. Ismail, A.R. The influence of perceived social media marketing activities on brand loyalty: The mediation effect of brand and value consciousness. *Asia Pac. J. Mark. Logist.* **2017**, *29*, 129–144. [CrossRef]
26. Iqbal, N.; Tufail, M.S.; Mohsin, M.; Sandhu, M.A. Assessing social and financial efficiency: The evidence from mi-crofinance institutions in Pakistan. *Pak. J. Soc. Sci.* **2019**, *39*, 149–161.
27. Sivapalan, A.; von der Heidt, T.; Scherrer, P.; Sorwar, G. A consumer values-based approach to enhancing green consumption. *Sustain. Prod. Consum.* **2021**, *28*, 699–715. [CrossRef]
28. Zafar, A.U.; Shen, J.; Shahzad, M.; Islam, T. Relation of impulsive urges and sustainable purchase decisions in the personalized environment of social media. *Sustain. Prod. Consum.* **2021**, *25*, 591–603. [CrossRef]
29. Alfahad, B.S.M.; Alabdullah, S.F.I.; Ahmad, M. Investigation of the critical factors influencing low-cost green sus-tainable housing projects in Iraq. *Math. Stat. Eng. Appl.* **2022**, *71*, 310–329.
30. Yue, T.; Liu, J.; Long, R.; Chen, H.; Li, Q.; Liu, H.; Gu, Y. Effects of perceived value on green consumption intention based on double-entry mental accounting: Taking energy-efficient appliance purchase as an example. *Environ. Sci. Pollut. Res.* **2021**, *28*, 7236–7248. [CrossRef] [PubMed]
31. Martinho, G.; Pires, A.; Portela, G.; Fonseca, M. Factors affecting consumers' choices concerning sustainable packaging during product purchase and recycling. *Resour. Conserv. Recycl.* **2015**, *103*, 58–68. [CrossRef]
32. Giantari, K.; Sriathi, A.; Ekawati, N.W.; Yasa, N.; Setini, M. Integrated social media marketing with elaboration likelihood model (ELM) in Bali Indonesia. *Int. J. Innov. Creat. Change* **2020**, *13*, 913–930.
33. Miller, N.; Maruyama, G.; Beaber, R.J.; Valone, K. Speed of speech and persuasion. *J. Personal. Soc. Psychol.* **1976**, *34*, 615. [CrossRef]
34. Gupta, A.; Verma, H.; Jain, V.K.; Kumar, P. Modelling drivers of millennials' green consumption behaviour: An interpretive structural modelling approach. *Int. J. Econ. Bus. Res.* **2022**, *24*, 73–79. [CrossRef]
35. Liao, Y.-K.; Wu, W.-Y.; Pham, T.-T. Examining the Moderating Effects of Green Marketing and Green Psychological Benefits on Customers' Green Attitude, Value and Purchase Intention. *Sustainability* **2020**, *12*, 7461. [CrossRef]
36. Vazifehdoust, H.; Taleghani, M.; Esmaeilpour, F.; Nazari, K.; Khadang, M. Purchasing green to become greener: Factors in-fluence consumers' green purchasing behavior. *Manag. Sci. Lett.* **2013**, 2489–2500. [CrossRef]
37. Paul, J.; Modi, A.; Patel, J. Predicting green product consumption using theory of planned behavior and reasoned action. *J. Retail. Consum. Serv.* **2016**, *29*, 123–134. [CrossRef]
38. Yadav, R.; Pathak, G.S. Young consumers' intention towards buying green products in a developing nation: Extending the theory of planned behavior. *J. Clean. Prod.* **2016**, *135*, 732–739. [CrossRef]
39. Yeğin, T.; Ikram, M. Analysis of Consumers' Electric Vehicle Purchase Intentions: An Expansion of the Theory of Planned Be-havior. *Sustainability* **2022**, *14*, 12091. [CrossRef]
40. Petty, R.E.; Cacioppo, J.T. The effects of involvement on responses to argument quantity and quality: Central and peripheral routes to persuasion. *J. Personal. Soc. Psychol.* **1984**, *46*, 69. [CrossRef]
41. Halim, E.; Karami, R.H. Information systems, social media influencers and subjective norms impact to purchase intentions in e-commerce. In Proceedings of the 2020 International Conference on Information Management and Technology (ICIMTech), Bandung, Indonesia, 13–14 August 2020; IEEE: New York, NY, USA; pp. 899–904.
42. Baranow, R. *The Impact of Influencer Marketing in the Fitness Industry on Consumers' Trust*; Modul University: Vienna, Austria, 2019.
43. Santos, J.P.M.D.S.D.G. The Role of Fitness Influencers on the Fitness and Wellness Industry: A Consumer Trust & Brand Equi-ty Perspective. Ph.D. Thesis, Universidade NOVA de Lisboa, Lisbon, Portugal, 2022.
44. Bilal, H.S.M.; Amin, M.B.; Hussain, J.; Ali, S.I.; Razzaq, M.A.; Hussain, M.; Lee, S. Towards user-centric inter-vention adap-tiveness: Influencing behavior-context based healthy lifestyle interventions. *IEEE Access* **2020**, *8*, 177156–177179. [CrossRef]
45. Devi, S.; Mahapatra, S.N. Social media influencers: Key to influence consumer's intention to purchase fitness products. *Int. J. Heal. Sci.* **2022**, 3181–3188. [CrossRef]
46. Hu, S.; Zhu, Z. Effects of Social Media Usage on Consumers' Purchase Intention in Social Commerce: A Cross-Cultural Em-pirical Analysis. *Front. Psychol.* **2022**, *13*, 837752. [CrossRef]
47. Majeed, M.; Owusu-Ansah, M.; Ashmond, A.-A. The influence of social media on purchase intention: The mediating role of brand equity. *Cogent Bus. Manag.* **2021**, *8*, 1944008. [CrossRef]
48. Sokolova, K.; Perez, C. You follow fitness influencers on YouTube. But do you actually exercise? How parasocial relation-ships, and watching fitness influencers, relate to intentions to exercise. *J. Retail. Consum. Serv.* **2021**, *58*, 102276. [CrossRef]

49. Hou, Y.; Chen, S.; Yao, Z.; Huang, Q.; Shen, X.; Cao, L.; Cheng, J.; Gui, F.; Zhang, Y.; Wang, X. Green Building Consumption Perception and Its Impact on Fitness Service Purchasing Intentions: An Extended Institutional Analysis and Development Decision-Making Model Analysis. *Buildings* **2023**, *13*, 2536. [CrossRef]
50. Lucas, S.; Pinheiro, M.D.; de la Cruz Del Río-Rama, M. Sustainability Performance in Sport Facilities Management. In *Sports Management as an Emerging Economic Activity: Trends and Best Practices*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 113–138.
51. Ahmad, T. Innovation in Green Building Projects: An Exploratory Inquiry. *Buildings* **2023**, *13*, 2359. [CrossRef]
52. Morán-Gámez, G.; Fernández-Martínez, A.; Biscaia, R.; Nuviala, R. Measuring Green Practices in Sport: Development and Validation of a Scale. *Sustainability* **2024**, *16*, 494. [CrossRef]
53. Quan, L.; Koo, B.; Han, H. Exploring the factors that influence customers' willingness to switch from traditional hotels to green hotels. *J. Travel Tour. Mark.* **2023**, *40*, 185–202. [CrossRef]
54. Campos, P.d.O.; Lima, A.A.L.d.S.; Costa, C.S.R.; da Costa, M.F. The influence of voluntary simplicity and environmental ac-tivism on sustainable fashion purchase intention. *J. Fash. Mark. Manag. Int. J.* **2023**, *27*, 352–369. [CrossRef]
55. Channa, N.A.; Tariq, B.; Samo, A.H.; Ghumro, N.H.; Qureshi, N.A. Predicting consumers' intentions to purchase eco-friendly athletic wear in a moderated model of individual green values and gender. *Int. J. Sports Mark. Spons.* **2022**, *23*, 410–436. [CrossRef]
56. Adel, A.M.; Dai, X.; Roshdy, R.S. Investigating consumers' behavioral intentions toward suboptimal produce: An extended theory of planned behavior—A cross-cultural study. *Br. Food J.* **2022**, *124*, 99–139. [CrossRef]
57. Jaiswal, D.; Kant, R. Green purchasing behaviour: A conceptual framework and empirical investigation of Indian consumers. *J. Retail. Consum. Serv.* **2018**, *41*, 60–69. [CrossRef]
58. Chauhan, H.; Pandey, A.; Mishra, S.; Rai, S.K. Modeling the predictors of consumers' online purchase intention of green products: The role of personal innovativeness and environmental drive. *Environ. Dev. Sustain.* **2021**, *23*, 16769–16785. [CrossRef]

buildings

MDPI

Article

The Multilevel Chain Mediating Mechanism of College Faculty's Felt Responsibility on Students' Engagement in Green Building Learning

Sen Chen [1,†], Yuyang Hou [1,†], Yujie Zhang [1,†], Zhenning Yao [1,†], Xinyi Shen [1], Luning Cao [1], Haohao Yang [2], Xinbo Wang [1], Fuwei Gui [1], Junyang Cheng [1] and Qian Huang [3,*]

1 Graduate Department, Xi'an Physical Education University, Xi'an 710068, China; rockychensen@126.com (S.C.); yuyanghou2424@163.com (Y.H.); 19909453720@163.com (Y.Z.); yaozhenning3@126.com (Z.Y.); sxy1997713@163.com (X.S.); cln1999@126.com (L.C.); 18392557108@163.com (X.W.); gfw0305@126.com (F.G.); cjy109917@163.com (J.C.)
2 School of Music, Shaanxi Normal University, Xi'an 710119, China; y_oooh@126.com
3 School of Sports Engineering and Information Technology, Wuhan Sports University, Wuhan 430079, China
* Correspondence: huangqian168@126.com
† These authors contributed equally to this work.

Abstract: The limitations surrounding the education and teaching of green building courses in higher education institutions are becoming increasingly evident. The roles of instructors, the learning environments of green building-related courses, and the impact of student engagement in these courses are attracting significant academic interest. This study delves into the cross-level mediating roles of the green building learning climate and helping behaviors, exploring the link between instructors' sense of responsibility and student engagement. It employs a multi-layer structural equation model for statistical analysis, utilizing paired survey data from 543 students and 51 instructors of green building courses, based on social cognitive theory. This paper incorporates the educational psychology concepts of "climate" and "mutual aid" with the green building learning climate and mutual aid behaviors. It provides a theoretical analysis of how instructors' sense of responsibility in colleges influences students' learning of green building knowledge and skills. By merging the ideas of "climate" and "mutual aid", this study aims to theoretically examine the impact of instructors' responsibility on student engagement with green building concepts. This approach seeks to offer new theoretical insights for pedagogical studies in green building courses.

Keywords: green building; learning engagement; felt responsibility; pedagogical research

1. Introduction

Since the dawn of the 21st century, a growing awareness among nations globally has emerged regarding the critical importance of enhancing the quality of higher education. University educators, as the primary drivers of students' academic experiences, play a crucial role in fostering comprehensive human capital development and nurturing a new generation of skilled talents [1,2]. Contemporary architectural educators in Chinese universities operate within a traditional tri-level administrative hierarchy: "university-college-department". This structure primarily focuses on fulfilling teaching obligations and adopts a unidirectional approach to imparting knowledge, tailored to the specific requirements of various disciplines. The prevailing ethos is to teach for the sake of teaching, or merely to fulfill teaching hour quotas. Consequently, fostering student innovation and managing the educational process are not considered primary responsibilities of these educators. The development of students' comprehensive abilities is often viewed as a secondary function, only addressed after regular teaching tasks are completed. Consequently, university classrooms, particularly in emerging disciplines like green building, have evolved into passive, task-focused environments, akin to "graduate production workshops". This approach has revealed several deficiencies in the educational processes and teaching practices of these innovative fields [3], such as the principles of green building, and the technical and practical knowledge, which the existing teaching system has not been completely covered. Moreover, students find it difficult to learn from the current, more diffuse curriculum system. For example, the principles, as well as technical and practical knowledge of green building, have not been fully covered by the existing teaching system, and it is difficult for students to deeply understand the connotation of green building and effectively master the green building evaluation technology and innovative design methods from the current curriculum system [4], as well as other constraints and difficulties.

Green building education, evolving from conventional architectural pedagogy, aligns with architectural student development programs, emphasizing practical, hands-on learning through project-based and engineering-centric approaches [5]. This approach necessitates the completion of time-sensitive tasks. However, a lack of a focused curriculum often leaves students reliant on extensive instructor guidance to master complex concepts. The course content, predominantly theoretical, frequently remains detached from practical real-world applications. This disconnect is compounded by the delayed integration of internships and practical social experiences, leading to a discrepancy between academic learning and the professional skills required. Educators, constrained by pedagogical limitations, struggle to impart practical insights. This restricts students' exposure to real-world scenarios and experiential learning, which are essential for the effective assimilation and application of knowledge in the green building sector [6].

In practice, various factors, such as economic and geographic constraints, limit students' opportunities for field trips or participation in green building projects. This limitation adversely affects their motivation and learning outcomes. Consequently, the challenge of effectively engaging students in green building studies, ensuring they acquire both theoretical knowledge and practical skills, has emerged as a critical issue in this field. In response to these problems, some scholars in the current academic world have started from the student's perspective and carried out in-depth explorations on learning methods of green building [7], educational model [8], curriculum design [9], practical application [10], etc., achieving relatively fruitful results. And the perspectives of teaching academic competence [11], teachers' norms [12], and teachers' morality [13] have been the usual entry points for academia to address issues related to student learning statuses, attitudes, learning effects, etc., making student learning attitudes and outcomes paramount within the academic sphere. However, a review of the existing literature reveals a notable gap in research concerning the nuanced relationship between the teaching responsibilities of green building lecturers and student learning engagement. A thorough examination of university students' engagement in green building-related knowledge and skills is vital. Such a study not only aids students in comprehensively understanding and applying principles of environmental, social, and economic sustainability in building design, construction, and operation but also enhances their learning effectiveness and overall development. This approach offers a holistic view of the green building learning process, elucidating the link between teaching methods and student outcomes. It highlights student engagement, attitudes, academic performance, and achievements, allowing for comparisons across various levels of engagement. Furthermore, considering that most college students live away from their parents and have limited social interactions, the influence of teachers and peers becomes a critical factor in their learning engagement. In our study, we observed that green building education courses in Chinese universities are predominantly offered as electives or online modules. This format often leads to issues such as diminished attention, suboptimal learning outcomes, and indiscriminate course selection by students [14]. The casual nature of these courses tends to lessen both student engagement and teacher responsibility. In an environment where the value of the classroom experience is already underappreciated, commitment to learning from students and a sense of responsibility among teachers naturally wane. Consequently, it is crucial to examine the involvement of university students in green building education and the commitment of educators from the perspectives of educational professionals and their peers. This approach is vital for gaining a thorough understanding of the dynamics influencing the efficacy of green building education in China's higher education institutions.

As China increasingly prioritizes environmental protection at the macro level, and as awareness of energy conservation and carbon reduction permeates public consciousness, knowledge and technologies related to green building are continuously evolving. To stay abreast of these changes, college students must invest considerably in independent research. Additionally, they require innovative guidance from their teachers throughout their academic journey to effectively grasp and adapt to these evolving concepts [15]. Because the process of teaching green building-related knowledge is a "bilateral" process, which requires the active guidance of teachers and the cooperation of students, the responsible attitude of green building lecturers becomes a crucial factor affecting students' learning outcomes [16]. Teachers possessing a strong sense of responsibility extend beyond imparting course-specific knowledge; they focus on nurturing college students' critical thinking, independent exploration, team communication, cooperation, and practical application skills. Such educators act as guides, helpers, and facilitators for students, and as architects of the educational environment. They prioritize students' practical application abilities, shifting from a teaching-centric to a learning-centric approach. These teachers are pivotal in bridging the gap between student learning and university teaching, forming a unique connection that enhances both aspects [17]. This is a unique link between student learning and university teaching, one where students can be deeply inspired by their interest in learning, fully engage them in green building learning, and ultimately enable them to effectively master core green building skills.

Social cognitive theory, an evolution of learning theory, emerged as a distinct research area in the 1970s and 1980s and swiftly became a significant field within psychology in the 1990s. Albert Bandura, leveraging his extensive psychological expertise, approached human functioning as a focal point. He integrated this with pre-existing social learning theories to propose a model where human functioning is influenced by a dynamic interplay among individual factors, environmental elements, and behavior [18]. According to social cognitive theory [19], the learning process, particularly in the context of green building knowledge, is influenced by multiple factors. First, the learning outcomes of students are shaped by teachers' personal preferences, attitudes, wills, emotions, and other individual cognitive and qualitative elements. Second, in the interaction between students' individual green building behaviors and learning environments, the ambiance of the learning environment significantly affects students' learning behaviors. Third, while the learning outcomes are impacted by environmental factors, individual students possess the agency to shape a conducive learning environment tailored to their needs. This adaptive capacity hinges on the student's cognitive understanding and proactive engagement in the learning process. This framework underscores the importance of considering both internal and external factors in educational settings, particularly in specialized areas like green building education.

This research transcends the traditional "teacher–student" dichotomy in higher education research perspectives. Drawing from social cognitive theory, it analyzes how the characteristic of felt responsibility among university instructors can enhance student engagement in green building learning. This study delves into this role process in-depth, elucidating the pathways through which student-level helping behaviors and teacher-level green building learning climate influence the relationship between instructors' felt responsibility and students' engagement in green building learning. These mechanisms are integrated into a comprehensive cross-level research framework. Through in-depth investigation and addressing related questions, this research aims to improve the effectiveness of green building courses for college students and offer valuable insights for the development of green building teaching theories.

2. Literature Review and Research Hypotheses

2.1. Green Building Teachers' Felt Responsibility and Students' Green Building Learning Engagement

Learning engagement is defined as the positive learning behaviors exhibited by students in specific educational contexts. It encompasses their effort to maintain these behaviors persistently and their dedication to learning. This engagement involves overcoming challenges and reaping the rewards of their endeavors, leading to positive internal emotional states [20]. Reflecting on the research concerning learning engagement, early scholars have predominantly based their studies on the "time on task theory". This theory posits a significant positive correlation between the amount of time students dedicate to learning and their academic achievements; essentially, the more time spent learning, the greater the learning outcomes. In the 1960s, scholars introduced the "Quality of Effort Theory", suggesting that students' learning engagement depends not only on the time invested in learning but also on the intensity of effort they exert [21]. In the 1990s, scholars conducted more in-depth research on learning engagement, such as Astin's study [22], which was based on the "engagement theory" and explored the psychological and behavioral aspects of learning time engagement and effort. Marks [23] and other scholars believe that learning engagement includes the operational experiences of students, highlighting that learning engagement involves the emotional and psychological engagement of students. Simply put, emotional engagement refers to the expression of emotions, while psychological engagement refers to mental activities and mental feelings [24,25]. In recent years, Cornell et al. [26] noted that the degree of each learner's engagement in learning activities is related to their own objective situations, needs, engagements, and gains, while the degree of student engagement is closely related to school conditions and teachers' personal teaching styles. Researchers contend that the key elements influencing students' learning engagement encompass not only personal factors but also external environmental aspects, such as the learning environment and teaching methods employed by instructors. They assert that these external environmental factors are equally pivotal in shaping students' learning engagement. Schaufeli et al. [27] focused on student learning engagement based on work engagement research. They believe that this state is also reflected in the learning process of students, as a psychological state in which an individual engages in learning or works with a positive and enthusiastic mindset, is attracted to the work or learning task, and is willing to actively work hard [28]. Therefore, some scholars believe that learning engagement involves a continuous and stable combination of positive cognition, behavior, and heightened emotions and feelings in the learning process [29,30]. Schaufeli et al. [31] also explored the connotation of learning engagement in depth, and classified it into the three dimensions: dedication, concentration, and vitality. Dedication refers to student satisfaction and pleasure in learning, as well as pride and meaning in learning. In the context of learning engagement, "Dedication" pertains to the learners' enjoyment, satisfaction, and sense of achievement in their educational pursuits. "Concentration" reflects the depth of their focus and immersion in learning activities. "Vitality" relates to the student's time and energy commitment, coupled with their resilience and motivation to navigate academic challenges. Qiao Xiaolong, a notable Chinese scholar, offers a nuanced perspective by bifurcating learning engagement into emotional and behavioral dimensions. According to Qiao, this encompasses the intensity of students' behavioral involvement in learning scenarios and the quality of their emotional experiences during these engagements, highlighting a dual focus on action and affect in the learning process [32].

In summary, according to international scholars, engagement in green building learning is a multifaceted construct involving both behavioral and emotional inputs. This concept encompasses the cognitive, behavioral, and affective contributions of students in the learning process, which are interdependent, mutually influential, and equally crucial. A comprehensive understanding of student engagement in green building learning requires an assessment across cognitive, behavioral, and affective dimensions. It is important to recognize that this form of engagement is the outcome of interactions between the learner and the learning environment, contributing to academic achievement. The ’subject’ aspect involves the time and energy students actively dedicate to educational activities. The ’object’ aspect encompasses the organizational and managerial roles of teachers, including teaching leadership, the creation of a conducive learning climate, and the facilitation of student participation in various learning practices. Therefore, college students’ engagement in green building learning can be defined as the investment of time, energy, resources, and emotional and cognitive efforts in learning and practicing within the realm of green building, reflecting a deep level of individual engagement.

In every profession, practitioners must adhere to established professional standards, abide by specific ethical codes, and accept responsibilities pertinent to their roles. Within the educational sphere, a concept termed “teacher felt responsibility” emerges, originating from a profound comprehension of the educator’s role. This sense of duty is inherent in teachers who deeply understand their students’ expectations and the interplay between education and society. Consequently, professionals experience varying degrees of responsibility throughout their careers, with this phenomenon being particularly pronounced and distinctive in education. Scholars have varied in their definitions of teacher’s felt responsibility. For example, Yuan [33] suggests that a teacher’s felt responsibility refers to the duties and responsibilities that an educator should undertake in the process of education, including guiding, evaluating, and caring for students. The teacher’s felt responsibility reflects the educator’s sense of responsibility to students and society in the educational practice. Dao [34] believes that teachers’ felt responsibility refers to the teachers’ in-depth understanding and subjective awareness of their educational duties based on their firm beliefs and concepts about education. In terms of measuring teachers’ felt responsibility, Lauermann [35] points out that there are three ways to measure teachers’ felt responsibility, namely, teachers’ sense of professional responsibility as a stable personality trait, teachers’ sense of professional responsibility as the appearance of contextualized action representations, and teachers’ sense of professional responsibility as a component of the subject’s social role. In the specialized domain of green building education, the notion of teachers’ felt responsibility acquires distinct meaning. Building on the previous discussion, this responsibility in green building education encompasses a range of aspects. It includes the obligation of educators to instill environmental consciousness in students, balance the theoretical and practical facets of green building, and foster a learning environment conducive to this field. Such responsibility requires college educators to acknowledge their professional duty as an essential societal role, which involves not just teaching technical knowledge and skills in building technology but also emphasizing innovative educational strategies and methodological applications. The ultimate goal is to nurture students’ capacities for independent and critical thinking. Social cognitive theory elucidates the process of generating meaning and behavior in the relationship between the individual and the environment and emphasizes that behavior and environment are interdependent and mutually determined [36]. Within this framework, the felt responsibility of green building teachers, recognized as an environmental factor, is interdependent with and mutually influences student learning behaviors. This positive environmental influence will likely invigorate student engagement in learning activities. Crucially, the felt responsibility of green building teachers can provide constructive learning guidance, ignite students’ intrinsic motivation, and enhance their willingness to participate actively in learning. Furthermore, social cognitive theory posits that students’ academic achievements are shaped by the interaction between the individual and the environment. Consequently, under the tutelage of teachers with a strong sense of felt responsibility, students are more inclined to see themselves as active learners rather than passive recipients of information, thereby fostering increased engagement in acquiring green building knowledge and skills. Based on this, this paper proposes the following hypotheses:

Hypothesis 1 (H1). *Felt responsibility of college faculty has a positive effect on college students’ engagement in green building learning.*

2.2. Mediating Role of Helping Behavior

Helping behavior has its origins in altruism and refers to the behavior of an individual who provides help to others without compensation in a given situation [37]. This behavior may be selfless or based on some expectation of reward. While previous scholars have focused on helping behavior at the giver level, this study focuses more on the effects of helping behavior on the recipient. In general, helping behavior can be divided into explanatory helping behavior and informational helping behavior [38]. Bargh et al. found that these two types of helping behaviors will have different effects on recipients [39].

In educational settings, perceptions of a teacher's felt responsibility are closely linked to factors such as commitment, positive attitudes toward teaching, teachers' confidence in their impact, students' academic achievements, interactive behaviors, and overall learning status. This sense of responsibility represents a stable psychological tendency, highlighting teachers' capacity to harmonize external professional expectations with their internal motivations and needs.

From the basic starting point of social cognitive theory, human activities are determined by the interaction of three factors: individual behavior, individual cognition/other individual characteristics, and the external environment in which the individual is located; people's beliefs and motives tend to dominate and guide their behaviors in a powerful way. Therefore, based on social cognitive theory, we believe that college teachers' felt responsibility influences their teaching behaviors in the teaching process, and that this sense of responsibility motivates college teachers to create good learning environments for students, better respond to students' needs, and guide the development of cooperative and mutual support behaviors among students. Specifically, driven by felt responsibility, college teachers' facilitation of students' helping behaviors can be categorized into the following areas: First, support for students' helping behaviors [40]. Teachers' felt responsibility often motivates them to focus on students' comprehensive development, encompassing academic performance, mental health, and social needs. The perception of their responsibility to provide support and guidance to students ensuring each one progresses, motivates teachers to guide students in providing academic support and encouragement to one another. Second, providing feedback and guidance on helping behaviors among students [41]: Teachers in higher education see themselves as responsible for ensuring that students are clear about their learning goals, and fostering mutual support among students to help them overcome difficulties. This felt responsibility perception contributes to a positive teacher–student relationship and helps to increase the motivation of students to cooperate with and help each other. Third, creating a supportive learning environment: Teachers believe that they have a responsibility to provide conditions that are conducive to students' mutual supportive learning, including a positive classroom climate and opportunities to encourage students to actively participate in collaborative discussions. Such supportive aids can encourage students to be more proactive in seeking help and participating in learning [42].

Green building is a discipline that encompasses the principles of environmentally friendly, sustainable, and high-performing building design and construction, and aims to develop students' knowledge and skills in adopting environmentally friendly and sustainable practices in the construction field. Students enrolled in green building courses often face numerous challenges. While some of these can be overcome through individual efforts, others require external assistance. In this context, teachers are a pivotal source of support within the university's support network, significantly impacting students' learning experiences and outcomes. Strati [43] found that students' perceived teacher support is closely related to their level of learning engagement; meanwhile, Sawka [44] believes that teachers' positive attitudes, academic expectations, and motivational behaviors toward students can effectively increase students' learning engagement, especially teachers' emotional support, which is more effective than other aspects of support, and is also more effective than other aspects of support. The positive predictive effect of emotional support is stronger than that of other types of support. Social cognitive theory suggests that students' social behaviors can be formed or changed by observing and learning from model behaviors, and that student behaviors depend on the teachers' model behaviors and the learning climate [45]. Therefore, we hypothesize that the helping behaviors of college teachers can, to some extent, help students construct green building knowledge, develop related skills, and promote students' overall development in academic and social domains by providing cognitive support, affective support (respect, understanding, and encouragement, etc., from green building teachers), and social support (unpaid tutoring or helping behaviors, etc., from green building teachers) [46,47], which will ensure that students are fully engaged in their green building studies. Based on this, this paper proposes the following hypotheses:

Hypothesis 2 (H2). *Helping behavior mediates the relationship between college faculty's felt responsibility and college students' engagement in green building learning.*

In practice, universities place significant emphasis on fostering a campus atmosphere that resonates with the concept of harmony between humans and nature. This is evident in the design of many university libraries, where the architecture not only serves an academic purpose but also aligns with environmental aesthetics. Prominent examples include the Library of the University of Oxford in the United Kingdom, Heidelberg University Library in Germany, and Stanford University Library in the United States. These institutions have seamlessly integrated their library buildings into the natural environment, a design choice that subtly cultivates and reinforces student awareness and appreciation for green initiatives. This architectural approach reflects a broader educational philosophy, one that extends beyond traditional learning spaces and seeks to imbue students with a deeper, more intrinsic understanding of sustainable and environmentally conscious living.

2.3. Mediating Role of Green Building Learning Climate

The learning climate (within the educational realm) is a multifaceted concept. It is perceived as an intricate, dynamic system encompassing cognitive, affective, social, and physical components. These elements interact to form the totality of a learner's experience within a specific educational setting [48]. The first researcher to link the concept of climate to schools was Halpin, while Way et al. were the first to take the novel step of measuring climate as an environmental variable from an educational and pedagogical perspective [49].

Green building, as an emerging discipline, emphasizes innovation, multidisciplinary cooperation, and practical participation as its main themes. The course content focuses on the sustainability and eco-friendliness of building design, construction, and operation [50]. However, taking the interdisciplinarity of green building-related knowledge points as an example, the knowledge systems and ways of thinking of the various disciplines within the green building curriculum are different, which will likely lead to learning and communication difficulties for students. Therefore, for students studying green building-related courses, the classroom learning climate will have an important impact on students' learning effectiveness. The green building learning climate is mainly composed of two aspects: (1) The control of the classroom learning climate for students with teachers as the main body [51]. A positive learning climate in green building education, characterized by rigorous pedagogical approaches, effective classroom instruction, and responsible teaching ethos, enhances student engagement. The attention green building educators give to student needs, their teaching methodologies and strategies, and the fostering of open and effective communication and a safe learning environment act as external stimuli. These factors ignite and amplify students' intrinsic motivation to learn. (2) Students themselves as the main body of the learning climate control [52], through the green building learning attitudes and behaviors fostered by different learning climates. Specifically, students generally perceive that there is an atmosphere within the group that encourages individuals to continuously learn new knowledge about green building and encourages the continuous improvement of self-worth through knowledge-sharing.

In the learning context of green building courses, learning is the primary task of students, and the learning climate is considered an important influence on students' knowledge of green building [53]. Social cognitive theory suggests that individual behavior and cognition are always influenced by the surrounding environment. The young college students in this study, who have not yet entered society, are mainly influenced by their families and schools. Regarding the direct contact with college students, the teaching staff is one of the significant factors in the school dimension. Teachers' sense of responsibility for teaching reflects their professional cognition, emotions, and beliefs, and is a prerequisite for realizing their professional purposes, so teachers' sense of responsibility makes them more student-centered, more focused on the positive cultivation of students, and more attentive to the creation of the teaching environment. Therefore, teacher factors, such as teacher engagement, teacher expectations, and teacher attitudes, become important components of the green building learning climate. It can be seen that teachers' own moral attributes will have a significant impact on the learning climate [54,55]. At the same time, the shaping of a moral sense or sense of responsibility is closely related to the perception of the environment, the smoothness of communication within the classroom, and the ideal perception of the teacher–student relationship, which will subconsciously affect the sense of responsibility in the classroom, and as the teacher–student relationship strengthens, the teacher's sense of responsibility will gradually increase [56]. Therefore, in an actual green building course, the stronger the teacher's felt responsibility perception, the more likely it will directly affect the students' learning climate.

Social cognitive theory states that students' behaviors will change due to various environmental factors around them, and that controlling and changing environmental factors can effectively improve the effectiveness of students' learning behaviors and stimulate cooperative and supportive behaviors [57]. The link between team or group climate and cooperative behavior has garnered attention in the academic world. For example, Ho [58] said that when there is a high psychological climate of cooperation in an organization, the members of the organization will have a high degree of harmonious passion, which leads to further interpersonal helping behavior. In addition, Byoung et al. [59] showed that when there is a high degree of fairness in the team climate, the members of the team believe that their own helping behaviors will be praised and rewarded by the recipients; this is a very important factor in the development of cooperative behavior in an organization. When the team has a high level of fairness, internal members believe that their helping behavior will be praised and rewarded by the recipients, and they tend to help other members of the team in this case. Learning climate is one of the most important factors determining students' learning status. In the green building classroom, the influence of the overall learning climate of the classroom is indispensable to establishing trust, respect, and cooperation between teachers and students and between students and students, and in cultivating students' helping behaviors. When students perceive a good learning climate in a green building course, they will show positive emotions and pay more attention to the needs of their classmates around them, which in turn affects the helping behavior in a green building course [60].

To summarize, the teachers' own sense of responsibility is an important factor affecting the green building learning climate, and a positive green building learning climate motivates students to offer help within the course. Social cognitive theory points out that three factors (individual, behavior, and the environment) can interact with and influence each other. Specifically, teachers in green building courses who feel responsibility may attach more importance to the development and growth of students and actively solve teaching problems, e.g., by providing opportunities for students to participate in green building-specific project practices and foster active student learning. And in this case, students are drawn by the high moral standards of the teacher to create a good green building learning climate. Under the influence of the positive learning climate, some students will be driven to help their neighboring classmates and then generate helping behavior. Therefore, we believe that teachers translate their moral perceptions into their impact on the green building student climate, and the positive learning climate fosters helping behaviors among students in the green building course. Based on this, the following hypotheses are proposed in this paper:

Hypothesis 3 (H3). *The green building learning climate mediates the relationship between teachers' felt responsibility perceptions and helping behaviors in higher education.*

Based on this, this paper proposes a cross-layer chain mediation model, as shown in Figure 1, where college teachers' felt responsibility knowledge will positively influence college students' engagement in green building learning through a green building learning climate and inter-student helping behavior. When the level of college teachers' felt responsibility knowledge is higher, the positive influence on the green building learning climate will increase, and the helping behavior among students will be more effective in transmitting the positive influence of college teachers' felt responsibility knowledge on engagement in green building learning. In summary, this paper proposes the following hypotheses:

Hypothesis 4 (H4). *College faculty's felt responsibility indirectly (and in an orderly manner) influences college students' engagement in green building learning through the green building learning climate and helping behaviors.*

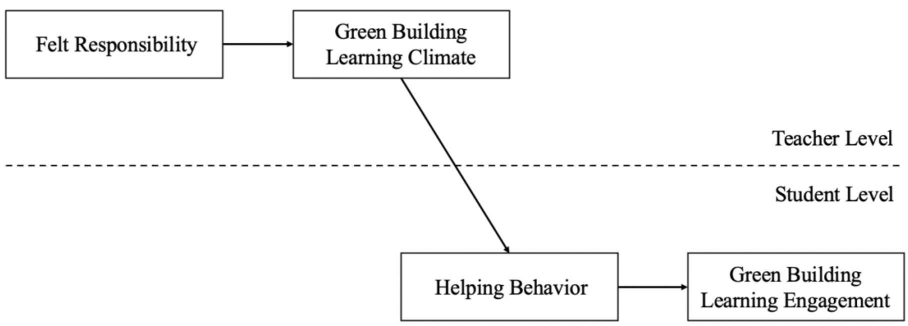


Figure 1. Theoretical research model.

3. Study Design

3.1. Data Collection

This study consisted of green building course instructors and their students at several universities in central and eastern China, with no fewer than 10 students per class (832 students in total) selected as the study population. A paired method was used to collect data at the instructor and student levels. The universities selected for this study are all public comprehensive universities in China, and the green building-related courses are taught by traditional lecturers, who use slides to assist in explaining green building-related knowledge during lectures. The content of the lectures varies slightly from university to university, but the main content of the lectures involves green building design, supplemented by lectures on land conservation and greenery protection, building energy consumption, the economic analysis of building energy savings across the entire lifecycle, as well as the application of Revit 2013–2024 and other quantitative software. With the support and cooperation of partner universities, the purpose, process, and use of the study were explained to the classroom teachers, and two versions of self-assessment questionnaires, the teacher version (felt responsibility) and the student version (participation in green building learning, the green building learning climate, and helping behaviors), were distributed; 687 questionnaires were recovered from the classrooms of the classes led by the 62 classroom teachers. To ensure the accuracy, completeness, and authenticity of the raw data, the raw data of the questionnaires were individually reviewed, resulting in

543 valid questionnaires from 51 classroom teachers, with a validity rate of the recovered questionnaires at 68.15%.

3.2. Measurement Tools

In this paper, a 5-point Likert scale was used to measure the extent to which the measurement questionnaire matched the management reality, and all the variable items involved in the study were translated and back-translated according to the translation and back-translation procedures proposed by Brislin [61] in order to ensure the accuracy of the meaning of the Chinese measurement items.

(1) Perception of responsibility among university teachers: This study utilized a research scale developed by Zhou Xihua, composed of four dimensions: perception of professional responsibility, emotional engagement in professional responsibility, awareness of professional responsibility, and professional responsible behavior. For the purposes of this research, six specific items from two dimensions—perception of professional responsibility and professional responsible behavior (items 1, 2, 3, and 10, 11, 12)—were selected. These items were further adjusted and modified based on the scale developed by Morrison et al. [62], culminating in a 5-item scale for this paper. An example item is: 'Are you enthusiastic about uncovering students' eagerness to learn, specifically directing them to actively learn knowledge or skills related to green architecture?' The Cronbach's alpha value for this scale was 0.85.

(2) Engagement in green building learning. Fang Laitan et al. [63] introduced Schaufeli et al.'s [64] learning engagement scale (UWES-S) into China, and then translated the Chinese version of the learning engagement scale, which focuses on the three aspects of learning engagement, namely, vitality, dedication, and concentration. In this paper, we simplify the question items according to the characteristics of the research content, and form a 5-item scale, such as "You have a clear purpose to study green building related courses, and you are willing to take the initiative to explore the knowledge and skills related to green building". The Cronbach's alpha value is 0.956.

(3) Green building learning climate: This paper refers to the organizational climate and innovation climate scale (which has been widely researched and applied in the world and proven to apply to students [65])—TCI [66] based on the descriptions of some of the sub-dimensions in the scale, and it draws on the "Teenagers' Perceived Campus Climate Scale" compiled by Jia [67] and so on. The scale includes three dimensions: teacher support, peer support, and autonomy opportunities. This paper selected the teacher support part of the three dimensions that matched the content of this paper as the basis, and modified some of the terminology, such as adding the term "green building" to form a four-question questionnaire for the green building learning climate. "In the green building learning process, you are able to communicate your problems or deficiencies with the teacher under the teacher's guidance". The Cronbach α value is 0.884.

(4) Helping behavior: Drawing on Sparrowe et al.'s [68] research on helping behavior, this paper deletes and adjusts some of the questions or expressions, forming a four-question questionnaire for helping behavior. For example, "You are willing to share your green building expertise with others or learn green building related skills together". The Cronbach's alpha value is 0.923.

4. Analysis of Empirical Results

4.1. Data Aggregation Test

Organizational-level data of college teachers' felt responsibility and engagement in green building learning are aggregated from individual-level data, and the feasibility of data aggregation needs to be tested. Currently, ICC(1), ICC(2), and r_{wg} are usually used as indicators of the data aggregation test, and the range of values of the cut-off criteria should be greater than 0.05, 0.70, and 0.70. In this paper, the value of ICC(1) for college teachers' felt responsibility is 0.258, the value of ICC(2) is 0.787, the mean value of r_{wg} is 0.705, and the values of the intra-group variance and the inter-group variance are 0.370

($p < 0.01$), 1.738 ($p < 0.01$); the ICC(1) value for green building learning climate was 0.316, ICC(2) was 0.831, r_{wg} mean value was 0.711, and the within-group variance and between-group variance values were 0.368 ($p < 0.01$), 2.177 ($p < 0.01$). The above results indicate that the felt responsibility knowledge and green building learning climate have 25.8% and 31.60% of variance between groups, respectively, and the consistency of the group means is reliable, which meets the requirements for data aggregation.

4.2. Validation Factor Analysis

In order to obtain reliable estimates for multilevel data, a validated factor analysis model for the four variables of felt responsibility, engagement in green building learning, green building learning climate, and helping behavior, was constructed using multilevel validated factor analysis (MCFA) [69]. The results, as shown in Table 1, show that the model fit indexes of the four-factor model were met ($\chi^2/df = 1.98$; RMSEA = 0. 043; CFI = 0.983; TLI = 0.98; SRMR = 0.025), and the model fit of the four-factor model was good ($\chi^2/df < 3$, CFI and TLI were both greater than 0.9, RMSEA < 0.1, and SRMR < 0.08). Meanwhile, the four-factor model outperformed the model fit indicators of the other models, indicating good discriminant validity of the variables.

Table 1. Model comparison table.

Mold	(Math.) Factor	Chi-Square	DF	Chi-Square/DF	CFI	TLI	RMSEA	SRMR
quadruple factor	FR, GBLC, HB, GBSE	255.801	129	1.98	0.983	0.98	0.043	0.025
triple factor	FR + GBLC, HB, GBSE	1024.29	132	7.76	0.881	0.862	0.112	0.083
bi-factor	FR + GBLC + HB, GBSE	1919.739	134	14.32	0.754	0.72	0.159	0.121
one factor	FR + GBLC + HB + GBSE	3001.633	135	22.23	0.619	0.568	0.198	0.145

4.3. Descriptive Statistical Analysis

The correlation coefficients are 0.400, 0.318, and 0.350, and the correlation coefficients are greater than 0, which means that there is a positive correlation between teachers' felt responsibility and green building learning climate, helping behavior, and engagement in green building learning. The mean, standard deviation, and correlation coefficient of each latent variable are shown in Table 2.

Table 2. Mean, standard deviation, and Pearson correlation coefficient table.

	Average Value	(Statistics) Standard Deviation	Higher Education Teachers Felt Responsibility Knowledge	Green Building Learning Climate	Helping Behavior	Green Building Learning Engagement
High School Teachers' Felt Responsibility Knowledge (Within-Level)	3.476	0.705	1			
Green building learning climate (Within-level)	3.158	0.732	0.400 **	1		
High School Teachers' Felt Responsibility Knowledge (Between-Level)	3.476	0.4	-	-		
Green Building Learning Climate (Between-level)	3.158	0.448	-	-		
helping behavior	3.572	1.07	0.318 **	0.478 **	1	
Green building learning engagement	3.344	1.123	0.350 **	0.485 **	0.630 **	1

Note(s): * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.4. Hypothesis Testing

In this paper, the hypothesized model is tested by robust maximum likelihood (MLR) using Mplus 8.3 software. Among the advantages of MSEM is that it can analyze more levels of mediation models that cannot be specifically analyzed using the simpler HLM approach [70]. In this paper, a multilevel structural equation modeling approach is used to synthesize inter-conceptual relationships at each level, aiming to test the relationship between college faculty members' felt responsibility and the impact on students' engagement in green building learning. This examination considers the mediating effects of the green building learning climate and helping behaviors, with a focus on the nested nature of the data and the exploration of multiple pathways.

This paper is specifically divided into three models to carry out the analysis (See Table 3), firstly, to test the main effect of the predictor variable at the teacher level (college teachers felt the responsibility to know) on the outcome variable at the student level (engagement in green building learning), the *p*-value is less than 0.05 ($\gamma = 0.357, p < 0.05$), and the 95% confidence interval does not include 0, which indicates that the main effect is significant, and Hypothesis 1 is valid.

Next is the mediating effect of helping behavior. College teachers' felt responsibility has a significant positive effect on helping behavior ($\gamma = 0.312, p < 0.05$), and helping behavior has a significant positive effect on engagement in green building learning ($\gamma_{between-level} = 0.932, p < 0.01, \gamma_{within-level} = 0.606, p < 0.01$). The direct effect of college teachers' felt responsibility on engagement in green building learning ($\gamma = 0.056, p > 0.05$) is not significant, so the mediating effect with helping behavior as the mediator is fully mediated, and Hypothesis 2 is valid.

Similarly, the teacher-level variable, green building learning climate, was introduced as a mediator between college teachers' felt responsibility perception and helping behavior. College teachers' felt responsibility is not significant on helping behavior; college teachers' felt responsibility has a significant positive effect on the green building learning climate ($\gamma = 0.389, p < 0.01$), and green building learning climate has a significant positive effect on helping behavior ($\gamma = 0.466, p < 0.01$). So, the green building learning climate is a full mediator between college teachers' felt responsibility and helping behavior, and Hypothesis 3 is established.

Table 3. Model Validation.

		Estimate	S.E.	Est./S.E.	*p*-Value	Lower 2.5%	Upper 2.5%
main effect	High school faculty felt responsibility to know → engagement in green building learning	0.357	0.126	2.831	0.005	0.11	0.604
Mediating effects of helping behavior	High school faculty felt responsibility to know → engagement in green building learning	0.056	0.151	0.369	0.712	–0.241	0.352
	High school teachers felt responsibility → helping behavior	0.312	0.118	2.653	0.008	0.082	0.543
	Helping behavior → green building learning engagement (Between-level)	0.932	0.261	3.565	0	0.42	1.445
	Helping behavior → green building learning engagement (Within-level)	0.606	0.036	16.788	0	0.536	0.677
	intermediary effect	0.293	0.041	7.083	0	0.212	0.374
Mediating effects of the green building learning climate	High school teachers felt responsibility → helping behavior	0.162	0.124	1.314	0.189	–0.08	0.405
	High school faculty felt responsibility → green building learning climate	0.389	0.105	3.713	0	0.183	0.594
	Green building learning climate → helping behavior	0.466	0.081	5.72	0	0.305	0.624
	intermediary effect	0.181	0.054	3.337	0.001	0.074	0.287

Finally, to test the chain-mediated relationship proposed in Hypothesis 4—that college teachers' felt responsibility positively and indirectly influences students' engagement in green building learning in an orderly manner through the green building learning climate and helping behavior—the product of the cross-level three-part path coefficients (college teachers' felt responsibility knowledge–green building learning climate, green building learning climate–helping behavior, helping behavior—engagement in green building learning) was calculated to test this chain-mediated effect. As shown in Table 4, the cross-level chain-mediated effect was 0.159 ($p < 0.05$), with 95% confidence intervals not including 0. This indicates that the chain mediation effect is significantly established, validating Hypothesis 4. Since only the chain mediation effect is significantly established in this model, and neither the rest of the mediation effects nor the direct effect is established, this indicates that the chain mediation effect proposed in Hypothesis 4 is a full chain mediation effect.

Table 4. Chain-mediation effect test table.

	Estimate	S.E.	Est./S.E.	*p*-Value	Lower 2.5%	Upper 2.5%
chain broker	0.159	0.065	2.438	0.015	0.031	0.286
Mediating effects of the green building learning climate	0.011	0.061	0.185	0.853	–0.109	0.131
mediating effect	0.136	0.121	1.128	0.259	–0.100	0.373
High school teachers felt responsibility → helping behavior	0.062	0.13	0.478	0.633	–0.193	0.318

Meanwhile, in order to more intuitively show the chain-mediated effects of green building learning climate and helping behavior between the perceived responsibility of college faculty and student engagement in green building learning, this paper presents a chain-mediated effect estimation diagram, as shown in Figure 2.

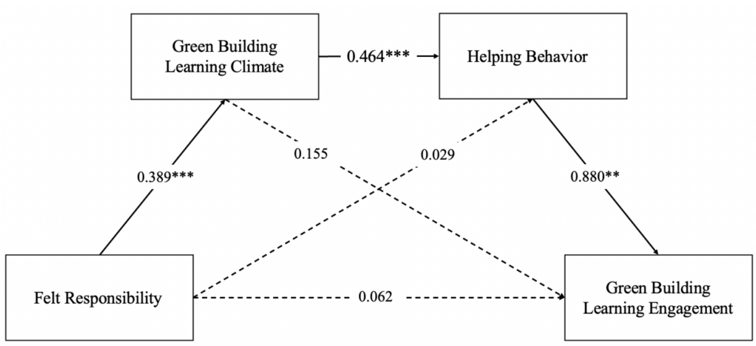


Figure 2. Estimated chain-mediation effect. ** $p < 0.05$, *** $p < 0.01$.

5. Conclusions and Discussion

This study introduces two cross-level mediating variables—green building learning climate and helping behavior—to integrate social cognitive theory into the analysis of how teachers of college-level green building courses' perceived responsibility influences student engagement with green building-related knowledge and skills. This approach offers a fresh perspective from educational management. We employed the multilevel structural equation modeling (MSEM) method to examine the cross-level mediation mechanism linking teachers' perceived responsibility and students' learning engagement. The empirical results show that college teachers' felt responsibility knowledge is positively correlated with engagement in green building learning; helping behavior plays a fully mediating role between green building learning climate and engagement in green building learning; green building learning climate plays a fully mediating role between college teachers' felt responsibility knowledge and helping behavior; and college teachers' felt responsibility knowledge indirectly and sequentially affects students' engagement in green building learning through green building learning climate and helping behavior. The findings of this paper have some theoretical and practical implications.

(1) Helping behavior is an important mediating variable that influences students' green building learning engagement.

The conclusions reached in this study are more similar to the findings of previous scholars and further refine the process of the role of helping behaviors [71,72]. This cultural backdrop fosters a learning environment where mutual assistance among students becomes a vital component in enhancing individual green building learning efforts. Positive student interactions and robust peer support significantly contribute to the effectiveness of green building education. Additionally, mutual help behaviors among students can mitigate the adverse effects of 'peer pressure'. These behaviors stem from two emotional pathways: 'benefiting oneself by helping others' and 'value highlighting'. They promote a sense of cooperative and mutually beneficial relationships, thereby augmenting students' engagement in learning about green building concepts, knowledge, and skills.

(2) Green building learning climate can indirectly influence students' engagement in green building learning through helping behaviors.

The conclusions reached in this study are more similar to the findings of previous scholars [51,73]; specifically, the zone of proximal development (ZPD) emphasizes that when students are in an active learning environment, they can collaborate with more experienced people (e.g., classmates) to solve knowledge problems, strengthen their own learning, and stimulate their own learning potential. For learning green building knowledge in university classrooms, this implies that students in a positive green building learning environment are more likely to assist each other in exploring their learning, fostering a collective learning culture in green building teaching [74], which makes students more willing to collaborate in their learning and gradually form beneficial interactions.

By making learning challenging yet attainable, a positive learning environment is established. This approach motivates students to engage more deeply in green building studies, thereby indirectly enhancing their learning engagement in this field.

(3) The direct effect of college faculty's perceived responsibility on students' engagement in green building learning is not significant.

Faculty-level teachers' perceived responsibility does not have a direct impact on students' engagement in green building learning. This is because it primarily reflects the work ethic and attitude of educators specializing in green building, and it remains uncertain whether this individual characteristic can translate into student engagement in green building courses. The influence of educators' perceived responsibility on students' learning engagement is indirect and gradual, mediated through the green building learning climate and helping behaviors, which collectively inspire students to actively participate in green building courses.

At the same time, social cognitive theory's application in teaching green building courses at the college level is multifaceted, encompassing aspects such as the teacher's role, the learning environment, and student participation. This theory shifts the focus from mere knowledge transfer by the teacher to a more dynamic role, involving guidance and fostering students' social participation and interaction. Thus, green building teachers' perceived responsibility can inspire them to approach their teaching tasks with seriousness and responsibility, serving as positive role models. This modeling effect resonates with students, contributing to a favorable green building learning climate. According to social cognitive theory, the learning climate and environment are pivotal in determining learning outcomes. In green building courses, teachers with a strong sense of responsibility enhance students' understanding and acceptance of green building concepts by creating supportive learning environments. This approach not only promotes students' interest in green building but also fosters a positive identification with the curriculum.

Furthermore, the social cognitive theory highlights that learning is inherently social. Within a positive green building learning climate, the teachers' sense of responsibility can encourage cooperative behaviors among students, leading to a mutually supportive and collaborative learning model. This collaborative approach enables students to co-construct knowledge, solve problems collectively, and grow through interactions, ultimately amplifying the overall learning effectiveness.

This paper responds to the call for a comprehensive, multi-level exploration of green building education in colleges and universities. Adopting an integrated, multidisciplinary approach, we introduce "felt responsibility" and "helping behaviors" as new variables into the realm of building education. Our goal is to blend traditional educational psychology theories with practical green building education, fostering innovation and expansion in the field. Our research synthesizes psychological, educational, and architectural theories to construct an interdisciplinary analytical model. This model not only offers a fresh theoretical perspective on the complexities of green building education but also lays down new theoretical foundations and research directions for the field and related areas. It provides insights for enhancing and reforming university education, emphasizing the importance of teachers recognizing and exercising their teaching responsibility. Effective teaching strategies in green building courses can significantly improve teaching effectiveness and student learning experiences. Teachers should increase their responsibility in teaching green building subjects, actively participate in students' learning processes, and tailor teaching content and methods to students' academic needs and interests. Moreover, green building educators should aim to foster students' critical thinking and innovation skills, perhaps through case studies, interactive teaching, and a cooperative learning environment. This is vital for developing skilled green building professionals who can meet the industry's future demands.

Lastly, peer assistance and the learning climate transcend specific course contexts, such as green building education, to influence the broader spectrum of teaching and learning. The centrality of teacher–student and peer interactions to the educational climate is undeniable. A positive learning climate, characterized by strong teacher–student connections and supportive teacher behaviors, significantly elevates student achievement and satisfaction. This leads to enhanced learning experiences and increased interest. Likewise, positive peer relationships contribute to a supportive learning climate, boosting engagement levels. In the context of higher education, the emphasis on thorough instruction, efficient classroom management, and dedicated teaching attitudes underscores the significance of a nurturing learning climate. This study highlights the learning climate and peer support as crucial determinants of engagement. It advocates for educational institutions and faculties to acknowledge the paramount importance of a teaching-led climate, augmented by interpersonal and management support, to foster comprehensive development. Initiatives should focus on promoting student autonomy, igniting interest in learning, and cultivating an active and positive classroom climate. The diversity of student capabilities, as illuminated by the theory of multiple intelligences, necessitates the expansion of teaching resources and development opportunities to accommodate varied learner needs. Moreover, fostering strong interpersonal relationships is essential for educational activities and mutual support, positioning teachers as pivotal in enhancing motivation and academic self-efficacy. This creates a purer and more relaxed learning climate conducive to peer assistance.

Despite its contributions, this paper has limitations. It does not account for the varying emphasis on green building education across different universities, and it relies on cross-sectional questionnaire data, limiting our ability to establish causal relationships. Future studies are encouraged to adopt a longitudinal approach, gathering data at various intervals to capture the dynamic evolution and interactions among the college faculty's sense of responsibility, the green building learning climate, helping behaviors, and student contributions to green building education. This method will facilitate a comprehensive understanding of the developmental trajectories and critical junctures within these interactions. Additionally, a longitudinal framework will provide insights into the stability and consistency of these relationships over time, contributing to the robustness of research findings in this domain. While we find that teachers' sense of responsibility positively influences student engagement in green building learning, future research should explore additional mediating or moderating factors like ambivalence, self-educational expectations, and psychological distress to fully understand this relationship. Also, expanding the research to include diverse geographic, racial, and national contexts would provide a broader perspective on green building education globally. Our study, positioned at the forefront of multidisciplinary research with a decentralized emphasis, invites future investigations within the realm of educational psychology to further validate our findings. This approach would enrich the understanding and applicability of our conclusions across diverse educational contexts and frameworks.

Author Contributions: S.C.: Data curation, Formal analysis, Software; Y.H.: Data curation, Methodology, Supervision; Y.Z.: Investigation, Supervision; Z.Y.: Investigation, Validation; X.S.: Writing—original draft; L.C.: Writing—original draft; H.Y.: Visualization, Supervision, Validation; X.W.: Visualization; F.G.: Visualization; J.C.: Visualization; Q.H.: Project administration, Validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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

References

1. Haidt, J. The emotional dog and its rational tail: A social intuitionist approach to moral judgment. *Psychol. Rev.* **2001**, *108*, 814. [CrossRef] [PubMed]
2. Kreber, C.; Cranton, P.A. Exploring the scholarship of teaching. *J. High. Educ.* **2000**, *71*, 476–495. [CrossRef]
3. Liu, Q.; Wang, H. A survey on the current situation of hidden truancy of college students in a local institution. *J. Henan Inst. Sci. Technol.* **2012**, 54–56.
4. Wang, B.; Li, N. Exploration on the Construction of New Engineering Specialties in Architecture with the Cultivation of Green Building Innovation and Practice Ability as the Core Development Direction. *J. High. Educ.* **2022**, *8*, 89–93.
5. Kingsland, A.J. Time expenditure, workload, and student satisfaction in problem-based learning. *New Dir. Teach. Learn.* **1996**, *1996*, 73–81. [CrossRef]
6. Wilhelm, W.B. Marketing education for sustainability. *J. Adv. Mark. Educ.* **2008**, *13*, 8–20.
7. Cole, L.B. Green building literacy: A framework for advancing green building education. *Int. J. STEM Educ.* **2019**, *6*, 18. [CrossRef]
8. Cole, L.B.; Altenburger, E. Framing the Teaching Green Building: Environmental education through multiple channels in the school environment. *Environ. Educ. Res.* **2019**, *25*, 1654–1673. [CrossRef]
9. Alkathiri, M.S. *Preparing Doctoral Students for the Professoriate: An Ethnographic Study of Students' Experiences in a Formal Preparatory Course*; The University of North Dakota: Grand Forks, ND, USA, 2016.
10. Zou, P.X.; Couani, P. Managing risks in green building supply chain. *Archit. Eng. Des. Manag.* **2012**, *8*, 143–158. [CrossRef]
11. Martin, E.; Benjamin, J.; Prosser, M.; Trigwell, K. Scholarship of teaching: A study of the approaches of academic staff. In *Improving Student Learning: Improving Student Learning Outcomes*; Oxford Centre for Staff Learning and Development: Oxford, UK, 1999; pp. 326–331.
12. Warnick, B.R.; Bitters, T.A.; Falk, T.M.; Kim, S.H. Social media use and teacher ethics. *Educ. Policy* **2016**, *30*, 771–795. [CrossRef]
13. Cardilini, A.P.; Risely, A.; Richardson, M.F. Supervising the PhD: Identifying common mismatches in expectations between candidate and supervisor to improve research training outcomes. *High. Educ. Res. Dev.* **2022**, *41*, 613–627. [CrossRef]
14. Jie, G. An Analysis of Current Status and Strategy Optimization for Elective Courses—Taking a University in Jiangsu as an Example. *J. Chang. Univ.* **2012**.
15. Feden, P.D. About Instruction: Powerful New Strategies Worth Knowing. *Educ. Horiz.* **1994**, *73*, 18–24.
16. Weston, C.B.; McAlpine, L. Making explicit the development toward the scholarship of teaching. *New Dir. Teach. Learn.* **2001**, *2001*, 89–97. [CrossRef]
17. Nicholls, G. Scholarship in teaching as a core professional value: What does this mean to the academic? *Teach. High. Educ.* **2004**, *9*, 29–42. [CrossRef]
18. Bandura, A. *Social Foundations of Thought and Action*; Prentice Hall: Englewood Cliffs, NJ, USA, 1986; Volume 1986.
19. Bandura, A.; Freeman, W.H.; Lightsey, R. Self-efficacy: The exercise of control. *J. Cogn. Psychother.* **1999**, *13*, 158. [CrossRef]
20. Skinner, E.A.; Belmont, M.J. Motivation in the classroom: Reciprocal effects of teacher behavior and student engagement across the school year. *J. Educ. Psychol.* **1993**, *85*, 571. [CrossRef]
21. Newmann, F.M.; Wehlage, G.G. Five standards of authentic instruction. *Educ. Leadersh.* **1993**, *50*, 8–12.
22. Astin, A.W. Student involvement: A developmental theory for higher education. In *College Student Development and Academic Life*; Routledge: London, UK, 2014; pp. 251–262.
23. Marks, H.M. Student engagement in instructional activity: Patterns in the elementary, middle, and high school years. *Am. Educ. Res. J.* **2000**, *37*, 153–184. [CrossRef]

24. Park, S.; Holloway, S.D.; Arendtsz, A.; Bempechat, J.; Li, J. What makes students engaged in learning? A time-use study of within-and between-individual predictors of emotional engagement in low-performing high schools. *J. Youth Adolesc.* **2012**, *41*, 390–401. [CrossRef]
25. Vayre, E.; Vonthron, A.M. Psychological engagement of students in distance and online learning: Effects of self-efficacy and psychosocial processes. *J. Educ. Comput. Res.* **2017**, *55*, 197–218. [CrossRef]
26. Cornell, D.; Shukla, K.; Konold, T.R. Authoritative school climate and student academic engagement, grades, and aspirations in middle and high schools. *Aera Open* **2016**, *2*, 2332858416633184. [CrossRef]
27. Schaufeli, W.B.; Bakker, A.B.; Salanova, M. The measurement of work engagement with a short questionnaire: A cross-national study. *Educ. Psychol. Meas.* **2006**, *66*, 701–716. [CrossRef]
28. Schaufeli, W.B.; Martinez, I.M.; Pinto, A.M.; Salanova, M.; Bakker, A.B. Burnout and engagement in university students: A cross-national study. *J. Cross-Cult. Psychol.* **2002**, *33*, 464–481. [CrossRef]
29. Fredricks, J.A.; Blumenfeld, P.C.; Paris, A.H. School engagement: Potential of the concept, state of the evidence. *Rev. Educ. Res.* **2004**, *74*, 59–109. [CrossRef]
30. Liu, K.; Yao, J.; Tao, D.; Yang, T. Influence of individual-technology-task-environment fit on university student online learning performance: The mediating role of behavioral, emotional, and cognitive engagement. *Educ. Inf. Technol.* **2023**, *28*, 15949–15968. [CrossRef] [PubMed]
31. Schaufeli, W.; Salanova, M. Work engagement: On how to better catch a slippery concept. *Eur. J. Work Organ. Psychol.* **2011**, *20*, 39–46. [CrossRef]
32. Qiao, X. Middle School Students' Mathematics Learning Self-Determination and Its Relationship with Mathematics Learning Engagement. Master's Thesis, Henan University, Kaifeng, China, 2006.
33. Yuan, J. Study on the Definition of Educational Responsibility of Teachers in Colleges and Universities in China in the New Era. *Int. J. Educ. Humanit.* **2023**, *10*, 127–130. [CrossRef]
34. Dao, T.T.T. Renewing the training model for managers of public higher education institutions in vietnam, meeting the requirements of self-control, self-responsibility. *Adv. Soc. Sci. Res. J.* **2019**, *5*. [CrossRef]
35. Lauermann, F.V. Teacher Responsibility: Its Meaning, Measure, and Educational Implications. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 2013.
36. Sun, Y.; Yang, H.; Wu, X.; Jiang, Y.; Qian, C. How Safety Climate Impacts Safety Voice—Investigating the Mediating Role of Psychological Safety from a Social Cognitive Perspective. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11867. [CrossRef]
37. Liu, Y.; Li, Y.; Tu, Y. Why are employees willing to help? The effect of more and stronger helping-ministerial exchange on helping behavior. *Psychol. J.* **2016**, *48*, 385–397.
38. Swing, S.R.; Peterson, P.L. The relationship of student ability and small-group interaction to student achievement. *Am. Educ. Res. J.* **1982**, *19*, 259–274. [CrossRef]
39. Bargh, J.A.; Schul, Y. On the cognitive benefits of teaching. *J. Educ. Psychol.* **1980**, *72*, 593. [CrossRef]
40. Tranquility. New development on the research of teachers' sense of responsibility. *Exam. Wkly.* **2009**, 209–210.
41. Lauermann, F.; Karabenick, S.A. Taking teacher responsibility into account (ability): Explicating its multiple components and theoretical status. *Educ. Psychol.* **2011**, *46*, 122–140. [CrossRef]
42. Ying, L. *The Meaning and Characterization of Teachers' Sense of Responsibility*; Shanghai Education Research: Shanghai, China, 1997, pp. 38–48.
43. Strati, A.D.; Schmidt, J.A.; Maier, K.S. Perceived challenge, teacher support, and teacher obstruction as predictors of student engagement. *J. Educ. Psychol.* **2017**, *109*, 131. [CrossRef]
44. Sawka, K.D.; McCurdy, B.L.; Mannella, M.C. Strengthening emotional support services: An empirically based model for training teachers of students with behavior disorders. *J. Emot. Behav. Disord.* **2002**, *10*, 223–232. [CrossRef]
45. Han, Z.; Wang, Q.; Yan, X. How responsible leadership predicts organizational citizenship behavior for the environment in China. *Leadersh. Organ. Dev. J.* **2019**, *40*, 305–318. [CrossRef]
46. Babad, E. Measuring and changing teachers' differential behavior as perceived by students and teachers. *J. Educ. Psychol.* **1990**, *82*, 683. [CrossRef]
47. Pekrun, R.; Goetz, T.; Titz, W.; Perry, R.P. Academic emotions in students' self-regulated learning and achievement: A program of qualitative and quantitative research. *Educ. Psychol.* **2002**, *37*, 91–105. [CrossRef]
48. Ramsden, P. Student learning and perceptions of the academic environment. *High. Educ.* **1979**, *8*, 411–427. [CrossRef]
49. Way, N.; Reddy, R.; Rhodes, J. Students' perceptions of school climate during the middle school years: Associations with trajectories of psychological and behavioral adjustment. *Am. J. Community Psychol.* **2007**, *40*, 194–213. [CrossRef] [PubMed]
50. Wang, J.; Liu, F.; Wang, Y. Exploration and Research on Teaching Reform of Architectural Technology Series Courses-Oriented by Green Building Education. *Archit. Cult.* **2022**, 45–47.
51. Hornstra, L.; Stroet, K.; Weijers, D. Profiles of teachers' need-support: How do autonomy support, structure, and involvement cohere and predict motivation and learning outcomes? *Teach. Teach. Educ.* **2021**, *99*, 103257. [CrossRef]
52. Rayens, W.; Ellis, A. Creating a student-centered learning environment online. *J. Stat. Educ.* **2018**, *26*, 92–102. [CrossRef]
53. Ofoghi, N.; Sadeghi, A.; Babaei, M. Impact of class atmosphere on the quality of learning (QoL). *Psychology* **2016**, *7*, 1645–1657. [CrossRef]

54. Roeser, R.W.; Eccles, J.S. Adolescents' perceptions of middle school: Relation to longitudinal changes in academic and psychological adjustment. *J. Res. Adolesc.* **1998**, *8*, 123–158. [CrossRef]
55. Anderson, C.S. The search for school climate: A review of the research. *Rev. Educ. Res.* **1982**, *52*, 368–420. [CrossRef]
56. Weiner, B. *Judgments of Responsibility: A Foundation for a Theory of Social Conduct*; Guilford Press: New York, NY, USA, 1995.
57. Miri, M.R.; Baghernezhad Hesary, F.; Morowatisharifabad, M.A.; Sharifzade, G.R.; Dastjerdi, R. Female Adolescents and Life Skills based on the Social Cognitive Theory: A Qualitative Study. *Int. J. Pediatr.* **2019**, *7*, 9841–9851.
58. Ho, V.T.; Kong, D.T.; Lee, C.H.; Dubreuil, P.; Forest, J. Promoting harmonious work passion among unmotivated employees: A two-nation investigation of the compensatory function of cooperative psychological climate. *J. Vocat. Behav.* **2018**, *106*, 112–125. [CrossRef]
59. Choi, B.K.; Moon, H.K. Prosocial motive and helping behavior: Examining helping efficacy and instrumentality. *J. Manag. Psychol.* **2016**, *31*, 359–374. [CrossRef]
60. Konicek, V. Adult-centered classroom: A distinct learning atmosphere for college students. *Adult Learn.* **1996**, *7*, 13–18. [CrossRef]
61. Brislin, R.W. Translation and content analysis of oral and written materials. In *Handbook of Cross-Cultural Psychology: Methodology*; Allyn and Bacon: Boston, MA, USA, 1980; pp. 389–444.
62. Morrison, E.W.; Phelps, C.C. Taking charge at work: Extrarole efforts to initiate workplace change. *Acad. Manag. J.* **1999**, *42*, 403–419. [CrossRef]
63. Fang Laitan, S.K.; Fenghua, Z. A study on the reliability of the Chinese version of the learning engagement scale. *Chin. J. Clin. Psychol.* **2008**, *16*, 618–620.
64. Schaufeli, W.B.; Salanova, M.; González-Romá, V.; Bakker, A.B. The measurement of engagement and burnout: A two sample confirmatory factor analytic approach. *J. Happiness Stud.* **2002**, *3*, 71–92. [CrossRef]
65. Loo, R. Assessing "team climate" in project teams. *Int. J. Proj. Manag.* **2003**, *21*, 511–517. [CrossRef]
66. West, M.A.; Anderson, N.R. Innovation in top management teams. *J. Appl. Psychol.* **1996**, *81*, 680. [CrossRef]
67. Jia, Y.; Way, N.; Ling, G.; Yoshikawa, H.; Chen, X.; Hughes, D.; Ke, X.; Lu, Z. The influence of student perceptions of school climate on socioemotional and academic adjustment: A comparison of Chinese and American adolescents. *Child Dev.* **2009**, *80*, 1514–1530. [CrossRef]
68. Sparrowe, R.T.; Soetjipto, B.W.; Kraimer, M.L. Do leaders' influence tactics relate to members' helping behavior? It depends on the quality of the relationship. *Acad. Manag. J.* **2006**, *49*, 1194–1208. [CrossRef]
69. Geldhof, G.J.; Preacher, K.J.; Zyphur, M.J. Reliability estimation in a multilevel confirmatory factor analysis framework. *Psychol. Methods* **2014**, *19*, 72. [CrossRef]
70. Zhang, Z.; Zyphur, M.J.; Preacher, K.J. Testing multilevel mediation using hierarchical linear models: Problems and solutions. *Organ. Res. Methods* **2009**, *12*, 695–719. [CrossRef]
71. Wan, K.; Rao, A.; Xu, R. What Factors Influence Learners' Online Learning Engagement?—Analyzing the Development of Online Learning in the Intelligent Era. *Educ. Acad. Mon.* **2021**, *6*, 97–104.
72. Jing, M.; Zhanji, F. Teaching and Learning Strategies for Student Differences in Resources: Mutual Learning. *Educ. Theory Pract.* **2021**, *41*, 7–10.
73. La Salle, T.P.; Rocha-Neves, J.; Jimerson, S.; Di Sano, S.; Martinsone, B.; Majercakova Albertova, S.; Gajdošová, E.; Baye, A.; Deltour, C.; Martinelli, V.; et al. A multinational study exploring adolescent perception of school climate and mental health. *Sch. Psychol.* **2021**, *36*, 155. [CrossRef]
74. Bruner, J. Vygotsky's zone of proximal development: The hidden agenda. *New Dir. Child Dev.* **1984**, *23*, 93–97. [CrossRef]

buildings

MDPI

Article

Quantifying the Impact of Carbon Reduction Interventions and Incentive Mechanisms in Campus Buildings: A Case Study from a Chinese University

Li Xue [1], Hejun Xu [2,*], Zixuan Zhang [3] and Nan Li [4]

1 School of Management, Shenyang Jianzhu University, Shenyang 110168, China; xueli1965@sjzu.edu.cn
2 School of Civil Engineering and Architecture, Jiangsu University of Science and Technology, Zhenjiang 212013, China
3 School of Qilu Transportation, Shandong University, Jinan 250100, China; 202335497@mail.sdu.edu.cn
4 School of Business Administration, South China University of Technology, Guangzhou 510641, China; 202220132320@mail.scut.edu.cn
* Correspondence: 202300000210@just.edu.cn; Tel.: +86-17688413806

Abstract: With the development of sustainable cities, densely populated higher education institutions increasingly emphasize the sustainability of campuses and their impact on the environment. However, there is a lack of means to quantify emission reduction measures. This study aims to propose an evaluation framework that can quantify energy conservation and emission reduction measures and incentive policies. To this end, this study adopts a mixed methods approach, using questionnaires to assess the effectiveness of management and communication interventions and the impact of incentives on residents' willingness to participate in emission reduction efforts. The survey results show that although the support for the intervention measures is slightly higher than the average, specific measures such as adjusting dormitory lights-out time and providing sports equipment show superior emission reduction potential. Universities could reduce carbon emissions by about 560 tons per year without incentives and just using interventions. However, when incentives and interventions are combined, the university's annual emissions reductions are expected to increase to 800 to 1045 tons. Research also highlights the importance of understanding the relationship between occupant behavior, energy consumption, and building carbon emissions. By quantifying the impact of carbon reduction measures and incentives on the daily behaviors of residents, universities can more effectively implement sustainable campus strategies.

Keywords: sustainable campus; resident behavior; carbon emissions; incentive mechanism

1. Introduction

Environmental changes caused by the rapid development of human civilization have gradually emerged in recent years. Exchanges between international trade, national economic structures, renewable energy consumption, and human capital will all have certain effects on carbon emissions [1]. Growing urbanization has accelerated and strengthened the impact of economic development on carbon emissions to a certain extent [2]. Building plays an important role in urbanization. As an energy-intensive industry, the construction industry contributes significantly to global energy consumption and carbon emissions [3]. In November 2022, the United Nations Environment Programme (UNEP) released the "Global Construction Industry Status Report 2022", which highlighted that in 2021, carbon dioxide emissions from the construction industry accounted for about 37% of global emissions. Carbon dioxide emissions during the operation period reached a record high of approximately 10 billion tons, an increase of around 5% year-on-year and 2% higher than the previous peak [4]. Reducing greenhouse gas (GHG) emissions and building sustainable cities and societies have become top priorities for governments and people around the world.

Universities are recognized as essential contributors to sustainable development [5]. The current series of studies on sustainable campuses often focus on increasing campus renewable energy production and reducing campus building energy consumption. Campus buildings are usually large in number and densely populated. For example, universities and other educational institutions in the European Union account for 16% of non-residential buildings [6]. At the same time, there are more than 3000 colleges and universities in mainland China, with 36 million students [7]. Students usually live in dormitory buildings on campus, so the dormitory buildings are endowed with significant characteristics, such as a large population density, intensive energy use, and relatively concentrated carbon emissions. According to previous studies, the average active-period student emits four times as much greenhouse gas as the entire population [8]. At present, the carbon emissions of dormitory buildings during daily use are often measured by energy consumption. For example, in a study on the full-cycle carbon emissions of Fuzhou University City, the energy consumption of the building in its use stage is based on average water and energy costs over the last five years [9]. In recent years, some scholars have begun determining the impact of people's energy behavior patterns on energy conservation and reducing greenhouse gas emissions through surveys and other methods. Zheng et al. applied Ecological Footprint Evaluation (EFE) and machine learning to comprehensively evaluate campus sustainability and students' carbon emissions, pointing out that changing existing high-carbon behaviors is crucial to low-carbon campus success [10].

The above studies explain the relationship between occupant behavior, energy consumption, and building carbon emissions. However, these studies have not analyzed in-depth the relationship between a specific type of behavior and carbon emissions. For example, universities in mainland China will lecture on low-carbon emission reduction almost every semester, including the location of energy output sources such as faucets, light switches, etc., and put up slogans such as "Save water and electricity." It is worth discussing which occupant behaviors these measures to reduce occupant carbon emissions will affect and how much influence they will have. Suppose the specific impact of these carbon reduction measures on the daily behavior of residents can be calculated. In that case, the school will undoubtedly be able to implement relevant, sustainable campus strategies more efficiently.

Individual carbon emission behavior can usually be explained by theories such as the Theory of Planned Behavior (TPB), the Norm Activation Model (NAM), the Value Belief Norm (VBN), and the Attitude-Behavior-External Conditions (ABC) model [11]. Among them, TPB assumes that individuals act intelligently based on available information and consider the meaning of their actions implicitly or explicitly. Therefore, if some incentive mechanisms related to higher education are combined with the implementation of resident-related emission reduction intervention measures, according to the discussion of TPB, rewards may promote residents' enthusiasm for emission reduction and achieve better results.

This research proposes an evaluation framework that can quantify the impact of interventions and incentive mechanisms to reduce carbon emissions in campus buildings. The framework will help obtain the final expected results under multiple incentives and provide guidance for sustainable campus construction. This article first reviews relevant research on campus carbon emissions. Subsequently, this study lists the various behaviors of residents and the improvement strategies and interventions for each behavior and determined the emission reductions of each carbon reduction intervention through questionnaires. Finally, this study obtained respondents' responses to the incentive mechanisms through a five-level scale survey and gave the expected emission reduction effects under various incentive combinations. This research can help campus administrators start with common behaviors in life, develop better emission reduction strategies and policy tools, and adopt more accurate and practical solutions to reduce carbon emissions in campus buildings.

2. Related Works

2.1. Campus Building Carbon Emission

The current calculation framework for campus carbon emissions during daily use is usually based on the Life Cycle Assessment (LCA) method. The specific calculation process uses the carbon emission factor method [12]. Therefore, as long as the calculated target energy consumption is obtained, the carbon emissions can be obtained directly. Existing research usually uses historical data and questionnaire statistics to get the energy consumption value of the target object. Larsen et al. calculated the carbon footprint of teachers and students of the Norwegian University of Science and Technology using 2009 financial account data [13]. The study focused on financial data and did not discuss related measures such as energy conservation and emission reductions. Huang et al. used the average annual energy consumption for the past five years as the basis for calculating the carbon emissions of Fuzhou University City during its use phase [9]. However, they did not consider the impact of the intervention. Leticia et al. calculated the university's carbon footprint by considering data on goods and services consumed by De Montfort University in 2008–09 [14]. Similarly, this study also mainly focused on the measurement of the carbon footprint and ignored the process of "how to reduce the carbon footprint." A study analyzed the greenhouse gas emissions of the University of Genoa (UNIGE) in Italy and Florida International University (FIU) in Miami, USA. It used campus building design and renovation models to reduce campus carbon emissions [15].

Statistical analysis is also widely used in practical research as an essential carbon emission assessment method. For example, Du et al. used statistical analysis methods to provide information on the behavior of residents in Hong Kong through a case study of a high-rise student apartment building, producing new data and new models [16]. A statistical analysis assessed energy use patterns in twenty-eight University of Johannesburg residence halls during the 2016 academic year [17]. A recent review of research identified the use of spatial planning and landscape, renewable and clean energy, energy systems, thermal envelopes, green transportation, management and control, human-related performance and intelligence, and other methods [18].

2.2. User Behavior of Building Energy

Once the value of energy consumption is obtained, the corresponding carbon emissions can be calculated. Some studies have shown that the energy use behavior of various occupants and buildings will affect energy consumption [19]. Li et al. found through a structured survey that 65% of student behavior was categorized as daily life, 20% as transportation, and 15% as academic activities such as learning [20]. There is a significant potential for substantial energy savings by changing the behavior of occupants with regards to energy consumption habits [21,22], and the energy consumption of the same house can vary by more than twofold depending on the behavior of the occupants [23,24]. A study created three behavior patterns (proactive, intermediate, and careless) to evaluate user interactions with air conditioning systems, lighting, natural ventilation, and internal shading devices. The results showed that the current user behavior is between intermediate and careless [25]. A review of research on the impact of occupant behavior on building energy consumption states that occupant behavioral efficiency is considered an effective and economical approach compared to retrofit techniques. However, future improvements in the classification, quantification, and validation of behavioral inputs are needed [26].

Research on building energy user behavior also includes social psychology and other behavioral aspects. Wang et al. summarized four classic behavioral theories and conceptual models, including TPB, in their study [11]. Si et al. used TPB to understand people's water-saving intentions [27], and Chen et al. used TPB to explain how individuals' intentions to participate in carbon reduction affect their final behavior [28].

2.3. Research Framework

Through the previous literature review, this study found that although teams have conducted relevant research on sustainable campus buildings, the research mainly focused on the calculation of carbon emissions on the campus as a whole. In other words, the current research focuses on "how much carbon is emitted" rather than "how to reduce carbon emissions". At the same time, most existing emission reduction strategies focus on building design and renovation. Although some research has pointed out that modifying occupant behavior is an effective and economical method, detailed behavioral input and quantification methods are lacking. Therefore, this study will focus on the changes in emission reductions from residents' behavior, aiming to explore the impact of interventions and incentives on carbon emission reductions for campus dormitory residents in combination with the TPB.

The specific research process is divided into three parts:

1. Using college students in Shenyang City, Liaoning Province, China as the data source, investigate their daily living behavior.
2. Design corresponding interventions for the above behaviors, investigate the respondents' acceptance of these carbon reduction measures, and then estimate the amount of carbon emission reductions under the intervention.
3. Based on the relevant policies of TPB and the university, design a corresponding incentive mechanism and investigate the respondents' willingness to implement intervention measures under the incentive mechanism, so as to understand the promotion and expected effects of various rewards on intervention measures.
4. The flow chart of this study is shown in Figure 1.

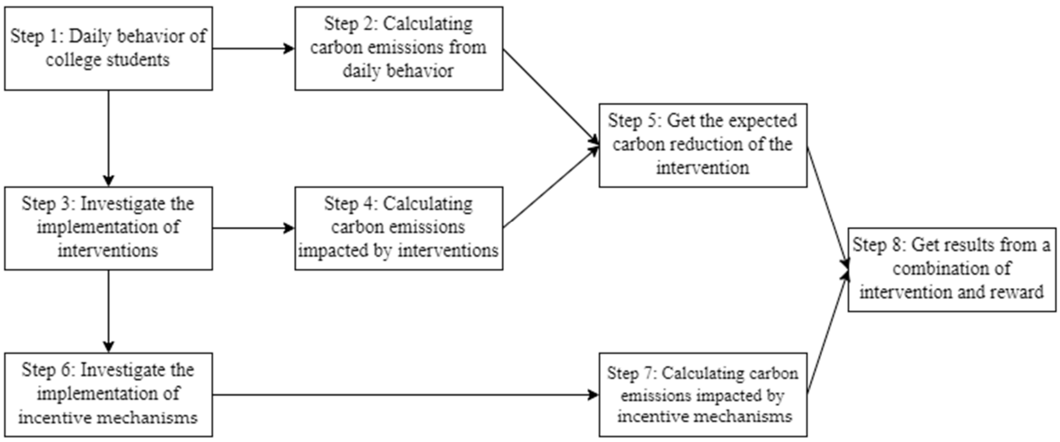


Figure 1. The flow chart.

3. Methodology

3.1. Daily Behavior of Residents

As mentioned in Section 2.3, this study first investigates the daily residential behavior of college students. The Hong Kong Environment and Ecology Bureau has developed an online carbon emissions calculator based on residents' daily behaviors in four aspects: food, clothing, housing, and transportation [29]. The calculator conducts a detailed survey of residents' clothing and shoe purchases, eating habits and consumption, energy consumption, and frequency of transportation. Based on various surveys conducted by this calculator, this study summarizes the daily behaviors of college students that produce carbon emissions, as shown in Table 1. This study is dedicated to quantifying the behavior of college students resident in dormitories, so their transportation travel is not within the boundaries of this study system, and so transportation is not involved in Table 1.

Table 1. Various behaviors of residents that generate carbon emissions.

Type	Activity
Clothing	Buying new clothes and shoes
Food	Frequency of eating red meat Weekly red meat consumption Number of prepackaged drinks purchased per week
Living	Electricity (in room) Electricity (public space) Water

3.2. Interventions

Based on the above-mentioned daily behaviors that generate carbon emissions and some regulations of university dormitories, this study set up various intervention measures. Among them, energy consumption in dormitories can be reduced through a series of measures from the perspective of managers, such as managers directly reducing the free electricity quota for each dormitory, further increasing the price of water- and electricity-consuming equipment in the building to reduce use, etc. This type of intervention is called "managerial intervention" in this study. Corresponding to this is "advocacy intervention", such as posting posters and holding lectures. Table 2 shows the various measures of the two major categories of intervention.

Table 2. Two categories of intervention.

Type	Interventions
Managerial intervention	Reduce the monthly free electricity amount for dormitories Reduce the monthly supply of garbage bags in dormitories Increase washing machine charging standards Increase dormitory electricity prices Charge for hot water in water room Increase charging standards for floor water dispensers Hair dryer and microwave oven charges Adjust dormitory lights-out time
Advocacy intervention	Provide sporting goods Conduct online lectures Post water and electricity conservation slogans in stairwells, corridors, and water rooms

3.3. Incentive Mechanism

Among the above-mentioned intervention measures, management-type interventions will inevitably reduce the quality of life of residents, while advocacy-type interventions are mostly a relatively common publicity method. Both types of intervention may not necessarily produce very good expected results. This study believes that incentives can motivate residents to accept these interventions to a certain extent and achieve a low-carbon lifestyle based on TPB. Based on the policies of each school, this study proposes twelve incentive mechanisms in three categories, involving students' spiritual honor rewards, material rewards, and academic rewards. Table 3 introduces the specific measures of these incentive mechanisms.

Table 3. Incentive mechanisms.

Type	Rewards
Honor rewards	Receive beautiful certificates and medals Complete a charity donation in the name of the winner and obtain an electronic certificate The deeds of the winners will be displayed in a prominent location (such as the corridor) for publicity The winners' deeds are publicized on the school and college's self-media platform
Material rewards	The winner can receive a cash equivalent to the energy reduction Winners can receive exquisite cultural and sports products The winner can get tokens or points, which can be used for daily consumption in school Cooperate with popular platforms to provide winners with interesting prizes (such as skins and heroes in Honor of Kings or League of Legends)
Academic rewards	The winner can get a school-level honorary title (plus one point for postgraduate admission) The corresponding score of the winner will get a full score at the end of the semester Winners can have priority to move into a four-person dormitory after the end of the school year Winners can participate in the research of low-carbon project teams and have the opportunity to publish high-quality papers

4. Data Analysis

4.1. Intervention Questionnaire Analysis

This study collected the influencing factors of students' carbon emission behaviors through an extensive questionnaire. After designing the questionnaire, the team used online social media and offline posters to promote the questionnaire to college students in Shenyang, Liaoning Province, China. Finally, 533 valid questionnaires were successfully collected. This study first used a five-point Likert scale to survey respondents' support for each intervention, with 1 being "very unsupportive" and 5 being "very supportive". The results showed that the average score of the five-level scale was 3.25, which was only slightly higher than the average, indicating that the respondents were not willing to participate in the intervention. The highest-scoring intervention, "Adjust dormitory lights-out time," also scored only 3.5 points. The scores for "Provide sporting goods", "Conduct online lectures", and "Post water and electricity conservation slogans in stairwells, corridors and water rooms" were all below 3.1. It can, therefore, be presumed that these interventions will have little effect.

After determining the main intervention measures of this study, this study combined the questionnaire survey with the students' living habits based on existing research. It estimated the carbon emission reduction of each measure.

4.1.1. Questionnaire Test

First, a reliability analysis was conducted on the questionnaire (all analyses in this study came from SPSSPRO). The results showed that the Cronbach's α coefficient value of the questionnaire was 0.989, indicating that the reliability of the questionnaire was very good.

Next, this study conducted a structural equation model analysis on the questionnaire. According to the two major types of intervention in Section 3, the measures of managerial interventions are set as factor 1 in the model, and the measures of advocacy interventions are set as factor 2. It can be seen from the calculation results in Appendix B and from the model path coefficient table that in factor 1, the significance p values of the second intervention to the eighth intervention in the management interventions and factor 2 are all

0.000, so the null hypothesis is rejected. At the same time, the standard loading coefficients are all greater than 0.4, which can be considered to have a sufficient variance explanation rate to indicate that each variable can be displayed for the same factor. In the same way, based on the fact that the significant p values of the second and third measures in the advocacy interventions are also 0.000, the null hypothesis is rejected. At the same time, the standard loading coefficients are all greater than 0.4. It can, therefore, be considered to have a sufficient variance explanation rate to indicate that each variable can be displayed for the same factor.

Finally, from the model path coefficient table, it can be seen that based on the paired term F1 -> F2, the significance p value is 0.000 ***, and being significant at that level, then the null hypothesis is rejected. Therefore, this path is effective, and its influence coefficient is 0.866.

In summary, the various intervention measures involved in the questionnaire are reasonably set and the data collected by the questionnaire are reliable, so further research can be conducted based on this questionnaire.

4.1.2. Managerial Intervention

Starting from question 2, this study analyzes the respondents' implementation level of each intervention measure one by one and then calculates the specific carbon reduction amount of each measure using the carbon emission factor method [30]. There are some measures that cannot be applied to all universities in Shenyang. For example, the price of electricity in public universities usually follows a unified standard, so the price of electricity in dormitories cannot be increased rashly. Finally, this study retained eight intervention measures in the carbon reduction estimation process. Several deleted measures can be used as a reference for universities to formulate subsequent policies. The carbon emission factors used in the study are shown in Table 4.

Table 4. Carbon emission factor [29,31].

Carbon Source	Unit	Carbon Emission Factor ($kgCO_2e$/unit)
Electricity	kWh	1.0826
Water	t	0.213
Laundry detergent	t	5930

First, the questionnaire indicated that nearly half of the students may or are very likely to reduce electricity consumption following a reduction in the monthly free electricity quota in the dormitory. When implementing electricity-saving related measures, 43.64% of the students would be willing to persist every week for more than four days. This could save about 0.1 kWh of power consumption per day and 1.8 kWh per month. According to the carbon emission factor, carbon emission reductions per person per month resulting from the intervention are 1.95 $kgCO_2e$.

Faced with a rise in the cost of operating the washing machines, the questionnaire found that 50.3% of students would choose to wash their clothes by hand as much as possible, and 32.12% would reduce their machine washing by at least once a week. Therefore, this research assumes that half of the students would reduce their machine washing frequency by three times a month, and the other half would remain unchanged. According to the instructions for the drum washing machines commonly used in the dormitory building, the power consumption of each standard washing process is 0.88 kWh, and the water consumption is 50 L. Therefore, this measure can reduce per capita electricity consumption by 1.32 kWh and per capita water consumption by 75 L. At the same time, reducing the number of machine washes will also reduce the consumption of laundry detergent. Calculated using 60 g of laundry detergent each time, the consumption of laundry detergent per capita will be reduced by 90 g per month after implementing this measure. Using the carbon emission factor method, the monthly carbon emission reduction of this measure can be calculated as 1.978 $kgCO_2e$.

A total of 75.15% of the students indicated that charging for hot water in the water room would prompt them to reduce excessive water use. The capacity of the thermos commonly used by students is 3 L. Based on this intervention, students were willing to reduce their water consumption to 1 L (six people in the dormitory use up two pots of hot water daily) and then reduce the amount of hot water by 0.5 L daily. According to the ratio obtained from the questionnaire, the per capita water savings after taking this measure is 0.375 L per day. The hot water room uses a stainless steel large-capacity water boiler with a rated power of 12 kW; the power consumption for boiling 100 L of water is about 12 kWh. Therefore, this measure could also reduce per capita electricity consumption by 0.045 kWh per day. After calculations, the monthly carbon emission reduction of this intervention is 1.46 kgCO_2e.

By raising the drinking water charge, the questionnaire suggests that 56.97% of the students would seek to reduce their water costs. After field research and one-on-one dialogue, this study found that each student would seek to reduce their water charge by about CNY 2 per week, calculated based on 0.35 CNY/L. Students willing to reduce their consumption of direct drinking water did so by 7 L of water per week (1 L of water per day). The average daily water reduction of all students was 0.5697 L. The total power of the direct drinking water dispenser in the dormitory building is 425W. It is operational 24 h a day because the power supply is used for filtering water. Therefore, this intervention will not affect the power consumption of the direct drinking water machine, regardless of whether the water is saved. The monthly carbon emission reduction of this measure is 0.0036 kgCO_2e.

The questionnaire shows that more than half of the students would use hair dryers and microwave ovens less than once a week if they were subject to a charge. In this study, half of the students indicated they would reduce their use of hair dryers and microwave ovens by 5 min a week. According to the rated power of the products, this measure can reduce per capita electricity consumption by 0.083 kWh per week. The action, therefore, has an carbon emission reduction of 0.36 kgCO_2e per month.

After adjusting the lights-off time inside the dormitory to midnight, an investigation showed that students went to bed about an hour earlier than before. This study estimates that the electricity consumption of equipment such as computers, mobile phones, and dormitory lights for college students is about 0.1 kWh per hour, and the monthly EPR of this measure is 3.25 kgCO_2e.

4.1.3. Advocacy Intervention

Educational advocacy measures generally include activities such as low-carbon lectures, courses, the provision of sporting goods, and the display of water-saving and electricity-saving slogans in stairwells, corridors, and water rooms. Such measures aim to show students specific low-carbon and related carbon emission behaviors and change their thinking. From a cultural point of view, this ideological education work guides students' carbon-saving awareness toward tangible measures to reduce carbon emissions and accelerate the promotion of low-carbon work.

According to the questionnaire, 48.48% of students would spend more than half an hour outdoors every day following the provision of sporting goods. This study assumes that half of the students exercise for half an hour daily; therefore, this measure could reduce electricity consumption per capita by 0.025 kWh, and the monthly carbon emission reduction is 0.81 kgCO_2e.

A total of 88.48% of students indicated that water- and electricity-saving slogans and conducting online lectures in stairwells, corridors, and water rooms could prompt them to reduce excessive electricity consumption. We surveyed the students after viewing sample banners and three low-carbon education lectures. The results showed that students actively reduced their excessive electricity consumption within the first week after the first lecture (see Figure 2). However, as time passed, some students began to ignore related carbon behaviors, and only 41.82% were willing to persist. Within 1–2 weeks of the second lecture, the students' low-carbon behavior continued to rise, and the rate increased to 71.52%, then slowly decreased to 45.45% over time. After the third lecture, student behavior began to decline after maintaining a slow growth and remained unchanged at 52.73%. Therefore, this study argues that 52.73% of students can adhere to the above-mentioned energy-saving habits, and this ratio is also used as the reduction factor for carbon emission reduction.

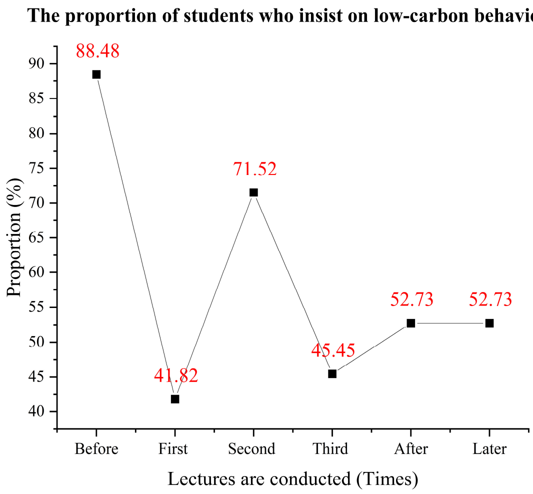


Figure 2. Energy conservation awareness after three lectures.

According to the results of the questionnaire and the simulation experiment, this study determined the specific carbon reduction per day for each intervention measure, as shown in Table 5.

Table 5. Carbon emission reduction of every intervention.

Activity	Saving Electricity (kWh)	Saving Water (L)	Saving Laundry Detergent (kg)	Reduction CO_2 (kge)
Reduce the monthly free electricity	1.8			1.949
Raise the washing machine charges	1.32	75	0.09	1.979
Charge for water room hot water	1.35	11.25		1.464
Raise the water fee		17.09		0.004
Adjust the lights-off time inside the dormitory	3			3.248
Hair dryer and microwave fee	0.33			0.357
Provide sporting goods	0.75			0.812
Posters and lectures		Reduction factor is 0.5273		
Total	4.508	54.491	0.047	5.174

4.2. Reward Questionnaire Analysis

This study set up a scenario: if the respondent, through his or her own efforts, ranks among the top in the dormitory building in terms of carbon reduction during that semester, he or she will be awarded the title of "Carbon Reduction Pacesetter." Under this assumption, the winners were surveyed on their satisfaction with twelve types of incentives in three categories. This study also conducted a survey using a five-point scale, with 1 indicating "very dissatisfied" with the reward and 5 indicating "very satisfied".

4.2.1. Questionnaire Test

First, a reliability analysis was conducted on the questionnaire. The Cronbach's α coefficient value was 0.962, indicating that the reliability of the questionnaire was very good.

Next, a structural equation model analysis was performed on the questionnaire. According to the three types of incentive mechanisms in Section 3, the model sets the four incentive measures of honor rewards as factor 1, the four incentive measures of material rewards as factor 2, and the four incentive measures of academic rewards as factor 3. It can be seen from the model path coefficient table that the confirmatory analysis based on factor f1 shows that the principal component composed of variables within this factor has a low level of explanation. The second, third, and fourth incentive measures in factor 2 and the significant *p* value of factor 3 are all 0.000, so the null hypothesis is rejected. At the same time, their standard loading coefficients are all greater than 0.4, which can be considered to have a sufficient variance explanation rate. It means that each variable can be displayed for the same factor.

Similarly, in factor 3, the significant *p* values of the second, third, and fourth incentive measures are all 0.000; then, the null hypothesis is rejected. At the same time, their standard loading coefficients are all greater than 0.4, and it can be considered that they have a sufficient variance explanation rate to perform various functions. Variables can appear for the same factor.

Next, from the model path coefficient table, we can see that based on the paired term f1 -> f2, the significance *p* value is 0.887. If it is not significant at that level, the null hypothesis cannot be rejected, and so this path is invalid. Based on the pairing term f1 -> f3, the significance *p* value is 0.887, and it is not significant at the horizontal level, so the null hypothesis cannot be rejected, and so this path is invalid. Based on the pairing term f2 -> f3, the significance *p* value is 0.000 ***, and it is significant at that level, so the null hypothesis is rejected, and so this path is valid, and its influence coefficient is 1.199.

In summary, the questionnaire has extremely high reliability, indicating that the data are relatively reliable. However, several measures of honorary awards are significantly different from the other two types of awards, and further analysis needs to be combined with the data.

4.2.2. Rewards Promote Intervention

Judging from the questionnaire data, the overall satisfaction level of respondents with honors and awards is low, and the highest score for "charitable donation" did not exceed 3.4 points. The other two types of rewards have higher scores, with the highest score 3.8 and the second highest score 3.79, both coming from material rewards. Academic rewards are relatively average, with all four measures reaching 3.6 points or above, which is higher than the overall average of 3.5.

Next, this study discusses the degree of implementation of intervention measures under incentive measures based on the degree of satisfaction with each incentive measure. The authors believe that in each incentive measure, respondents who chose "very satisfied" and "satisfied" will persist in implementing the intervention, while others will implement it in accordance with their proportion in the intervention questionnaire. This allows an estimate of the expected carbon reductions of the intervention based on each incentive. The results are shown in Table 6.

When the incentive mechanism is taken into account, even a low-scoring incentive can significantly increase the amount of carbon reduction per person per month. This is mainly because the previous interventions were only completed voluntarily by the respondents. After participating in the incentive mechanism, respondents who are satisfied with the reward will do their best to their reduce carbon emissions for the reward, and it is no longer based on basic consciousness and public welfare. Interventions, therefore, do not result in severe reductions. This is also consistent with the TPB mentioned many times in the literature review.

Finally, taking into account the length of schooling of college students (9 months per year) and the total number of students living on campus in various universities in Shenyang (general universities comprise mainly undergraduates, about 12,000 people), this study estimates that under the joint action of incentive measures and intervention mechanisms, an ordinary university can reduce carbon emissions by more than 800 tons a year, up to a maximum of about 1045 tons. If only intervention measures are taken into account, and only residents' voluntary efforts to reduce carbon emissions are considered, the university will reduce carbon emissions by approximately 560 tons per year.

Table 6. Incentive mechanism promotes carbon emission reductions.

Activity	Reduction Factor	Electricity Savings (kWh)	Water Savings (L)	Laundry Detergent Savings (kg)	Reduction CO_2 (kge)
Receive beautiful certificates and medals	0.737	6.743	79.956	0.069	7.726
Complete a charity donation in the name of the winner and obtain an electronic certificate	0.729	6.698	77.288	0.066	7.659
The deeds of the winners will be displayed in a prominent location (such as the corridor) for publicity	0.715	6.455	74.375	0.065	7.389
The winners' deeds are publicized on the school and college's self-media platform	0.728	6.479	76.968	0.069	7.440
The winner can receive a cash equivalent to the energy reduction	0.844	8.375	94.459	0.085	9.589
Winners can receive exquisite cultural and sports products	0.784	7.896	88.796	0.079	9.034
The winner can get tokens or points, which can be used for daily consumption in school	0.817	8.026	90.237	0.082	9.195
Cooperate with popular platforms to provide winners with interesting prizes (such as skins and heroes in Honor of Kings or League of Legends)	0.848	8.457	95.985	0.085	9.682
The winner can get a school-level honorary title (plus one point for postgraduate admission)	0.806	7.898	89.125	0.081	9.050
The corresponding score of the winner will get a full score at the end of the semester	0.839	8.266	92.201	0.084	9.468
Winners can have priority to move into a four-person dormitory after the end of the school year	0.827	7.903	90.963	0.082	9.067
Winners can participate in the research of low-carbon project teams and have the opportunity to publish high-quality papers	0.804	7.858	88.358	0.080	9.003

5. Discussion and Conclusions

Although the campus area of colleges and universities only accounts for 3–7% of the urban construction area, its dense population has become a severe challenge for sustainable urban development. This study proposed a series of methods to quantify the impact of various carbon reduction interventions in campus buildings on the occupants, as well as the role of incentive mechanisms in promoting these interventions. This study designed a questionnaire on intervention measures and a satisfaction survey on incentive mechanisms and calculated the carbon reduction amount of each measure and the expected value of each incentive mechanism based on the carbon emission factor method. Finally, it was concluded that the monthly carbon reduction of residents under intervention measures alone was

5.174 kgCO_2e. Among the multiple intervention measures, adjusting the dormitory lights-out time was expected to have the highest emissions reduction, which could reduce carbon emissions by 3.248 kg of CO_2e per month without considering discounts. The university's total annual carbon reduction was approximately 560 tons. After considering incentives, the monthly carbon reduction could reach 7.389 to 9.682 kgCO_2e, and the university's annual carbon reduction could reach 800–1045 tons.

The calculation results of this study can intuitively find the positive impact of incentive mechanisms, and the 12 incentive measures in this study can increase per capita carbon reduction to a certain extent. Among the measures, the average satisfaction with incentives such as honorary rewards was low, while the average satisfaction with incentives such as material rewards and academic rewards was higher. Therefore, we call on universities to consider supporting incentive measures, especially material and academic rewards, when formulating emission reduction policies. At the same time, even if incentives are not considered, various interventions can achieve a certain degree of carbon emission reduction. Therefore, we recommend that colleges and universities not only consider incentive measures but also adhere to implementing relevant intervention policies. In addition, this study's findings clearly reveal the carbon emission reduction potential of interventions and incentive mechanisms. However, forcing students to reduce carbon emissions through external forces is not enough. Creating a culture of sustainable development within the campus community will be more effective in achieving a low-carbon life. The authors plan to conduct a series of people-centered studies in the future to explore the core factors that influence people's formation of low-carbon values. Finally, the results show that electricity plays an important role in reducing carbon emissions. Therefore, the team recommends that universities adopt more targeted interventions or rewards for electricity-saving behaviors, such as addressing luminous lights on campus, that buildings use energy-saving products, and that air conditioning in public areas be set to a relatively higher temperature in summer.

This study also has certain limitations. First, the research sample was collected from college students in Shenyang City, Liaoning Province, China. This forms the geographical limitation of the research to a certain extent. For example, the university energy structure and residents' behavioral habits in tropical areas such as Hong Kong, Singapore, and Manila differ entirely from those of respondents in Shenyang. This study will be followed up with research teams from the City University of Hong Kong and the National University of Singapore to study the daily behaviors of college students in tropical areas. Second, the research objects of this study are limited to university dormitory buildings and resident behaviors. In fact, university teaching buildings, libraries, and office buildings all consume a lot of energy. Therefore, the team will explore the future role of campuses in sustainable cities and societies more fully. We have currently completed a study on carbon reduction for campus office buildings and are currently under review. Finally, this study focused on quantifying reward mechanisms but ignored students' perceptions of existing reward mechanisms. In future research, we will discuss incentives that are more popular among students and the possibility for students to increase their environmental awareness further through future studies.

Author Contributions: Conceptualization, H.X.; Methodology, H.X. and N.L.; Software, L.X. and H.X.; Validation, L.X. and Z.Z.; Formal analysis, Z.Z.; Data curation, N.L.; Writing—original draft, L.X. and Z.Z.; Writing—review & editing, L.X., H.X. and N.L.; Supervision, L.X. and H.X.; Funding acquisition, H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Jiangsu University of Science and Technology, grant number 1122932310, Title: "Doctoral Research Start-up Fund of Jiangsu University of Science and Technology: 1122932310".

Data Availability Statement: The questionnaire data used in this study and related analysis results are presented in the Appendices A and B.

Acknowledgments: Thanks to Qingyun Wang of Fudan University for her support of this research.

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

Appendix A. Survey on Intention of Carbon Saving Measures in Student Dormitories

Appendix A.1. Question 1: In order to Reduce Carbon Emissions, Your Support of the Following Interventions? [Matrix Scale Questions]

Questions\Options	Very Unsupportive	Not Supportive	Generally	Supportive	Very Supportive	Average Score
Reduce the monthly free electricity amount for dormitories	48 (9.09%)	71 (13.33%)	152 (28.48%)	187 (35.15%)	75 (13.94%)	3.32
Reduce the monthly supply of garbage bags in dormitories	45 (8.48%)	116 (21.82%)	155 (29.09%)	158 (29.7%)	59 (10.91%)	3.13
Increase washing machine charging standards	58 (10.91%)	71 (13.33%)	155 (29.09%)	171 (32.12%)	78 (14.55%)	3.26
Increase dormitory electricity prices	45 (8.48%)	61 (11.52%)	158 (29.7%)	174 (32.73%)	95 (17.58%)	3.40
Charge for hot water in the water room	42 (7.88%)	74 (13.94%)	149 (27.88%)	197 (36.97%)	71 (13.33%)	3.34
Increase charging standards for floor water dispensers	48 (9.09%)	81 (15.15%)	149 (27.88%)	187 (35.15%)	68 (12.73%)	3.27
Hair dryer and microwave oven charges	39 (7.27%)	65 (12.12%)	171 (32.12%)	181 (33.94%)	77 (14.55%)	3.36
Adjust dormitory lights-out time	26 (4.85%)	65 (12.12%)	149 (27.88%)	204 (38.18%)	89 (16.97%)	3.5
Provide sporting goods	61 (11.52%)	94 (17.58%)	197 (36.97%)	139 (26.06%)	42 (7.88%)	3.01
Conduct online lectures	55 (10.3%)	84 (15.76%)	207 (38.79%)	142 (26.67%)	45 (8.48%)	3.07
Post water and electricity conservation slogans in stairwells, corridors, and water rooms	61 (11.52%)	84 (15.76%)	200 (37.58%)	155 (29.09%)	33 (6.06%)	3.03
Subtotal	528 (9.04%)	866 (14.77%)	1842 (31.4%)	1895 (32.34%)	733 (12.45%)	3.25

Appendix A.2. Question 2: When the Monthly Free Electricity Amount in the Dormitory Is Reduced or the Electricity Price Is Increased, Will You Try to Save Electricity in the Dormitory as Much as Possible? [Single-Choice Question]

Options	Subtotal	Proportion
Very unlikely	48	9.09%
Impossible	74	13.94%
Generally	145	27.27%
Possible	194	36.36%
Very likely	71	13.33%
Number of valid entries for this question	533	

Appendix A.3. Question 3: When Implementing Power-Saving Measures, How Many Days per Week Are You Willing to Stick to Power-Saving Behavior? [Single Choice Question]

Options	Subtotal	Proportion
0	68	12.73%
1 day	68	12.73%
2 days	65	12.12%
3 days	100	18.79%
4 days	42	7.88%
5 days	48	9.09%
6 days	19	3.64%
7 days	123	23.03%
Number of valid entries for this question	533	

Appendix A.4. Question 4: When Reducing the Monthly Supply of Garbage Bags in the Dormitory, Will You Try Your Best to Avoid Unnecessary Garbage Generation? [Single-Choice Question]

Options	Subtotal	Proportion
Yes	320	60%
No	213	40%
Number of valid entries for this question	533	

Appendix A.5. Question 5: When Reducing the Monthly Supply of Garbage Bags in the Dormitory, Will the Amount of Garbage Be Reduced Every Month? [Single-Choice Question]

Options	Subtotal	Proportion
1–5 kg	287	53.94%
6–15 kg	142	26.67%
16–30 kg	48	9.09%
31–45 kg	26	4.85%
46–60 kg	13	2.42%
Or enter another quantity (kg)	17	3.03%
Number of valid entries for this question	533	

Appendix A.6. Question 6: When the Charging Standard for Washing Machines Is Increased, Will You Choose to Wash Clothes by Hand as Much as Possible? [Single-Choice Question]

Options	Subtotal	Proportion
Yes	268	50.3%
No	265	49.7%
Number of valid entries for this question	533	

Appendix A.7. Question 7: After Increasing the Charging Standard for Washing Machines, How Many Times a Week Will the Number of Machine Washes Be Reduced? [Single Choice Question]

Options	Subtotal	Proportion
0	152	28.48%
1	171	32.12%
2	136	25.45%
3	52	9.7%
4	6	1.21%
5	16	3.03%
Or enter the quantity (times)	0	0%
Number of valid entries for this question	533	

Appendix A.8. Question 8: After Charging for Hot Water in Bathrooms, Will You Reduce Excessive Water Use? [Single Choice Question]

Options	Subtotal	Proportion
Yes	401	75.15%
No	132	24.85%
Number of valid entries for this question	533	

Appendix A.9. Question 9: When the Charging Standard for Floor Water Dispensers Is Increased, Will You Reduce the Cost of Water Supply? [Single Choice Question]

Options	Subtotal	Proportion
Yes	304	56.97%
No	229	43.03%
Number of valid entries for this question	533	

Appendix A.10. Question 10: How Much Will Your Weekly Expenses Be Reduced after Increasing the Charging Standard for Floor Water Dispensers? [Single Choice Question]

Options	Subtotal	Proportion
0	149	27.88%
CNY 0.1–1	110	20.61%
CNY 1.1–2	145	27.27%
CNY 2.1–3	65	12.12%
CNY 3.1–4	58	10.91%
Or enter other quantity (yuan)	6	1.21%
Number of valid entries for this question	533	

Appendix A.11. Question 11: When Sporting Goods Are Provided, How Long Will Your Daily Outdoor Exercise Time Increase? [Single Choice Question]

Options	Subtotal	Proportion
0	84	15.76%
0–1 h	258	48.48%
1–2 h	139	26.06%
2–3 h	48	9.09%
Or enter the quantity (h)	4	0.61%
Number of valid entries for this question	533	

Appendix A.12. Question 12: When the Hair Dryer and Microwave Oven Are Charged for, How Much Will the Number of Times You Use Them per Week Decrease? [Single Choice Question]

Options	Subtotal	Proportion
0	168	31.52%
1	132	24.85%
2	165	30.91%
3	45	8.48%
4	19	3.64%
Or enter the quantity (times)	4	0.61%
Number of valid entries for this question	533	

Appendix A.13. Question 13: After Browsing Slogans or Lectures on Low-Carbon Energy Conservation, Are You Willing to Reduce Excessive Electricity Consumption? [Single Choice Question]

Options	Subtotal	Proportion
Yes	472	88.48%
No	61	11.52%
Number of valid entries for this question	533	

Table A1. Reliability analysis of intervention questionnaires.

Cronbach's α	Standardized Cronbach's α	Number of Items
0.989	0.989	11

Table A2. Table of factor loading coefficients.

Factors	Variables	Non-Standard Load Factors	Standard Load Factors	z	S.E.	p
F1	Question 1	1	0.996	-	-	-
	Question 2	0.789	0.904	4.627	0.171	0.000 ***
	Question 3	0.87	0.99	13.344	0.065	0.000 ***
	Question 4	0.94	0.975	9.118	0.103	0.000 ***
	Question 5	1.069	0.991	13.813	0.077	0.000 ***
	Question 6	0.978	0.99	13.022	0.075	0.000 ***
	Question 7	1.076	0.987	11.881	0.091	0.000 ***
	Question 8	1.156	0.979	9.857	0.117	0.000 ***
F2	Question 9	1	0.993	-	-	-
	Question 10	1.085	0.992	12.693	0.085	0.000 ***
	Question 11	1.106	0.991	12.182	0.091	0.000 ***

*** $p < 0.01$.

Table A3. Table of factor loading coefficients.

Latent Variables	Latent Variables	Non-Standard Coefficient	Standard Coefficient	Standard Error	Z	*p*
F1	F2	0.867	0.866	0.232	3.736	0.000 ***

*** $p < 0.01$.

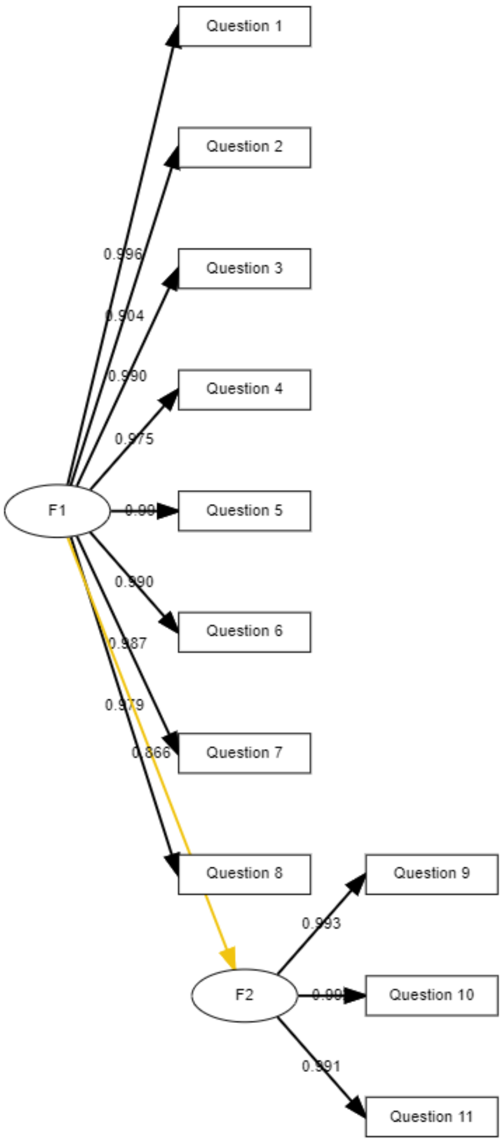


Figure A1. Structural Equation Model Path Diagram. The yellow arrow indicates the influence relationship between factors, and the black arrow indicates the influence relationship between a certain factor and its various components.

Appendix B. If You Live in the Dormitory, You Can Get Rewards for Low-Carbon Energy Saving

In dormitory life, the top resident in carbon reduction can get the title of "Carbon Reduction Model". Please express your satisfaction with the specific reward effect of this title. A score of 1 means very dissatisfied, and a score of 5 means very satisfied.

Questions\Options	Very Dissatisfied	Not Satisfied	Generally	Satisfied	Very Satisfied	The Average Score
Receive beautiful certificates and medals	84	116	96	130	107	3.11
Complete a charity donation in the name of the winner and obtain an electronic certificate	87	63	156	109	118	3.36
The deeds of the winners will be displayed in a prominent location (such as the corridor) for publicity	90	90	141	101	111	3.15
The winners' deeds are publicized on the school and college's self-media platform	85	84	138	134	92	3.12
The winner can receive a cash equivalent to the energy reduction	41	18	117	190	167	3.80
Winners can receive exquisite cultural and sports products	67	79	97	162	128	3.38
The winner can get tokens or points, which can be used for daily consumption in school	47	41	118	186	141	3.62
Cooperate with popular platforms to provide winners with interesting prizes (such as skins and heroes in Honor of Kings or League of Legends)	35	34	102	199	163	3.79
The winner can get a school-level honorary title (plus one point for postgraduate admission)	41	44	134	160	154	3.64
The corresponding score of the winner will get a full score at the end of the semester	45	40	97	170	181	3.75
Winners can have priority to move into a four-person dormitory after the end of the school year	48	51	96	167	171	3.68
Winners can participate in the research of low-carbon project teams and have the opportunity to publish high-quality papers	50	63	108	136	176	3.61
Subtotal	720	723	1400	1844	1709	3.50

Table A4. Reliability analysis of intervention questionnaires.

Cronbach's α	Standardized Cronbach's α	Number of Items
0.962	0.962	12

Table A5. Table of factor loading coefficients.

Factors	Variables	Non-Standard Load Factors	Standard Load Factors	z	S.E.	p
f1	Question 1	1	0.063	-	-	-
	Question 2	23.67	0.748	0.142	166.986	0.887
	Question 3	13.204	0.69	0.142	93.207	0.887
	Question 4	24.39	1	0.142	171.828	0.887
f2	Question 5	1	0.987	-	-	-
	Question 6	0.494	0.941	5.639	0.088	0.000 ***
	Question 7	0.829	0.985	9.426	0.088	0.000 ***
	Question 8	0.992	0.987	9.666	0.103	0.000 ***

Table A5. *Cont.*

Factors	Variables	Non-Standard Load Factors	Standard Load Factors	z	S.E.	p
f3	Question 9	1	0.914	-	-	-
	Question 10	1.204	0.993	4.828	0.249	0.000 ***
	Question 11	1.083	0.994	4.862	0.223	0.000 ***
	Question 12	0.897	0.941	3.895	0.23	0.000 ***

*** $p < 0.01$.

Table A6. Table of factor loading coefficients.

Latent Variables	Latent Variables	Non-Standard Coefficient	Standard Coefficient	Standard Error	Z	p
f1	f2	42.990	0.707	303.432	0.142	0.887
f1	f3	−14.539	−0.333	102.600	−0.142	0.887
f2	f3	0.861	1.199	0.203	4.243	0.000 ***

*** $p < 0.01$

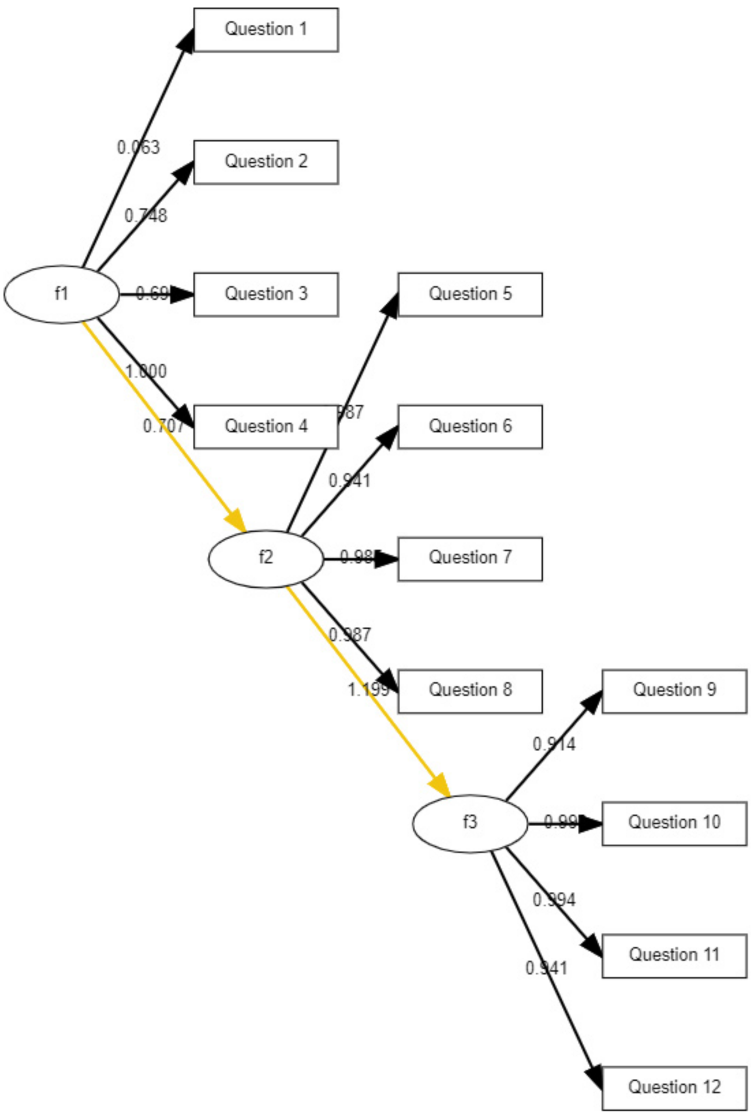


Figure A2. Structural Equation Model Path Diagram.

References

1. Li, R.; Wang, Q.; Liu, Y.; Jiang, R. Per-capita carbon emissions in 147 countries: The effect of economic, energy, social, and trade structural changes. *Sustain. Prod. Consum.* **2021**, *27*, 1149–1164. [CrossRef]
2. Wang, Q.; Wang, X.; Li, R. Does urbanization redefine the environmental Kuznets curve? An empirical analysis of 134 Countries. *Sustain. Cities Soc.* **2022**, *76*, 103382. [CrossRef]
3. Xu, H.; Kim, J.I.; Zhang, L.; Chen, J. LOD2 for energy simulation (LOD2ES) for CityGML: A novel level of details model for IFC-based building features extraction and energy simulation. *J. Build. Eng.* **2023**, *78*, 107715. [CrossRef]
4. Zhang, B.; Wang, Q.; Wang, S.; Tong, R. Coal power demand and paths to peak carbon emissions in China: A provincial scenario analysis oriented by CO2-related health co-benefits. *Energy* **2023**, *282*, 128830. [CrossRef]
5. Sedlacek, S. The role of universities in fostering sustainable development at the regional level. *J. Clean. Prod.* **2013**, *48*, 74–84. [CrossRef]
6. Ding, Y.; Ivanko, D.; Cao, G.; Brattebø, H.; Nord, N. Analysis of electricity use and economic impacts for buildings with electric heating under lockdown conditions: Examples for educational buildings and residential buildings in Norway. *Sustain. Cities Soc.* **2021**, *74*, 103253. [CrossRef]
7. Edwards, K.T. Venus in the Unvisible: Accounting for AntiBlackness in the International Higher Education Research Archive. *Educ. Stud.* **2023**, *59*, 440–452. [CrossRef]
8. Tan, H.; Chen, S.; Shi, Q.; Wang, L. Development of green campus in China. *J. Clean. Prod.* **2014**, *64*, 646–653. [CrossRef]
9. Huang, L.; Liu, Y.; Krigsvoll, G.; Johansen, F. Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou. *J. Clean. Prod.* **2018**, *173*, 151–159. [CrossRef]
10. Zheng, N.; Li, S.; Wang, Y.; Huang, Y.; Bartoccid, P.; Fantozzid, F.; Huang, J.; Xing, L.; Yang, H.; Chen, H.; et al. Research on low-carbon campus based on ecological footprint evaluation and machine learning: A case study in China. *J. Clean. Prod.* **2021**, *323*, 129181. [CrossRef]
11. Wang, T.; Shen, B.; Han Springer, C.; Hou, J. What prevents us from taking low-carbon actions? A comprehensive review of influencing factors affecting low-carbon behaviors. *Energy Res. Soc. Sci.* **2021**, *71*, 101844. [CrossRef]
12. Abd Rashid, A.F.; Yusoff, S. A review of life cycle assessment method for building industry. *Renew. Sustain. Energy Rev.* **2015**, *45*, 244–248. [CrossRef]
13. Larsen, H.N.; Pettersen, J.; Solli, C.; Hertwich, E.G. Investigating the Carbon Footprint of a University—The case of NTNU. *J. Clean. Prod.* **2013**, *48*, 39–47. [CrossRef]
14. Ozawa-Meida, L.; Brockway, P.; Letten, K.; Davies, J.; Fleming, P. Measuring carbon performance in a UK University through a consumption-based carbon footprint: De Montfort University case study. *J. Clean. Prod.* **2013**, *56*, 185–198. [CrossRef]
15. Del Borghi, A.; Spiegelhalter, T.; Moreschi, L.; Gallo, M. Carbon-Neutral-Campus Building: Design Versus Retrofitting of Two University Zero Energy Buildings in Europe and in the United States. *Sustainability* **2021**, *13*, 9023. [CrossRef]
16. Du, J.; Pan, W. Diverse occupant behaviors and energy conservation opportunities for university student residences in Hong Kong. *Build. Environ.* **2021**, *195*, 107730. [CrossRef]
17. Ayeleru, O.O.; Adeniran, J.A.; Ntsaluba, S.; de Koker, J.J. Comparative study on energy consumption at the University of Johannesburg residences. In Proceedings of the 2017 International Conference on the Domestic Use of Energy (DUE), Cape Town, South Africa, 4–5 April 2017; IEEE: New York, NY, USA, 2017; pp. 67–75.
18. Aghamolaei, R.; Fallahpour, M. Strategies towards reducing carbon emission in university campuses: A comprehensive review of both global and local scales. *J. Build. Eng.* **2023**, *76*, 107183. [CrossRef]
19. Xu, X.; Zou, P.X.W. Analysis of factors and their hierarchical relationships influencing building energy performance using interpretive structural modelling (ISM) approach. *J. Clean. Prod.* **2020**, *272*, 122650. [CrossRef]
20. Li, X.; Tan, H.; Rackes, A. Carbon footprint analysis of student behavior for a sustainable university campus in China. *J. Clean. Prod.* **2015**, *106*, 97–108. [CrossRef]
21. Ouyang, J.; Hokao, K. Energy-saving potential by improving occupants' behavior in urban residential sector in Hangzhou City, China. *Energy Build.* **2009**, *41*, 711–720. [CrossRef]
22. Chen, S.; Wang, X.; Lun, I.; Chen, Y.; Wu, J.; Ge, J. Effect of inhabitant behavioral responses on adaptive thermal comfort under hot summer and cold winter climate in China. *Build. Environ.* **2020**, *168*, 106492. [CrossRef]
23. Ueno, T.; Sano, F.; Saeki, O.; Tsuji, K. Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Appl. Energy* **2006**, *83*, 166–183. [CrossRef]
24. Al-Kababji, A.; Alsalemi, A.; Himeur, Y.; Fernandez, R.; Bensaali, F.; Amira, A.; Fetais, N. Interactive visual study for residential energy consumption data. *J. Clean. Prod.* **2022**, *366*, 132841. [CrossRef]
25. Hax, D.R.; Leitzke, R.K.; da Silva, A.C.S.B.; da Cunha, E.G. Influence of user behavior on energy consumption in a university building versus automation costs. *Energy Build.* **2022**, *256*, 111730. [CrossRef]
26. Chen, S.; Zhang, G.; Xia, X.; Chen, Y.; Setunge, S.; Shi, L. The impacts of occupant behavior on building energy consumption: A review. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101212. [CrossRef]
27. Si, H.; Duan, X.; Zhang, W.; Su, Y.; Wu, G. Are you a water saver? Discovering people's water-saving intention by extending the theory of planned behavior. *J. Environ. Manage.* **2022**, *311*, 114848. [CrossRef] [PubMed]
28. Chen, M.-F. Extending the theory of planned behavior model to explain people's energy savings and carbon reduction behavioral intentions to mitigate climate change in Taiwan–moral obligation matters. *J. Clean. Prod.* **2016**, *112*, 1746–1753. [CrossRef]

29. Xue, L.; Li, C.; Cai, E.; Wan, W.; Wei, S.; Yu, Z.; Xu, H. Evaluation of the impact of moral dissonance-based low-carbon interventions on consumer behavior. *J. Clean. Prod.* **2023**, *425*, 138947. [CrossRef]
30. Su, X.; Huang, Y.; Chen, C.; Xu, Z.; Tian, S.; Peng, L. A dynamic life cycle assessment model for long-term carbon emissions prediction of buildings: A passive building as case study. *Sustain. Cities Soc.* **2023**, *96*, 104636. [CrossRef]
31. Li, X.; Wang, C.; Kassem, M.A.; Wu, S.-Y.; Wei, T.-B. Case Study on Carbon Footprint Life-Cycle Assessment for Construction Delivery Stage in China. *Sustainability* **2022**, *14*, 5180. [CrossRef]

buildings

MDPI

Article

Nature-Based Solutions and Climate Resilience: A Bibliographic Perspective through Science Mapping Analysis

Farnoosh Vazin [1], Daniel W. M. Chan [2], Toktam Hanaee [1,*] and Hadi Sarvari [3,*]

[1] Department of Urbanism, Mashhad Branch, Islamic Azad University, Mashhad 9187147578, Iran; far.vazin@mshdiau.ac.ir
[2] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; daniel.w.m.chan@polyu.edu.hk
[3] Department of the Built Environment, Birmingham City University, City Centre Campus, Millennium Point, Birmingham B4 7XG, UK
* Correspondence: t.hanaee@mshdiau.ac.ir (T.H.); hadi.sarvari@bcu.ac.uk (H.S.); Tel.: +44-75-8743-0750 (H.S.)

Abstract: Currently, urban areas are confronting considerable challenges stemming from climate change. These challenges possess the potential to have profound implications for the well-being of residents, their means of making a living, and their own assets. Consequently, it is imperative to identify effective solutions that mitigate these effects on the urban environment. Nature-based solutions (NBSs), involving the utilization of natural resources and ecosystem services to alleviate the effects of climate change, have the potential of enhancing our capacity to develop cities that are more resistant to these challenges. To this end, this paper aims to extract some bibliographic data from available research articles on NBSs and climate resilience sought from the common search engines of Scopus, Web of Science, and Lens Base, and then the RStudio version 2022.12.00+353, VoSviewer version 1.6.20, and Biblioshiny-Bibliometrics version 2017 software tools were adopted to collate and analyze the literature data through science mapping analysis. In doing so, it was advocated that these two topics have not been extensively studied in their relationship to each other and that there is a large extent of existing knowledge gaps, the filling of which can foster the development of these ideas and thus help develop our cities in combating against climate change. Exploring the effectiveness of NBSs in boosting climate resilience is a critical research gap. More empirical studies are envisaged to assess the scalability and transferability of those effective NBSs in various regions or countries. Another research gap exists in comprehending the long-term effects on ecosystem services and community welfare. Research on socio-economic advantages, trade-offs, and unintended outcomes is essential for making well-informed decisions when applying various NBSs worldwide.

Keywords: nature-based solutions (NBSs); climate resilience; climate change; bibliographic review; science mapping analysis

1. Introduction

The idea of nature-based solutions (NBSs) has developed as a broad term that includes concepts like green/blue/nature infrastructure, the ecosystem approach, and ecosystem services. Essentially, an NBS involves drawing insights from and utilizing nature to establish a sustainable and resilient urban environment, given the significant climate change challenges that cities are experiencing and will continue to face. These challenges have the potential to have serious repercussions on human health, livelihoods, and assets, particularly impacting the urban poor, informal settlements, and other vulnerable communities [1]. Climate change impacts encompass a range of issues, from an uptick in extreme weather events and flooding to heightened temperatures and health concerns. It is estimated that 90 of the world's largest cities, home to nearly 50% of the world's population, are located on ocean coasts. These areas, dangerously vulnerable to volatile weather and rising sea levels, face such a real and present danger that the United Nations estimates that nearly

200 million people a year will be displaced by rising sea levels by 2050 [2]. Building climate resilience cities, and along with that trying to slow down the process of global warming is important because if greenhouse gas emissions cannot be completely halted now, the earth will continue to warm steadily due to the accumulation of carbon dioxide in the atmosphere, so pragmatic mitigation strategies as well as effective adaptation measures have to be executed as early as possible [3]. Engaging in proactive measures to combat climate change is imperative for fostering international cooperation and policy development. Collaboration between countries, researchers, and policymakers is essential in formulating and implementing effective strategies or measures to reduce carbon emissions and adapt to a changing climate.

In addition to adapting cities to the phenomena associated with climate change, reducing their impact on the city, and reducing the emission and absorption of greenhouse gases in the atmosphere have become all the more vital nowadays. For this reason, a global plausible solution with minimal side effects on the ecosystem needs to be put forward to address this problem. NBSs can help us improve our capacity to build resilient cities at a lower cost than other strategies.

Urban climate resilience in cities refers to the capacity to sustain human and ecosystem functions in the face of disasters or crises, while also being able to adapt to sudden changes and continue to progress. This concept, also known as adaptive capacity, denotes a city's ability to effectively manage and swiftly recover from challenges or emergencies [4]. A resilient city possesses a resilient infrastructure and has the capacity to transform a crisis into an opportunity for positive growth [5]. NBSs involve the strategic preservation or rehabilitation of natural environments to complement traditionally built infrastructure, known as gray infrastructure. This approach has the potential to diminish the risk of disasters and enhance the resilience and cost-effectiveness of services in developing nations [6]. In the fields of disaster risk management (DRM) and water security, NBSs can serve as eco-friendly infrastructure tactics that complement conventional gray infrastructure systems [7]. NBSs also have the potential to promote community welfare, generate ecological advantages, and make advancements toward Sustainable Development Goals (SDGs) in ways that gray infrastructure alone is incapable of achieving [8]. Hard structures are indisputable and known to be an efficient way to mitigate the risk of climate hazards [9]. However, these structures often negatively impact the landscape and limit opportunities for multifunctional value. NBSs represent a multifaceted approach defined as strategies or interventions derived from natural systems, and are characterized by their cost-effectiveness, as well as their ability to yield environmental, social, and economic advantages. NBSs aim to bolster resilience by drawing inspiration from nature and harnessing its support to address a variety of challenges [10]. It is a well-established fact that defining NBSs requires the integration of various scientific fields and experts with different backgrounds who approach NBSs from their own disciplinary standpoints [11]. Dorst et al. [12] proposed that NBSs should mainly address sustainability challenges that result from urbanization and climate change. In contrast, Kabisch et al. [13] highlighted the positive contribution of NBSs toward biodiversity restoration. Frantzeskaki et al. [14], on the other hand, viewed NBSs primarily through a socio-ecological lens. However, some studies emphasize the multifunctionality of NBSs and their capability to tackle multiple societal challenges at once [15]. Furthermore, an apparent tendency exists to conflate the existing related actions with the NBS concept, such as managing green–blue infrastructure (GBI), conservation strategies, implementing ecological/environmental engineering projects, and ecosystem-based management. Generally, aside from these cases, NBSs can provide numerous general and collateral benefits, including improving air quality by reducing carbon dioxide levels in the atmosphere, revitalizing and renovating public spaces and enhancing the quality of people's lives, fostering biodiversity, improving micro-climates, and enhancing urban landscapes [16]. In the urban context, various terminologies can be employed to refer to NBSs. These include green infrastructure (GI), ecosystem-based adaptation (EbA), low-impact development (LID), water-sensitive urban design (WSUD), and best management practices [17]. These solutions have significant potential in urban settings as they can offer a wide range of ecosystem services [18–20]. NBSs can be employed independently or in conjunction with conventional infrastructure, facilitating urban resilience to climate change and enhancing resource management. Designing an NBS in the present context involves allocating space for natural elements and devising technical measures that are harmonized with the established surroundings, thereby establishing a new man-made green system capable of being integrated with our urban environment [21].

One of the primary knowledge gaps pertains to the long-term effectiveness and scalability of NBSs in different geographic regions and climatic conditions. Researchers are yet to fully understand how various nature-based interventions interact with complex environmental systems and how their efficacy evolves over time. Another prime area of concern that requires more attention is the economic valuation of NBSs and their cost-effectiveness as compared to traditional engineering approaches. Assessing the economic benefits and drawbacks of investing in NBSs can provide valuable insights for policymakers and stakeholders in prioritizing climate adaptation strategies.

The primary aim of this study is to investigate the prospective developments concerning both micro and macro intricacies associated with NBSs and climate resilience through a bibliographic review through the science mapping analysis of published research articles over these two domains. This endeavor will rely on existing research studies conducted on these two domains as a foundational basis for further exploration.

2. Methods of the Literature Search

A bibliographic review is significant within the realm of academic research as it entails the examination of various topics, keywords, and authors with the aim of establishing correlations among them while pinpointing the prevailing trends and focal points in scholarly publication pursuits. Such comprehensive assessments provide researchers with valuable insights into the evolutionary path of antecedent scholarly endeavors and offer glimpses into prospective developments [22]. This analysis aims to identify the predominant keywords in the article title, author-provided keywords, and abstract, thereby establishing a network that interconnects these keywords. The intensity of these connections is determined by the co-occurrence of these specific keywords across various articles. Therefore, the resulting network visualization illustrates both the frequency of a particular keyword across articles and its association with other linked keywords within the same articles [23].

By illuminating the interrelationships among different facets of research, bibliographic reviews serve to highlight the interconnectedness of certain domains while also pinpointing areas devoid of such connections. This discernment serves to unveil overlooked domains ripe for exploration. In addition, the use of previous studies that have used the bibliographic method to examine their topics and on the basis that bibliography can help to better analyze data in different topics and increase the citation approaches of the articles, the two research articles entitled "Artificial intelligence and machine learning in energy system: A bibliographic perspective [23]" and "Green marketing: A bibliographic perspective [24]" were investigated as the background references of using the bibliographic approach. Notably, the field of bibliometrics boasts numerous dedicated software tools tailored for facilitating in-depth bibliographic analyses [25]. However, the VoSviewer version 1.6.20 software tool, is considered one of the most suitable tools for generating network maps and organizing data. Co-developed by Waltman and van Eck [26], this software is freely available for use. The visual representations produced by VoSviewer encompass various entities like keywords, publications, and researchers that cater to the user's interests. Each map focuses on a single type of entity, with the potential links between them being illustrated by arcs. These elements and connections collectively form a network, where entities are often organized into clusters based on thematic similarities. VoSviewer is employed to conduct bibliographic analyses and explore interconnections among different areas of research. The program generates network and bibliometric visualizations illustrating the relationships among data elements through shared keywords, authors, journals, and similar criteria [26]. Initially, our search was focused on a specific set of terms: "nature-based solution" (as title keywords) and "climate resilience" (in the context of topics) (WoS: "nature based*"(Title) and "climate resilien*"(topic), Scopus: (TITLE-ABS-KEY ("climate resilien*") and TITLE-ABS-KEY ("nature based*"), Lens: Title: ("climate resilien*") OR (Abstract: ("climate resilien*") OR Full text: ("climate resilien*") AND (Title: ("nature based*") OR (Abstract: ("nature based*") OR (Keyword: ("nature based*") OR Field of study: ("nature based*")). The above protocols and word search forms are different depending on each database and the search limits within it. These aimed at identifying relevant academic literature in the specified field. Further, we extracted bibliographic data related to both NBSs and climate resilience from Scopus, Web of Science (WoS), and Lens Base. This search process was carried out in 2023 without any time frame restriction, and includes all the articles written and published in this field. In the second part, we merged the bibliographic files from three databases and removed the data that had been published twice using RStudio version 2022.12.00+353 software tool. Finally, we used the software tools (VoSviewer and Biblioshiny-Bibliometrics) for the bibliographic analysis. In total, 142 sources were extracted from the three search engine databases mentioned after removing identical data. Figure 1 illustrates the comprehensive process encompassing the initial keyword selection, data extraction from the Scopus, WoS, and Lens databases, as well as the subsequent classification and mapping of the obtained search results. In this research, a number of different disciplines, including environmental science, environmental studies, ecology, urban studies, regional urban planning, green sustainable science technology, water resources, biodiversity conservation, physical geography, etc. have been emphasized on this topic. By using these topics and the knowledge available in different disciplines, different research strategies can approach issues related to nature.

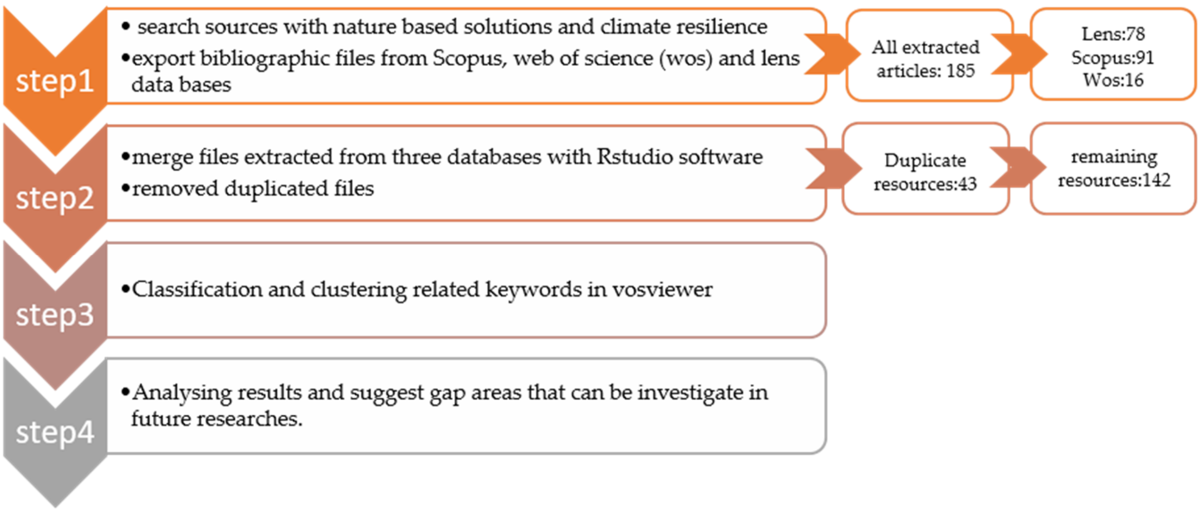


Figure 1. Overall literature search and analysis procedures of the study.

3. Results of the Bibliographic Review and Science Mapping Analysis

Combining NBSs with climate resilience is a new topic and the first few studies were published in 2014. Since 2019, a lot of attention has been paid to this topic and it is increasing day by day until it peaks between 2021 and 2022. The focus and number of publications in this area have grown incredibly in 6 years compared to 2014. This investigation exclusively incorporated published documents from the earlier half of 2023. Therefore, the decline did not stem from a reduction in NBS publications. Figure 2 shows the number of published articles on NBSs and climate resilience between 2014 and mid-2023.

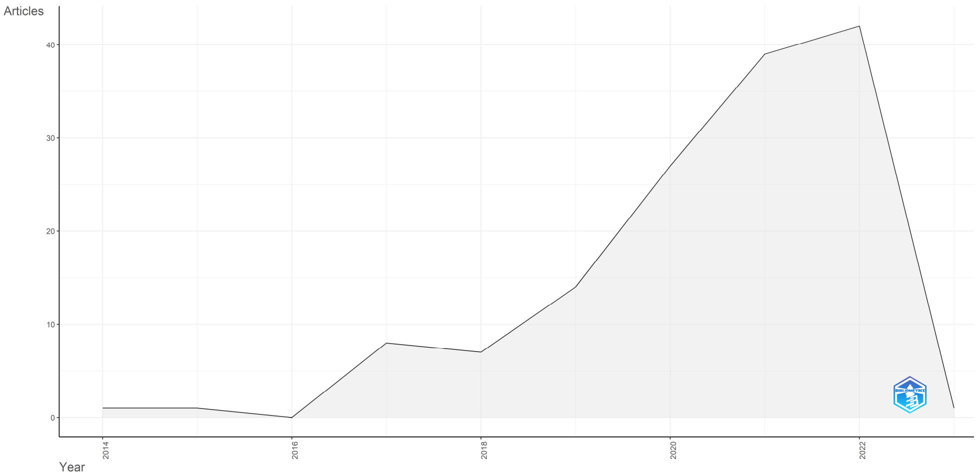


Figure 2. The number of published papers related to NBSs and climate resilience (2014–mid-2023) in Biblimetrix software v. 2017.

3.1. Co-Occurrence Analysis

Figure 3 depicts the interrelations among NBSs and climate resilience within the domain of climate change. The schematic delineates six principal clusters, symbolizing distinct realms of inquiry, which collectively delineate the intricate framework of this nexus. These categories encompass resilience and adaptation (green), water management (orange), coastal zone dynamics (purple), sustainable development considerations (blue), ecosystem services evaluation (red), and disaster risk mitigation strategies (yellow).

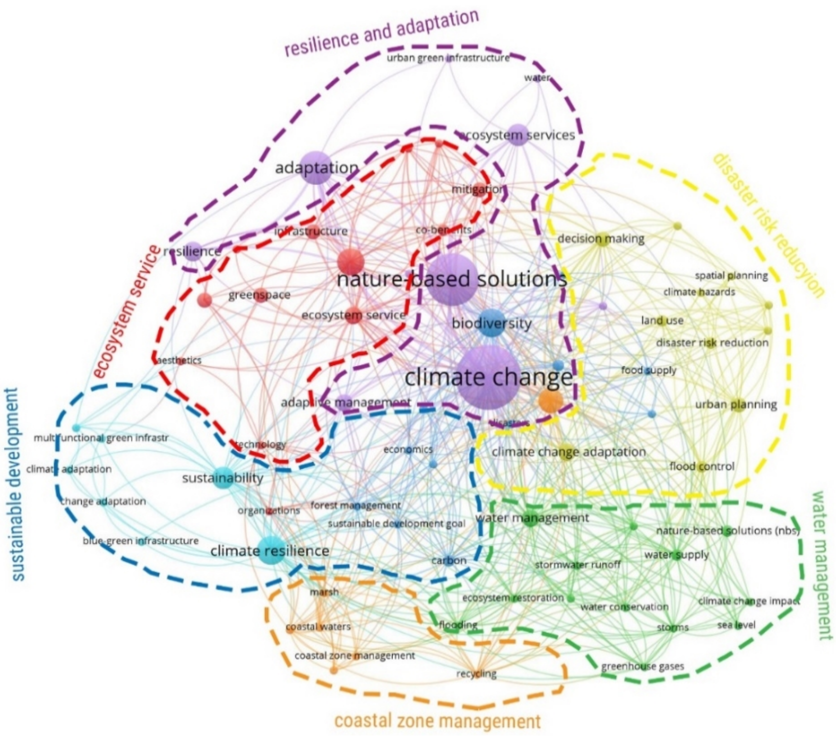


Figure 3. A comprehensive network of climate change, NBSs, and climate resilience with other climate change-related areas such as water management, coastal zone, sustainable development, ecosystem service, disaster risk reduction, and adaptation.

The network connections depicted in Figure 4 exemplify the opportunity to expand scholarly inquiries into unexplored domains. These uncharted research frontiers predominantly encompass subjects pertaining to technology, economics, coastal areas, spatial organization, urbanization, sea level fluctuations, food provisioning, and resource allocation.

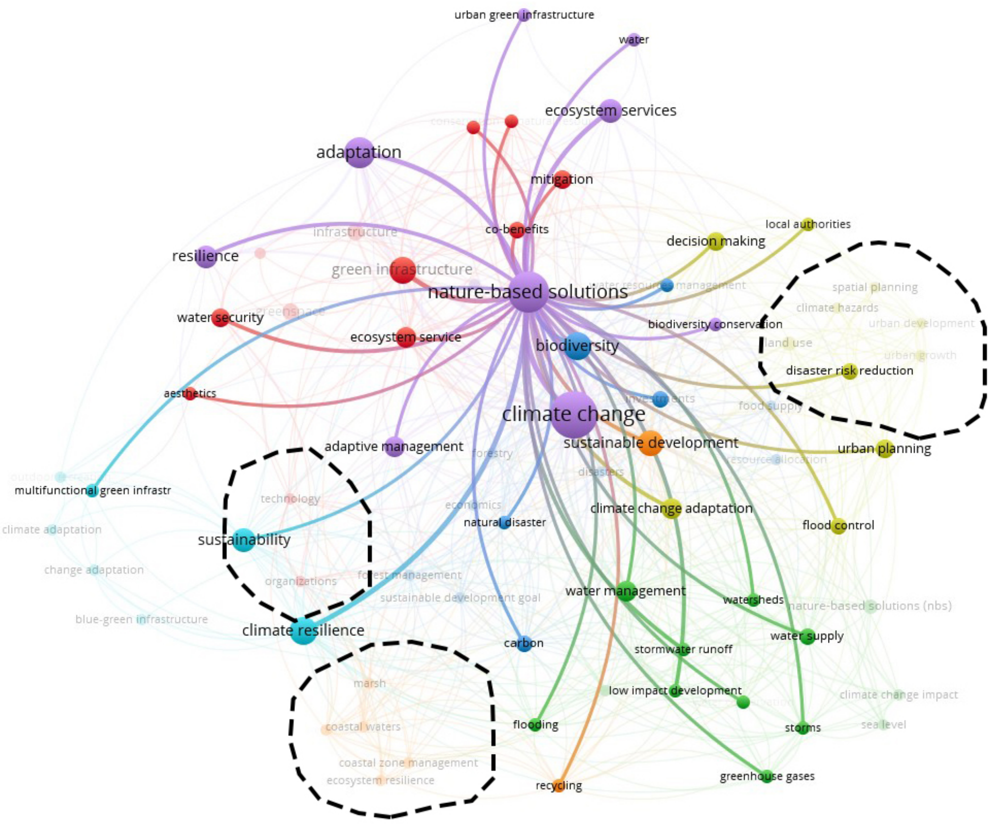


Figure 4. Network connections between NBSs and unresearched gap areas.

In the case of climate resilience, a smaller network was formed, as shown in Figure 5, related to the topic of NBSs. The existence of an unknown research area, despite there being more articles on climate resilience than on NBSs, may indicate a research gap in this area, but as it is a relatively new area like NBSs, it is yet to expand to other areas. The potential area for expanding the use of climate resilience in addition to those mentioned in the section on NBS may be local authorities, land use, spatial planning, economics, resurce allocation, common interests, and biodiversity conservation. In order to explain why two separate graphs have been presented for NBSs and climate resilience, an example from the mentioned graphs is provided. For instance, the use of technology as a separate solution alongside NBSs or as a complement to enhance climate resilience has been highlighted in articles that address the intersection of these two concepts. Therefore, in the graph depicting climate resilience studies (Figure 3), a strong relationship and bold line between the two terms, i.e., technology and climate resilience, can be observed. On the other hand, in the graph of NBSs (Figure 4), this term has a faint relationship. This indicates that there has been limited quantitative research on the impact of technology on improving the performance of NBSs or on the effects for managing these solutions and the extent of assistance that technology can provide in this regard. Another example regarding spatial planning and its impact on increasing climate resilience or its influence on how NBSs are designed in urban areas can be considered.

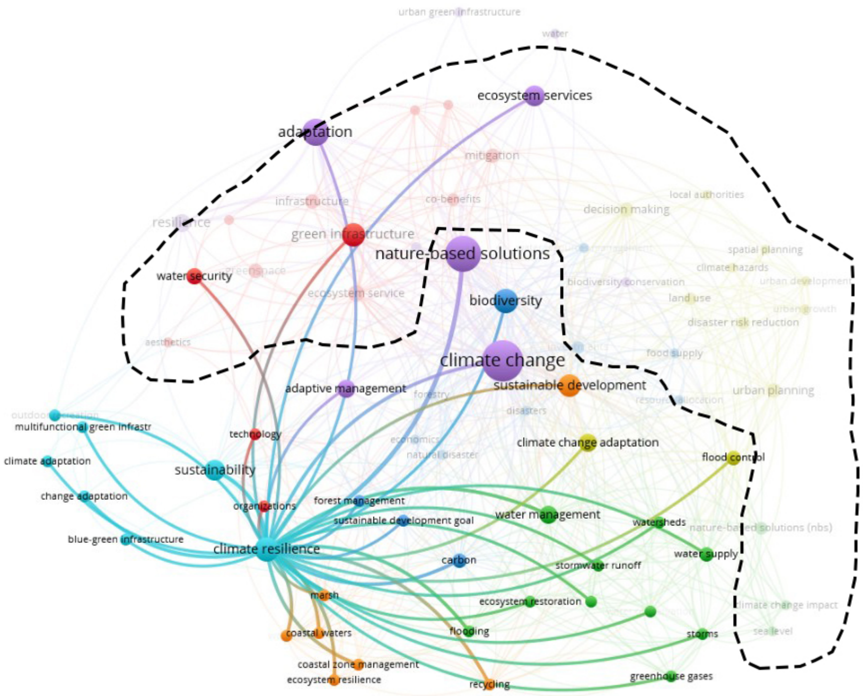


Figure 5. Network connections between climate resilience and unresearched gap areas.

3.2. Research Trends

To explore the prevailing research direction concerning climate change, with a particular focus on NBSs and enhancing resilience to climate impacts, we employed the VoSviewer software to develop a chronological representation of the scholarly publications in the field. Figure 6 shows the research trend in NBSs and climate resilience. As the trend analysis requires reviewing all the papers available in the areas of NBSs and climate resilience, we used all the papers available in Scopus, WoS, and Lense, as mentioned earlier, and combined these data into one comprehensive file.

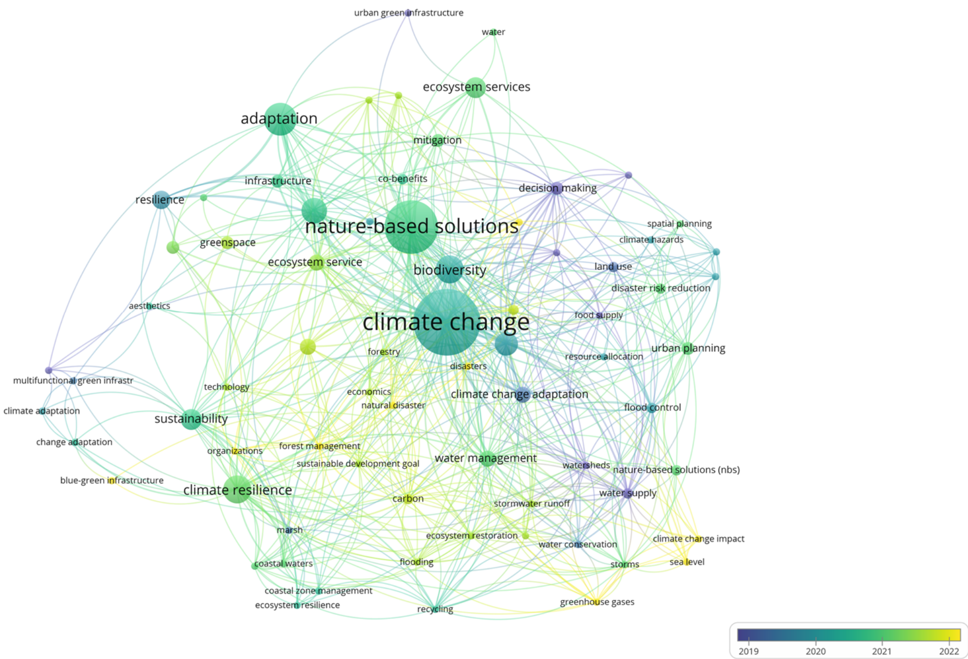


Figure 6. Research trends of NBS- and climate resilience-related topics in the climate change field.

Regarding the main topics in the field of climate resilience and NBSs, as shown in Figure 6, our results show that in the period of 2019 to 2021, most research papers examine climate change adaptation, food supply, water management, land use, spatial planning, sustainability, and sustainable development, etc. During the period of 2021 to 2022, concepts such as disaster risk reduction, ecosystem services, blue–green infrastructures, carbon dioxide, forest management, sea level rise, and flood management dominated the majority of research papers, as shown in Figure 7. Sustainability-related topics such as environmental impacts, global warming, greenhouse gases, carbon dioxide, climate resilience, adaptation strategies, ecosystem services, green infrastructures, biodiversity, and climate change have also received much attention and were repeated in several studies as the main keywords. In addition, flooding and coastal zone management were widely addressed. However, if the area of the circles is considered, even though these topics have been raised in recent years, they still have a relatively small share of studies dedicated to them, emphasizing their novelty in the realm of NBSs and climate resilience. This does not imply that these topics have been saturated and thoroughly explored from all dimensions; rather, it indicates that there are still many theoretical gaps to be addressed. The diagram reflects the approximate number of documents available on each topic based on the area of each circle, clearly showing the relative attention given to this subject as compared to the others. As observed, coastal management has allocated a small circle to itself in the diagram.

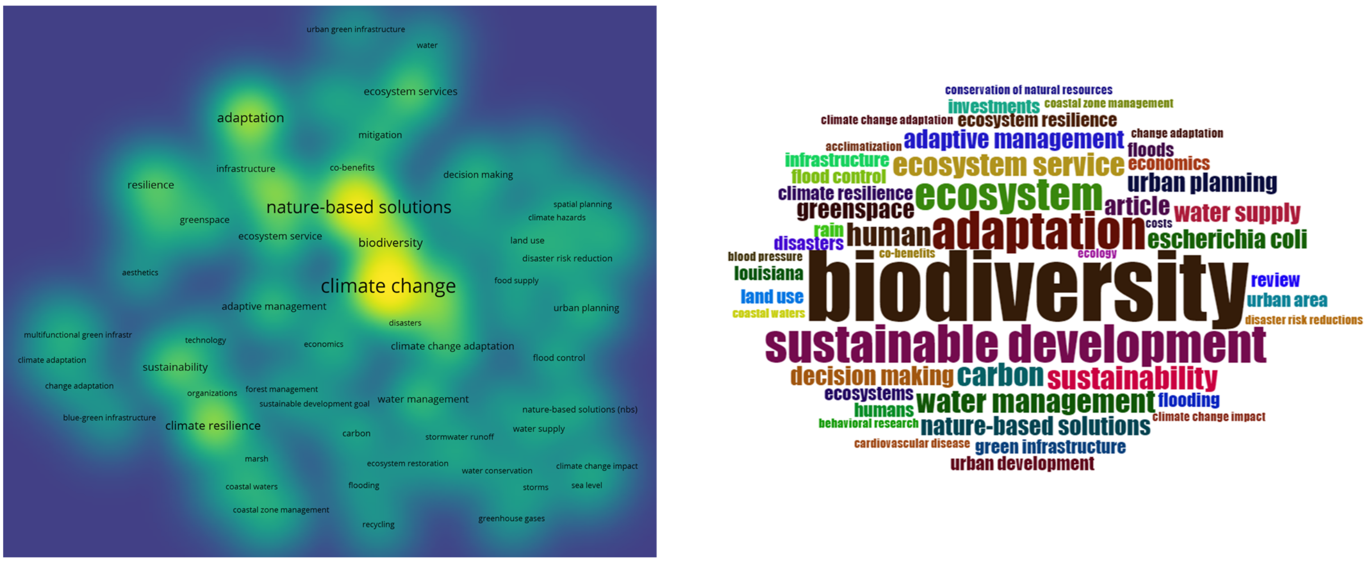


Figure 7. The main focus of the research topics of NBSs and climate resilience (keyword density).

In Figure 8, it can see that the ten topics related to climate change and resilience have seen the largest increase in articles in recent years, with NBSs growing the most, with a steep increase that started in 2020 and peaked between 2022 and 2023. At the next level are topics directly related to climate change and its causes, of which the growth began in 2018 and peaked in 2022 and 2023. The next tiers include topics related to green infrastructure, climate resilience, ecosystem services, greenhouse gas reduction measures, and water resource sustainability and protection. As can be seen, issues related to climate resilience have increased since 2020. In 2022 and 2023, there was a relatively large growth in the academic community. In general, it can be said that 2020 represents a turning point for the expansion of research related to NBSs and climate resilience and, due to its novelty, offers high potential for further research in this area.

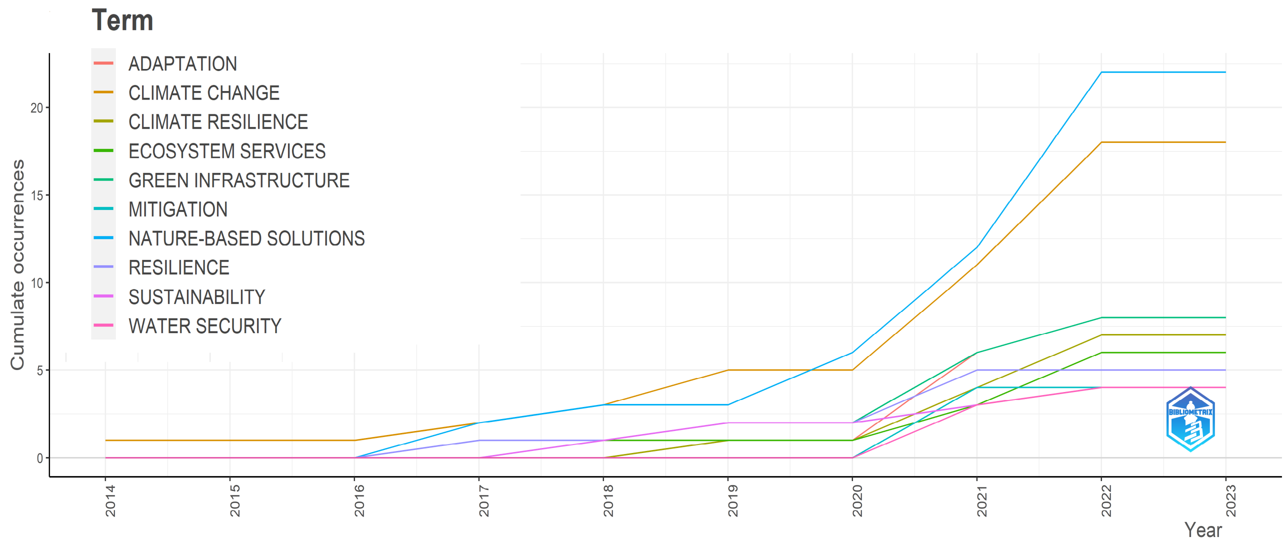


Figure 8. Ten major topics that have grown the most in recent years (2014–mid-2023) in Biblimetrix software version 2017.

3.3. Research Gaps

Based on our findings, a compilation of research gaps in NBSs and climate resilience is presented in Table 1. The highlighted challenges have garnered substantial attention within the research community in recent years. Furthermore, the discourse delves into specific topics that remain underexplored or have only been marginally investigated. A thorough examination of these subjects through additional studies has the potential to advance the field considerably. We propose that integrating technology NBSs to mitigate climate-related risks, along with the exploration of diverse renewable energy sources, will significantly bolster forthcoming research efforts in these realms to yield a holistic outcome. As delineated in Table 1, certain subjects have been extensively explored while others have garnered less scrutiny. The limited connection between these subjects could stem from insufficient research endeavors or the feeble association denoted by the scant number of studies conducted on the particular subject matter. In the provided sources, each of them has referred to these gaps as research voids in the field of climate resilience and NBSs, and the images in Table 1 can potentially reflect the accuracy of these opinions that have been cited in the conclusions. These voids may be even more extensive but require examination in each specific area and must be addressed as conclusions by documents studied in this regard. For example, the possibility of designing multi-purpose areas for climate flexibility and recreation should be examined separately and in detail in a document and ultimately concluding that there is an apparent knowledge gap in this area. That is, while the article is bibliographic and should gather information from other articles to identify potential research voids and the paths that researchers have taken in this field, researchers can use this document to better select their study areas in the common subject of NBSs and climate resilience. Therefore, first, research voids have been collected as much as possible from published documents that have referred to them as research voids, and on the other hand, using the VOSviewer chart and showing the weak relationship with the mentioned voids, the accuracy of the information stated in the sources has been addressed.

Table 1. Research gaps in NBSs and climate resilience.

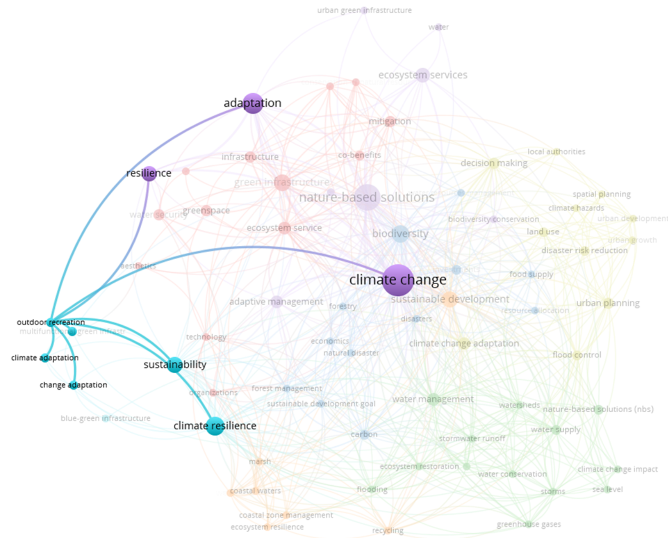
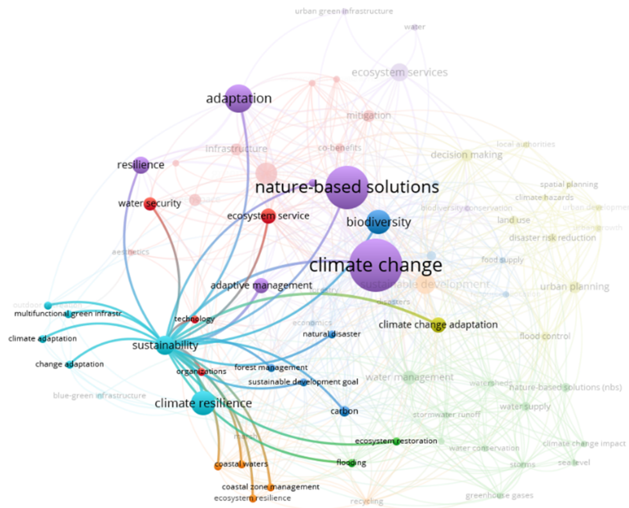
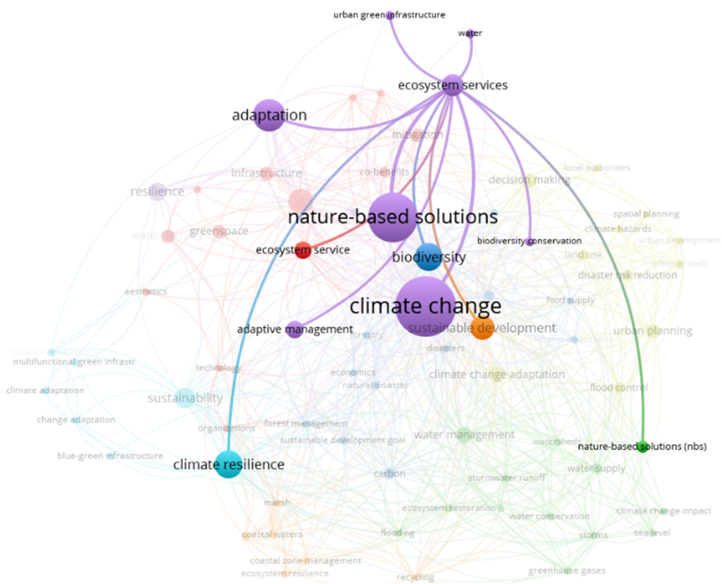
Research Gap	Connections
Connections with outdoor recreation • designing multifunctional areas for climate resilience and recreation [27] • the role of NBSs in shaping multifunctional land use [28] • multifunctional outdoor recreation and flood management in flood-prone areas [29]	
Sustainability • ways in which water management can improve sustainability [30] • using ecosystem services for greater sustainability [31] • using NBSs for economic sustainability in cities [32]	
Ecosystem services • using technology to expand ecosystem services [20] • using ecosystem services to support nutrient cycling food supply and resource allocation [33] • ways in which ecosystem services can contribute to sustainability [31] • using ecosystem services for cultural purposes and nature recreation [34] • using ecosystem services for wastewater management [35] • using technology to improve ecosystem services and resilience [36] • using urban and spatial planning to improve or extend the resilience of urban ecosystems (how can we improve ecosystem resilience through urban and spatial planning strategies?) [37]	

Table 1. *Cont.*

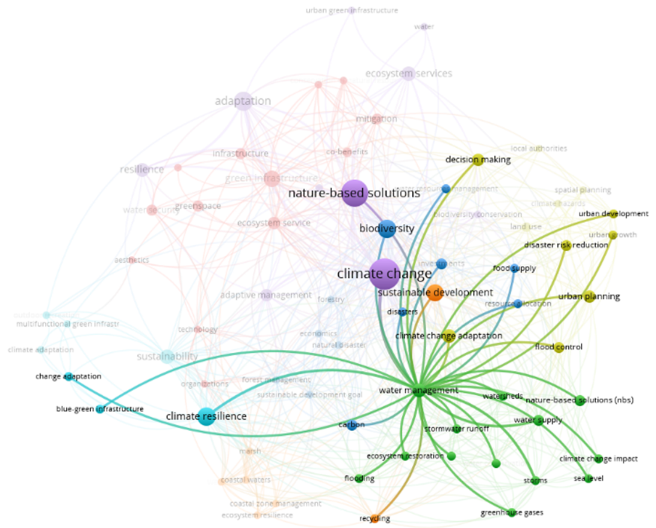
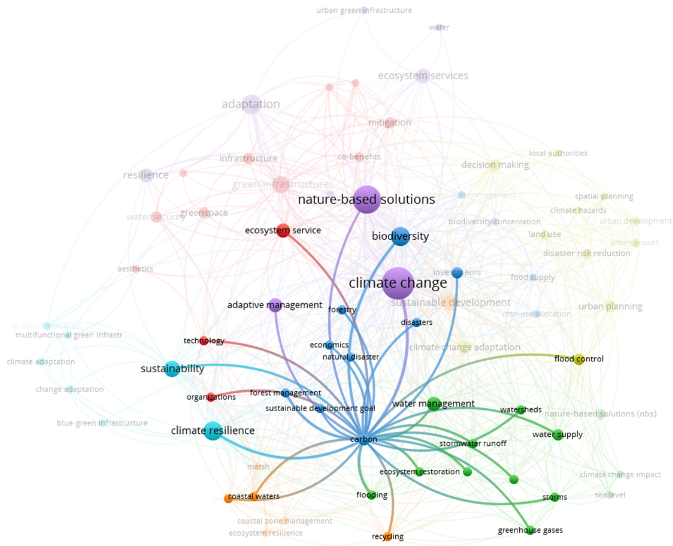
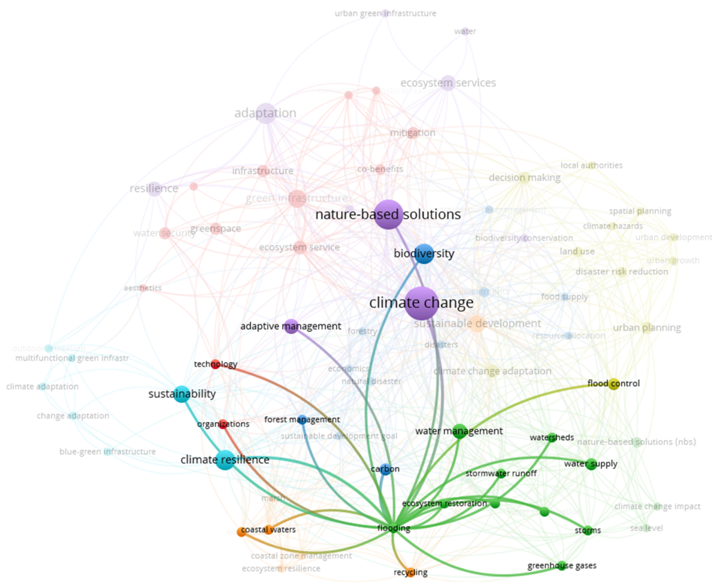
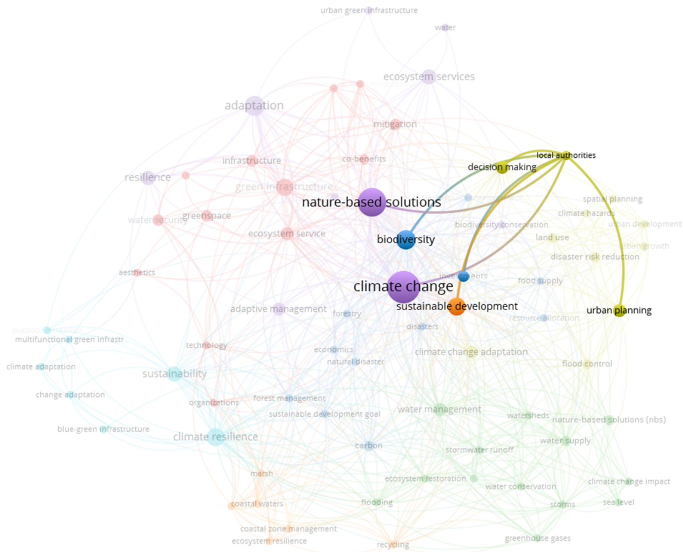
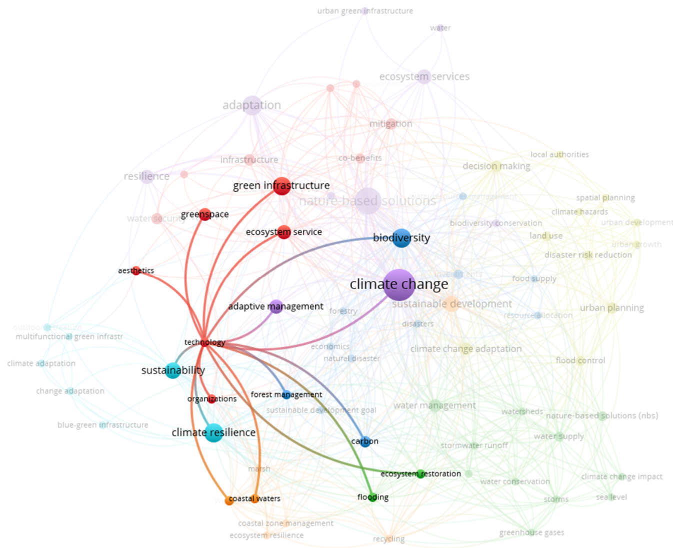
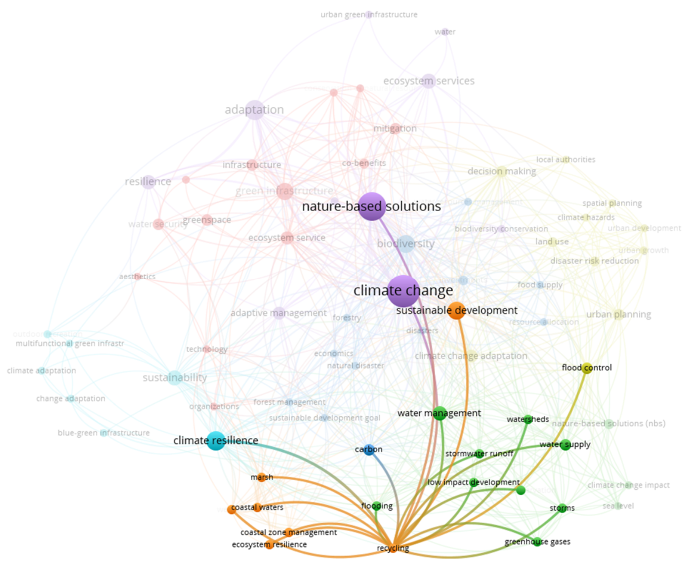
Research Gap	Connections
Water management • improving wastewater treatment by using the functions of NBSs [38] • forecasting the quantity of refuse and developing an intelligent system within water treatment facilities to facilitate immediate anticipatory management of sewage treatment [39] • creating an intelligent microgrid for waste management [40] • leveraging the Internet of Things (IoT) for the purpose of effectively handling domestic waste [41] • using ecosystem services for wastewater treatment [42]	
Mitigate and absorb carbon dioxide • investigating crucial elements in the cultivation of algal biomass and lipids for the generation of sustainable energy sources [43] • predicting future biomass yields of crops [44] • investigating the impact of climate change on carbon flux as a major driver of algal biofuel production [45] • technology potential for carbon uptake from the air and other resources [46] • prediction of renewable energy production [47] • accurate prediction of CO2 emissions [48]	
Flooding • the floating city and the use of NBSs to improve performance [49] • the role of ecosystem services in mitigating or preventing flooding [50] • sponge city with integrated NBSs and monitoring technology for wastewater management and reuse [51] • flood energy management for renewable energy generation [52]	

Table 1. *Cont.*

Research Gap	Connections
Local authorities and stakeholders • rules and instructions for using NBSs to mitigate climate hazards [53] • the role of local officials and shareholders in the degree to which nature-based strategies are feasible [54] • the importance of multifunctional space and economic benefits and the impact on the extent to which NBS plans are implemented [55]	
Technology • the combined performance of technology and NBSs for a more advantageous conclusion [56] • the role of technology in improving the efficiency of ecosystem services [56] • use of technology in urban agriculture and improvement of biomass production [57] • use of technology for the modeling and prediction of climate hazards [58]	
recycling • developing an intelligent microgrid to enhance the efficiency of waste management [40] • leveraging the Internet of Things for the purposes of household waste management [41] • bio-oil from recyclable sources and the role of NBSs in its production [59]	

3.4. Academic Journals in the NBS and Climate Resilience Fields

In order to enhance comprehension of the studies pertaining to nature-based solutions (NBSs) and the enhancement of climate resilience, an examination was conducted on the content published in prominent journals within this domain. As depicted in Figure 9, the primary journals wherein a significant volume of research on NBSs and climate resilience is disseminated are presented. The figure also illustrates the prevailing research trajectory through an analysis of the research articles submitted to various journals. It is evident from the data that initial research contributions on each topic are typically debuted in journals such as *Water* and *Coastal Management*, *Ecology and Society*, and the *Journal of Climate Change*. Subsequently, following the presentation of concepts in these journals, scholarly publications provide more specialized applications of research findings within these domains. Recent publications in the areas of NBSs and climate resilience have been published in journals such as *Frontiers in Sustainable Cities*, *Climate Change*, *Land Use Policy*, *Forest Ecology*, *and Management*.

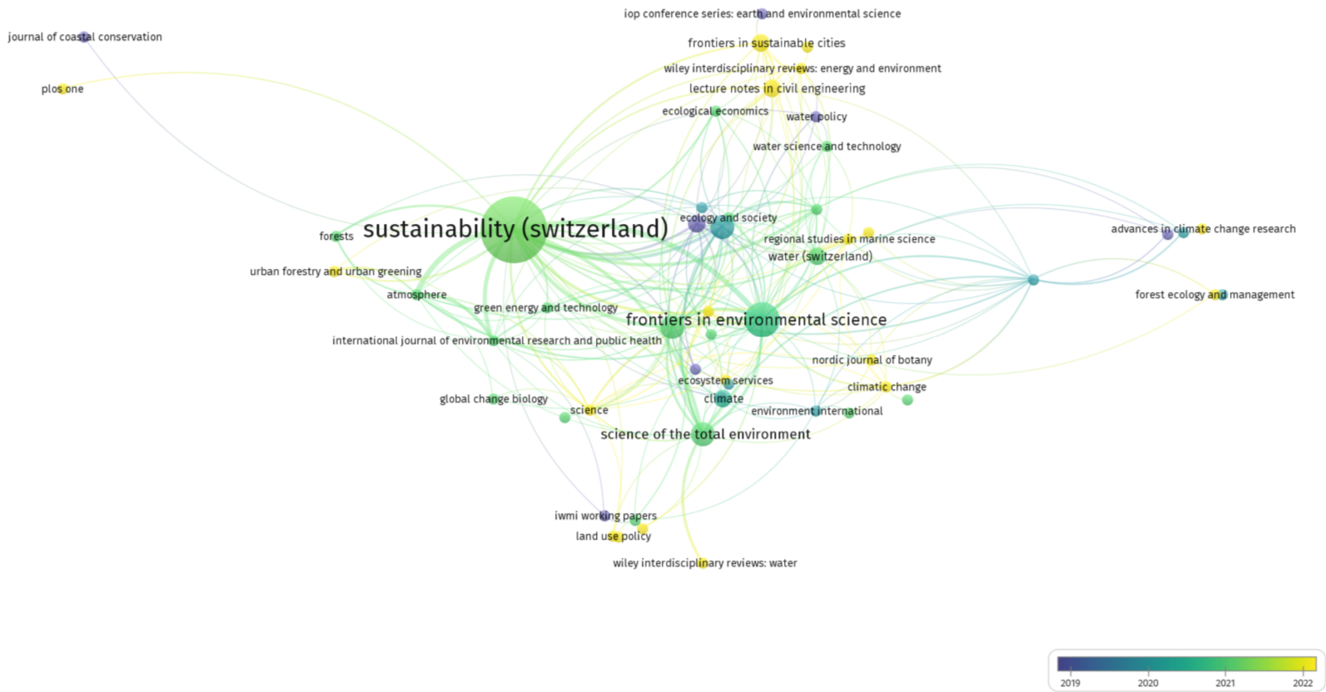


Figure 9. Primary publications in the field of natural and built environments and topics related to climate resilience within the discourse of climate change, along with an analysis of research distribution among various academic journals and identification of the journal with the highest volume of publications.

As revealed in Figures 10 and 11, most citations in the areas of NBSs and climate resilience are found in journals such as Environmental Science and Policy, Frontiers of Environmental Sciences, and general environmental science journals. Figure 10 additionally displays the quantity of academic papers that were submitted to a variety of scholarly journals from 2014 to 2022.

As can be discerned, the journals Sustainability (Switzerland), Frontiers in Environmental Science, and Science of the Total Environment published most of these research papers.

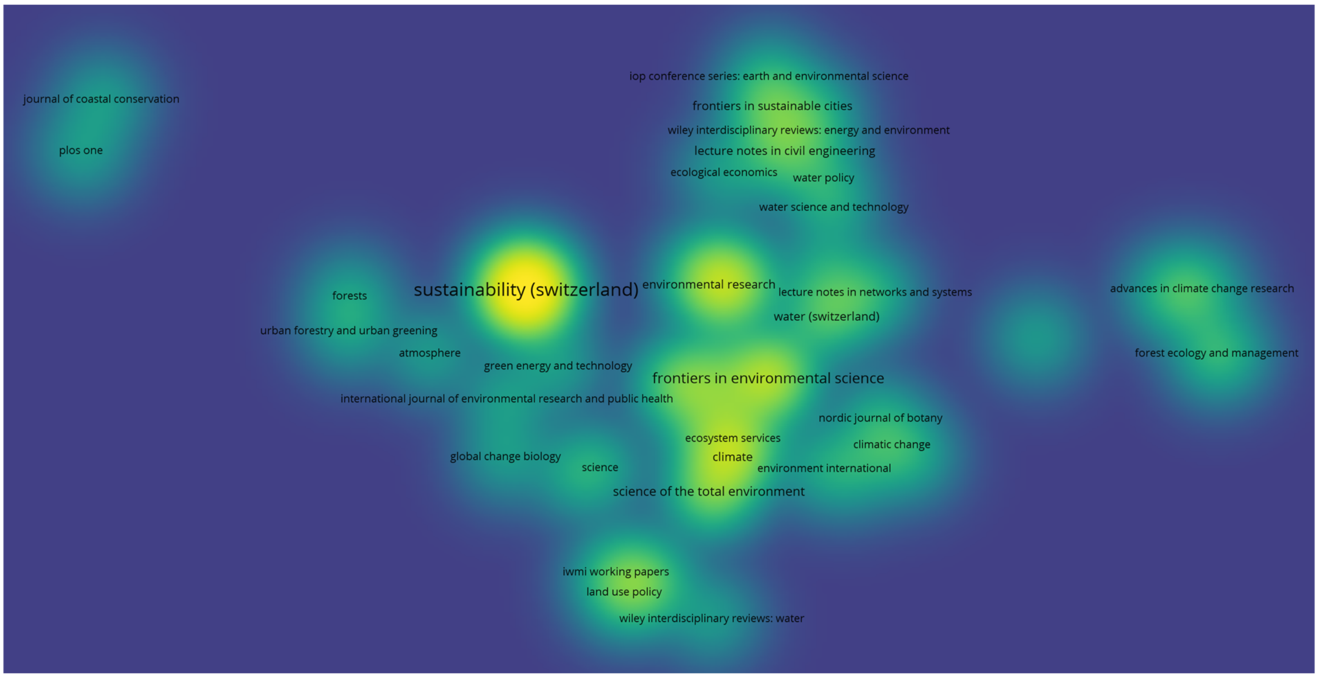


Figure 10. The number of research studies published in different academic journals.

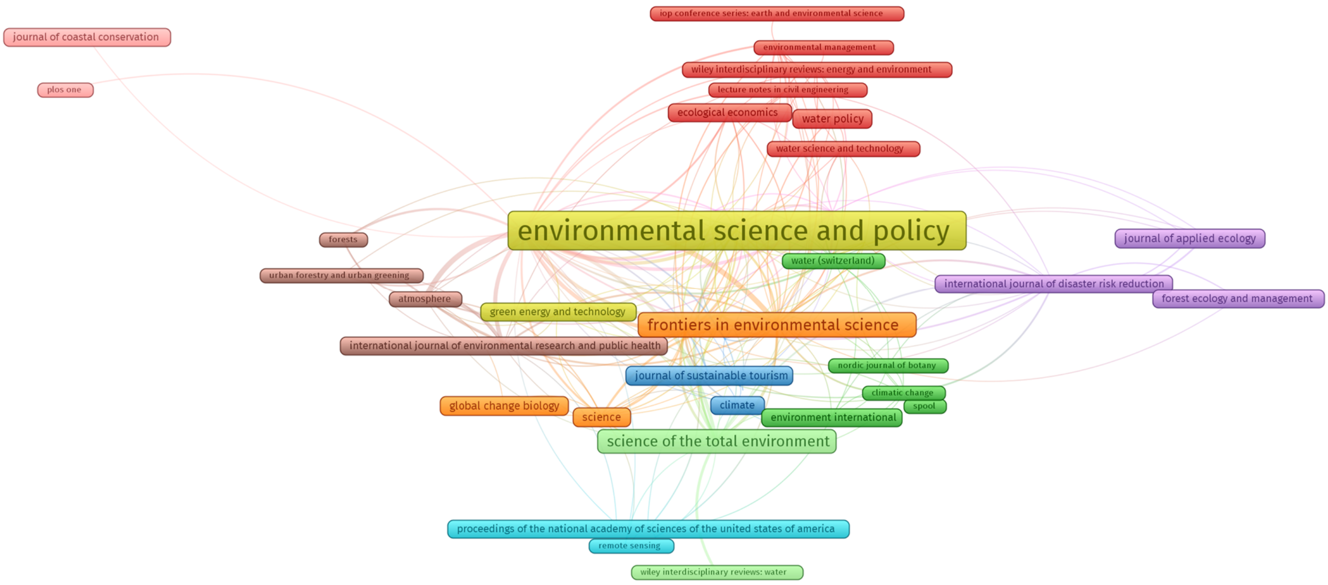


Figure 11. Primary journals within the field of natural and built systems and topics related to climate resilience in the domain of climate change, and the journals that have received higher citations.

3.5. Authors and Pioneering Countries Researching within the NBS and Climate Resilience Fields

Figure 12 shows the authors with the most publications, such as Frantzeskaki, Berry, Anderson, Losada, Raymond, etc., and each cluster shows the group of authors who have worked in the field of NBSs and climate resilience. Figure 13 shows the authors most frequently cited on the topic of climate resilience and NBSs.

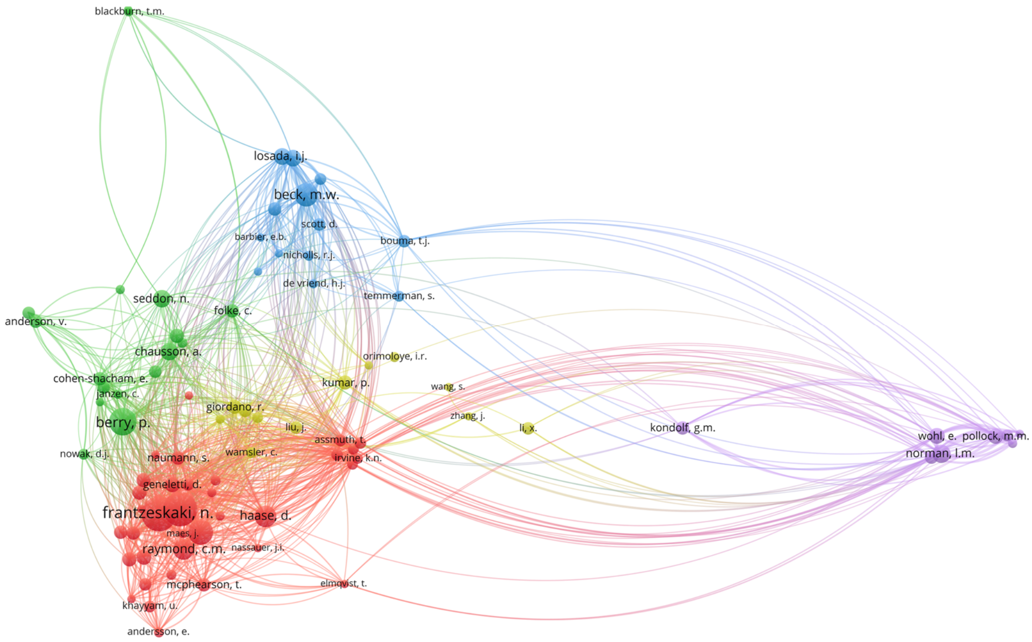


Figure 12. Authors that research NBSs and climate resilience, and their corresponding number of published documents.

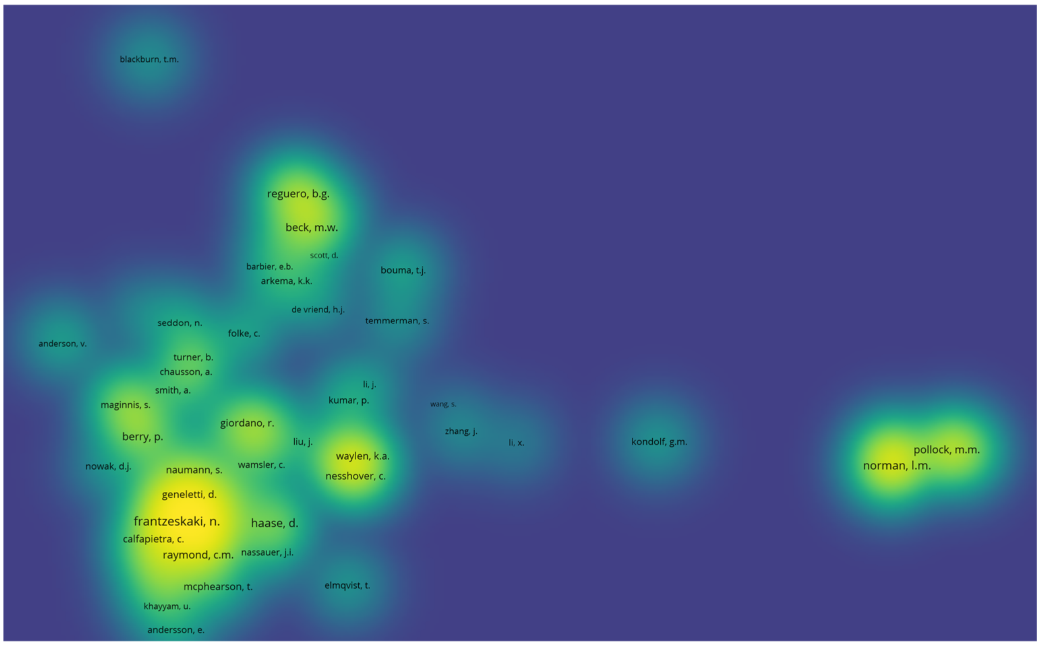


Figure 13. Distribution of the most cited authors within the NBS and climate resilience fields.

The countries where most research on NBS and climate resilience has been conducted are shown in Figure 14. Of the countries listed, the United States, the United Kingdom, and the Netherlands top the list. The most recent countries to conduct research on NBS and climate resilience between 2021 and 2022 are Germany, Spain, Japan, France, Switzerland, the United States, and Australia. This shows that the most important countries have joined within one year, indicating the importance of the topic.

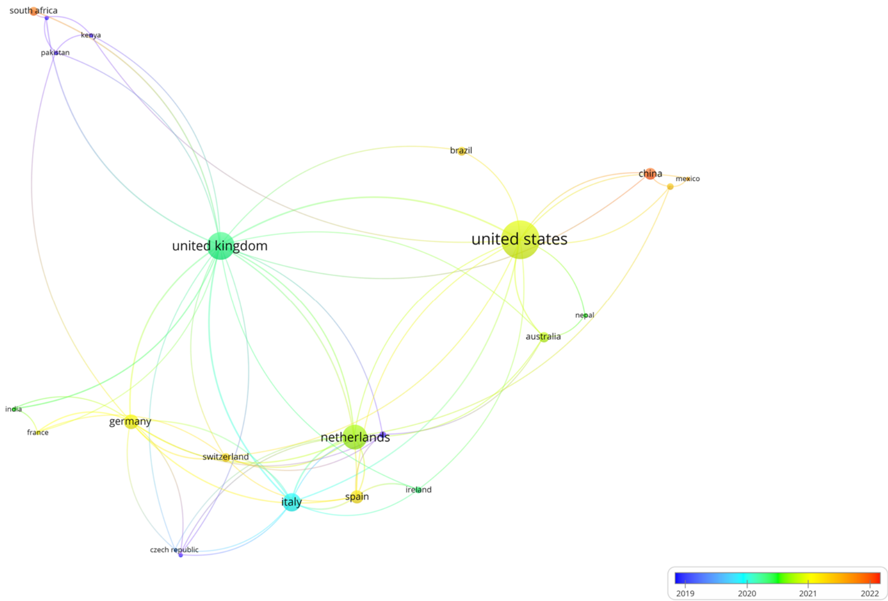


Figure 14. Countries that work within the NBS and climate resilience fields.

4. Discussion of the Review Findings and Conclusions

The results show that in 2014, the first studies were published in small numbers. Since 2017, NBSs and climate resilience became more important, especially after 2019, when the number of articles on NBSs and climate resilience increased. Within 6 years, the number increased tenfold compared to 2014. By analyzing the occurrence of keywords related to NBSs and climate resilience in the articles, it was determined that the existing literature can be categorized into six overarching groups: resilience and adaptation, water management, coastal areas, sustainable development, ecosystem services, and disaster risk reduction. Our study has uncovered many neglected areas where NBSs and climate resilience can be implemented. Some of these areas that need further investigation are outdoor recreation, sustainability, water management, ecosystem services, carbon mitigation and absorption, flooding, local government authorities and stakeholders, technology, and recycling. In relation to nature-oriented approaches, apart from the uninvestigated domains identified in the preceding sections, there exist concerns pertaining to technological advancements, economic considerations, coastal management, land use strategies, urban expansion, sea level escalation, food provisioning, and allocation of resources. Regarding climate resilience, the issues mentioned included local governance, land use, spatial planning, economics, resource allocation, co-benefits, biodiversity conservation, and many other applications. We also examined in detail the journals in which the studies were published. Research indicates that recent publications addressing NBSs and climate resilience tend to be featured in emerging academic journals over time. Notably, *Sustainability (Switzerland)*, *Frontiers in Environmental Science*, and *Science of the Total Environment* stand out as the primary platforms for disseminating articles on the subject matter.

As can be seen in the development graph in Figure 15, some topics in the articles are mainly used side by side and in conjunction with each other and have formed a group, or topics such as NBSs with a sponge city with a medium level of topic development. Based on nature, along with seeing its benefits, these topics have little relevance and require high development. Topics related to water management have little development in the articles and are one of the new emerging topics in this area of the study. On the other hand, topics related to climate resilience, green infrastructure, and adaptation strategies have high relevance and low development, and are among the basic topics for all topics in this study area. Topics such as green roofs, food security, urban agriculture, co-benefits of NBSs, spatial planning to reduce disaster risk, and the use of blue–green infrastructure are among the topics with applications that still require more research and knowledge, and positions such as sustainable development, climate adaptation, climate change mitigation, biodiversity, and sponge cities are among the driving and stimulating topics in this collection of articles. For this reason, issues related to economic water management and the benefits of using NBSs, as well as land use planning to reduce the risk of natural hazards and the use of water and green infrastructure, may be appropriate topics for further research.

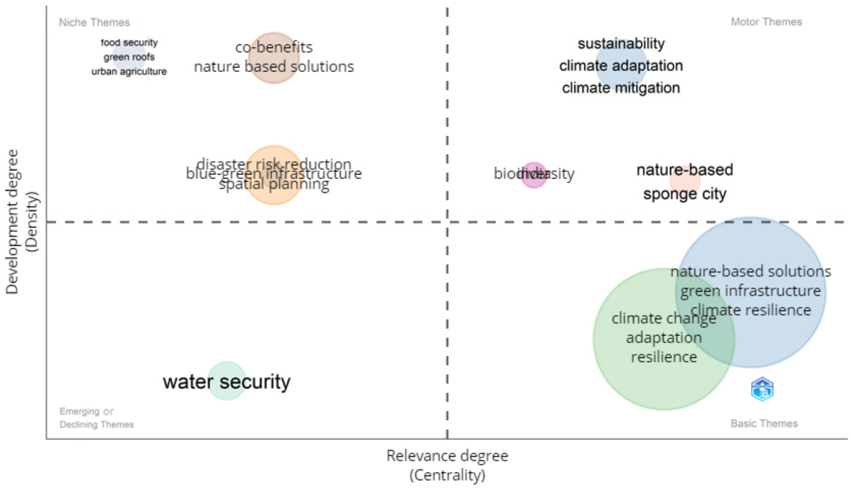


Figure 15. Development plot for NBSs and climate resilience research.

The perceived challenges that need to be addressed by NBSs are multi-dimensional and complex; therefore, the selection and evaluation of NBSs and related actions require the involvement of a wide spectrum of stakeholders, multidisciplinary teams, policymakers, and decision makers. Each policy or NBS implementation process should consider how to effectively monitor and evaluate the impact of interventions. One of the limiting factors is the lack of comprehensive and sufficient information and data regarding the impact, effectiveness, and consequences of NBSs on climate resilience. Sometimes, it is difficult to gain access to large and diverse datasets that are not always available for use and investigation. Another prime concern in this field is that some research studies may face methodological limitations, and their results may not be generalizable to other times and places. They may also encounter several profound challenges such as cultural resistance, resource management, and high costs. Moreover, sudden changes in urban development, social development patterns, and weather conditions can lead to serious drawbacks and damages to the implemented nature-based and climate resilient solutions. Therefore, future research in this area should aim to reduce uncertainties as much as possible, despite being time-consuming and costly.

In general, it can be said that the application of climate resilience issues and NBSs has received a lot of attention, as it is a very new topic that has experienced significant growth in recent years but has not been considered in many aspects that we have talked about in this research. One of the key issues is how to combine technology in a way that co-exists with NBSs, and whether these two can be used together in urban spaces and to what extent they can influence each other. Another aspect that warrants further examination is the capability of NBSs to establish versatile and multi-purpose areas to enhance climate resilience or leverage ecosystem services for this purpose. It can be noted that although the use of NBSs can increase climate resilience and prevent or reduce risks, and is very effective, many countries, especially in Asia and Africa, have not yet moved into this area or have only a small share of such studies despite facing such risks daily. It has been noted that most nature-based interventions can be implemented at different scales and a low cost, and with the help of nature due to the economic crisis in the world that most countries face and the high cost of implementing other strategies to reduce natural hazards. Nowadays, this can be regarded as a vital breakthrough.

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

Funding: This research received no external funding.

Data Availability Statement: The original contributions and data presented in the study are included in the article, and further inquiries can be directed to the corresponding authors.

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

References

1. World Bank. *Analysis of Heat Waves and Urban Heat Island Effects in Central European Cities and Implications for Urban Planning*; eLibrary, World Bank Group: Washington, DC, USA, 2020. [CrossRef]
2. Harms, A. Under the climate radar: Disaster and displacement in the Bengal Delta. In *Climate Justice and Migration: Mobility, Development, and Displacement in the Global South*; Heinrich Böll Stiftung: Berlin, Germany, 2020; pp. 150–155.
3. Clarke, B.; Otto, F.; Stuart-Smith, R.; Harrington, L. Extreme weather impacts of climate change: An attribution perspective. *Environ. Res. Clim.* **2022**, *1*, 012001. [CrossRef]
4. Lehmann, S. Nature in the Urban Context: Renaturalisation as an Important Dimension of Urban Resilience and Planning. *Modulo Arquit. CUC* **2021**, *26*, 161–190. [CrossRef]
5. Lehmann, S. Growing biodiverse urban futures: Renaturalization and rewilding as strategies to strengthen urban resilience. *Sustainability* **2021**, *13*, 2932. [CrossRef]
6. Ozment, S.; Ellison, G.; Jongman, B. *Nature-Based Solutions for Disaster Risk Management: Booklet*; United Nations Office for Disaster Risk Reduction (UNDRR): Geneva, Switzerland; The World Bank: Washington, DC, USA, 2019.
7. Ferreira, C.S.; Kalantari, Z.; Hartmann, T.; Pereira, P. *Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects*; Springer Nature: Berlin, Germany, 2022.
8. Scheiffer, R.G. Nature Based Solutions for Water Sensitive Communities: Governance Challenges and Opportunities in the Subsystem Vale do Lobo, Campina de Faro aquifer, Loulé, Portugal. Ph.D. Thesis, Universidade do Algarve, Faro, Portugal, 2023.
9. Bosher, L.; Dainty, A. Disaster risk reduction and 'built-in'resilience: Towards overarching principles for construction practice. *Disasters* **2011**, *35*, 1–18. [CrossRef] [PubMed]
10. Faivre, N.; Fritz, M.; Freitas, T.; De Boissezon, B.; Vandewoestijne, S. Nature-Based Solutions in the EU: Innovating with nature to address social, economic, and environmental challenges. *Environ. Res.* **2017**, *159*, 509–518. [CrossRef] [PubMed]
11. Wild, T.; Freitas, T.; Vandewoestijne, S. *Nature-Based Solutions: State of the Art in EU-Funded Projects*; Publications Office of the European Union: Luxembourg, 2020.
12. Dorst, H.; Van der Jagt, A.; Raven, R.; Runhaar, H. Urban greening through nature-based solutions–Key characteristics of an emerging concept. *Sustain. Cities Soc.* **2019**, *49*, 101620. [CrossRef]
13. Kabisch, N.; Frantzeskaki, N.; Pauleit, S.; Naumann, S.; Davis, M.; Artmann, M.; Haase, D.; Knapp, S.; Korn, H.; Stadler, J.; et al. Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecol. Soc.* **2016**, *21*, 39. [CrossRef]
14. Frantzeskaki, N.; McPhearson, T.; Collier, M.J.; Kendal, D.; Bulkeley, H.; Dumitru, A.; Walsh, C.; Noble, K.; Van Wyk, E.; Ordonez, C.; et al. Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience* **2019**, *69*, 455–466. [CrossRef]
15. Dumitru, A.; Wendling, L. *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*; European Commission EC: Brussels, Belgium, 2021.
16. Sowińska-Świerkosz, B.; García, J. What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. *Nat.-Based Solut.* **2022**, *2*, 100009. [CrossRef]
17. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L. SUDS, LID, BMPs, WSUD, and more–The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
18. Coutts, C.; Hahn, M. Green infrastructure, ecosystem services, and human health. *Int. J. Environ. Res. Public Health* **2015**, *12*, 9768–9798. [CrossRef]
19. Pacetti, T.; Castelli, G.; Bresci, E.; Caporali, E. Water values: Participatory water ecosystem services assessment in the Arno River basin, Italy. *Water Resour. Manag.* **2020**, *34*, 4527–4544. [CrossRef]
20. Sarvari, H.; Rakhshanifar, M.; Tamošaitienė, J.; Chan, D.W.M.; Beer, M. A Risk Based Approach to Evaluating the Impacts of Zayanderood Drought on Sustainable Development Indicators of Riverside Urban in Isfahan-Iran. *Sustainability* **2019**, *11*, 6797. [CrossRef]

21. Matthews, J.; Cruz, E.O.D. *Integrating Nature-Based Solutions for Climate Change Adaptation and Disaster Risk Management: A Practitioner's Guide*; ADB Publications: Metro Manila, Philippines, 2022. [CrossRef]
22. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
23. Entezari, A.; Aslani, A.; Zahedi, R.; Noorollahi, Y. Artificial intelligence and machine learning in energy systems: A bibliographic perspective. *Energy Strategy Rev.* **2023**, *45*, 101017. [CrossRef]
24. Lievano Pulido, Y.P.; Ramon-Jeronimo, M.A. Green Marketing: A Bibliographic Perspective. *Sustainability* **2023**, *15*, 16674. [CrossRef]
25. Daneshgar, S.; Zahedi, R.; Farahani, O. Evaluation of the concentration of suspended particles in subway stations in Tehran and its comparison with ambient concentrations. *Ann. Environ. Sci. Toxicol.* **2022**, *6*, 19–25. [CrossRef]
26. Van Eck, N.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
27. Scott, M.; Lennon, M.; Haase, D.; Kazmierczak, A.; Clabby, G.; Beatley, T. Nature-based solutions for the contemporary city/Re-naturing the city/Reflections on urban landscapes, ecosystems services and nature-based solutions in cities/Multifunctional green infrastructure and climate change adaptation: Brownfield greening as an adaptation strategy for vulnerable communities?/Delivering green infrastructure through planning: Insights from practice in Fingal, Ireland/Planning for biophilic cities: From theory to practice. *Plan. Theory Pract.* **2016**, *17*, 267–300. [CrossRef]
28. Zwierzchowska, I.; Fagiewicz, K.; Poniży, L.; Lupa, P.; Mizgajski, A. Introducing nature-based solutions into urban policy–facts and gaps. Case study of Poznań. *Land Use Policy* **2019**, *85*, 161–175. [CrossRef]
29. Chou, R.-J. Achieving successful river restoration in dense urban areas: Lessons from Taiwan. *Sustainability* **2016**, *8*, 1159. [CrossRef]
30. Sabale, R.; Venkatesh, B.; Jose, M. Sustainable water resource management through conjunctive use of groundwater and surface water: A review. *Innov. Infrastruct. Solut.* **2023**, *8*, 17. [CrossRef]
31. Yu, P.; Zhang, S.; Yung, E.H.K.; Chan, E.H.W.; Luan, B.; Chen, Y. On the urban compactness to ecosystem services in a rapidly urbanizing metropolitan area: Highlighting scale effects and spatial non–stationary. *Environ. Impact Assess. Rev.* **2023**, *98*, 106975. [CrossRef]
32. Almenar, J.B.; Petucco, C.; Sonnemann, G.; Geneletti, D.; Elliot, M.; Rugani, B. Modeling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem, em services, system dynamics, and life cycle thinking: An application to urban forests. *Ecosyst. Serv.* **2023**, *60*, 101506. [CrossRef]
33. Alcalá-Herrera, R.; Moreno, B.; Aguirrebengoa, M.; Winter, S.; Robles-Cruz, A.B.; Ramos-Font, M.E.; Benítez, E. Role of Agricultural Management in the Provision of Ecosystem Services in Warm Climate Vineyards: Functional Prediction of Genes Involved in Nutrient Cycling and Carbon Sequestration. *Plants* **2023**, *12*, 527. [CrossRef] [PubMed]
34. Kalinauskas, M.; Bogdzevič, K.; Gomes, E.; Inácio, M.; Barcelo, D.; Zhao, W.; Pereira, P. Mapping and assessment of recreational cultural ecosystem services supply and demand in Vilnius (Lithuania). *Sci. Total Environ.* **2023**, *855*, 158590. [CrossRef]
35. Ding, T.; Fang, L.; Chen, J.; Ji, J.; Fang, Z. Exploring the relationship between water-energy-food nexus sustainability and multiple ecosystem services at the urban agglomeration scale. *Sustain. Prod. Consum.* **2023**, *35*, 184–200. [CrossRef]
36. Pattanayak, S.; Arputham, R.M.; Goswami, M.; Rana, N.P. Blockchain Technology and Its Relationship with Supply Chain Resilience: A Dynamic Capability Perspective. *IEEE Trans. Eng. Manag.* **2023**, *71*, 10398–10412. [CrossRef]
37. Wang, L.; Gong, W.; Wang, C.; Li, W. Spatial-temporal evolution and influencing factors of urban ecosystem resilience in the Yellow River Basin. *Glob. NEST J.* **2023**, *25*, 66–76. [CrossRef]
38. Velasco, P.; Devanadera, M.C.; Dalisay, M.; Mueca, C.; Estorba, D.S.; Lecciones, A. Nature-based solutions for domestic wastewater treatment in the Philippines. In *Regional Perspectives of Nature-Based Solutions for Water: Benefits and Challenges*; Pachova, N., Velasco, P., Torrens, A., Jegatheesan, V., Eds.; Springer: Cham, Switzerland, 2023; pp. 175–201.
39. Xu, Y.; Wang, Z.; Nairat, S.; Zhou, J.; He, Z. Artificial Intelligence-Assisted Prediction of Effluent Phosphorus in a Full-Scale Wastewater Treatment Plant with Missing Phosphorus Input and Removal Data. *ACS EST Water* **2023**, *4*, 880–889. [CrossRef]
40. Mottahedi, S. Microgrid Energy Management System Control Using Reinforcement Learning. Ph.D. Dissertation, The Pennsylvania State University, State College, PA, USA, 2022.
41. Saad, M.; Ahmad, M.B.; Asif, M.; Khan, M.K.; Mahmood, T.; Mahmood, M.T. Blockchain-Enabled VANET for Smart Solid Waste Management. *IEEE Access* **2023**, *11*, 5679–5700. [CrossRef]
42. Ruíz Ordoñez, D.M.; Camacho De Angulo, Y.V.; Pencué Fierro, E.L.; Figueroa Casas, A. Mapping Ecosystem Services in an Andean Water Supply Basin. *Sustainability* **2023**, *15*, 1793. [CrossRef]
43. Coşgun, A.; Günay, M.E.; Yıldırım, R. Exploring the critical factors of algal biomass and lipid production for renewable fuel production by machine learning. *Renew. Energy* **2021**, *163*, 1299–1317. [CrossRef]
44. Maddison, A.L.; Camargo-Rodriguez, A.; Scott, I.M.; Jones, C.M.; Elias, D.M.; Hawkins, S.; Massey, A.; Clifton-Brown, J.; McNamara, N.P.; Donnison, I.S. Predicting future biomass yield in Miscanthus using the carbohydrate metabolic profile as a biomarker. *GCB-Bioenergy* **2017**, *9*, 1264–1278. [CrossRef] [PubMed]
45. Schmidt, A.; Creason, W.; Law, B.E. Estimating regional effects of climate change and altered land use on biosphere carbon fluxes using distributed time-delay neural networks with Bayesian regularized learning. *Neural Netw.* **2018**, *108*, 97–113. [CrossRef] [PubMed]

46. Rubin, E.S.; Mantripragada, H.; Marks, A.; Versteeg, P.; Kitchin, J. The outlook for improved carbon capture technology. *Prog. Energy Combust. Sci.* **2012**, *38*, 630–671. [CrossRef]
47. Liu, Z.; Cui, Y.; Wang, J.; Yue, C.; Agbodjan, Y.S.; Yang, Y. Multi-objective optimization of multi-energy complementary integrated energy systems considering load prediction and renewable energy production uncertainties. *Energy* **2022**, *254*, 124399. [CrossRef]
48. Wen, L.; Yuan, X. Forecasting CO_2 emissions in China's commercial department, through BP neural network based on random forest and PSO. *Sci. Total Environ.* **2020**, *718*, 137194. [CrossRef] [PubMed]
49. Cesarini, G.; Crosti, R.; Secco, S.; Gallitelli, L.; Scalici, M. From city to sea: Spatiotemporal dynamics of floating macro litter in the Tiber River. *Sci. Total Environ.* **2023**, *857*, 159713. [CrossRef]
50. Unguendoli, S.; Biolchi, L.G.; Aguzzi, M.; Pillai, U.P.A.; Alessandri, J.; Valentini, A. A modeling application of integrated nature-based solutions (NBS) for coastal erosion and flooding mitigation in the Emilia-Romagna coastline (Northeast Italy). *Sci. Total Environ.* **2023**, *867*, 161357. [CrossRef]
51. Qi, B.; Xu, P.; Wu, C. Analysis of the Infiltration and Water Storage Performance of Recycled Brick Mix Aggregates in Sponge City Construction. *Water* **2023**, *15*, 363. [CrossRef]
52. Xu, Z.; Mo, L.; Zhou, J.; Zhang, X. Optimal dispatching rules of hydropower reservoir in flood season considering flood resources utilization: A case study of Three Gorges Reservoir in China. *J. Clean. Prod.* **2023**, *388*, 135975. [CrossRef]
53. Dhyani, S.; Karki, M.; Gupta, A.K. Opportunities and advances to mainstream nature-based solutions in disaster risk management and climate strategy. In *Nature-Based Solutions for Resilient Ecosystems and Societies. Disaster Resilience and Green Growth*; Dhyani, S., Gupta, M., Karki, A., Eds.; Springer: Singapore, 2020; pp. 1–26. [CrossRef]
54. Bush, J. The role of local government greening policies in the transition towards nature-based cities. *Environ. Innov. Soc. Transit.* **2020**, *35*, 35–44. [CrossRef]
55. Alves, A.; van Opstal, C.; Keijzer, N.; Sutton, N.; Chen, W.S. Planning the multifunctionality of nature-based solutions in urban spaces. *Cities* **2024**, *146*, 104751. [CrossRef]
56. Hossain, M.K. Role of Information and Communication Technology (ICT) in Following Global Standard for NbS: The Bangladesh Perspective. In *Regional Perspectives of Nature-Based Solutions for Water: Benefits and Challenges*; Pachova, N., Velasco, P., Torrens, A., Jegatheesan, V., Eds.; Springer International Publishing: Cham, Switzerland, 2023; Chapter 9; pp. 225–247.
57. Bhattarai, K.; Adhikari, A.P. Promoting Urban Farming for Creating Sustainable Cities in Nepal. *Urban Sci.* **2023**, *7*, 54. [CrossRef]
58. Antwi-Agyakwa, K.T.; Afenyo, M.K.; Angnuureng, D.B. Know to Predict, Forecast to Warn: A Review of Flood Risk Prediction Tools. *Water* **2023**, *15*, 427. [CrossRef]
59. Brigagão, G.V.; Araújo, O.D.Q.F.; de Medeiros, J.L.; Mikulcic, H.; Duic, N. A techno-economic analysis of thermochemical pathways for corncob-to-energy: Fast pyrolysis to bio-oil, gasification to methanol and combustion to electricity. *Fuel Process. Technol.* **2019**, *193*, 102–113. [CrossRef]

buildings

MDPI

Article

Intelligent Systems Integrating BIM and VR for Urban Subway Microenvironmental Health Risks Management

Qiwen Chen [1], Chenhui Li [1], Xiaoxiao Xu [1], Peng Mao [1,*] and Lilin Xiong [2,*]

1 Department of Engineering Management, School of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China; chenqiwen@njfu.edu.cn (Q.C.); 18907567350@163.com (C.L.); xxx@njfu.edu.cn (X.X.)
2 Department of Environmental Health, Nanjing Municipal Center for Disease Control and Prevention, Nanjing 210003, China
* Correspondence: maopeng@njfu.edu.cn (P.M.); hzxionglilin@163.com (L.X.)

Abstract: With the rapid development and construction of urban subways, various risks associated with human health and wellbeing within subway microenvironments have seriously increased. However, only a few intelligent systems have been validated as suitable for facilitating the management of subway environments. Field tests can be time-consuming and inefficient, and questionnaires often lack true intuitiveness for participants. Therefore, to enhance subway environment management, this study proposed intelligent systems that integrate building information modeling (BIM) and virtual reality (VR) for managing health risks in urban subway microenvironments. The systems were developed using Revit 2021, Navisworks 2020, Unity 2019, MYSQL 8.0, and Visual Studio 2019. Additionally, they were applied in scenarios for environmental assessment and passenger coping capability enhancement, differentiated into an expert visual-based health risk assessment system and a gamified simulation system for passenger risk prevention. The feasibility of the approach was validated with the case of Xinzhuang subway station of Line 3 in Nanjing, China. The findings revealed that the assessment system enabled experts to have a better and straight understanding of subway microenvironmental health risks and the gamification simulation system significantly enhanced the passengers' coping capacity. The integration of BIM and VR, with its design features such as visibility, optimization, and simulation, compensated for BIM's lack of providing an immersive experience for systems. The intelligent systems introduced in this study present novel models for environmental assessment and passenger training, catering to both subway operators and researchers. The innovative systems serve as a cornerstone in guaranteeing the health and safety of public transportation operations.

Keywords: urban subway; building information modeling; virtual reality; risk assessment; microenvironmental health risks; coping capacity

1. Introduction

Urban subways, renowned for their speed and capacity, are prevalent across 79 countries, including Japan, the United States, Korea, China, Brazil, Chile, and Colombia [1,2]. Globally, subway networks spanned approximately 36,854.20 km in 2021, facilitating nearly 39.67 billion passenger journeys [3]. Despite being a vital mode of transport, exposure to microenvironments within subways—such as platforms, halls, and carriages—poses significant health risks. Airborne particles in these areas often contain heightened levels of iron, manganese, chromium, nickel, and copper, posing severe health hazards [4,5]. Furthermore, concentrations of PM, CO_2, VOCs, bacteria, and fungi in underground stations exceed permissible limits set by WHO, ASHRAE, and US EPA by 1.1–13.2 times [6]. Excessive exposure to respirable particulate matter can exacerbate chronic health conditions like lung dysfunction and chronic obstructive pulmonary disease [7]. The predominantly underground nature of subways, with limited natural ventilation, can also facilitate virus transmission [8], leading to concerns about passenger safety and health [9].

The growing concern over health risks in urban subway microenvironments has spurred interest [10]. Addressing these concerns requires intelligent systems. Current research often relies on field tests and questionnaires to study subway microenvironmental health risks [11–13]. For instance, questionnaires involving 399 subway construction professionals aimed to understand factors impacting the safety of Chinese subway projects [11]. Additionally, tools like air velocity meters and portable CO_2 analyzers were used to assess environmental quality in Nanjing's subway system [13]. However, field tests are time-consuming and inefficient [14,15], often taking months or years to complete [16]. They also lack comprehensive scenarios [17,18], rarely covering extreme risk levels simultaneously. Ethical concerns further limit extreme scenario testing due to potential health risks to participants [19,20]. Questionnaires, while overcoming some field test limitations, have their drawbacks. Participants can only visualize scenarios through descriptions on paper, lacking the immersive experience of subway microenvironments [21]. To address these challenges, this study proposes intelligent systems capable of constructing comprehensive subway microenvironmental scenarios, efficiently collecting data, and providing an immersive experience to enhance passenger coping abilities.

This study integrated building information modeling (BIM) with virtual reality (VR) for the management of health risks in the urban subway microenvironment. In a broader context, BIM involves collaboration among individuals, information systems, databases, and software. It can encompass hardware, tangible and intangible resources, as well as knowledge. BIM in a stricter sense refers to the semantic database associated with the construction object, which accompanies it throughout its life cycle [22]. The rapid development of BIM and VR lays the foundation for establishing the approach. BIM, which is widely applied in the construction field, possesses characteristics of visualization and simulation. It also demonstrates a high capability to build a 3D subway environment with various scenarios. It could play a promising role in the operation of subways, especially in the management of microenvironments such as platforms, station halls, and carriages [23,24]. Moreover, VR allows for human-computer interaction through computer-generated simulations, creating a virtual environment. With the application of BIM and VR, participants can immerse themselves in subway platforms, halls, and carriages with different levels of humidity, light brightness, crowd density, and other site conditions in virtual environment.

This study aimed to overcome the shortcomings of lengthy and incomplete field tests and the lack of intuitiveness in questionnaires by creating a BIM and VR-combined system to facilitate subway environment management. Based on different application functions, systems included the assessment of health risks and the improvement of behavioral capacity by building a visualized 3D scene with BIM and providing an immersive experience with VR. Firstly, research on subway microenvironmental health risks using standard approaches and research applying BIM or VR are introduced respectively. Then, this study constructed a framework based on the proposed BIM-VR approach to develop an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. Finally, the feasibility of systems was validated through a case study of Nanjing Subway Line 3 (Xinzhuang Station). This study introduced intelligent systems for assessing health risks intuitively and easily and improving passenger coping capacity in the subway microenvironment, which plays a pioneering and fundamental role for the healthy and safe operation of the public transportation. Actually, the intelligent system developed in this paper has already been applied as a data collection system in the study by Chen et al. (2024) to propose a decision support system for iterative intervention management of subway microenvironmental health risks [10].

2. Background

2.1. Research on Subway Microenvironmental Health Risk Using Standard Approaches

The concept of the microenvironment appears in the biological field initially, which refers to the intercellular matrix and the body fluid components within it [25]; it was subsequently expanded to numerous other fields. Concerning subways, the microenvironment is defined as an environment including the thermal environment, acoustic environment, light environment, or air quality, which is directly related to human activities [13]. Subway platforms, halls, and carriages are special microenvironments [26,27]. Since urban subways are relatively confined and full of passengers, they pose a significant threat to the health and comfort of passengers [10,28]. Continuous exposure to urban subways can lead to rapid changes in heart rate, pulmonary dysfunction, and cardiovascular diseases [29,30] but few intelligent systems have been proposed on how to assess the level of environmental risk intuitively and easily.

Currently, studies on subway microenvironmental health risks commonly employ methods such as field tests or questionnaires. However, both methods have significant limitations. Fewer intelligent systems have been proposed to address the shortcomings of the two methods and to better manage subway environments. Firstly, due to its advantages of reliable data and high accuracy, field tests are commonly employed in subway environmental management. Instruments such as portable carbon dioxide samplers and indoor air quality meters are commonly used in field tests. For example, in Barmparesos et al.'s (2016) study, CO_2 levels in the Athens subway system were measured using portable carbon dioxide samplers [31]. Similarly, the temperature and humidity in Shanghai metro stations were measured using indoor air quality meters [32]. However, field tests tend to be time-consuming and inefficient, and often require several months or even years to complete. Hsu et al. (2020) expended nine months exploring the air pollutants of the Taiwan subway [15]. Passi et al. (2021) even devoted nearly three years [14]. The field test can certainly provide accurate physicochemical data on the subway [33], but the approach is not comprehensive enough to assess the microenvironmental risks of the subway. For example, Martins et al. (2015) measured $PM_{2.5}$ exposure concentrations in subway carriages, with a minimum of 20.2 μgm^{-3} and a maximum of 91.3 μgm^{-3} but no intermediate concentrations (between 70 μgm^{-3} and 80 μgm^{-3}) of $PM_{2.5}$ exposure were obtained in the test [17]. And the average $PM_{2.5}$ concentration in the Hong Kong and Guangzhou subway was 10.2 μgm^{-3}, and 55 μgm^{-3}, respectively [18]. These values are significantly lower than that of ambient air quality standards (GB3095-2012) [34]. Therefore, the test data for Hong Kong and Guangzhou subway lack the scenarios with severe air quality microenvironments. The field test was conducted on the condition that scenarios were not comprehensive. Scenarios with different risk levels, especially extreme ones, rarely appear concurrently. Moreover, it is difficult to create scenarios of extreme conditions in real life too. Even if extreme scenarios could be created, it would challenge the health of subjects, which is a serious violation of the ethical principle (never endangering human health) [19,20]. Therefore, field tests inevitably have limitations of being incomplete and time-consuming.

Questionnaires can potentially overcome the above-mentioned limitations of field tests. The questionnaire is also a well-established approach to study subway microenvironmental health risk. Yang et al. (2022) applied questionnaires to analyze the thermal comfort of the subway in Harbin (China) on 19 and 21 December 2019 [12]. Han et al. (2015) designed questionnaires using thermal, air, light, acoustic, and overall comfort as the comfort measurement dimensions [35]. His team spent nearly 16 days in 2014 conducting a questionnaire survey of on-site passengers. Furthermore, Mao et al. (2022) also used questionnaires to investigate the sensitivity of subway passengers to microenvironmental health risks [36]. However, one limitation of this approach was that an immersive experience of the subway environment could not be achieved since subjects could only visualize various scenarios through descriptions from the paper [21], which was not intuitive, not to mention not experiencing the illumination and crowd density of subway microenvironments immersively.

2.2. Research Applying BIM or VR

BIM stands for building information modeling, which refers to the semantic database linked to the construction object, providing continuous support throughout its life cycle [22].

Simulating a 3D state will help optimize the management of buildings [37,38]. Therefore, BIM is widely used in the management of shopping malls, houses, schools, transportation infrastructure, etc. [39,40]. BIM, as a maturing technology, has the potential to build a figurative 3D urban subway based on two-dimensional information. It has been applied in the performance management of subway station, safety design for emergency evacuation of subway stations [41], and thermal comfort monitoring of subways [24]. However, the BIM platform fails to provide an immersive experience for systems. Therefore, VR is introduced. As technology advances, VR, AR, and MR are products of the integration of virtual and real worlds, with an increasing number of scholars integrating these technologies with BIM to achieve more powerful functionalities. For example, a BIM-AR system was proposed by implementing marker-based AR, enabling the viewing, interaction, and collaboration with 3D and 2D BIM data via AR among geographically dispersed teams [42]. El Ammari et al. (2019) achieved remote interactive collaboration in facilities management by integrating MR with BIM. In this study, VR technology was selected for integration with BIM [43]. VR can be defined as a three-dimensional computer-generated simulated environment, which attempts to replicate real world or imaginary environments and interactions, thereby supporting work, education, recreation, and health [44]. VR generates a virtual environment via computers and creates an immersive experience with the supplement of various devices such as HMDs, glasses, and multiple displays [45]. Introducing VR can lead to a better interactive immersive experience [46,47]. It provides experts with visual panoramic views of subways and engages passengers in immersive risk-coping behavior simulation.

The idea of combining BIM and VR has been widely applied in architecture, engineering, and construction [48]. Complemented with BIM, VR enables systems to provide an immersive experience for their users. However, VR has not been fully advanced in supporting construction information interoperability and with collaboration, which can be facilitated with BIM [49]. Therefore, on one hand, intelligent systems developed based on VR can provide users with immersive subway scene experiences. On the other hand, intelligent systems can also design different scenarios for simulation according to needs and quickly collect data through computer software, effectively addressing the incompleteness and time-consuming issues associated with field tests. The management efficiency of BIM-VR has been amply proved by cases such as building seismic loss prediction [50], on-site assembly services in prefabricated construction [26], and construction fire safety [51]. However, due to the complexity of large infrastructures such as the subway, the integration of BIM and VR is still at the infancy stage. Standard approaches (e.g., field tests and questionnaires) are still extremely popular for studying the management of subway microenvironmental health risks.

Therefore, to bridge the gaps from these existing standard research approaches, this study proposed intelligent systems for the management of the subway microenvironment. Based on different application functions, systems included the assessment of health risks and the improvement of behavioral capacity by building a visualized 3D scene with BIM and providing an immersive experience with VR. The goal of the research was to develop systems that combine BIM and VR to display the microenvironment of subways through virtual reality, facilitating the management of subway environments.

3. Methodology

3.1. Proposed Approach

Based on the proposed approach shown in Figure 1, researchers in this study developed systems to assess the risk levels of the subway microenvironment and coping capability, which allows for the interactive transmission information of dual users (experts and passengers).

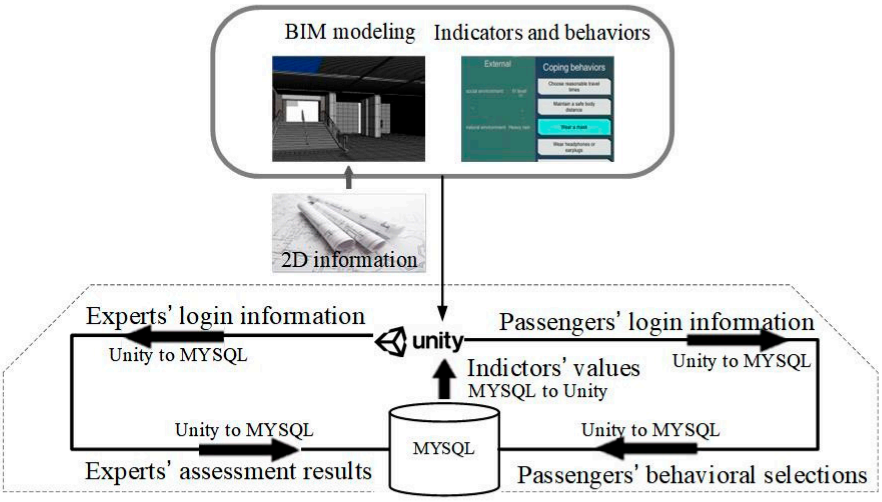


Figure 1. Proposed BIM-VR approach.

The specific BIM-VR approach should perform the following functions.

(1) Building a 3D visualization model based on 2D information via BIM.

BIM is an ideological concept that simulates the design, construction, and operational management processes of a project using 3D digital models [52]. Revit, as a specific BIM implementation software, was utilized to create and simulate a 3D digital model of the subway. This software enables the integration of information from basic components such as columns, beams, slabs, walls, and detailed components like holes, pipes, and preburied items [53]. It accurately constructs models based on 2D information and presents them in a three-dimensional format, providing a visual model that facilitates roaming simulation [54].

(2) Integrating three-dimensional BIM files, indicators, and coping behaviors to achieve a roaming experience.

Unity demonstrates an excellent compatibility with Revit, which supports FBX format files exported from Revit. BIM docks with Unity without obvious barriers, which can substantially ensure the integrity of the physical model of the urban subway. Moreover, as a powerful 3D game development engine, Unity is lightweight and functionally stable. It can operate safely and stably under Mac or Windows systems. Developers can apply Visual Studio as the C# script editor whose codes could program indicators and coping behaviors into the expert visual-based health risk assessment system and the passenger risk prevention gamification simulation system to construct the roaming VR scenario.

(3) Combining VR with MYSQL to facilitate the transmission of information from dual-users.

On one hand, Unity should read the indictors' values from MYSQL for systems development. On the other hand, the log-in information and the results of experts' risk assessment or the passengers' selections of coping behaviors need to be saved into MYSQL. Programming languages such as C# can implement the lap between Unity and MYSQL, which enables the interaction and transmission of dual-user.

Based on the proposed BIM-VR approach, we utilized Revit to construct a three-dimensional model of the subway, while interaction design was achieved via VR software such as Unity and external devices like head-mounted devices. In terms of data flow, this study combined Unity and MYSQL software to import expert and passenger information and save results. Ultimately, we developed an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. During application, both experts and passengers wore head-mounted devices to enter the three-dimensional model of the subway station, experiencing textures on the walls, brightness of lights, and other elements. Through immersive roam in the subway station, they provided their respective risk assessments or coping behaviors.

3.2. Framework Development

This study investigated risk assessment and prevention gamification simulation systems of the urban subway microenvironment based on the BIM-VR framework. The framework consisted of the following parts: (1) setting indicators and coping behaviors; (2) building information modeling; (3) accepting front-end work for system development; (4) developing an expert visual-based health risk assessment system; and (5) developing a passenger risk prevention gamification simulation system. The system overcame the limitations of unintuitive questionnaires and time-consuming field tests by introducing the BIM-VR approach, assessing the risk level of the subway microenvironment, and enhancing passenger risk-avoidance coping capability. The BIM-VR framework is shown in Figure 2, and the software used is listed in Table 1.

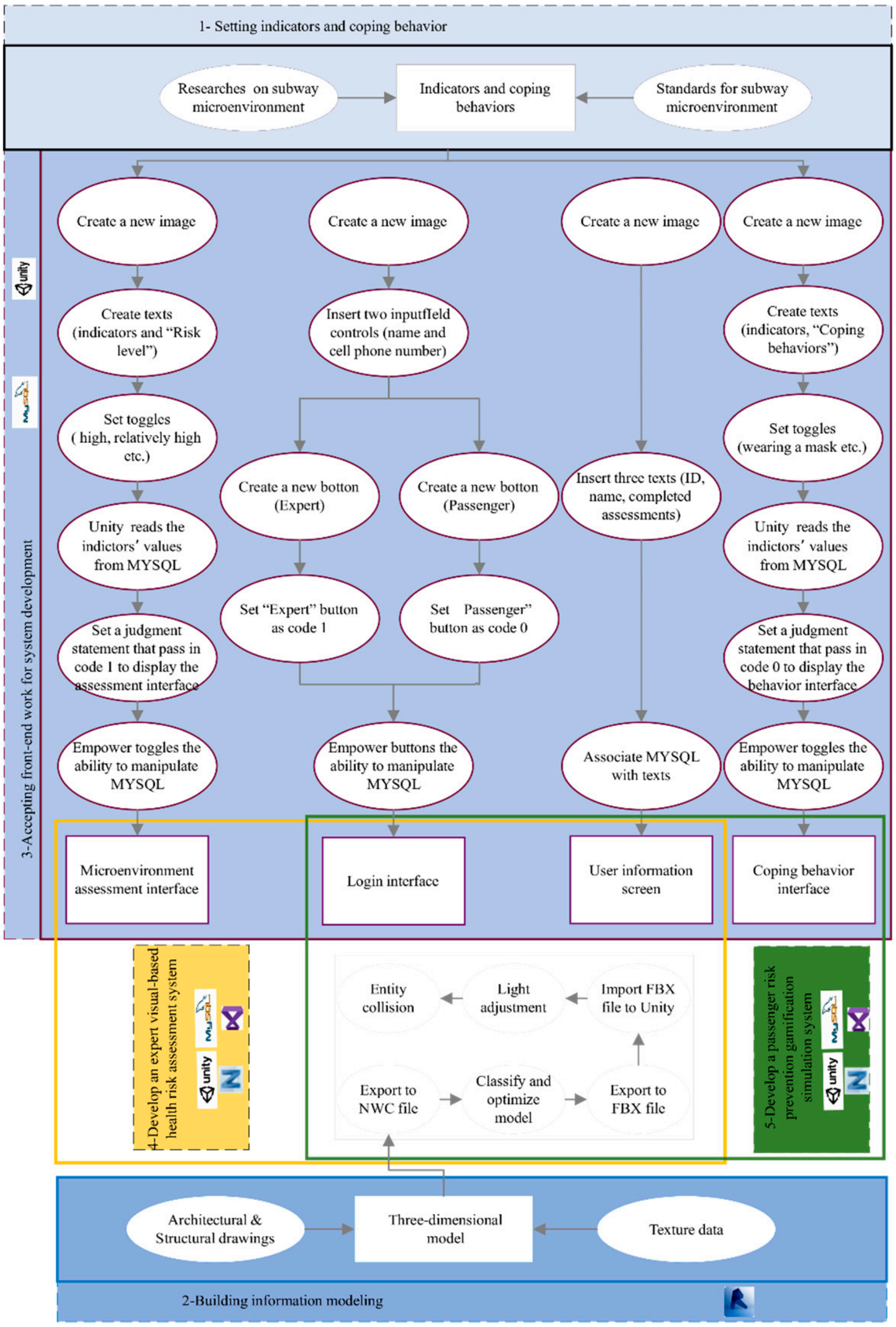


Figure 2. BIM-VR framework.

Table 1. Software used in the paper.

Software	Software		Function
BIM	Revit 2021		build a 3D model of the urban subway
	Navisworks 2020		classify and optimize the model
VR	Unity 2019	unity	provide an immersive experience for systems
	MYSQL 8.0	MySQL	import and export of simulation data
	Visual Studio 2019		function as the C# script editor

The different colors in Figure 2 respectively represent the five different steps: setting indicators and coping behaviors, building information modeling, accepting front-end work for system development, developing an expert visual-based health risk assessment system, and developing a passenger risk prevention gamification simulation system. As shown in Table 1, this study involved five software applications: Revit, Navisworks, Unity, MYSQL, and Visual Studio. Firstly, Revit is a BIM software that supports parametric modeling. Users can define the properties and behaviors of building elements by setting parameters and constraints, enabling intelligent modeling. Secondly, Navisworks is a project collaboration and coordination software used in the architecture, engineering, and construction industries. Its advantage lies in its ability to integrate model data from different design software, facilitating project collaboration and clash detection. Thirdly, Unity is used for developing VR, AR, and other interactive applications. It features powerful graphics rendering capabilities and user-friendly development tools. Additionally, MYSQL is an open-source relational database management system known for its stability, reliability, high performance, ease of use, and deployment. Lastly, Visual Studio is an integrated development environment used for developing various types of software applications. Its strengths include powerful development tools, extensive plugin support, intelligent code editor, and convenient debugging capabilities. For the above reasons, we chose these five software applications.

3.2.1. Setting Indicators and Coping Behaviors

It is crucial to establish subway microenvironmental health risk indicators. These indicators can be derived from existing research on subway microenvironments [55–57] or based on standards such as the Ambient Air Quality Standards (GB3095-2012) and the Code for the Design of Subway (GB50157-2013) [34,58]. Additionally, for the simulation of risk avoidance games for passengers, it is recommended to categorize and list common coping behaviors based on previous studies [59,60]. The specific indicators and coping behaviors could be changed according to the actual application. Furthermore, assigning values to indicators should align with real-world scenarios and research requirements.

3.2.2. Building Information Modeling

This study employed BIM to depict the 3D representation of the subway microenvironment as the foundational step for developing subsequent systems. The initial phase of BIM modeling involved data collection, which comprised two key types of data. Firstly, architectural and structural drawings of the subway were essential, encompassing plan drawings, elevation drawings, section drawings, and detailed drawings of large samples. Secondly, texture data for the 3D model, such as material properties, coloring, gloss, and saturation of components, was crucial. In the subsequent step, Revit was utilized to process this data. Specifically, Revit was employed to construct internal elements like columns, beams, walls, and rebars of the subway, with adjustments made to their dimensions and materials through input parameters. This process resulted in the creation of a comprehensive 3D model of the urban subway. The details of the whole BIM model are presented in Figure 3.

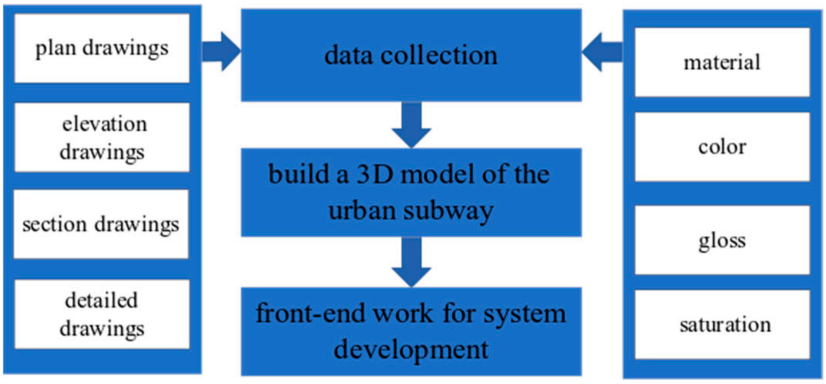


Figure 3. Details of building information modelling.

3.2.3. Accepting Front-End Work for System Development

The login interface and user information screen were created. Once users inputted their information and logged in, this data was connected to MySQL for storage. After logging in, the user information screen was displayed in the top left corner of the page, including the user's ID, name, and completed assessments. The new image (user information screen) and three new texts (ID, name, completed assessments) were created. The texts associated with MYSQL to display the latest ID, name, and completed assessments. The user information screen is shown in the upper left corner of Figures 4 and 5.

Figure 4. Details of building information modelling (floor one).

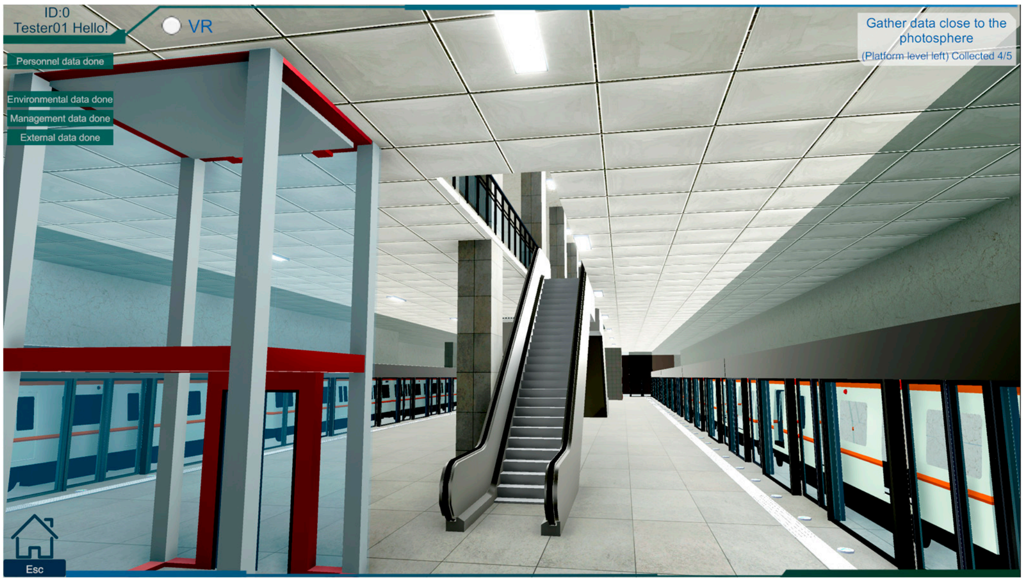


Figure 5. Details of building information modelling (floor two).

Two microenvironmental management interfaces of experts' assessment and passengers' coping behaviors were designed to achieve different functions. An image as a background in the panel and some new texts (indicators, "Risk level" or "Coping behaviors") were created. Control toggles that were already filled with the risk level ("high, relatively high, medium, relatively low, and low") or specific coping behaviors such as "wear a mask" were set on the right side of the interfaces (Figures 6 and 7). Then, indicators' values in MYSQL were read by Unity. The judgment statements that passed in code 1 to display the assessment interface and passed in code 0 to display the coping behavior interface were set in the interface code. Thus, selecting the "Expert" button led to the expert vision-based health risk assessment system, whereas the "Passenger" button led to the passenger risk prevention gamification simulation system. Systems recorded assessment results and behavior selections in MYSQL by empowering toggles to manipulate MYSQL.

Figure 6. The experts' assessment interface.

Figure 7. The passengers' coping behaviors interface.

3.2.4. Developing an Expert Visual-Based Health Risk Assessment System

Firstly, the three-dimensional model was exported to a NWC file. With some of the nonvisible structural components hidden by Navisworks, the model was classified, optimized, and exported as an FBX file. The optimized FBX file was imported into Unity for light adjustment and entity collision to truly visualize the subway microenvironment scene. The illumination was adjusted by the light source setting function of the Unity software for realistic visual perception. To enhance the realism of roaming in the subway scene, this study controlled the "S", "W", "A", and "D" to shift the collider forwards and backwards, or laterally (colliding in the scene), and finally achieving the unity-based 3D subway station (Figures 8 and 9). Experts needed to roam the subway and continuously collect subway microenvironmental indicators. Eventually, all indicators were displayed in the microenvironment assessment interface. Experts were placed in the model of the 3D urban subway scene and delivered risk level assessments (high, relatively high, medium, relatively low, and low) based on the indicators displayed on the interface.

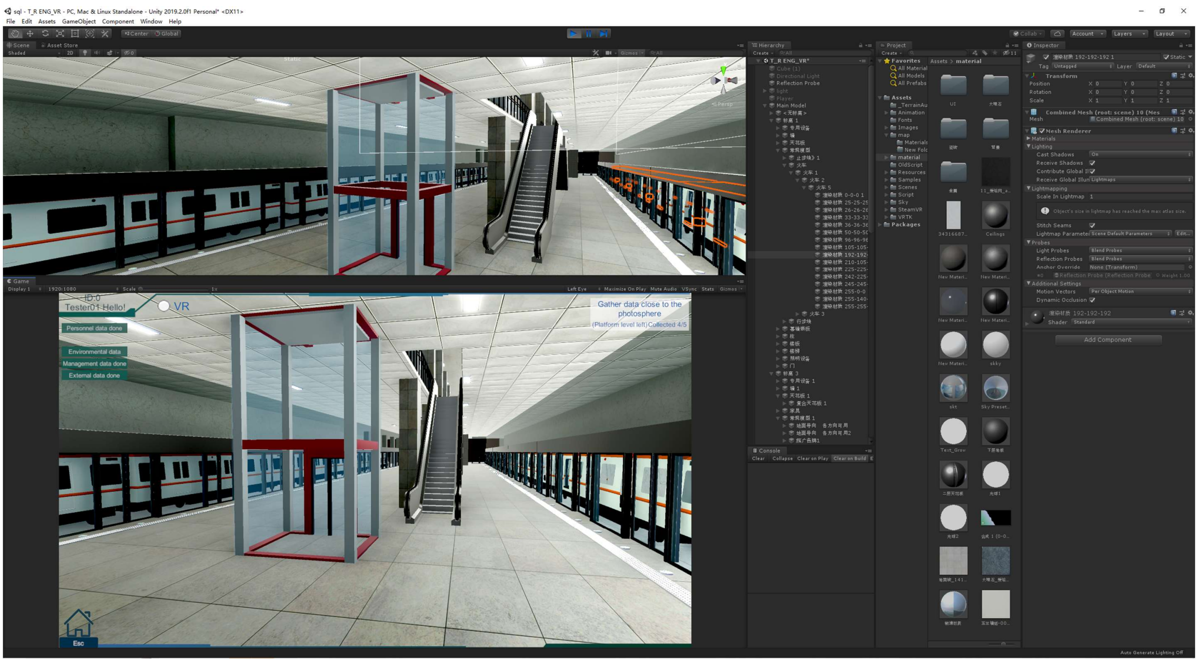


Figure 8. Unity-based subway station 3D rendering (floor two).

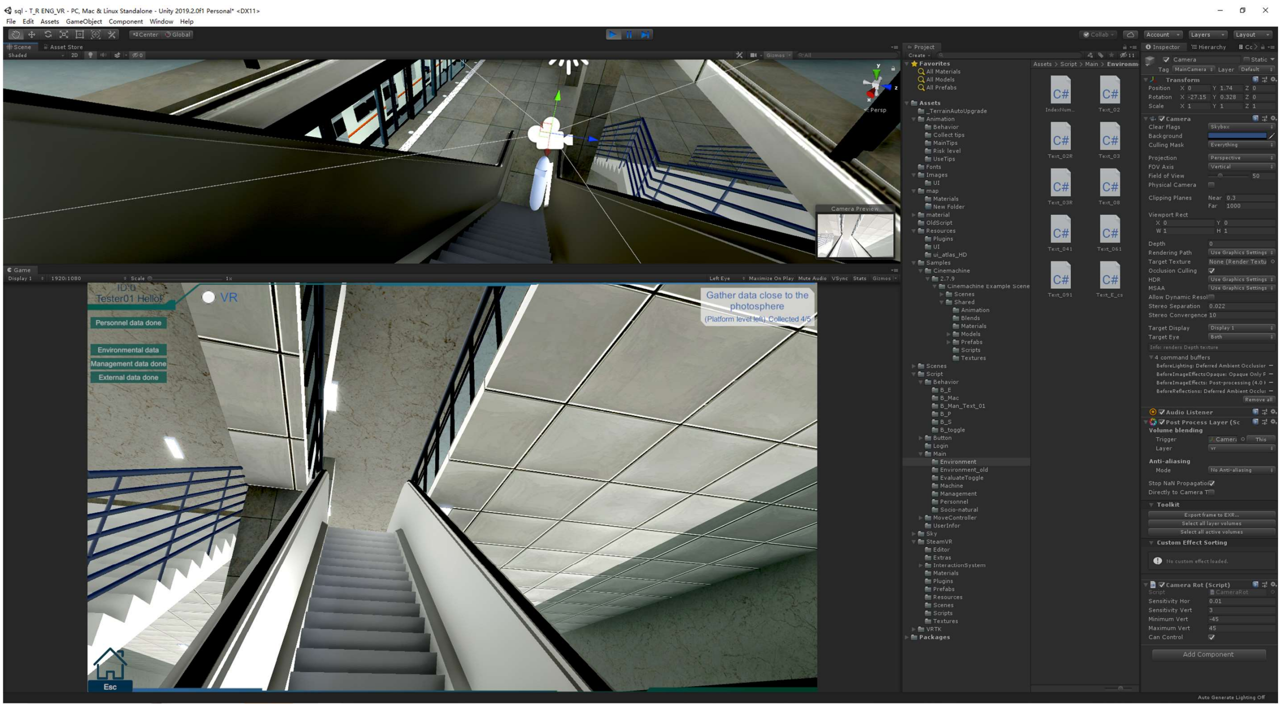


Figure 9. Unity-based subway station 3D rendering (elevator).

3.2.5. Developing a Passenger Risk Prevention Gamification Simulation System

Based on the urban subway model constructed via Revit and Unity, the same approach as an expert visual-based health risk assessment system was adopted to develop a passenger risk prevention gamification simulation system. Furthermore, passengers could immersively roam the interior of the 3D subway. The indicators and coping behaviors of passengers were displayed within the coping behavior interface. Passengers could choose their risk coping behaviors based on the information displayed in the interface.

4. Case Study

4.1. Setting of the Risk Indicators and Coping Behaviors

For the case study validating the proposed approach, we utilized BIM-VR systems based on Xinzhuang subway station of Line 3 in Nanjing. To comprehensively identify effective risk indicators, a search was conducted on "Web of Science" using the search string TS = [("subway" OR "metro" OR "underground") AND ("microenvironment" OR "environment") AND ("health risk" OR "risk")]. The results are presented in Table 2. It is essential to note that while these risk indicators are provided, their determination was not the primary focus of this study and could be adjusted based on specific practical considerations. The indicators are numbered in Table 2, such as A1 and A2.

Using a similar approach, we derived coping behaviors from the literature, identifying nine types, which are listed in Table 3. Further research may adjust these coping behaviors according to specific practical circumstances.

Table 2. Subway microenvironmental health risk indicators.

First-Level Indicators	Second-Level Indicators	References
Internal environment	Illumination (A1)	[13,61,62]
	temperature (A2)	[55]
	humidity (A3)	[56,57]
	wind (A4)	[18,63]
	noise (A5)	[64,65]
	PM_{10} (A6)	[66]
	$PM_{2.5}$ (A7)	[66,67]
	CO_2 (A8)	[68]
	CO (A9)	[27]
	TVOC (A10)	[68,69]
	bacterium (A11)	[56]
	flow density (A12)	[18]
External environment	natural environment (A13)	[70,71]
	social environment (A14)	[61,63]
Personnel	educational level (B1)	[72,73]
	technology level (B2)	[74–76]
	emergency skills (B3)	[72,77]
Equipment	infrastructure location pass rate (C1)	[77]
	emergency location pass rate (C2)	[77]
	infrastructure integrity (C3)	[78]
	emergency integrity (C4)	[74,79]
	maintenance pass rate (C5)	[75,78]
	emergency effectiveness (C6)	[78,80]
Management	safety knowledge pass rate (D1)	[81]
	emergency drill effect (D2)	[82,83]
	supervision system integrity (D3)	[76,84]
	emergency plan integrity (D4)	[82,83]
	supervision strength (D5)	[85,86]
	risk investigation strength (D6)	[86,87]
	organizational coordination (D7)	[82,88]

Table 3. Subway microenvironmental health risk coping behaviors.

Coping Behaviors	References	Coping Behaviors	References
Choose reasonable travel time	[36]	Wear headphones or earplugs	[36]
Wear a mask	[36]	Give suggestions to operating companies	[36]
Maintain a safe body distance	[59,60]	Avoid touching escalator, seat, handrail, and other	[89,90]
Stay calm and follow the instructions of the staff	[91]	Evacuate according to safety evacuation signs	[91]
Sound the emergency alarm	[92]		

4.2. Virtual Simulation

A total of 20 experts and 20 passengers were recruited in the case study, as a simulation typically involves dozens of individuals [42,93]. The information about the experts is shown in Table 4. Additionally, we randomly recruited 20 students who frequently use the subway to participate in the experiment as passengers. Since the purpose of this experiment was to verify that this system can be used for training and improving passengers' coping skills, the selection of subjects met the experimental needs.

Table 4. Expert structure.

Employer	Years of Employment	Educational Qualification	Count
round1			
subway department	5–10	master	3
subway department	5–10	bachelor	1
subway department	Over 10	master	2
subway department	Over 10	bachelor	3
university	Over 10	doctor	5
center for disease control	Over 10	doctor	6
round2			
subway department	5–10	master	2
subway department	5–10	bachelor	1
subway department	Over 10	master	2
university	Over 10	doctor	2
center for disease control	Over 10	doctor	3

Participants were given brief information about the study's purpose before deciding whether to participate. This study was conducted with the explicit consent of all participants, who were informed that the data would be used for research purposes. Each expert conducted 50 experiments, and 10 out of the initial 20 experts were selectively invited for a second round of experiments. The second round also included a passenger risk prevention gamification simulation, which provided standard answers for passenger coping behaviors. Additionally, each passenger then completed 10 experiments. To evaluate the effectiveness of passenger training based on Ebbinghaus' forgetting curve and the decline in memory retention over time, each passenger repeated the same 10 experiments two days later [94]. In total, the two rounds of experiments yielded 1500 expert samples and 400 passenger samples, with a 100% response rate.

On one hand, the experts logged in by entering their names, numbers, and clicking the "Expert" button. Upon accessing the visual risk assessment interface, experts roamed from the entrance to the interior of the subway station, a virtual environment built using Revit and Unity. During this immersive experience, they continuously collected subway microenvironmental indicators. All collected indicators were displayed on the microenvironment assessment interface, where experts provided a health risk assessment of the subway microenvironment. Since MYSQL was integrated with Unity, the results were recorded in MYSQL. Repeating the above steps (Figure 10), each expert evaluated 50 sets of scenarios, the data of which were randomly assigned.

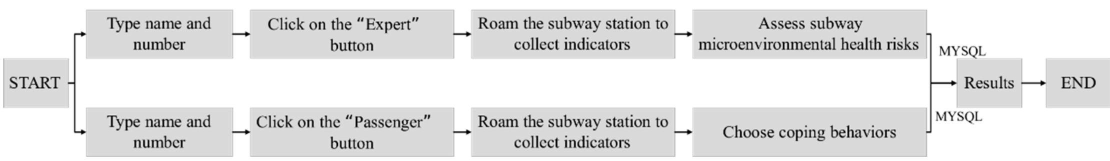


Figure 10. Work steps of the virtual simulation.

On the other hand, passengers logged in by entering their names, numbers, and clicking the “Passenger” button to start the gamification simulation. They navigated different locations within the Xinzhuang station system to collect indicators (Figure 11). Based on the information displayed on the subway microenvironment coping behavior interface, passengers selected coping behaviors from the options provided. Each passenger repeated these steps for 10 sets of scenarios. As MYSQL was integrated with Unity, all results were recorded in MYSQL. The entire immersive simulation process is illustrated in Figure 10.

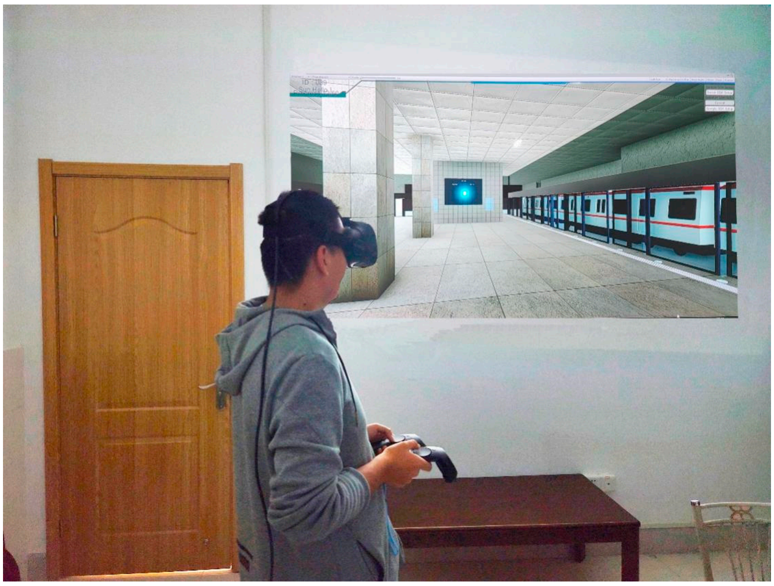


Figure 11. Immersive VR simulation.

5. Results

5.1. Expert Visual-Based Health Risk Assessment System

The results of the experts’ risk level assessments in different scenarios (random combinations of temperature, humidity, passenger flow, etc.) were exported from MYSQL, facilitating the quantitative study of subway microenvironmental health risks. The BP neural network, with its ability to synthesize complex relationships among multiple indicators and learn from data, objectively reflects the intrinsic connections between various indicators and health risks. Thus, we predicted the experts’ risk results based on BP neural networks due to their suitability for analyzing the combined effects of numerous factors on subway microenvironmental health risks. The BP neural network calculates predicted outputs through forward propagation, computes errors at each layer, and then updates weights through error backpropagation until the error is minimized, achieving fitting to the training data [10]. Additionally, permutation feature importance provides a robust method for gaining insight into how the model makes predictions on a broad scale and is a common method to obtain indicator importance. Therefore, this study applied permutation feature importance to further analyze the expert samples. The core idea of permutation feature importance is to assess the impact of each feature on model predictions by permuting the features in the model and observing the change in model performance. Specifically, we built nonlinear relationships between indicators and risks using BP neural networks and explained the model to determine indicator importance through permutation feature importance.

Throughout the experiment, we iteratively adjusted the learning rate and the number of hidden layers and neurons to optimize the model’s performance. One successful network structure consisted of 30 neurons in the input layer, four hidden layers with fourteen, nine, four, and five neurons, respectively, and five neurons in the output layer. This model was trained for 1000 iterations with a learning rate of 0.01, achieving remarkably high accuracy.

Figures 12 and 13 display the accuracy of the neural network's training and testing phases. Blue dots represent predictions that matched the actual results, while red dots represent predictions that did not match. As shown in Figure 12, the neural network model achieved an accuracy rate of 95.92% on the training set. Figure 13 illustrates that the model achieved an impressive test accuracy rate of 94.67%, indicating its strong predictive performance.

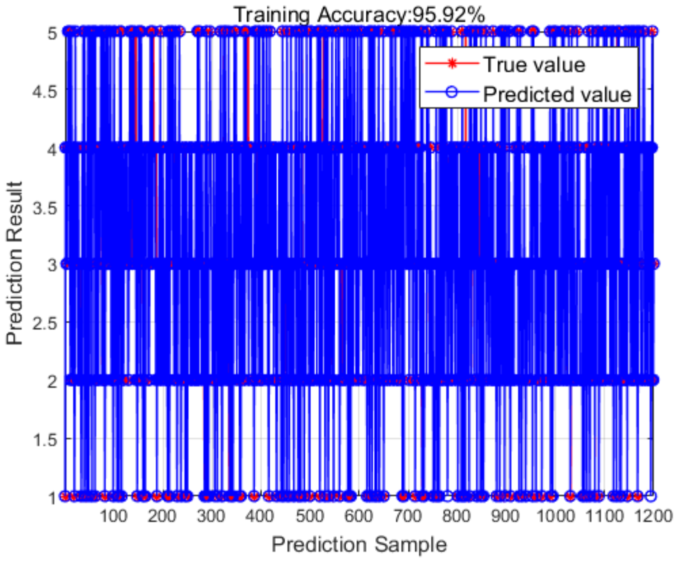


Figure 12. Prediction results of training.

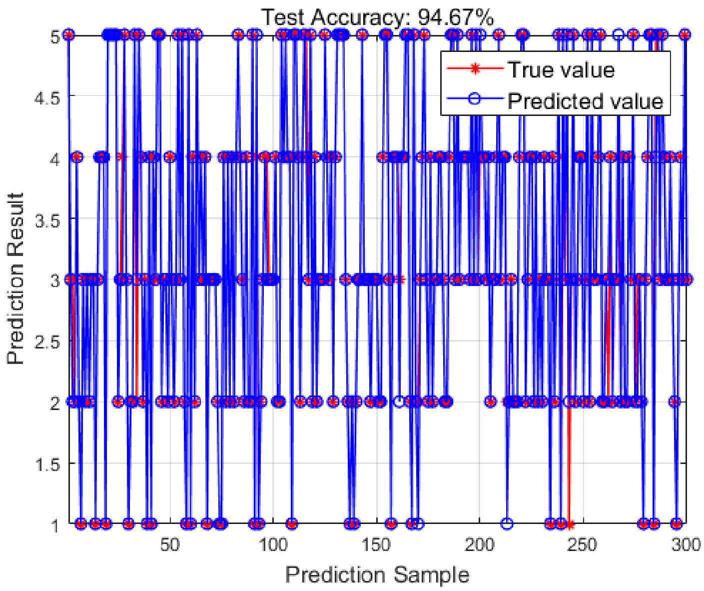


Figure 13. Prediction results of testing.

Next, each indicator was permutated 1000 times since the importance may have been unstable [10]. As shown in Figure 14, a deeper exploration of the importance for each indicator was demonstrated using box plots. The box plot in Figure 14 displays the distribution of the data, including the median, lower quartile, upper quartile, minimum, and maximum values. Subway microenvironmental health risks are influenced by the combined effects of multiple indicators, including key and secondary ones. Permuting important indicators can lead to significant fluctuations in intervention results, while permuting less important indicators has minimal impact. Figure 14 illustrates the fluctuation of indicator features based on their importance levels through feature permutation. As shown in Figure 14, indicators B1 and D1 were the most important, while C2 was the least important. This meant that the educational level and safety knowledge pass rate had the greatest influence on the health risk, while the emergency location pass rate had the least influence. This was conducive to comprehensive management of subway microenvironments health risks. Currently, the health risk control of subway operators is mainly guided by standard codes. But these codes are limited to identifying, for example, the threshold values and measurement methods of noise. The existing research on subway control measures also focuses on measures taken for certain factors, such as the development of intelligent ventilation control systems [95], dynamic gain timing ventilation control systems for subway internal ventilation, and magnetic hybrid filters for heavy metal pollution [96]. It was supposed that corresponding control measures should be taken whenever the factor exceeds the threshold, just like the physician treats the head when it aches, and treats the foot when it aches. However, in a complex subway microenvironment, several factors may exceed threshold values simultaneously. Leadership behaviors were crucial in this context [97]. For instance, if relatively unimportant indicators like C2, A3, and D5 exceed threshold values, subway operators may consider ignoring them if the overall underground microenvironmental health risk is acceptable. However, if important indicators such as B1, D1, A6, and A7 exceed threshold values, operators need to pay significant attention. Based on these results, subway operators can determine which factors should be prioritized and implement multimeasure controls to effectively manage excessive factors.

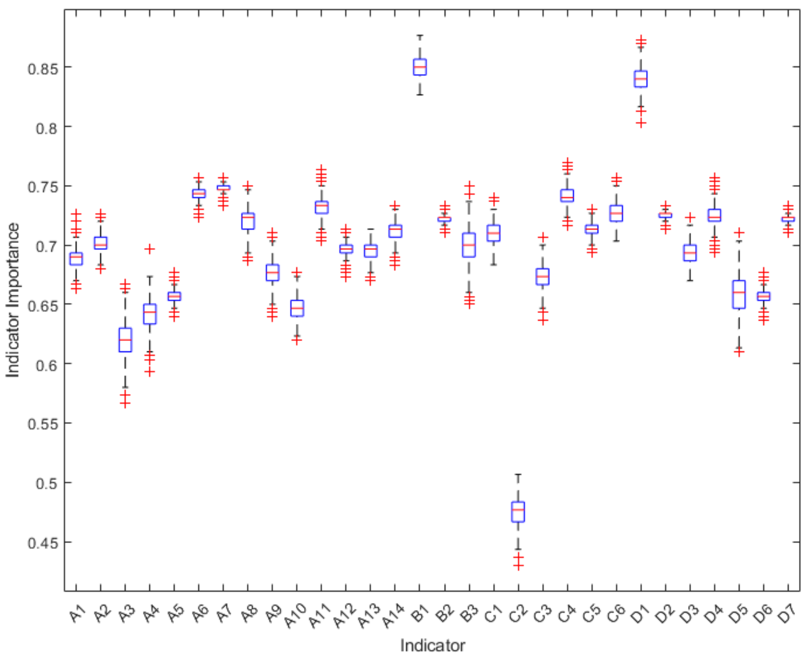


Figure 14. Indicator importance box chart.

In the future, the expert visual-based health risk assessment system could be combined with other approaches to further expand its functions, such as neural networks [98], particle swarm optimization [99], and genetic algorithms [100]. In addition, the hyperparameters of the predictive model could also be further optimized to achieve higher accuracy [101]. Moreover, the combination of an expert visual-based health risk assessment system, the Internet of Things (IoT), and Blockchain will optimize the importation of field data. When IoT is introduced, data such as the concentration of $PM_{2.5}$, humidity, and temperature, can be linked to the IoT by measuring instruments and importing data into the risk assessment system in real-time. The introduction of blockchain can ensure the reliability and security of data in the BIM-VR intelligent system [102]. The above two ideas to achieve functional expansion are not conflicting and it is suggested that these two ideas combined lead the direction of future research to realize the development of an intelligent and real-time expert visual-based health risk assessment system.

5.2. Passenger Risk Prevention Gamification Simulation System

The results from the passengers can also be exported from MYSQL, facilitating the quantitative study of the effectiveness of passenger training. Jaccard Similarity, a measure used to compare the similarity between samples, was calculated by determining the ratio of the intersection to the union of two sets. We calculated the Jaccard Similarity between the expert's standard answers and the passengers' answers, and plotted it as a scatter plot. As shown in Figure 15, the horizontal axis represents passengers, and the vertical axis represents similarity, with colors distinguishing different groups of experiments: blue for the initial round and red for the follow-up round after two days. The heights of the dots in Figure 15 indicate the Jaccard Similarity scores, where higher dots signify greater similarity. It should be noted that Jaccard Similarity values range from 0 to 1, where 0 indicates no overlap between the two sets and 1 indicates complete similarity. As seen in Figure 15, passengers' performance in the first round was relatively poor, with seven passengers scoring as low as 0%, highlighting their limited awareness of protection measures and weak risk coping capacity. However, the red dots, representing the follow-up round, were generally higher than the blue dots, demonstrating that the simulation system effectively improved passengers' awareness and encouraged them to take appropriate measures to reduce health risks.

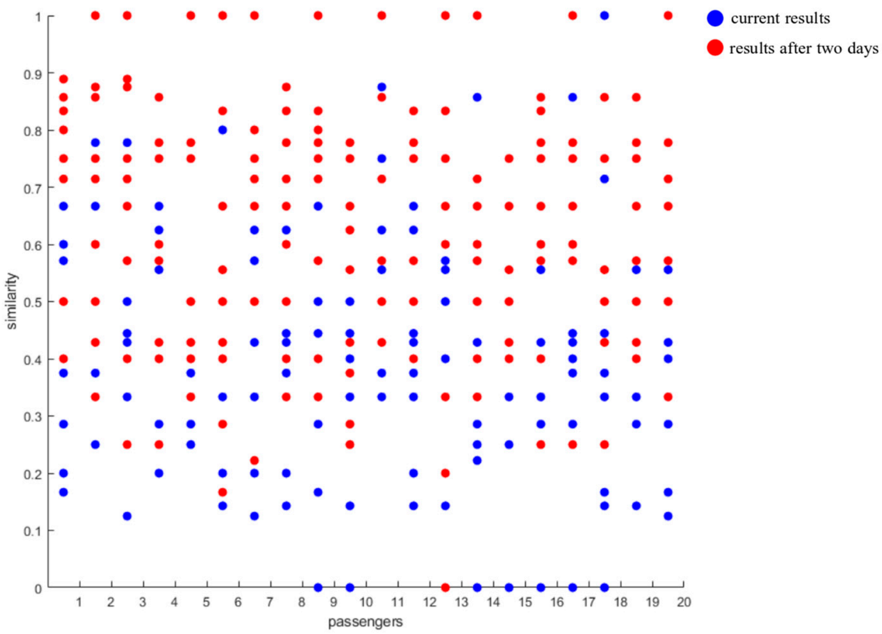


Figure 15. Similarity box chart.

Note: Redder colors represent an increase in similarity, while bluer colors represent a decrease in similarity. The numerical values represent the difference in similarity between the two rounds.

To better illustrate the improvement in similarity, we have depicted Figure 16. This study computed the similarity difference of each experimental subject. In Figure 16, redder colors indicate a greater increase in similarity, while bluer colors indicate a greater decrease. Additionally, the intensity of colors represents the magnitude of the values; deeper reds signify larger increases, while deeper blues signify larger decreases. The numerical values represent the difference in similarity between the two rounds. Overall, the trend showed that 92% of the region was in red, indicating a substantial increase in similarity. This further validated the fact that the passenger risk prevention gamification simulation system effectively enhanced passengers' risk coping capacity through continuous training.

While the study achieved good results, further in-depth analysis of passenger data is worth discussing. The system developed in this study, based on the extensive volume of passenger simulation results, can be integrated with data analysis software such as SPSS and Stata to delve deeper into population characteristics. This includes investigating whether passengers' coping behaviors vary based on factors like education level, age, gender, and occupation. Exploring these differences in characteristics can optimize the passenger risk prevention gamification simulation system. The system has the potential to incorporate more elements from passengers' perspectives in the future, simulating and training habitual behaviors. Moreover, we can categorize the population based on these characteristic differences and develop personalized passenger risk prevention gamification simulation systems for different categories of people. This approach would enhance the system's effectiveness by tailoring it to specific demographics and behaviors, ultimately improving passengers' risk coping capacities.

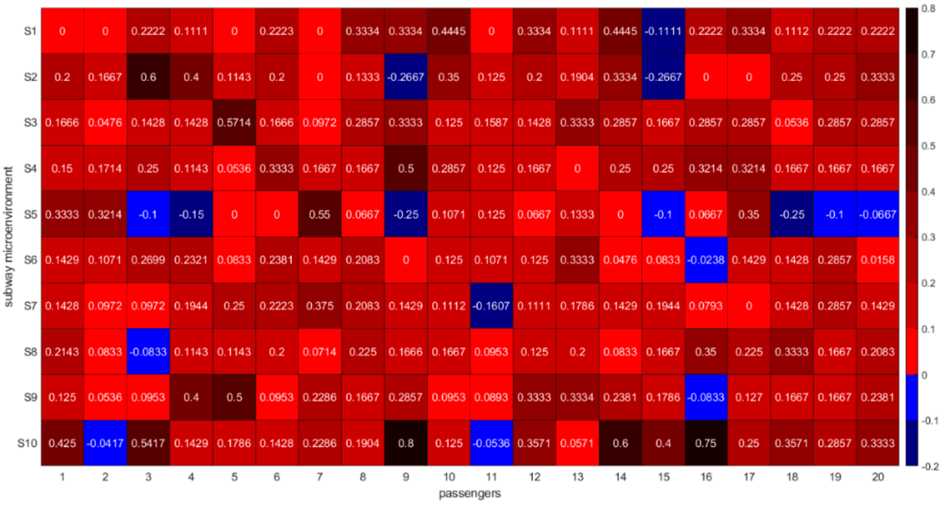


Figure 16. Passenger similarity difference heat map.

5.3. Results of Subject Evaluation with Questionnaire Surveys

Apart from the quantitative analysis of expert and passenger results, we designed a simulated feedback questionnaire based on references of Zhang et al. (2023) [103]. After each participant completed the entire 4.2 virtual simulation, they sat quietly in the laboratory for 10 min as a buffer period. Then, we invited the participants to rate our system based on their experimental experience using a five-point Likert scale. All participants provided their feedback and rated the system on a 5-Point Likert Scale after the entire test was completed. In this scale, 1 represents strongly disagree, and 5 represents strongly agree. The questionnaire data are summarized in Table 5.

Table 5. Results of the five-point Likert questionnaire evaluation.

Question	Average Scores of Experts	Average Scores of Passengers
1. The simulation system is helpful.	3.75	3.65
2. The virtual environment is in line with reality.	4.15	3.8
3. The logistic of actions in VR is in line with reality.	3.75	4.15
4. The instructions for roaming and collecting indicator are easy to follow.	3.5	3.75
5. I can get a better understanding of subway microenvironmental health risks.	3.55	3.95
6. I feel fairly comfortable when using the system, e.g., no dizziness.	3.25	3.1
7. The system provides better visualization for better understanding.	3.7	3.9
8. I am more confident to copy with risks easily and correctly through repeated training. (only for passengers)	-	3.65

Based on the scores, the overall system performance was satisfactory. The simulation system received positive feedback from both experts and passengers, indicating an improved understanding of subway microenvironmental health risks. Additionally, the majority of passengers expressed confidence in their ability to handle microenvironmental health risks better through repeated training.

6. Discussion

In the field of architecture, building information modeling (BIM) stands out as a widely embraced modeling tool among engineers, often described as "a digital representation of physical and functional characteristics of a facility" due to its robust modeling capabilities. BIM serves as both a tool and a concept that evolves with advancing technological trends [104]. However, it is crucial to note that BIM's primary application has traditionally been during the design or construction phases, focusing on tasks like cost control and clash detection. For instance, Li et al. (2020) introduced a budget control method for port construction projects leveraging BIM technology to alleviate practical economic pressures and establish effective cost control environments [105]. Similarly, Luo et al. (2022) employed BIM to create a sustainable multidisciplinary evaluation framework for subway pipeline clash detection and analysis [106]. Despite its extensive use, the architecture field has long advocated for comprehensive lifecycle management, underscoring the importance of safety and smooth operation during the operational phase [107]. However, the value of BIM during this phase has not been thoroughly explored. Therefore, this study pioneers the application of BIM in the operational phase of large-scale infrastructure projects, aiming to broaden the scope of BIM utilization throughout the entire project lifecycle.

Furthermore, when evaluating the environmental health of large-scale infrastructure like subway stations, sluices, dams, and high-speed rail stations, conventional methods typically involve questionnaires and field tests [108–110]. For example, Lee et al. (2018) utilized a thermal-optical elemental analyzer and an organic carbon analyzer to measure particulate matter in subway environments [111]. However, the time-consuming nature of field tests has been a longstanding concern in academia. Therefore, questionnaires that can be completed in the short term are commonly used for environmental risk assessments. For instance, Yang et al. (2022) conducted thermal comfort surveys in the Harbin subway in China [12]. Moreover, Han et al. (2015) conducted surveys based on five dimensions: heat, air, light, sound, and overall comfort [35]. Our research methodology was inspired by the work of Wu et al. (2011) and Nie (2020) [112,113]. In the former's study, questionnaires were used for strategic environmental assessment, but the scholars noted that the data collected from questionnaires was often incomplete and insufficient. Similarly, in our study, without the use of virtual technology, the scenarios for expert risk assessment and passenger training would be limited, as extreme subway microenvironments are rarely encountered in real-life situations. In Nie's study (2020), marine architecture in coastal cities was designed using "BIM plus VR", which compensated for the limitations of traditional architectural design methods through features like visibility, optimization, and simulation. Therefore, drawing inspiration from Nie (2020) [113], our study aimed to address the limitations of questionnaires and field tests in environmental assessment by integrating BIM and VR technologies. This integration allows experts to conduct subway microenvironment assessments efficiently and comprehensively, enhancing the overall quality and depth of the assessment process.

Additionally, for training related to large-scale infrastructure, passengers typically rely on methods such as field exercises, video watching, and brochures to enhance their coping capacity. However, the audience for field exercises was limited, and the effectiveness of methods like video watching and brochure reading was often constrained. Our research drew inspiration from Rajabi et al. (2022) [114], who utilized VR technology to design and model a virtual scenario evaluating the impact of education and anticipation on residents' decision-making under earthquake stress conditions. VR's visual effects are often more engaging and appealing to passengers. This study aimed to depart from traditional methods by leveraging VR technology to enhance the coping capacity of subway passengers. Previously, the advantages of VR in providing immersive and engaging virtual environments have been extensively utilized by Van and De (2009) and Wang et al. (2018) for specialized training of healthcare workers, mining workers, and construction practitioners [115,116]. It has been demonstrated that VR training can significantly improve safety awareness and behavioral capacity among users [117,118]. This study further confirmed these findings, highlighting the significant potential of VR for behavioral training purposes.

In conclusion, this study contributed significantly from both practical and academic perspectives. Practically, our research has revolutionized traditional subway risk management by introducing intelligent systems that provide immersive experiences of subway microenvironments for experts and passengers. These systems offer innovative models for environmental assessment and passenger training, aiding subway operators and researchers efficiently collecting comprehensive subway environmental data and policymakers in informing government policies on subway environmental management. This is highly beneficial for managing complex projects [119]. From an academic viewpoint, this study fostered interdisciplinary integration among urban planning, environmental science, and technology development. By integrating various software tools like Revit, Navisworks, Unity, MYSQL, and Visual Studio, we comprehensively simulated subway infrastructure microenvironmental conditions. Moreover, it expanded the application scope of BIM technology, leveraging it to play a more extensive role throughout the entire lifecycle of construction projects. The intelligent systems play a pioneering and foundational role in ensuring the healthy and safe operation of public transportation.

Nonetheless, it is important to acknowledge the limitations of this study. Firstly, although VR devices have been improved, from desktop 3D graphics to head-mounted devices (e.g., HMDs) and VR glasses (e.g., Oculus Rift), they can rarely achieve the simulation of all senses (touch, hearing, sight, taste, and smell). Due to the limitation of this technology, only the sense of sight is realized in the systems. It is encouraged to use more advanced devices in the near future to achieve immersive sensory experiences encompassing vision, hearing, touch, and smell such as sEMG wearable sensors [120]. Additionally, it must be acknowledged that due to psychological and experiential differences in VR simulations, there may be discrepancies between the results obtained from case studies and actual values. Therefore, in future research, it is advisable to conduct standardized psychological tests and VR simulation training before VR simulation to reduce the probability of experts and passengers making erroneous judgments due to psychological stress. Lastly, due to resource constraints, the case study in this research only involved 20 passengers and 20 experts, making it inadequate to test intelligent systems on a wide range of people. It is suggested to expand the scope of validation in future research to include individuals of different ages and educational backgrounds, thus broadly verifying the practicality and effectiveness of the intelligent systems. At the same time, we also hope that complex guidelines could be simplified, making BIM-VR applications more accessible to urban planners and civil engineers [121].

7. Conclusions

Subway microenvironmental risks pose a significant threat to the health of passengers. However, few intelligent systems are proposed to facilitate the management of subway environments. This study proposed novel intelligent systems for enhancing subway environment management. Based on different application functions, the systems included an expert visual-based health risk assessment system and a passenger risk prevention gamification simulation system. It also validated the feasibility by using the Xinzhuang Station in Nanjing Subway Line 3 as the case study. The case study results demonstrate that the intelligent systems developed in this study are viable. Additionally, with the assistance of a passenger risk prevention gamification simulation system, the passengers' coping capacity was greatly enhanced. The feedback questionnaire further affirmed the value of the intelligent systems.

This study has significantly advanced interdisciplinary integration among urban planning, environmental science, and technology development. It combined various software tools like Revit, Navisworks, Unity, MYSQL, and Visual Studio to comprehensively simulate the subway infrastructure's microenvironmental conditions. This has expanded BIM technology's application scope, empowering it to play a more extensive role across construction project lifecycles. Practically, the intelligent systems proposed offer innovative models for environmental assessment and passenger training, benefiting subway operators and researchers in data collection and government authorities in policy formulation. While this study focused on subway microenvironmental health risks, its framework is adaptable to various research objects like public buildings (office buildings, shopping malls, hotels, libraries, airports, etc.,) residential buildings, and industrial structures. Furthermore, there is potential for integrating different virtual technologies like AR, VR, MR, etc., with BIM and traditional architectural software to create more intelligent systems with improved information exchange and sensory realism.

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

Funding: This research was funded by the National Natural Science Foundation of China (72071115), Nanjing Medical Science and Technology Development Fund (ZKX21053) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX22_0302).

Data Availability Statement: The data from this article can be found online at https://github.com/Qiwenchen12/BIM-VR.git (accessed on 5 May 2024).

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. Sun, Q.; Yu, W. Comparison of Chinese and foreign urban rail transit system and analysis on their development trend. In *Asia-Pacific Power and Energy Engineering Conference*; IEEE Computer Society: Washington, DC, USA, 2011; pp. 1–4. [CrossRef]
2. He, S.J.; Zhi, J.Y. Study on Occupancy Behaviors of Passengers in the Subway Cabin: An Observation in Chengdu, China. *J. Adv. Transp.* **2022**, *2022*, 8781489. [CrossRef]
3. Han, B.; Yang, Z.; Yu, Y.; Qian, L.; Chen, J.; Ran, J.; Sun, Y.; Xi, Z.; Lu, F. Statistical analysis of urban rail transit operation in the world in 2020: A review. *Urban Rapid Rail Transit* **2021**, *34*, 5–11. [CrossRef]
4. Cheng, Y.H.; Yan, J.W. Comparisons of particulate matter, CO, and CO_2 levels in underground and ground-level stations in the Taipei mass rapid transit system. *Atmos. Environ.* **2011**, *45*, 4882–4891. [CrossRef]
5. Moreno, T.; de Miguel, E. Improving air quality in subway systems: An overview. *Environ. Pollut.* **2018**, *239*, 829–831. [CrossRef]
6. Yang, J.; Fan, X.; Zhang, H.; Zheng, W.; Ye, T. A review on characteristics and mitigation strategies of indoor air quality in underground subway stations. *Sci. Total Environ.* **2023**, *869*, 161781. [CrossRef] [PubMed]
7. McCreanor, J.; Cullinan, P.; Nieuwenhuijsen, M.J.; Stewart-Evans, J.; Malliarou, E.; Jarup, L.; Harrington, R.; Svartengren, M.; Han, I.-K.; Ohman-Strickland, P.; et al. Respiratory effects of exposure to diesel traffic in persons with asthma. *N. Engl. J. Med.* **2007**, *357*, 2348–2358. [CrossRef]
8. Miller, D.; King, M.F.; Nally, J.; Drodge, J.R.; Reeves, G.I.; Bate, A.M.; Cooper, H.; Dalrymple, U.; Hall, I.; López-García, M.; et al. Modeling the factors that influence exposure to SARS-CoV-2 on a subway train carriage. *Indoor Air.* **2022**, *32*, e12976. [CrossRef]
9. Wang, J.; Zhao, L.; Zhu, D.; Gao, H.O.; Xie, Y.; Li, H.; Xu, X.; Wang, H. Characteristics of particulate matter (PM) concentrations influenced by piston wind and train door opening in the Shanghai subway system. *Transp. Res. Part D Transp. Environ.* **2016**, *47*, 77–88. [CrossRef]
10. Chen, Q.; Mao, P.; Zhu, S.; Xu, X.; Feng, H. A decision-aid system for subway microenvironment health risk intervention based on backpropagation neural network and permutation feature importance method. *Build. Environ.* **2024**, *253*, 111292. [CrossRef]
11. Zhang, S.; Sunindijo, R.Y.; Loosemore, M.; Wang, S.; Gu, Y.; Li, H. Identifying critical factors influencing the safety of Chinese subway construction projects. *Eng. Constr. Archit. Manag.* **2021**, *28*, 1863–1886. [CrossRef]
12. Yang, B.; Yang, C.; Ni, L.; Wang, Y.; Yao, Y. Investigation on thermal environment of subway stations in severe cold region of China: A case study in Harbin. *Build. Environ.* **2022**, *212*, 108761. [CrossRef]
13. Mao, P.; Li, J.; Xiong, L.; Wang, R.; Wang, X.; Tan, Y.; Li, H. Characterization of urban subway microenvironment exposure—A case of Nanjing in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 625. [CrossRef] [PubMed]
14. Passi, A.; Nagendra, S.S.; Maiya, M.P. Assessment of exposure to airborne aerosol and bio-aerosol particles and their deposition in the respiratory tract of subway metro passengers and workers. *Atmos. Pollut. Res.* **2021**, *12*, 101218. [CrossRef]

15. Hsu, W.T.; Chen, J.L.; Lung, S.C.C.; Chen, Y.C. PM2.5 exposure of various microenvironments in a community: Characteristics and applications. *Environ. Pollut.* **2020**, *263*, 114522. [CrossRef] [PubMed]
16. Correia, C.; Martins, V.; Cunha-Lopes, I.; Faria, T.; Diapouli, E.; Eleftheriadis, K.; Almeida, S.M. Particle exposure and inhaled dose while commuting in Lisbon. *Environ. Pollut.* **2020**, *257*, 113547. [CrossRef] [PubMed]
17. Martins, V.; Minguillón, M.C.; Moreno, T.; Querol, X.; de Miguel, E.; Capdevila, M.; Centelles, S.; Lazaridis, M. Deposition of aerosol particles from a subway microenvironment in the human respiratory tract. *J. Aerosol Sci.* **2015**, *90*, 103–113. [CrossRef]
18. Xu, B.; Hao, J. Air quality inside subway metro indoor environment worldwide: A review. *Environ. Int.* **2017**, *107*, 33–46. [CrossRef]
19. Sandvik, K.B.; Jacobsen, K.L.; McDonald, S.M. Do no harm: A taxonomy of the challenges of humanitarian experimentation. *Int. Rev. Red Cross* **2017**, *99*, 319–344. [CrossRef]
20. LaFrance, M. The disappearing fourth wall: Law, ethics, and experimental theatre. *Vand. J. Ent. Tech. L.* **2012**, *15*, 507–582.
21. Patten, M. *Questionnaire Research: A Practical Guide*; Routledge: London, UK, 2016.
22. Borkowski, A.S. A Literature Review of BIM Definitions: Narrow and Broad Views. *Technologies* **2023**, *11*, 176. [CrossRef]
23. Cheng, D.; Peng, S.; Wei, L.I.; Wu, X.; Chang, J.; Zhang, M.; Luo, Q. Application Research of BIM in the Whole Life Cycle of Metro Station. In Proceedings of the 2019 International Conference on Intelligent Informatics and Biomedical Sciences, Shanghai, China, 21–24 November 2019; pp. 79–85.
24. Marzouk, M.; Abdelaty, A. BIM-based framework for managing performance of subway stations. *Autom. Constr.* **2014**, *41*, 70–77. [CrossRef]
25. Wiig, H.; Tenstad, O.; Iversen, P.O.; Kalluri, R.; Bjerkvig, R. Interstitial fluid: The overlooked component of the tumor microenvironment? *Fibrogenesis Tissue Repair* **2010**, *3*, 12. [CrossRef] [PubMed]
26. Li, Z.; Che, W.; Frey, H.C.; Lau, A.K. Factors affecting variability in PM2. 5 exposure concentrations in a metro system. *Environ. Res.* **2018**, *160*, 20–26. [CrossRef] [PubMed]
27. Moreno, T.; Reche, C.; Rivas, I.; Minguillón, M.C.; Martins, V.; Vargas, C.; Buonanno, G.; Parga, J.; Pandolfi, M.; Brines, M.; et al. Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environ. Res.* **2015**, *142*, 495–510. [CrossRef] [PubMed]
28. Midander, K.; Elihn, K.; Wallén, A.; Belova, L.; Karlsson, A.K.B.; Wallinder, I.O. Characterisation of nano-and micron-sized airborne and collected subway particles, a multi-analytical approach. *Sci. Total Environ.* **2012**, *427*, 390–400. [CrossRef]
29. Buonanno, G.; Stabile, L.; Morawska, L. Personal exposure to ultrafine particles: The influence of time-activity patterns. *Sci. Total Environ.* **2014**, *468*, 903–907. [CrossRef] [PubMed]
30. Weichenthal, S.; Kulka, R.; Dubeau, A.; Martin, C.; Wang, D.; Dales, R. Traffic-related air pollution and acute changes in heart rate variability and respiratory function in urban cyclists. *Environ. Health Perspect.* **2011**, *119*, 1373–1378. [CrossRef] [PubMed]
31. Barmparesos, N.; Assimakopoulos, D.V.; Niki Assimakopoulos, M.; Tsairidi, E. Particulate matter levels and comfort conditions in the trains and platforms of the Athens underground metro. *AIMS Environ.* **2016**, *3*, 199–219. [CrossRef]
32. Ye, X.; Lian, Z.; Jiang, C.; Zhou, Z.; Chen, H. Investigation of indoor environmental quality in Shanghai metro stations, China. *Environ. Monit. Assess.* **2010**, *167*, 643–651. [CrossRef]
33. Dybwad, M.; Granum, P.E.; Bruheim, P.; Blatny, J.M. Characterization of airborne bacteria at an underground subway station. *Appl. Environ. Microbiol.* **2012**, *78*, 1917–1929. [CrossRef]
34. *GB3095-2012*; Ambient Air Quality Standards. Ministry of Environmental Protection, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China, 2012.
35. Han, J.E.; Kwon, S.B.; Chun, C.Y. A study on the evaluation of indoor environment and passengers comfort in the subway stations in summer. *J. Archit. Inst. Korea Plan. Des.* **2015**, *31*, 129–136. [CrossRef]
36. Mao, P.; Wang, X.; Wang, R.; Wang, E.; Li, H. Passengers' Sensitivity and Adaptive Behaviors to Health Risks in the Subway Microenvironment: A Case Study in Nanjing, China. *Buildings* **2022**, *12*, 386. [CrossRef]
37. Leite, F.; Akcamete, A.; Akinci, B.; Atasoy, G.; Kiziltas, S. Analysis of modeling effort and impact of different levels of detail in building information models. *Autom. Constr.* **2011**, *20*, 601–609. [CrossRef]
38. Bryde, D.; Broquetas, M.; Volm, J.M. The project benefits of building information modelling (BIM). *Int. J. Proj. Manag.* **2013**, *31*, 971–980. [CrossRef]
39. Becerik-Gerber, B.; Rice, S. The perceived value of building information modeling in the US building industry. *J. Inf. Technol. Constr.* **2010**, *15*, 185–201.
40. Costin, A.; Adibfar, A.; Hu, H.; Chen, S.S. Building Information Modeling (BIM) for transportation infrastructure–Literature review, applications, challenges, and recommendations. *Autom. Constr.* **2018**, *94*, 257–281. [CrossRef]
41. Tang, Y.; Xia, N.; Lu, Y.; Varga, L.; Li, Q.; Chen, G.; Luo, J. BIM-based safety design for emergency evacuation of metro stations. *Autom. Constr.* **2021**, *123*, 103511. [CrossRef]
42. Garbett, J.; Hartley, T.; Heesom, D. A multi-user collaborative BIM-AR system to support design and construction. *Autom. Constr.* **2021**, *122*, 103487. [CrossRef]
43. El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. *Autom. Constr.* **2019**, *107*, 102940. [CrossRef]
44. Abbas, J.R.; O'Connor, A.; Ganapathy, E.; Isba, R.; Payton, T.; MgGrath, B.; Tolley, N.; Bruce, I. What is Virtual Reality? A healthcare-focused systematic review of definitions. *Health Policy Technol.* **2023**, *12*, 100741. [CrossRef]

45. Delgado, J.M.D.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. *Adv. Eng. Inform.* **2020**, *45*, 101122. [CrossRef]
46. Shi, Y.; Du, J.; Lavy, S.; Zhao, D. A multiuser shared virtual environment for facility management. *Procedia Eng.* **2016**, *145*, 120–127. [CrossRef]
47. Lewińska, P.; Róg, M.; Żądło, A.; Szombara, S. To save from oblivion: Comparative analysis of remote sensing means of documenting forgotten architectural treasures–Zagórz Monastery complex, Poland. *Measurement* **2022**, *189*, 110447. [CrossRef]
48. Schiavi, B.; Havard, V.; Beddiar, K.; Baudry, D. BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction. *Autom. Constr.* **2022**, *134*, 104054. [CrossRef]
49. Rahimian, F.P.; Chavdarova, V.; Oliver, S.; Chamo, F.; Amobi, L.P. OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing. *Autom. Constr.* **2019**, *102*, 1–16. [CrossRef]
50. Xu, Z.; Zhang, H.; Lu, X.; Xu, Y.; Zhang, Z.; Li, Y. A prediction method of building seismic loss based on BIM and FEMA P-58. *Autom. Constr.* **2019**, *102*, 245–257. [CrossRef]
51. Chen, H.; Hou, L.; Zhang, G.K.; Moon, S. Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. *Autom. Constr.* **2021**, *125*, 103631. [CrossRef]
52. Rokooei, S. Building Information Modeling in Project Management: Necessities, Challenges and Outcomes. *Procedia Soc. Behav. Sci.* **2015**, *210*, 87–95. [CrossRef]
53. Rajabi, M.S.; Radzi, A.R.; Rezaeiashtiani, M.; Famili, A.; Rashidi, M.E.; Rahman, R.A. Key Assessment Criteria for Organizational BIM Capabilities: A Cross-Regional Study. *Buildings* **2022**, *12*, 1013. [CrossRef]
54. Rajabi, M.S.; Rezaeiashtiani, M.; Radzi, A.R.; Famili, A.; Rezaeiashtiani, A.; Rahman, R.A. Underlying Factors and Strategies for Organizational BIM Capabilities: The Case of Iran. *Appl. Syst. Innov.* **2022**, *5*, 109. [CrossRef]
55. Zhang, Y.; Li, X. Response-surface-model based on influencing factor analysis of subway tunnel temperature. *Build. Environ.* **2019**, *160*, 106140. [CrossRef]
56. Hoover, T.E.; Hitchcock, W.W.; Kennedy, W.D.; Guinan, J.W. Computer Simulation of Subway Environment. *Transp. Eng. J. ASCE* **1973**, *99*, 53–72. [CrossRef]
57. Kim, G.S.; Son, Y.S.; Lee, J.H.; Kim, I.W.; Kim, J.C.; Oh, J.T.; Kim, H. Air pollution monitoring and control system for subway stations using environmental sensors. *J. Sens.* **2016**, *2016*, 1–10. [CrossRef]
58. *GB50157-2013*; Code for the Design of Subway. Ministry of Housing and Urban-Rural Development: Beijing, China, 2013.
59. Shiraly, R.; Khoshdel, N.; Jeihooni, A.K.; McLaws, M.L. Nudging physical distancing behaviors during the pandemic: A field experiment on passengers in the subway stations of shiraz, Iran. *BMC Public Health* **2022**, *22*, 702. [CrossRef] [PubMed]
60. Park, J. Changes in subway ridership in response to COVID-19 in Seoul, South Korea: Implications for social distancing. *Cureus* **2020**, *12*, e7668. [CrossRef] [PubMed]
61. Han, J.; Kwon, S.B.; Chun, C. Indoor environment and passengers' comfort in subway stations in Seoul. *Build. Environ.* **2016**, *104*, 221–231. [CrossRef]
62. Xu, J.; Xiang, Z.R.; Zhi, J.Y.; Chen, Y.D.; Xu, X.F. Assessment of visual comfort in the lighting environments of subway cabins in China. *Int. J. Rail Transp.* **2023**, *11*, 406–427. [CrossRef]
63. Wen, Y.; Leng, J.; Yu, F.; Yu, C.W. Integrated design for underground space environment control of subway stations with atriums using piston ventilation. *Indoor Built Environ.* **2020**, *29*, 1300–1315. [CrossRef]
64. Xu, S.Y.; Jiang, C.; Huang, L. Public health impacts from subway noise: Case study Hong Kong. *J. Acoust. Soc. Am.* **2019**, *145*, 1867. [CrossRef]
65. Neitzel, R.; Gershon, R.R.; Zeltser, M.; Canton, A.; Akram, M. Noise levels associated with New York City's mass transit systems. *Am. J. Public Health* **2009**, *99*, 1393–1399. [CrossRef]
66. Nieuwenhuijsen, M.J.; Gomez-Perales, J.E.; Colvile, R.N. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. *Atmos. Environ.* **2007**, *41*, 7995–8006. [CrossRef]
67. Ham, W.; Vijayan, A.; Schulte, N.; Herner, J.D. Commuter exposure to PM2. 5, BC, and UFP in six common transport microenvironments in Sacramento, California. *Atmos. Environ.* **2017**, *167*, 335–345. [CrossRef]
68. Hwang, S.H.; Park, W.M. Indoor air quality assessment with respect to culturable airborne bacteria, total volatile organic compounds, formaldehyde, PM10, CO_2, NO_2, and O_3 in underground subway stations and parking lots. *Air Qual. Atmos. Health* **2019**, *12*, 435–441. [CrossRef]
69. Ji, W.; Liu, Z.; Liu, C.; Wang, C.; Li, X. Characteristics of fine particulate matter and volatile organic compounds in subway station offices in China. *Build. Environ.* **2021**, *188*, 107502. [CrossRef]
70. Mathew, A.P. Using the environment as an interactive interface to motivate positive behavior change in a subway station. In Proceedings of the CHI'05 Extended Abstracts on Human Factors in Computing Systems, Portland, OR, USA, 2–7 April 2005; pp. 1637–1640.
71. Xue, X.; Zhang, R.; Zhang, X.; Yang, R.J.; Li, H. Environmental and social challenges for urban subway construction: An empirical study in China. *Int. J. Proj. Manag.* **2015**, *33*, 576–588. [CrossRef]
72. Chan, E.Y.Y.; Huang, Z.; Hung, K.K.C.; Chan, G.K.W.; Lam, H.C.Y.; Lo, E.S.K.; Yeung, M.P.S. Health emergency disaster risk management of public transport systems: A population-based study after the 2017 subway fire in Hong Kong, China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 228. [CrossRef] [PubMed]

73. Wang, J.; Yan, W.; Xu, H.; Zhi, Y.; Wang, Z.; Jiang, J. Investigation of the probability of a safe evacuation to succeed in subway fire emergencies based on Bayesian theory. *KSCE J. Civ. Eng.* **2018**, *22*, 877–886. [CrossRef]
74. Miyako, J.; Nakagawa, K.; Sagisaka, R.; Tanaka, S.; Takeuchi, H.; Takyu, H.; Tanaka, H. Neurological outcomes of out-of-hospital cardiac arrest occurring in Tokyo train and subway stations. *Resusc. Plus* **2021**, *8*, 100175. [CrossRef]
75. Chen, H.; Chen, B.; Zhang, L.; Li, H.X. Vulnerability modeling, assessment, and improvement in urban metro systems: A probabilistic system dynamics approach. *Sustain. Cities Soc.* **2021**, *75*, 103329. [CrossRef]
76. Bo, Y.; Jun, Y.; Yi, H. Research on the Structure of Urban Rail Transit Talent Training System. In Proceedings of the 2020 International Conference on Big Data and Informatization Education, Zhangjiajie, China, 23–25 April 2020; pp. 221–224.
77. Liu, D.Q.; Sun, S.R.; Qian, Z.W. Discussion on Critical Factors in Passenger Evacuation based on the Environment Management of Metro Stations-A Case of Shanghai. *Ekoloji* **2019**, *28*, 359–364.
78. Deng, Y.; Song, L.; Zhou, J.; Wang, J. Evaluation and reduction of vulnerability of subway equipment: An integrated framework. *Saf. Sci.* **2018**, *103*, 172–182. [CrossRef]
79. Xu, X.; Song, B.; Li, C.; Hu, X. Study on the safety and disaster-prevention signing system of the subway based on site investigation at home and abroad. In Proceedings of the 2009 International Conference on Management and Service Science, Beijing, China, 20–22 September 2009; pp. 1–4.
80. Chen, T.; Zhang, S.Y.; Zhao, L.Z.; Xia, J.J.; Fu, X.C.; Bao, Z.M.; Chen, Y.; Zhang, X.Z.; Wang, R.J.; Hu, C.; et al. Comparison of safety equipment between London underground and Beijing subway. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *69*, 012179. [CrossRef]
81. Wang, J.H.; Yan, W.Y.; Zhi, Y.R.; Jiang, J.C. Investigation of the panic psychology and behaviors of evacuation crowds in subway emergencies. *Procedia Eng.* **2016**, *135*, 128–137. [CrossRef]
82. Xiong, G.; Shen, D.; Dong, X.; Hu, B.; Fan, D.; Zhu, F. Parallel transportation management and control system for subways. *IEEE Trans. Intell. Transp. Syst.* **2016**, *18*, 1974–1979. [CrossRef]
83. Zhu, Y.; Li, N. Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review. *J. Saf. Sci. Resil.* **2021**, *2*, 1–10. [CrossRef]
84. Long, X.; Wang, R.; Chen, B.; Wu, N. A system for remote monitoring information management and risk control in the underground engineering. In *Information Technology in Geo-Engineering*; IOS Press: Amsterdam, The Netherlands, 2010; pp. 338–344.
85. Luglio, D.G.; Katsigeorgis, M.; Hess, J.; Kim, R.; Adragna, J.; Raja, A.; Gordon, C.; Fine, J.; Thurston, G.; Gordon, T.; et al. PM 2.5 concentration and composition in subway systems in the Northeastern United States. *Environ. Health Perspect.* **2021**, *129*, 027001. [CrossRef] [PubMed]
86. Huang, H.; Sun, Y.; Xue, Y.; Wang, F. Inspection equipment study for subway tunnel defects by grey-scale image processing. *Adv. Eng. Inform.* **2017**, *32*, 188–201. [CrossRef]
87. Huang, Z.; Fu, H.L.; Fan, X.D.; Meng, J.H.; Chen, W.; Zheng, X.J.; Wang, W.; Zhang, J.B. Rapid surface damage detection equipment for subway tunnels based on machine vision system. *J. Infrastruct. Syst.* **2021**, *27*, 04020047. [CrossRef]
88. Loy-Benitez, J.; Li, Q.; Ifaei, P.; Nam, K.; Heo, S.; Yoo, C. A dynamic gain-scheduled ventilation control system for a subway station based on outdoor air quality conditions. *Build. Environ.* **2018**, *144*, 159–170. [CrossRef]
89. Vargas-Robles, D.; Gonzalez-Cedillo, C.; Hernandez, A.M.; Alcaraz, L.D.; Peimbert, M. Passenger-surface microbiome interactions in the subway of Mexico City. *PLoS ONE* **2020**, *15*, e0237272. [CrossRef]
90. Peimbert, M.; Alcaraz, L.D. Where environmental microbiome meets its host: Subway and passenger microbiome relationships. *Mol. Ecol.* **2023**, *32*, 2602–2618. [CrossRef] [PubMed]
91. Li, H.; Zhong, M.Y.; Shi, C.L.; Shi, J.H.; Chen, H.C.; Xu, Q.X. Experimental research on investigation of metro passenger evacuation behaviors in case of emergency. In *Pedestrian and Evacuation Dynamics*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 173–184. [CrossRef]
92. Rong, G.; Sainan, W.; Mengshi, H. Underground railway safety analysis and planning strategy: A case of Harbin metro line 1, China. *Procedia Eng.* **2016**, *165*, 575–582. [CrossRef]
93. Potseluyko, L.; Rahimian, F.P.; Dawood, N.; Elghaish, F.; Hajirasouli, A. Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector. *Autom. Constr.* **2022**, *142*, 104496. [CrossRef]
94. Murre, J.M.; Dros, J. Replication and analysis of Ebbinghaus' forgetting curve. *PLoS ONE* **2015**, *10*, e0120644. [CrossRef]
95. Heo, S.; Nam, K.; Loy-Benitez, J.; Li, Q.; Lee, S.; Yoo, C. A deep reinforcement learning-based autonomous ventilation control system for smart indoor air quality management in a subway station. *Energy Build.* **2019**, *202*, 109440. [CrossRef]
96. Son, Y.S.; Oh, Y.H.; Choi, I.Y.; Dinh, T.V.; Chung, S.G.; Lee, J.H.; Park, D.; Kim, J.C. Development of a magnetic hybrid filter to reduce PM10 in a subway platform. *J. Hazard. Mater.* **2019**, *368*, 197–203. [CrossRef] [PubMed]
97. Omer, M.M.; Mohd-Ezazee, N.M.A.; Lee, Y.S.; Rajabi, M.S.; Rahman, R.A. Constructive and Destructive Leadership Behaviors, Skills, Styles and Traits in BIM-Based Construction Projects. *Buildings* **2022**, *12*, 2068. [CrossRef]
98. Cui, P.; Ju, X.; Liu, Y.; Li, D. Predicting and improving the waterlogging resilience of urban communities in China—A case study of Nanjing. *Buildings* **2022**, *12*, 901. [CrossRef]
99. Ourang, S.; Ourang, A. Optimizing Power Balance and Communication links in Microgrids: A Clustering Approach Using Particle Swarm Optimization. *Asian J. Soc. Sci. Manag. Technol.* **2023**, *5*, 275–281.
100. Ma, W.; Almasifar, N.; Amini, R.; Ourang, A.; Mahariq, I.; Alhoee, J. Crashworthiness evaluation and optimization of full polypropylene sandwich tubes under low-velocity impact based on machine learning algorithms. *Structures* **2024**, *60*, 105901. [CrossRef]

101. Taheri, S.; Morteza, A.; Sadeghi, S. Deep Learning Hyperparameter Optimization: Application to Electricity and Heat Demand Prediction for Buildings. *Energy Build.* **2023**, *289*, 113036. [CrossRef]
102. Morteza, A.; Ilbeigi, M.; Schwed, J. A blockchain information management framework for construction safety. In Proceedings of the Computing in Civil Engineering, Orlando, FL, USA, 12–14 September 2021; pp. 342–349. [CrossRef]
103. Zhang, Z.; Wong, M.O.; Pan, W. Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction. *Autom. Constr.* **2023**, *150*, 104848. [CrossRef]
104. Borkowski, A.S. Evolution of BIM: Epistemology, genesis and division into periods. *J. Inf. Technol. Constr.* **2023**, *28*, 646–661. [CrossRef]
105. Li, Y.; Li, Q. The Application of BIM Technology in Budget Control of Port Construction Cost. *J. Coast. Res.* **2020**, *103*, 644–648. [CrossRef]
106. Luo, S.; Yao, J.; Wang, S.; Wang, Y.; Lu, G. A sustainable BIM-based multidisciplinary framework for underground pipeline clash detection and analysis. *J. Clean. Prod.* **2022**, *374*, 133900. [CrossRef]
107. Dong, Z.; Qin, R.; Zou, P.; Yao, X.; Cui, P.; Zhang, F.; Yang, Y. Occupational health risk assessment of PC production-caused pollution based on damage assessment and cyclic mitigation model. *Eng. Constr. Archit. Manag.* 2024; *ahead-of-print*. [CrossRef]
108. Hu, P.; Feng, L. The risk of water quality deterioration with urban flood control—A case in Wuxi. *Sustainability* **2023**, *16*, 185. [CrossRef]
109. Lan, F.; Haisen, W.; Yan, Y. Spatial–Temporal Variations of Water Quality in Urban Rivers after Small Sluices Construction: A Case in Typical Regions of the Taihu Lake Basin. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12453. [CrossRef]
110. Feng, L.; Hu, P.; Wang, H.; Chen, M.M.; Han, J. Improving City Water Quality through Pollution Reduction with Urban Floodgate Infrastructure and Design Solutions: A Case Study in Wuxi, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10976. [CrossRef]
111. Lee, Y.; Lee, Y.C.; Kim, T.; Choi, J.S.; Park, D. Sources and characteristics of particulate matter in subway tunnels in Seoul, Korea. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2534. [CrossRef]
112. Wu, J.; Chang, I.-S.; Bina, O.; Lam, K.-C.; Xu, H. Strategic environmental assessment implementation in China—Five-year review and prospects. *Environ. Impact Assess. Rev.* **2011**, *31*, 77–84. [CrossRef]
113. Nie, L. Visual Design of Marine Architecture in Coastal Cities Based on "BIM+VR". *J. Coast. Res.* **2020**, *112*, 421–424. [CrossRef]
114. Rajabi, M.S.; Taghaddos, H.; Zahrai, S.M. Improving emergency training for earthquakes through immersive virtual environments and anxiety tests: A case study. *Buildings* **2022**, *12*, 1850. [CrossRef]
115. Van Wyk, E.; De Villiers, R. Virtual reality training applications for the mining industry. In Proceedings of the 6th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, Pretoria, South Africa, 4–6 February 2009; pp. 53–63. [CrossRef]
116. Wang, P.; Wu, P.; Wang, J.; Chi, H.L.; Wang, X. A critical review of the use of virtual reality in construction engineering education and training. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1204. [CrossRef]
117. Shi, Y.; Du, J.; Ahn, C.R.; Ragan, E. Impact assessment of reinforced learning methods on construction workers' fall risk behavior using virtual reality. *Autom. Constr.* **2019**, *104*, 197–214. [CrossRef]
118. De-Juan-Ripoll, C.; Soler-Domínguez, J.L.; Guixeres, J.; Contero, M.; Álvarez Gutiérrez, N.; Alcañiz, M. Virtual reality as a new approach for risk taking assessment. *Front. Psychol.* **2018**, *9*, 1–8. [CrossRef]
119. Ourang, S. Evaluation of Inter-Organizational Coordination of Housing Services in Rural Alaska through Social Network Analysis. 2022. Available online: https://dr.lib.iastate.edu/handle/20.500.12876/105396 (accessed on 1 January 2024).
120. Mudiyanselage, S.E.; Nguyen, P.H.D.; Rajabi, M.S.; Akhavian, R. Automated workers' ergonomic risk assessment in manual material handling using sEMG wearable sensors and machine learning. *Electronics* **2021**, *10*, 2558. [CrossRef]
121. Ballesteros, L.M.S.; Ourang, S.; Pazdon, J.; Kuffel, K. Increasing safety in residential construction through a simplified earthquake- and typhoon-resistant guidelines. *J. Future Sustain.* **2023**, *3*, 119–124. [CrossRef]

buildings

MDPI

Article

Green Skepticism? How Do Chinese College Students Feel about Green Retrofitting of College Sports Stadiums?

Yuyang Hou [1,†], Sen Chen [1,†], Yujie Zhang [1,†], Zhening Yao [1,†] and Qian Huang [2,*]

[1] Graduate Department, Xi' an Physical Education University, Xi' an 710068, China; yuyanghouedu@163.com (Y.H.); rockychensen@126.com (S.C.); zhangyujiegou@163.com (Y.Z.); yaozhenning3@126.com (Z.Y.)
[2] School of Sports Engineering and Information Technology, Wuhan Sport University, Wuhan 430079, China
* Correspondence: huangqian168@126.com
† These authors contributed equally to this work.

Abstract: This paper examined the factors influencing Chinese college students' psychological perceptions of green retrofitting of college sports stadiums. It focused on the roles of green skepticism, future rational cognition, and future perceptual cognition. A total of 551 college students from five universities in Xi'an were tested. The results indicated that college students' green skepticism, future rational cognition, future perceptual cognition, and psychological perceptions of green retrofitting of college sports stadiums were at a moderate level and that green skepticism had a significant and negative influence on college students' psychological perceptions of green retrofitting of college sports stadiums. Green skepticism was a significant negative predictor of environmental values ($\beta = -0.183$, $p < 0.001$), natural empathy ($\beta = -0.164$, $p < 0.001$), and moral elevation ($\beta = -0.187$, $p < 0.001$). In addition, future rational cognition and future perceptual cognition served as parallel mediators in the college students' psychological perceptions of green retrofitting of stadiums. It is notable that the mediating effect of future rational cognition was greater than that of future perceptual cognition. The findings indicate that resolving green skepticism and enhancing transparency and trust are crucial for enhancing college students' psychological perceptions and the behavioral benefits of green retrofitting of college sports stadiums. Furthermore, the facilitating effect of future rational cognition and future perceptual cognition assists college students in making more rational and ethical decisions and in garnering broad support for environmental actions.

Keywords: green retrofitting of college sports stadiums; green skepticism; future orientation; college students' green awareness

1. Introduction

With the rapid expansion of the global economy, accompanied by uncontrolled industrialization, environmental pollution has become a significant global issue [1]. It is manifested in the increase of air and water pollution [2], the decrease of biodiversity [3], and extreme weather events caused by global warming, floods, droughts, heat waves, and the frequent occurrence of the El Niño phenomenon [4,5]. In addition, the overexploitation of renewable resources by extractive industries has exacerbated resource scarcity and increased risks in supply chains, such as oil, gas, and mineral resources [6]. The traditional model of economic growth, characterized by high energy consumption and pollution, has proven to be unsustainable. The impacts of environmental pollution on human health are also becoming increasingly significant, such as respiratory diseases caused by deteriorating air quality [7]. The emergence of this series of problems calls for more effective policies and measures to achieve sustainable economic development while protecting the natural environment. A study published in *Nature Sustainability* further emphasizes the current challenges of a low-carbon transition to sustainable development [8].

The construction industry involves the use of heavy machinery, which emits large amounts of air pollutants, including greenhouse gases, particulate matter, and diesel exhaust. These emissions contribute to serious environmental problems and climate change [9]. Fine dust from engineering operations during the construction of buildings has also been shown to be a significant hazard to the human body [10]. With a huge stock of existing buildings, construction is also one of the biggest opportunities to reduce energy waste and to curb air pollution and global warming [11]. In this context, green retrofitting (GR) has come into existence. GR is the process of renovating or adapting an existing building to meet green building requirements, in order to improve the environmental attributes of the building, including energy efficiency and resource utilization, to meet sustainable green building standards [12]. There are two main objectives of green retrofitting, which are to improve energy efficiency and to reduce the carbon emissions of existing buildings by retrofitting these buildings sustainably [13]. For buildings that have already been constructed, the option of demolishing them and rebuilding them can be a very resource-intensive and labor-intensive process. Green retrofitting or upgrading of existing buildings is more economical and practical than complete demolition and reconstruction. Maintaining and improving existing building structures is also often more sustainable than constructing new buildings, from the perspective of environmental protection and resource utilization.

That stadiums, as large-scale-infrastructure facilities, are an important source of carbon emissions cannot be ignored [14]. Conventional stadiums are often built with traditional materials, such as concrete and ceramic tiles, which produce formaldehyde, benzene, ammonia, volatile organic compounds, radon and its daughters, and suspended particulate matter, etc., which have a huge negative impact on athletes, spectators, and the surrounding environment when large-scale events with a large concentration of people are held [15]. And the spread of harmful air and pathogenic micro-organisms in traditional stadiums can easily become a source of cross-infection and plague in public organizations [16]. More importantly, physical pollution, such as noise pollution, light pollution, heat pollution, water pollution, etc., in stadiums also hinders the sustainable process of "green sports" nowadays. Therefore, in order to curb the large amount of carbon emissions and pollution from traditional stadiums, and to ensure the long-term well-being of spectators and athletes, there is an urgent need to advocate the GR of stadiums.

In the pursuit of sustainable development, when high-profile green propaganda does not match actual environmental practices, public trust will be seriously affected. Contemporary college students have been instilled with green concepts since they were young; in higher education, they are often the "vanguard" of environmental protection work, and they are usually more concerned about environmental issues and corporate social responsibility. When they find out that these so-called green renovation projects are only cosmetic, they are often disappointed, and this disappointment may turn into pessimism, making them skeptical of any project claiming to be green or sustainable, or even causing them to believe that it is a scam. College students may believe that even if there are genuine environmental initiatives, they may be overshadowed by the "greenwashing" behavior of managers, making the environmental industry as a whole seem untrustworthy. This perception of green skepticism extends beyond the campus and affects students' perceptions of green renovation projects for sports facilities in the broader social environment. When gymnasiums and other sports facilities claim to be green, these young environmental pioneers may be wary of the authenticity of the projects, questioning the real motives behind them and their actual effectiveness.

At present, research on green retrofitting of stadiums is often limited to sustainable design [17] and the return on investment of GR [18], etc., and there is almost no research on college students' psychological perceptions of the GR of buildings. Based on this, this study aimed to systematically explore the psychological perceptions of the Chinese college student population towards the green renovation of college sports stadiums, focusing on analyzing the impact of green skepticism on their psychological perceptions. The objective of this study was to construct an empirical model based on the VBN theory, in order to gain an in-depth understanding of the real feelings and attitudes of college students towards the green renovation of college sports stadiums. The model will reveal the psychological perceptions and cognitive behaviors in the process of green renovation, and it will provide scientific evidence and feasible suggestions to help the green renovation project better meet the expectations and needs of the college student population. Additionally, this study aimed to provide green renovation stakeholders with a novel perspective on understanding, to facilitate more efficacious communication and collaboration, and, consequently, to facilitate the seamless implementation and extensive acceptance of green renovation in sports venues. By addressing the deficiencies in existing research, this study contributes to the enrichment of both theory and practice in the field of green building retrofitting, as well as providing substantial support for future green retrofitting projects and helping to realize a more sustainable future.

2. Literature Review and Hypotheses

2.1. Green Skepticism and Psychological Perceptions of Green Renovation of Stadiums

"Green skepticism" is "consumer skepticism about the green features of a product [19]". Some researchers have found that green skepticism can be a potential cognitive response to the exposure of green information, and this response can influence consumers' evaluations of a brand [20,21]. In the field of "green marketing", the theoretical exploration of public attitudes has become somewhat clichéd. When products or services fail to meet public expectations regarding their environmental attributes during the marketing process, it can result in negative public evaluations. This often leads to public skepticism, known as green skepticism, towards the products or practices in question.

As the consumer goods market grows, the phenomenon of "greenwashing" has become more prevalent, leading consumers to easily become skeptical of products that claim to have green attributes or promote green messages [22]. "Greenwashing" refers to the practice of companies misleadingly advertising or marketing themselves as environmentally friendly, or creating a green-oriented image, while actually engaging in environmentally harmful activities [23]. Both actual and perceived instances of "greenwashing" impact the general public, leading to increased skepticism towards environmental claims. As a result, negative practices like "greenwashing" can intensify public distrust of environmental information. Therefore, the negative practice of "greenwashing" can lead to increased public skepticism towards environmental information, which in turn affects willingness to purchase and actual purchasing behavior. Public green skepticism arises partly because people are becoming weary of the green claims made by numerous products. Simply stating "I am green" is no longer sufficient to earn public trust. Instead, it is essential to provide clear and substantial evidence of genuine environmental benefits, to dispel public skepticism. On the other hand, there is still a lack of global environmental regulations that ensure transparency and sustainability standards [24]. As a result, an increasing number of people are questioning the green motives of managers or companies. They express uncertainty about the green attributes and functions of products and even doubt the real environmental benefits. This skepticism is growing in the construction sector [25], in particular.

Stadiums, as a type of sports facility, are characterized by their large footprint and extensive space. Green retrofitting of stadiums involves updating the technology and design of existing structures, to enhance their environmental performance. This includes improving energy efficiency, conserving resources, and reducing environmental impacts. Green retrofitting typically involves adopting energy-efficient technologies, using sustainable materials, and implementing measures to enhance the overall sustainability of the facility. Zakaria's study indicates that green retrofitting is the process of refurbishing or redecorating existing buildings, to meet green building standards, thereby improving their environmental attributes [12]. Liu, in his study, describes green retrofitting as an effective way of improving the performance of an existing building, in order to achieve low energy consumption and low carbon emissions [26]. The high emissions from building materials, significant energy consumption from internal energy-consuming equipment during stadium operations, carbon emissions during large-scale events, and concerns about whether building materials can be recycled or if they will cause pollution after a stadium is dismantled, all provide critical directions for the green retrofitting of stadiums. These factors emphasize the need for sustainability measures that address both operational efficiency and end-of-life environmental impact.

College students' psychological perceptions of green retrofitting of college sports stadiums mainly involve attitudes, feelings, and perceptions towards the environmental or sustainable transformation of urban stadiums, including the corresponding impact on college students' environmental values, natural empathy, and moral elevation. For example, by enhancing the energy efficiency of facilities, using sustainable materials, or increasing the use of natural light, stadiums can influence the emotional connection and identification that college students have with the natural environment. These changes can also affect how much importance students place on environmental issues within their own value systems. Conversely, if students perceive green transformations as mere cosmetic work or believe them to be false, this green skepticism may ultimately lead to diminished emotional connection/concern for the natural world. For example, Cheng, in his study [27], found a negative correlation between popular skepticism of green advertising and environmental engagement. Romani's study highlights that green skepticism can diminish moral elevation by influencing the relationship between consumers' perceptions of corporate social responsibility (CSR) motivations and their behavioral responses to CSR initiatives. This skepticism ultimately affects consumers' support for other green products. This suggests that when college students are skeptical about the environmental credentials of building retrofits, they may harbor doubts about the positive impact of these initiatives [28].

Green skepticism stems from the public's distrust of the green-related claims associated with a product. When consumers find that a green product is inferior to a traditional one, or that a company's green claims contradict its actual practices, this can lead to skepticism about both the product and the company [29]. When college students are exposed to such information, it can lead to a negative impression or evaluation of the associated green behaviors. This negative evaluation can adversely affect their future intentions or behaviors, particularly when such negative information resonates strongly with them. The prominence of these negative evaluations can influence their environmental values, natural empathy, and moral elevation, ultimately reducing their acceptance of green policies or behaviors. The effects of emotional expression on observers' affect, cognition, and behavior were overviewed in Van Kleef's study, which found that emotional expression affects observers' affective responses, reasoning processes, and behavior [30]. It is clear that when college students harbor green skepticism, they may find it challenging to develop positive attitudes towards ongoing green renovations in stadiums. This mistrust can diminish their emotional connection to the natural environment and the moral uplift that comes from adopting environmentally friendly behaviors. Ultimately, this can impact their overall attitudes and behaviors towards environmental actions. Based on this, the following hypotheses are proposed:

H1: *Green skepticism negatively affects the psychological perception of green renovation in college sports stadiums.*

2.2. The Mediating Role of Future Rational Orientation Perception

Orientation is the knowledge of determining one's own position relative to different points or objects, while perception is the mental process of attributing sensations to external objects [31]. Orientation perception is the capability of an organism to detect and interpret its own position and the orientation of objects within its environment relative to a spatial coordinate system, using its sensory system. This process involves integrating visual, auditory, tactile, and other sensory information with high-level cognitive processing in the brain. This integration helps determine the orientation and position of objects, which is crucial for everyday activities and spatial navigation. Orientation perception is not merely a straightforward sensory process; it is a complex outcome of multisensory integration and cognitive processing. The term "future rational orientation perception" refers to an individual's cognition and perception involved in rational future planning and decision making. It involves an individual's psychological tendency to make decisions about how to plan and prepare rationally in the present stage, with the aim of achieving expected benefits in the future. Carver's study indicates that individuals with a clear goal orientation are more likely to adopt a rational attitude in their planning and tend to be more consistent and logical in their behavior [32]. Meanwhile, Rappaport emphasizes the importance of future-oriented rational planning in business management and investment, and elaborates on how to maximize shareholder value through a systematic and rational approach to planning a firm's long-term strategy [33].

The phenomenon of green skepticism is gaining prominence as discussions about sustainable development and environmental responsibility deepen. As the backbone of social and environmental change, college students' environmental attitudes and behavioral choices are important for future sustainable development. When green skepticism arises, it can impact college students' perceptions of their own future rationality, potentially altering their long-term views on environmental behavior and diminishing their motivation to pursue green goals. This suggests that green skepticism may indirectly impair individuals' orientation towards perceived future rationality, influencing their commitment to sustainable actions [34]. Mohr et al.'s study further confirms this point: consumers with high levels of skepticism are more likely to harbor negative attitudes toward environmental claims. This skepticism affects their confidence in future environmental planning, impacting their willingness to support or engage in sustainability initiatives [19]. Thus, green skepticism may directly affect college students' trust and acceptance of environmental initiatives, which, in turn, may cause changes in their future rational orientation perceptions.

Future rational perception orientation, as a psychological tendency to focus on long-term benefits and rationally think about the future, may have an important impact on the psychological perception of green retrofitting of stadiums. For example, college students who are future-oriented in terms of the green retrofitting of stadiums tend to focus more on the long-term environmental benefits. They are more sensitive to the potential long-term value and actual impact of such green retrofits, particularly in terms of reducing energy consumption, lowering carbon emissions, and improving resource utilization efficiency. Simultaneously, these students are better equipped to rationally evaluate the economic benefits of green renovations. While such renovations may require an initial investment, they can lead to reduced operating costs and enhance the economic efficiency of venues over the long term. Therefore, these students are more likely to support and endorse green renovation measures, recognizing that the dual benefits to both the economy and the environment are worth pursuing. For instance, Carrus et al. discovered that perceived future rational orientation significantly enhances environmental behavior. Individuals with a high future rational orientation tend to hold positive psychological perceptions of green retrofit initiatives, seeing them as valuable investments in sustainability [35].

The VBN theory posits that an individual's environmental behavior is shaped by their fundamental values, environmental beliefs, and personal norms. Firstly, the perceived future rational orientation reflects the individual's emphasis on long-term benefits and sustainable development, which is closely related to the basic values espoused in the VBN theory. College students with a stronger future rational orientation are more inclined to prioritize environmental protection and sustainable development, and their attitudes toward green remodeling projects will be more positive. This positive attitude can mitigate their skepticism regarding green remodeling projects, which may be defined as a questioning and distrust of such projects. Secondly, an individual's perception of future rationality orientation can enhance their sense of responsibility and mission towards environmental issues. This belief motivates them to be more willing to accept and support green remodeling projects. Ultimately, an individual's perception of future rational orientation can influence their psychological perception of green remodeling projects by affecting their personal norms. This may lead them to perceive supporting green remodeling as a responsibility or duty. In the VBN theoretical model, future rational orientation perception is interconnected with beliefs and norms. College students' green skepticism can influence their ecological worldviews and beliefs, potentially leading to a decline in personal norms. This decline, in turn, can affect their future rational orientation perceptions and green psychological perceptions, altering how they perceive and react to environmental issues and initiatives. This interconnection underscores how skepticism can fundamentally shift the motivational drivers behind environmentally responsible behaviors. For example, Hansla et al. found that values and beliefs have a significant effect on green energy consumption attitudes based on VBN theory. Personal norms act as a mediating variable affecting consumer attitudes and willingness to pay for green electricity [36]. Luchs et al. showed that green skepticism reduces consumer support for sustainable products, and that future rational orientation perceptions can attenuate this negative effect. Even though skepticism exists, future rational orientation perception can motivate consumers to make more sustainable choices [37]. Based on this, this paper proposes the following hypotheses:

H2: *Perceived future rational orientation mediates between green skepticism and psychological perceptions of green retrofitting of college sports stadiums among college students.*

2.3. The Mediating Role of Future Perceptual Orientation Perception

The term "futuristic orientation perception" refers to the psychological process through which individuals perceive, anticipate, and respond to future emotions and events [38]. This concept encompasses the emotional anticipation of future scenarios, the predictive experiences of those emotions, and the behavioral motivations and decisions that are shaped by future expectations. Futuristic orientation perception involves imagining, planning, and emotionally investing in potential future events. It is a crucial cognitive and affective element for understanding and navigating future human behavior. Distinct from rational orientation perception, which focuses on logical and systematic planning, futuristic orientation emphasizes the impact of emotions and values on behavior, as well as the individual's emotional commitment to and anticipation of future situations. This includes emotional responses to expected future outcomes that align closely with personal values. From a neurocognitive perspective, futuristic orientation perception engages multiple brain regions responsible for prediction, planning, and emotional evaluation. This cognitive process is essential for understanding how individuals anticipate and prepare for future emotional states [39]. From a developmental psychology perspective, future-sensory oriented perception is a skill that individuals develop gradually as they mature. It encompasses how they comprehend, anticipate, and prepare for emotional engagement and behavior in future scenarios. This cognitive and affective ability tends to enhance with age and plays a significant role in self-development, decision making, and social adaptation [40].

In value–belief–norm (VBN) theory, self-transcendent values, such as social justice and harmony, are considered crucial for fostering environmentally responsible behavior [41].

College students' environmental attitudes and behavioral choices serve as the cornerstone of social and environmental change, with profound implications for future sustainable development. Green skepticism, in particular, can significantly influence their trust in and acceptance of environmental protection measures, thereby impacting their future perceptual orientation. Specifically, green skepticism may lead college students to engage in more thorough information gathering and verification to confirm the accuracy of environmental claims. This intensified search for information can heighten students' awareness of environmental issues, thereby deepening their understanding of the importance of environmental protection. Nguyen's study indicates that green skepticism can impact green purchasing intentions by diminishing consumers' environmental knowledge and concerns [42].

Green retrofitting of stadiums has emerged as a significant initiative for promoting sustainable development. While builders often highlight the environmental benefits of these retrofits, college students' psychological perceptions of such green renovations can be influenced by various factors, particularly their skepticism regarding the authenticity and effectiveness of the environmental measures. This green skepticism impacts their value beliefs and reality norms—core elements in VBN theory—including personal environmental values, ecological worldview, and perceived personal responsibility. In this context, green skepticism becomes a pivotal variable that prompts college students to critically reflect on environmental claims at an emotional level, encouraging them to reassess their personal environmental values [43].

This reframing not only alters college students' perceptions of environmental issues but may also bolster their emotional support for green renovation projects in college sports stadiums. For instance, research by Goh [29] suggests that students may experience pride and satisfaction from associating with the potential environmental benefits of green remodeling, stemming from the anticipation of improved environmental quality in the future. College students' skepticism about environmental measures extends beyond questioning their authenticity or effectiveness; it deeply influences their affective expectations and behavioral dispositions towards future environmental conditions, driving them to seek evidence that either confirms or refutes their skepticism. When this evidence is integrated with their perceptual perceptions, it shapes students' future perceptual orientations. As these orientations evolve, so do their psychological perceptions of green retrofit projects in college sports stadiums. If students perceive these renovation measures as effective solutions to future environmental challenges, they are likely to evaluate and support these projects more positively. Conversely, if their green skepticism leads them to doubt the future effectiveness of these projects, even well-publicized green initiatives may fail to secure their approval and support. For example, Khoshbakht et al.'s study indicates that college students' perceptions of green renovations in stadiums may be shaped by their environmental values and future-oriented perceptions. Features that promote environmental sustainability can significantly enhance users' overall satisfaction with the space and their sense of restorative experience, which are vital for advancing green retrofit projects. This research underscores the importance of aligning green initiatives with the values and future expectations of users, to foster greater acceptance and enthusiasm for these projects [44]. Similarly, Malekinezhad et al.'s research suggests that as college students' future orientations towards green retrofits in stadiums evolve, so too do their psychological perceptions of these projects. This indicates a dynamic relationship where changes in students' future-oriented thinking influence their attitudes and emotional engagements with green renovation efforts, potentially leading to more robust support for sustainable practices within their environments [45]. Based on this, the following hypotheses are proposed in this paper (the proposed model diagram for this paper is shown in Figure 1):

H3: *Perceived future skepticism orientation mediates between green skepticism and psychological perceptions of green retrofitting of college sports stadiums for college students.*

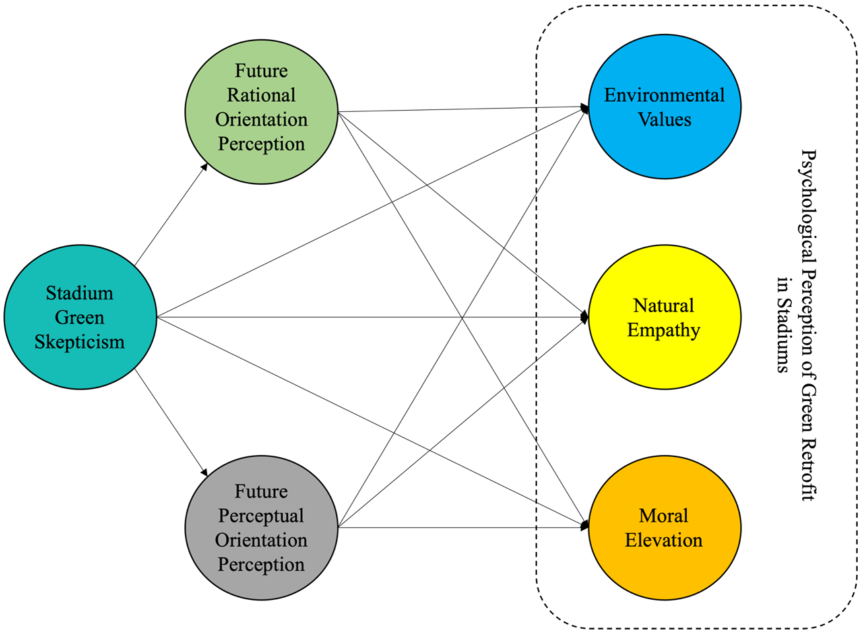


Figure 1. Diagram of the proposed model.

3. Methods

3.1. Subjects

Formal research was conducted on 23 April 2024, in five general colleges and universities in Xi'an City. 600 questionnaires were issued, and 592 questionnaires were recovered, of which 551 were valid questionnaires, with a validity rate of 93.07%, of which 267 were male and 284 were female; the age was 20.475 ± 1.158 years old, with a balanced proportion of the sample.

3.2. Measurement of Variables

Green skepticism mainly highlights the skepticism of consumers or social groups towards the green characteristics of a certain building or thing or green environmental protection publicity information. As the basis of this study, we organized and analyzed the focus of green skepticism by combining the similarities and differences between green skepticism and other variables, and incorporating them into the question items. Specifically, the measurement of green skepticism in this paper drew on the more mature scales of Mohr et al. [19], Laufer et al. [46], and Yeung et al. [47] in previous scientific research. We modified and improved the questions according to the characteristics of the research object in this paper, and we ultimately formed a 4-question scale for green skepticism in this study, such as "I have a conservative or skeptical attitude toward the real environmental protection effect of the stadium that can be achieved by the green renovation. I am conservative or skeptical about the real environmental effect that can be achieved after the green renovation of the stadium".

The measurement of the future orientation of green retrofitting of college sports stadiums in this paper drew on the specific scale of Heimberg [48], who first summarized the variable of future orientation for research and measurement. On this basis, we referred to scholars' studies on future orientation measurement in different fields (such as the future orientation scale for adolescents and the developmental orientation scale, etc.), screened out the scale items with high reliability and validity, and combined them with the core connotation of green retrofitting of stadiums to make streamlining modifications. Finally, a two-dimensional (future rational cognition, future perceptual cognition) six-item scale for green retrofitting of stadiums was developed, such as "When I hear about the green retrofitting of stadiums, I will outline in my mind what the transformed stadiums will look like". In this paper, the measurement of the variable of psychological perception of green retrofitting of stadiums was more innovative. We did not want to limit our perspective to traditional variables, such as the perceived value, perceived usefulness, or perceived environmental awareness of the green retrofitting of stadiums. This paper fully examined the scales of the variables from different sides, focused on the scales of the related studies of Lee [49] et al. and Diessner [50] et al., and, finally, drew the scales of this paper for a 10-item 3-dimension (environmental values, natural empathy, moral elevation) scale of the psychological perception of green renovation of stadiums, such as "After learning about the advantages of green renovation of stadiums, I will try to increase and persuade my friends and relatives to make more pro-environmental behaviors in my future life". A 5-point Likert scale was used, with scores ranging from 1 to 5, from "strongly disagree" to "strongly agree".

3.3. Questionnaire Distribution

Based on the stratified random sampling method, the questionnaires were filled out and recovered on-site by administrative classes in five general colleges and universities in Xi'an City, and the initial test and retest were conducted (the official questionnaires were distributed 2 weeks after the initial test questionnaires were distributed, in order to check the reliability of the retests); 150 questionnaires were distributed for the initial test, 122 valid questionnaires were obtained, and 100 valid questionnaires were obtained in the retests. The initial questionnaire was then subjected to item analysis, which was designed to determine the validity and appropriateness of the items on the questionnaire scale. The principle was to first sum up the analyzed items, then divide them into high and low subgroups (bounded by the 27% and 73% quartiles), and then use the t-test to compare the differences between the high and low subgroups. If there was a difference then it meant that the scale items were appropriately designed, and if vice versa then it meant that the scale items were unable to differentiate the information, that the design was irrational, and that it should be deleted. As shown in Table A1, 20 items—GS1, GS2, GS3, GS4, FROP1, FROP2, FROP3, FPOP1, FPOP2, FPOP3, EV1, EV2, EV3, EV4, NE1, NE2, NE3, ME1, ME2, ME3—were analyzed and summed up into high and low groups. The differences were compared, using the t-test, and the high and low groups showed significance for GS1, GS2, GS3, GS4, FROP1, FROP2, FROP3, FPOP1, FPOP2, FPOP3, EV1, EV2, EV3, EV4, NE1, NE2, NE3, ME1, ME2, and ME3, all of which were significant ($p < 0.05$), implying that a total of 20 items were well differentiated and did not need to be deleted from the analysis. Table A2 shows the decision value CR alone, as well as the correlation coefficient between the analyzed items and the total score of the scale; in this paper, the decision value CR of the scale showed significance, which meant that all items should be retained, and the correlation coefficients were all > 0.2, which also meant that all the items in this study could be retained.

All the samples were divided into two categories, according to number parity, which were used for exploratory and validation factor analysis, respectively. The KMO was 0.776, which was greater than 0.6, meeting the prerequisite requirements for factor analysis, meaning that the data could be used for factor analysis research, and the data passed the Bartlett's sphere test ($p < 0.05$), which indicated that the research data were suitable for factor analysis. A total of six factors were extracted from the factor analysis of this paper, and the eigenroot values were all greater than 1. The variance explained by the rotation of these six factors was 13.511%, 12.846%, 11.306%, 10.698%, 10.634%, and 9.648%, respectively, and the cumulative variance explained by the rotation was 68.643%. The data for this study were rotated, using the maximum-variance rotation method (varimax), in order to establish the correspondence between the factors and the study items. The above table shows the information extraction of the factors for the research items and the correspondence between the factors and the research items. From the above table, it can be seen that all the research items correspond to a common degree value higher than 0.4, which means that there is a strong correlation between the research items and the factors and that the factors can effectively extract the information. According to the results of factor analysis and the meanings of the items, the six common factors are named green skepticism, future rational orientation perception, future perceptual orientation perception, environmental values, natural empathy, and sense of moral elevation.

Subsequently, the paper was analyzed by validated factor analysis (CFA) for a total of six factors, as well as 20 analysis items. As can be seen from Table A3, the AVE values corresponding to a total of six factors were all greater than 0.5, and the CR values were all higher than 0.7, which meant that the data of this analysis had good convergent validity. From Table A4, the AVE square root value of each variable in this paper was greater than the maximum value of the absolute value of the correlation coefficient between the factors, implying that the variables in this paper had good discriminant validity.

4. Results

4.1. Common Method Bias Test

The Harman one-way test was used to test for common method bias. It was found that five factors had eigenvalues > 1 and that the first factor explained 31.874% of the variance. The critical criterion of 40% was not reached. In the validation factor analysis of adding a method factor to the full factor model, CMIN/DF, which is the relative ratio of chi-square and degrees of freedom, was less than 3, TLI, CFI was greater than 0.9, RMSEA and SRMR were less than 0.08, which indicated a good fit, and all of the above indicators were up to the standard. Taken together, most of the model fit indicators met the standard full factorial model fit status, indicating that this study did not have common method bias.

4.2. Descriptive Statistics and Correlation Analysis of Variables

As can be seen from Table 1, the variables involved in this study were generally at the medium level, and all of them showed significance between GS and FROP, FPOP, EV, NE, ME, with correlation coefficient values of −0.154, −0.129, −0.165, −0.139, −0.154. All of them had correlation coefficient values of less than 0, implying that there was a negative correlation between GS and FROP, FPOP , EV, NE, ME. All of them showed significance, with correlation coefficient values of 0.448, 0.380, 0.403, 0.523, and the correlation coefficient values were greater than 0, implying that there was a positive correlation between FROP and FPOP, EV, NE, ME, a total of 4 items. All of them showed significance between FPOP and EV, NE, ME, and the values of the correlation coefficients were 0.344, 0.400, 0.501, which meant that there was a positive correlation between FPOP and EV, NE, and ME.

Table 1. Means, standard deviations, and Pearson's correlation statistics for each variable.

	Average Value	**(Statistics) Standard Deviation**	**GS**	**FROP**	**FPOP**	**EV**	**NE**	**ME**
GS	3.287	1.06	1					
FROP	3.714	0.85	−0.154 **	1				
FPOP	3.642	0.862	−0.129 **	0.448 **	1			
EV	3.661	0.892	−0.165 **	0.380 **	0.344 **	1		
NE	3.677	0.865	−0.139 **	0.403 **	0.400 **	0.363 **	1	
ME	3.77	0.803	−0.154 **	0.523 **	0.501 **	0.441 **	0.468 **	1

Note: ** $p < 0.01$.

4.3. Parallel Mediation Effect Tests

(1) A latent variable direct effect model with GS as the independent variable, FOP dimensions as the dependent variable, and no mediator variables (FROP, FPOP) was developed, using Mplus, and the model was well-fitted, with $\chi^2/df = 1.201$, RMESA = 0.019, CFI = 0.996, TLI = 0.995, and SRMR = 0.022. The direct-effect modeling showed that GS had a significant negative predictive effect on EV ($\beta = -0.183$, SE = 0.05), NE ($\beta = -0.164$, SE = 0.05), and ME ($\beta = -0.187$, SE = 0.05) ($p < 0.001$), and hypothesis H1 of this paper was established.

(2) Parallel mediation effect test: FROP and FPOP were used as mediating variables, to establish the full model of the parallel mediation structural equation (as in Figure 2). The bias-corrected nonparametric percentile Bootstrap method was used, with 5000 repetitions of sampling, and 95% confidence intervals were computed, to test the differences between the specific mediation effect, total mediation effect, and total effect. The model fit data showed that $\chi^2/df = 2.04$, RMESA = 0.043, CFI = 0.969, TLI = 0.962, SRMR = 0.081, SRMR was greater than 0.08 but less than 0.1 standardized qualification, and the model indicators were up to standard. The amount of change compared with the direct effect model was $\Delta\chi^2$ = 232.96, $\Delta df = 84$, $p < 0.001$, indicating that the mediator model fit was significantly better than the direct effect model, and the inclusion of the mediator variables was reasonable.

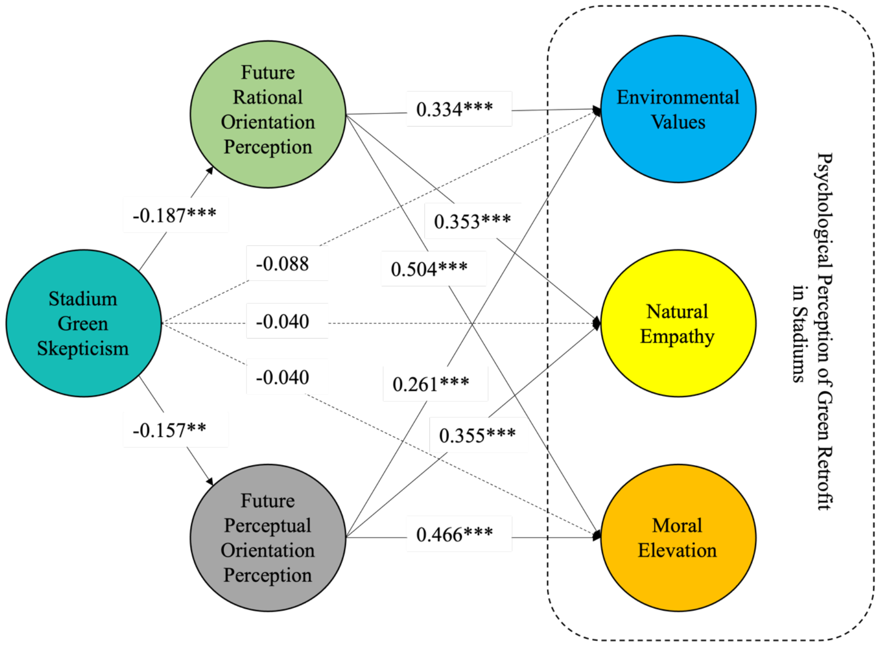


Figure 2. Estimated structural equation model.

Specific mediating effects Ind1 to 6 (mediating effect sizes ES = ab/c, 32.3%, 21.4%, 37.7%, 32.0%, 46.1%, and 34.3%, respectively, $p < 0.001$) corresponded to confidence intervals that did not contain 0, indicating that all six specific mediating effects were significant (e.g., Table 2). After the inclusion of the mediating variables, none of the three direct effects were significant (confidence intervals all containing 0), indicating that FROP and FPOP played a fully mediating role. The total indirect effects, TIE12 (−0.104), TIE34 (−0.122), and TIE56 (−0.164), and the total effects, TE12 (−0.192), TE34 (−0.175), and TE56 (−0.204), were significant (none of the confidence intervals contained 0). The confidence intervals corresponding to the dimension-specific indirect effects DIFF1, DIFF2, and DIFF3 analyzed in comparison all contained 0, indicating that there was no significant difference in the parallel mediated effects of Ind1 and Ind2, Ind3 and Ind4, and Ind5 and Ind6, and that hypotheses H2 and H3 of this paper are valid.

Table 2. Bootstrap test for concurrent mediated effects and comparison of specific mediated effects.

Trails	Efficiency Value	Magnitude of Effect	95% CI	
			Lower Limit	Limit
EV				
Ind1: GS→FROP→EV	−0.062 **	32.3%	−0.110	−0.026
Ind2: GS→FPOP→EV	−0.041 *	21.4%	−0.084	−0.013
Total indirect effect TIE12	−0.104 **	54.2%	−0.171	−0.046
Direct effect DE12	−0.088		−0.188	0.011
Total effect TE12	−0.192 ***		−0.289	−0.086
diff1=Ind1-Ind2	−0.017		−0.055	0.019
NE				
Ind3: GS→FROP→NE	−0.066 **	37.7%	−0.119	−0.029
Ind4: GS→FPOP→NE	−0.056 *	32.0%	−0.106	−0.019
Total indirect effect TIE34	−0.122 **	69.7%	−0.284	−0.054
Direct effect DE34	−0.054		−0.155	0.051
Total effect TE34	−0.175 **		−0.284	−0.061
diff2 = Ind3-Ind4	−0.007		−0.043	0.029
ME				
Ind5: GS→FROP→ME	−0.094 **	46.1%	−0.154	−0.041
Ind6: GS→FPOP→ME	−0.070 *	34.3%	−0.131	−0.023
Total indirect effect TIE56	−0.164 ***	80.4%	−0.254	−0.073
Direct effect DE34	−0.040		−0.129	0.050
Total effect TE34	−0.204***		−0.308	−0.090
diff3 = Ind5-Ind6	−0.016		−0.055	0.026

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

5. Discussion and Analysis

5.1. Current Status of College Students' Green Skepticism, Future Orientation of Green Retrofitting of Stadiums, and Psychological Perceptions of Green Retrofitting of Stadiums

(1) The findings of this study indicate that Chinese university students exhibit moderate levels of green skepticism, future orientation, and psychological perceptions of green retrofitting of sports venues. In contrast, Western countries have achieved higher levels in green initiatives, green purchasing, and other green behaviors. This discrepancy may be attributed to the pivotal role that education and advocacy have played in raising public environmental awareness in Western nations. Although various sectors of Chinese society are also striving to enhance public environmental consciousness through school education and media campaigns, the overall impact requires further improvement. Specifically, the promotion efforts at the grassroots community level need to be strengthened [17,51]. The findings of this study indicate that college students exhibit a moderate level of skepticism regarding about environmental issues, yet their overall stance remains neutral. College students are situated within a social environment and are susceptible to the influence of their peers, families, and society at large. Some college students may be influenced by the skeptical voices of their classmates or friends, which may result in a neutral attitude towards environmental issues. Furthermore, the advent of online media, which are accessible to all, has led to the dissemination of exaggerated or misleading information about the effectiveness of environmental protection measures. The inconsistency of such information further exacerbates the cognitive dissonance of college students, prompting them to doubt the effectiveness and truthfulness of environmental protection activities [52]. (2) The level of future orientation exhibited by college students is moderate. This indicates that students are not only concerned with the rational aspects of the environmental program, such as quality testing, environmental monitoring, and government planning, but also have a clear vision of the renovated venue and are optimistic about the future development of the environmental cause. The incorporation of enhanced environmental education and the demonstration of positive social and environmental impacts can further stimulate college students' intrinsic motivation and sense of responsibility, prompting them to participate more actively in environmental protection behaviors and, consequently, to increase their support for green renovation projects. (3) In conclusion, the overall psychological perception of green remodeling of college sports stadiums is moderate. Among the

aforementioned values, environmental values and natural empathy are at a medium level, indicating that the subjects demonstrate a certain degree of attention to environmental protection and an ability to empathize with the natural environment. However, there is still room for improvement in these aspects. In contrast, moral elevation is observed to exhibit a moderate-to-high level. According to the VBN theory, an individual's environmental behavior is driven by three key factors: their environmental values, ecological worldview, and sense of personal responsibility [53]. The results indicate that respondents perceive green retrofit in a morally elevated manner. This perception may have stimulated a normative sense in college students, prompting them to show more support and participation in green retrofit projects after recognizing the moral and ethical values behind them [54].

5.2. Influence of College Students' Green Skepticism on Psychological Perceptions of Green Renovation of Stadiums

Green skepticism can have a negative impact on college students' psychological perceptions of green renovations in college sports stadiums. The primary reason for this skepticism is that the environmental benefits of such projects often take a long time to manifest. This finding aligns with the results of other scholars' research. Goh and Balaji found that green skepticism affects consumers' purchase intentions for green products by reducing their environmental knowledge and concern, leading to a more negative attitude towards environmental initiatives. Similarly, He et al., in their study of Chinese residents' skepticism towards green retrofitting projects, discovered that green skepticism weakened their identification with green retrofitting, reduced their enthusiasm for participating in environmental projects, and negatively impacted their environmental values and empathy towards nature [29,55]. One primary reason for this skepticism is that the environmental benefits of such projects often take a long time to manifest. As a result, students may doubt the claims and actual effects of the renovations if they do not directly experience or perceive the outcomes. Furthermore, if the results of green retrofits are not quantitatively demonstrated, students may struggle to grasp the specific benefits of these initiatives intuitively. Additionally, students' expectations for green retrofits often encompass significant enhancements to their immediate experience of using the facility, such as improved comfort and functionality. When these expectations are not met, it can lead to increased skepticism about the efficacy of green retrofit projects. This disconnect between expectations and actual outcomes can undermine support for such initiatives among the student body.

Green skepticism can adversely affect the environmental values, natural empathy, and moral elevation in students' psychological perceptions of green renovations in college sports stadiums. For instance, research by Leonidou and Skarmeas found that consumers' skepticism towards corporate environmental activities leads to more negative reactions to environmental information, reduces their empathy towards nature, and diminishes their willingness to share green information with others [43]. Firstly, students' environmental values may be compromised when they doubt the authenticity and validity of the promoted green features. If students perceive that green retrofits are primarily driven by motives like obtaining government subsidies or enhancing image, rather than genuine intentions to mitigate environmental impacts, their view on the importance of environmental protection could become more cynical. Secondly, green skepticism may also weaken students' emotional connection to the natural world. If they suspect that college sports stadium green remodeling projects do not genuinely contribute to environmental protection, their likelihood of taking personal actions to support or improve the environment may decrease. Lastly, skepticism regarding the effectiveness and sincerity of green projects can lead to diminished interest among students in participating in or supporting future green initiatives. This erosion of trust and enthusiasm could significantly hinder the progress and acceptance of sustainable practices in college sports stadium management and beyond.

5.3. Parallel Mediation of Future Rational Orientation Perception, Future Perceptual Orientation Perception

In the context of how green skepticism affects the psychological perception of green retrofits in college sports stadiums among college students, both future rational orientation perception and future perceptual orientation perception serve as important mediatory roles. Contrary to the findings of this study, some scholars argue that the influence of rational cognitive orientation on green behavior is limited. For instance, Zarei discovered that green purchase intentions are more influenced by environmental attitudes and corporate capabilities rather than environmental knowledge. Similarly, Matthes' research on green advertising found that green consumers rated the informational utility of advertisements highly, while emotional appeals did not significantly affect their skepticism towards advertisements. This suggests that emotional factors also play a limited role in green skepticism [56,57]. On the one hand, rational orientation perception evaluates the scientific basis and actual benefits of green renovations by analyzing logic and evidence. If a retrofitted stadium can provide concrete data demonstrating improvements in energy efficiency and evidence of cost savings, those with a rational orientation perception are more likely to accept the positive impacts of the retrofit and consequently reduce their skepticism. On the other hand, affective orientation perception evaluates the social and cultural significance of the green retrofit through the resonance of emotions and values. College students' perceptions of perceptual orientation can help them overcome green skepticism when faced with green retrofitting of college sports stadiums. This is particularly effective if the retrofit project clearly communicates its positive social and environmental impacts. These emotional and value-based considerations play a crucial role in shaping students' acceptance and support for green initiatives.

Specifically, after learning about the green retrofit of college sports stadium projects, college students with a future rational orientation may focus on the tangible environmental benefits of these transformations, such as reduced energy consumption and carbon footprint, aligning these benefits with their core environmental values. The environmental beliefs of these students aid them in assessing the actual effects of these renovation measures through data and scientific evidence. This evaluative process aligns with the pathway described in VBN theory, which illustrates how beliefs influence behavior. By grounding their assessment in concrete evidence, these students can form a more informed and supportive stance towards the environmental initiatives undertaken in stadium renovations [58]. This evidence-based assessment can mitigate disapproval stemming from skepticism, resulting in a more substantial impact on psychological change. Conversely, future perceptions of perceptual orientation primarily derive from emotions and personal values, making college students more vulnerable to emotional influences. While individuals with a perceptual orientation may experience a sense of moral elevation when the green retrofits align with their personal environmental values, this sense of moral elevation may not be as strong or enduring as that experienced by rationally oriented individuals. The latter group's moral elevation is bolstered by logical and evidentiary support, which provides a more stable and compelling basis for their positive perceptions and actions towards green initiatives.

6. Conclusions and Shortcomings

6.1. Conclusions

Unlike other studies, such as green online purchasing behavior, green product trust, and green design of sports stadiums, this study integrated VBN theory into the analysis of how college students' green skepticism affects their psychological perceptions of green remodeling of college sports stadiums, introduced two mediating variables, future rational cognition and future perceptual cognition, and we adopted a structural equation modeling approach to investigate the parallel mediating mechanisms of future rational cognition and future perceptual cognition. The structural equation modeling method was used to study the parallel mediating mechanism between green suspicion and psychological perception of green renovation of college sports stadiums. The empirical results proved the following: that green skepticism negatively affects the psychological perception of green renovation in college sports stadiums; that future rational orientation perception mediates between green skepticism and psychological perception of green renovation in college sports stadiums; and that future perceptual orientation perception mediates between green skepticism and psychological perception of green renovation in college sports stadiums.

Starting from different perspectives and adopting a multidisciplinary and comprehensive approach, this study specifically classified college students' psychological perceptions of green renovation of college sports stadiums into three core components—environmental values, natural empathy, and sense of moral enhancement—and introduced two mediating variables–future rational perception and future perceptual perception—in order to analyze the complexity of the relationship between green skepticism and psychological perception of green renovation of college sports stadiums through the establishment of structural equation modeling. This model not only provides a novel theoretical framework for studying the complexity of green building remodeling, but also offers unique theoretical assumptions and avenues of exploration for future research on the phenomenon of green skepticism. At the level of practical contribution, the results of this study provide a special educational pathway for advocating the reduction of green skepticism in the college student population, increasing their green future orientation.

When college students or the community at large question green practices, they may have a more negative view of the importance of environmental protection, which may further cause them to take less personal action to adopt environmentally friendly behaviors. Therefore, all sectors of society should avoid the proliferation of green skepticism, and businesses, governments, and individuals should make efforts to take meaningful actions to protect the environment. For example, the government should strive to increase public trust in green behaviors or products, and, ultimately, promote widespread support for environmental actions.

6.2. Shortcomings and Prospects

Although this paper explored college students' green skepticism, future rational orientation cognition, future perceptual orientation cognition, and their psychological perceptions of green retrofitting of college sports stadiums in a more detailed way, it had some shortcomings. This paper mainly focused on the investigation of college students of some colleges and universities in the city of Xi'an, China, and the representativeness was not strong enough. At the same time, it failed to completely include college students from other universities. The link between green suspicion and psychological perception of green renovation of college sports stadiums among college students of different subdivided majors, whether there is any difference, and whether there is any difference in other psychological changes, due to that difference, need to continue to be explored in the future.

Future research should strive to improve the model, broaden the existing research ideas, and find out whether other variables play an influential role in the proposed model. For example, family culture variables should be taken into account, based on the original study, such as the family structure of college students and how the economic and cultural background of their parents plays a key role in their growth process. At the same time, the family atmosphere in the environment in which college students grow up and the family education they receive have a similar effect on their social cognition and psychological cognition. Based on this, future research can take this as a reference to further improve the completeness and timeliness of the topic of green retrofitting.

Author Contributions: Methodology, Y.H., S.C. and Z.Y.; Software, Y.H., S.C., Y.Z., Z.Y. and Q.H.; Validation, Y.Z.; Formal analysis, Y.H., S.C. and Y.Z.; Investigation, S.C.; Resources, Y.H.; Data curation, S.C., Y.Z., Z.Y. and Q.H.; Writing—original draft, Y.H., S.C., Y.Z. and Z.Y.; Writing—review & editing, S.C., Y.Z. and Z.Y.; Visualization, S.C., Y.Z., Z.Y. and Q.H.; Supervision, Z.Y.; Project administration, Q.H.; Funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest

Appendix A. Questionnaire

Variant	Dimension (Math.)	Subject	Score
Stadium green skepticism	Green skepticism	I'm not a big believer in most of the environmental and safety claims on some stadium green renovation package labels or advertising messages.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that most of the environmental information related to the green renovation of stadiums has been publicized to mislead the public and gain other benefits rather than for the true cause of green development.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I am conservative or skeptical about the true environmental results that can be achieved after a green renovation of a stadium.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that the green renovation process of some stadiums has been described or publicized with misleading words, in order to exaggerate their own green features.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
Future orientation of green retrofit of stadiums	Future rational orientation perception	When I hear about a green renovation of a stadium, I look out for information about the quality testing, environmental monitoring, and parametric performance indicators of that green renovation project.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		When I hear about green retrofitting stadiums, I focus on what green value can be delivered by greening stadiums.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		When I hear about the green retrofit of stadiums, I will pay more attention to the government's environmental plans or programs.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
	Future perceptual orientation perception	When I hear about the green renovation of stadiums, I sketch in my mind what the renovated venues will look like.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		When I hear about the green retrofit of stadiums, I'll have something to look forward to.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		When I hear about the green retrofit of stadiums, I will have more confidence in the upgrading of the environmental cause.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree

Variant	Dimension (Math.)	Subject	Score
Psychological perception of green retrofit in stadiums	Environmental values	For the survival and growth of future generations and the preservation of urban resources, I believe that green renovation and upgrading of stadiums and other buildings is very necessary.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I think if we don't green our stadiums, we're bound to have insurmountable environmental problems in the future.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that environmental pollution problems in one place can affect the health of residents in other areas and even globally.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that the green retrofit of stadiums is a practice that respects nature and harmonizes with the natural environment.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
	Natural empathy	I think that although people have the ability to modify nature, they should also follow the laws of nature.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that people's participation in sports or watching services needs to be based on the preservation of the natural environment.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		I believe that greening stadiums is a sign of the harmonious development of man and nature.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
	Sense of moral elevation	After learning about the advantages of greening stadiums, I will try to increase and persuade my friends and family to do more pro-environmental behaviors in the future as well.	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		With the general trend of low carbon emission reduction, I hope I can become a more environmentally conscious person too!	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree
		Would a green renovation of stadiums lead me to believe that the world is a more stable and better place?	1. strongly disagree 2. somewhat disagree 3. generally agree 4. somewhat agree 5. strongly agree

Appendix B

Table A1. Results of the item (differentiation) analysis.

	Group (Mean ± Standard Deviation)		*t (Decision Value)*	*p*
	Low Grouping (n = 61)	High Subgroup (n = 61)		
GS1	2.69 ± 0.92	4.33 ± 0.79	10.541	0.000 **
GS2	2.59 ± 0.88	4.33 ± 0.72	11.888	0.000 **
GS3	2.52 ± 0.87	4.31 ± 0.81	11.774	0.000 **
GS4	2.72 ± 1.02	4.15 ± 0.81	8.546	0.000 **
FROP1	2.74 ± 0.87	4.15 ± 0.93	8.639	0.000 **
FROP2	2.54 ± 0.96	4.21 ± 0.99	9.501	0.000 **
FROP3	2.48 ± 0.94	4.20 ± 0.96	9.981	0.000 **
FPOP1	2.84 ± 0.97	4.08 ± 0.88	7.429	0.000 **
FPOP2	2.72 ± 0.93	4.00 ± 0.84	7.968	0.000 **
FPOP3	2.90 ± 1.14	4.31 ± 0.81	7.902	0.000 **
EV1	2.61 ± 0.86	4.18 ± 0.81	10.415	0.000 **
EV2	2.59 ± 0.84	4.30 ± 0.67	12.377	0.000 **
EV3	2.61 ± 0.94	4.21 ± 0.82	10.09	0.000 **
EV4	2.66 ± 0.87	4.20 ± 0.87	9.751	0.000 **
NE1	2.70 ± 0.97	4.10 ± 1.01	7.757	0.000 **
NE2	2.70 ± 0.86	3.93 ± 1.14	6.723	0.000 **
NE3	2.77 ± 0.99	3.93 ± 1.15	5.983	0.000 **
ME1	2.49 ± 0.94	3.98 ± 0.99	8.519	0.000 **
ME2	2.59 ± 0.84	4.07 ± 1.03	8.65	0.000 **
ME3	2.52 ± 0.79	4.20 ± 1.03	10.073	0.000 **

Note: ** $p < 0.01$.

Table A2. Correlation of analytic items to total scale scores.

Sports Event	Decision Value (CR)	*p*-Value (CR)	Correlation with Scale Total Score	*p*-Value (Correlation with Scale Total Score)
GS1	10.541 **	0.000	0.596 **	0.000
GS2	11.888 **	0.000	0.640 **	0.000
GS3	11.774 **	0.000	0.628 **	0.000
GS4	8.546 **	0.000	0.581 **	0.000
FROP1	8.639 **	0.000	0.559 **	0.000
FROP2	9.501 **	0.000	0.616 **	0.000
FROP3	9.981 **	0.000	0.638 **	0.000
FPOP1	7.429 **	0.000	0.555 **	0.000
FPOP2	7.968 **	0.000	0.583 **	0.000
FPOP3	7.902 **	0.000	0.614 **	0.000
EV1	10.415 **	0.000	0.548 **	0.000
EV2	12.377 **	0.000	0.592 **	0.000
EV3	10.090 **	0.000	0.637 **	0.000
EV4	9.751 **	0.000	0.577 **	0.000
NE1	7.757 **	0.000	0.584 **	0.000
NE2	6.723 **	0.000	0.529 **	0.000
NE3	5.983 **	0.000	0.518 **	0.000
ME1	8.519 **	0.000	0.599 **	0.000
ME2	8.650 **	0.000	0.589 **	0.000
ME3	10.073 **	0.000	0.612 **	0.000

Note: ** $p < 0.01$.

Table A3. Model AVE and CR indicator results.

Factor	Mean Variance Extraction AVE Value	Combined Reliability CR
Green skepticism	0.635	0.874
Future rational orientation perception	0.636	0.84
Future perceptual orientation perception	0.532	0.773
Environmental values	0.654	0.883
Natural empathy	0.623	0.832
Moral elevation	0.634	0.838

Table A4. Distinguishing validity: Pearson correlation and AVE square root values.

	Green Skepticism	Future Rational Orientation Perception	Future Perceptual Orientation Perception	Environmental Values	Natural Empathy	Moral Elevation
green skepticism	0.797					
future rationality oriented cognition	0.501	0.798				
futuristic oriented cognition	0.568	0.481	0.730			
environmental values	0.514	0.468	0.465	0.809		
natural empathy	0.380	0.428	0.420	0.436	0.789	
moral elevation	0.509	0.366	0.519	0.428	0.380	0.796

References

1. Sun, J.; Wang, J.; Wang, T.; Zhang, T. Urbanization, economic growth, and environmental pollution: Partial differential analysis based on the spatial Durbin model. *Manag. Environ. Qual. Int. J.* **2019**, *30*, 483–494. [CrossRef]
2. Kjellstrom, T.; Lodh, M.; McMichael, T.; Ranmuthugala, G.; Shrestha, R.; Kingsland, S. Air and water pollution: Burden and strategies for control. In *Disease Control Priorities in Developing Countries*, 2nd ed.; The International Bank for Reconstruction and Development/The World Bank: Washington, DC, USA; Oxford University Press: New York, NY, USA, 2006.
3. Xing, L.; Wang, S. Can industrial agglomeration affect biodiversity loss? *Energy Environ.* **2023**, 0958305X231200575. [CrossRef]
4. Bhat, V.N. Impact of droughts on industrial emissions into surface waters. *Environ. Sci. Pollut. Res.* **2020**, *27*, 42806–42814. [CrossRef] [PubMed]
5. Cai, W.; Borlace, S.; Lengaigne, M.; Van Rensch, P.; Collins, M.; Vecchi, G.; Timmermann, A.; Santoso, A.; McPhaden, M.J.; Wu, L.; et al. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Clim. Chang.* **2014**, *4*, 111–116. [CrossRef]
6. Bell, J.E.; Autry, C.W.; Mollenkopf, D.A.; Thornton, L.M. A natural resource scarcity typology: Theoretical foundations and strategic implications for supply chain management. *J. Bus. Logist.* **2012**, *33*, 158–166. [CrossRef]
7. Santos, U.d.P.; Arbex, M.A.; Braga, A.L.F.; Mizutani, R.F.; Cançado, J.E.D.; Terra-Filho, M.; Chatkin, J.M. Environmental air pollution: Respiratory effects. *J. Bras. Pneumol.* **2021**, *47*, e20200267. [CrossRef]
8. Palmer, L. Green structural transformation. *Nat. Sustain.* **2023**, *6*, 877–878. [CrossRef]
9. Wang, B.Z.; Zhu, Z.H.; Yang, E.; Chen, Z.; Wang, X.H. Assessment and management of air emissions and environmental impacts from the construction industry. *J. Environ. Plan. Manag.* **2018**, *61*, 2421–2444. [CrossRef]
10. Cheriyan, D.; Choi, J.h. A review of research on particulate matter pollution in the construction industry. *J. Clean. Prod.* **2020**, *254*, 120077. [CrossRef]
11. Al-Kodmany, K. Green retrofitting skyscrapers: A review. *Buildings* **2014**, *4*, 683–710. [CrossRef]
12. Zakaria, R.B.; Foo, K.S.; Zin, R.M.; Yang, J.; Zolfagharian, S. Potential retrofitting of existing campus buildings to green buildings. *Appl. Mech. Mater.* **2012**, *178*, 42–45. [CrossRef]
13. Bu, S.; Shen, G.Q. A critical review of green retrofit design. In Proceedings of the International Conference on Construction and Real Estate Management 2013 (ICCREM 2013): Construction and Operation in the Context of Sustainability, Karlsruhe, Germany, 10–11 October 2013; pp. 150–158.
14. Triantafyllidis, S.; Ries, R.J.; Kaplanidou, K. Carbon dioxide emissions of spectators' transportation in collegiate sporting events: Comparing on-campus and off-campus stadium locations. *Sustainability* **2018**, *10*, 241. [CrossRef]
15. Watanabe, N.; Yan, G.; McLeod, C. The Impact of Sporting Events on Air Pollution: An Empirical Examination of National Football League Games. *Sustainability* **2023**, *15*, 5568. [CrossRef]

16. Szasz, A. *Shopping Our Way to Safety: How We Changed from Protecting the Environment to Protecting Ourselves*; University of Minnesota Press: Minneapolis, MN, USA, 2007.
17. Wergeland, E.S.; Hognestad, H.K. Reusing stadiums for a greener future: The circular design potential of football architecture. *Front. Sport. Act. Living* **2021**, *3*, 692632. [CrossRef] [PubMed]
18. Kozma, G.; Radics, Z.; Teperics, K. The Role of Sports Facilities in the Regeneration of Green Areas of Cities in Historial View: The Case Study of Great Forest Stadium in Debrecen, Hungary. *Buildings* **2022**, *12*, 714. [CrossRef]
19. Mohr, L.A.; Eroğlu, D.; Ellen, P.S. The development and testing of a measure of skepticism toward environmental claims in marketers' communications. *J. Consum. Aff.* **1998**, *32*, 30–55. [CrossRef]
20. Hastak, M.; Olson, J.C. Assessing the role of brand-related cognitive responses as mediators of communication effects on cognitive structure. *J. Consum. Res.* **1989**, *15*, 444–456. [CrossRef]
21. Obermiller, C.; Spangenberg, E.; MacLachlan, D.L. Ad skepticism: The consequences of disbelief. *J. Advert.* **2005**, *34*, 7–17. [CrossRef]
22. Delmas, M.A.; Burbano, V.C. The drivers of greenwashing. *Calif. Manag. Rev.* **2011**, *54*, 64–87. [CrossRef]
23. Parguel, B.; Benoît-Moreau, F.; Larceneux, F. How sustainability ratings might deter 'greenwashing': A closer look at ethical corporate communication. *J. Bus. Ethics* **2011**, *102*, 15–28. [CrossRef]
24. Chen, Y.S.; Chang, C.H. Greenwash and green trust: The mediation effects of green consumer confusion and green perceived risk. *J. Bus. Ethics* **2013**, *114*, 489–500. [CrossRef]
25. Do Paço, A.M.F.; Reis, R. Factors affecting skepticism toward green advertising. In *Green Advertising and the Reluctant Consumer*; Routledge: London, UK, 2016; pp. 123–131.
26. Liu, G.; Li, X.; Tan, Y.; Zhang, G. Building green retrofit in China: Policies, barriers and recommendations. *Energy Policy* **2020**, *139*, 111356. [CrossRef]
27. Cheng, Z.H.; Chang, C.T.; Lee, Y.K. Linking hedonic and utilitarian shopping values to consumer skepticism and green consumption: The roles of environmental involvement and locus of control. *Rev. Manag. Sci.* **2020**, *14*, 61–85. [CrossRef]
28. Romani, S.; Grappi, S.; Bagozzi, R.P. Corporate socially responsible initiatives and their effects on consumption of green products. *J. Bus. Ethics* **2016**, *135*, 253–264. [CrossRef]
29. Goh, S.K.; Balaji, M. Linking green skepticism to green purchase behavior. *J. Clean. Prod.* **2016**, *131*, 629–638. [CrossRef]
30. Ajzen, I. The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. [CrossRef]
31. Qiong, O. A brief introduction to perception. *Stud. Lit. Lang.* **2017**, *15*, 18–28.
32. Carver, C.; Scheier, M. *On the Self-Regulation of Behavior*; Cambridge University Press: New York, NY, USA, 1998.
33. Rappaport, A. *Creating Shareholder Value: A Guide for Managers and Investors*; Simon and Schuster: New York, NY, USA, 1999.
34. Jahdi, K.S.; Acikdilli, G. Marketing communications and corporate social responsibility (CSR): Marriage of convenience or shotgun wedding? *J. Bus. Ethics* **2009**, *88*, 103–113. [CrossRef]
35. Carrus, G.; Passafaro, P.; Bonnes, M. Emotions, habits and rational choices in ecological behaviours: The case of recycling and use of public transportation. *J. Environ. Psychol.* **2008**, *28*, 51–62. [CrossRef]
36. Hansla, A.; Gamble, A.; Juliusson, A.; Gärling, T. Psychological determinants of attitude towards and willingness to pay for green electricity. *Energy Policy* **2008**, *36*, 768–774. [CrossRef]
37. Luchs, M.G.; Kumar, M. "Yes, but this other one looks better/works better": How do consumers respond to trade-offs between sustainability and other valued attributes? *J. Bus. Ethics* **2017**, *140*, 567–584. [CrossRef]
38. Spinath, B.; Stiensmeier-Pelster, J. Goal orientation and achievement: The role of ability self-concept and failure perception. *Learn. Instr.* **2003**, *13*, 403–422. [CrossRef]
39. Bubić, A.; Abraham, A. Neurocognitive bases of future oriented cognition. *Rev. Psychol.* **2014**, *21*, 3–15.
40. Steinberg, L.; Graham, S.; O'brien, L.; Woolard, J.; Cauffman, E.; Banich, M. Age differences in future orientation and delay discounting. *Child Dev.* **2009**, *80*, 28–44. [CrossRef] [PubMed]
41. Stren, P. Toward a coherent theory of environmentally significant behaviour. *J. Soc. Issues* **2000**, *56*, 407–424. [CrossRef]
42. Nguyen, T.T.H.; Yang, Z.; Nguyen, N.; Johnson, L.W.; Cao, T.K. Greenwash and green purchase intention: The mediating role of green skepticism. *Sustainability* **2019**, *11*, 2653. [CrossRef]
43. Leonidou, C.N.; Skarmeas, D. Gray shades of green: Causes and consequences of green skepticism. *J. Bus. Ethics* **2017**, *144*, 401–415. [CrossRef]
44. Khoshbakht, M.; Gou, Z.; Xie, X.; He, B.; Darko, A. Green building occupant satisfaction: Evidence from the Australian higher education sector. *Sustainability* **2018**, *10*, 2890. [CrossRef]
45. Malekinezhad, F.; Courtney, P.; bin Lamit, H.; Vigani, M. Investigating the mental health impacts of university campus green space through perceived sensory dimensions and the mediation effects of perceived restorativeness on restoration experience. *Front. Public Health* **2020**, *8*, 578241. [CrossRef]
46. Laufer, W.S. Social accountability and corporate greenwashing. *J. Bus. Ethics* **2003**, *43*, 253–261. [CrossRef]
47. Yeung, S.P.M. Teaching approaches in geography and students' environmental attitudes. *Environmentalist* **2004**, *24*, 101–117. [CrossRef]
48. Heimberg, L.K. *The Measurement of Future Time Perspective*; Vanderbilt University: Nashville, TN, USA, 1963.
49. Lee, T.H.; Jan, F.H.; Yang, C.C. Conceptualizing and measuring environmentally responsible behaviors from the perspective of community-based tourists. *Tour. Manag.* **2013**, *36*, 454–468. [CrossRef]

50. Diessner, R.; Solom, R.D.; Frost, N.K.; Parsons, L.; Davidson, J. Engagement with beauty: Appreciating natural, artistic, and moral beauty. *J. Psychol.* **2008**, *142*, 303–332. [CrossRef] [PubMed]
51. Tan, Y.; Liu, G.; Zhang, Y.; Shuai, C.; Shen, G.Q. Green retrofit of aged residential buildings in Hong Kong: A preliminary study. *Build. Environ.* **2018**, *143*, 89–98. [CrossRef]
52. Abbas, J.; Aman, J.; Nurunnabi, M.; Bano, S. The impact of social media on learning behavior for sustainable education: Evidence of students from selected universities in Pakistan. *Sustainability* **2019**, *11*, 1683. [CrossRef]
53. Sharma, R.; Gupta, A. Pro-environmental behaviour among tourists visiting national parks: Application of value-belief-norm theory in an emerging economy context. *Asia Pac. J. Tour. Res.* **2020**, *25*, 829–840. [CrossRef]
54. Wu, L.; Zhu, Y. How love of nature promotes green consumer behaviors: The mediating role of biospheric values, ecological worldview, and personal norms. *PsyCh J.* **2021**, *10*, 402–414. [CrossRef] [PubMed]
55. He, Q.; Zhao, H.; Shen, L.; Dong, L.; Cheng, Y.; Xu, K. Factors influencing residents' intention toward green retrofitting of existing residential buildings. *Sustainability* **2019**, *11*, 4246. [CrossRef]
56. Zarei, A.; Maleki, F. From decision to run: The moderating role of green skepticism. *J. Food Prod. Mark.* **2018**, *24*, 96–116. [CrossRef]
57. Matthes, J.; Wonneberger, A. The skeptical green consumer revisited: Testing the relationship between green consumerism and skepticism toward advertising. *J. Advert.* **2014**, *43*, 115–127. [CrossRef]
58. Karimi, S. Pro-environmental behaviours among agricultural students: An examination of the value-belief-norm theory. *J. Agric. Sci. Technol.* **2019**, *21*, 249–263. [CrossRef]

buildings

MDPI

Article

The Influence of Social Mass Environmental Cognition on Consumption Intentions in Green Stadiums from the Perspective of CAC Modeling

Luning Cao [1,†], Yuyang Hou [1,†], Xinyi Shen [1], Shunan Feng [1], Chenfan Liu [2] and Qian Huang [3,*]

[1] Graduate Department, Xi'an Physical Education University, Xi'an 710068, China; cln1999@126.com (L.C.); yuyanghou2424@163.com (Y.H.); sxy1997713@163.com (X.S.); 19183856534@163.com (S.F.)
[2] School of Physical Education, Baoji University of Arts and Sciences, Baoji 721016, China; 13218528299@163.com
[3] School of Sports Engineering and Information Technology, Wuhan Sports University, Wuhan 430079, China
* Correspondence: huangqian@tea.xaipe.edu.cn
† These authors contributed equally to this work.

Abstract: The green transformation of sports stadiums has now become an inevitable trend for the sustainable development of sports. This study synthesized consumer behavior research and green consumption research, based on the CAC model, to explore the role of cognitive and affective interactions on the promotion of the intention behind green sports stadium consumption, discussing the role of environmental cognition at the cognitive level and subdividing its connotations into the three categories of a sense of environmental responsibility, environmental protection awareness, and green self-efficacy, introducing at the same time a natural connection into the field of green sports consumption, based on which the green perceived value and green trust fusion are jointly used as affective factor variables. The data from 463 questionnaires were used to construct a structural equation model for empirical analysis, and the following results were shown: First, environmental cognition, environmental responsibility, environmental awareness, and green self-efficacy have a positive effect on green stadium consumption; second, green building perceived value and trust play a mediating role in the relationship between environmental cognition and green stadium consumption intention; third, nature connection and green building perceived value and trust play a positive role in the relationship between environmental cognition and green stadium consumption intention. The purpose of this study was to explore the interaction between cognition and emotion on the the intention behind the consumption of green stadiums from the psychological level of consumers, so as to provide a reference for improving consumers' green sports consumption and accelerating the development of the green sports industry.

Keywords: green building stadiums; environmental cognition; green sports consumption; natural connections

1. Introduction

With the continuous improvement of income level and the living standard, more attention is increasingly paid to the pursuit of culture, sports and health, and other spiritual dimensions. The consumption of sports has gradually become a popular, spontaneous form of recreation. To stimulate domestic demand, the potential of consumption should be realized as mass consumption. In the 2015–2020 period, the scale of sports consumption by China's residents grew rapidly, from CNY 1 trillion in 2015 to CNY 1.8 trillion by 2020. Sports consumption is a significant consumer market in China, and it comprises an important strategy for the country to promote the reform of the supply-side structure of sports in order to stimulate sustainable economic growth [1]. For example, because leisure, fitness, sports, and other forms of mass entertainment have become sought-after, locations like stadiums are an important part of sports consumption [2]. The fact that people choose the venue to carry out the process of physical exercise, thereby implementing a method of sports consumption, is of great significance in promoting the rapid development of the sports industry and the prosperity of the sports market.

In recent years, the characteristics of high investment, high energy consumption, and the high emissions of sports stadiums have received widespread attention. Stadiums have damaged the surrounding ecological environment [3]. With the birth of the green building, people began to deeply reflect on the relationship between themselves and the natural world, and committed to ensuring the harmony and unity between buildings and nature. A green building refers to the construction process, which maximizes the conservation of resources, protects the environment, reduces pollution, and provides people with lively spaces that can be used suitably and efficiently, coexisting harmoniously with nature during the whole life cycle [4]. The green transformation of sports stadiums, with green buildings as the catalysts, has become an inevitable developmental trend. The environmental protection role of green sports stadiums is relies on green buildings, and the values of green, low-carbon, and sustainable development contained in green buildings can be reflected in the construction of sports stadiums. The birth of green stadiums also provides new choices for environmental sustainability regarding consumer behavior and green consumption-related decision-making. In contrast to traditional stadiums, green stadiums are chosen to effectively reduce the negative impact on the environment, for the sake of the consumers. If consumer stadium consumption behavior is intertwined with the green attributes, it can be transformed into green consumption behavior. Since green consumption is still in its infancy in China's economic and social fields, the lack of understanding of the connotative value, value-added services, and practical experience of green transformation of stadiums has led to the erroneous belief that the green amenities of stadiums have high-end and high-cost characteristics, and the resulting intention behind the green consumption of stadiums is relatively weak. In traditional Chinese culture, there is a profound understanding of man and nature: nature and man should form a harmonious symbiosis; the face of nature should be respected; there is a principle of conformity to nature and a principle of protecting nature. This tradition has laid the foundation for the cultural focus of our people on environmental protection, but it is undeniable that most consumers have not yet reached the level of moral cognition that allows them to view the green transformation of stadiums as improving the environment. The public is more concerned about individual observations, as well as fitness, leisure, and other activities [5]. Therefore, it is worthwhile to further discuss the factors influencing consumers' intention to utilize green sports stadiums. Existing research on consumer behavior mainly encompasses the three aspects of cognition, emotion, and intention [6]. Cognition comprises the values, beliefs, and ideas of consumers in regard to a certain phenomenon [7]. It is an important predictor of behavior, which is often based on people's cognitive results. Emotion is the intention to consume, further transformed into an important factor of behavior. It is the consumer's feelings and attitudes towards a certain phenomenon [8]. The consumer's decision-making is clearly influenced by emotional preference, which is the response and the evaluation of cognitive aspects. Due to the fact that individual cognitive resources are limited, it is not possible for an individual to make fully rational decisions. Emotional factors further advance cognitive factors, producing a reaction. Intention is the consumer's intent to perform a certain action, and the further generation of behavior is closely related to it [9].

In the field of green consumption, environmental cognition is an important factor in promoting consumers' green consumption behavior [10]. Some studies have pointed out that the explanatory power of environmental cognition on consumers' willingness to consume is not sufficient, and it is believed that the relationship between cognition and consumers' willingness to consume green is realized through another factor [11]. Consequently, the factor of emotion is introduced, which positively influences consumers' willingness to engage in green consumption [12]. It is posited that both cognitive and emotional factors simultaneously impact environmental behavior [13]. In addition, although consumers' aversion to involuntary green behaviors mandated by national policies has been moderated by the influence of traditional Chinese environmental protection culture, the significant impact of such emotions in this process cannot be overlooked. Therefore, building on existing research that explores the intention behind green stadium consumption as a special factor in green consumer decision-making, can environmental emotion, as a promoter of green consumer behavior, also influence green stadium consumption behavior? Does the affective promotion of green buildings extend to green stadiums? What is the mechanism through which environmental cognition and environmental emotion influence the intention behind the consumption of green stadiums? To address these questions, this study constructs a model of influencing factors on green stadium consumption based on the CAC model. Additionally, it examines the mediating role of the environmental affective component, providing an in-depth analysis and discussion of the facilitating factors for the intention behind green stadium consumption.

2. Literature Review and Hypothesis

The Cognitive–Affective–Conative (CAC) model is a significant cognitive psychology theory that elucidates the interactive relationship between cognition, emotion, and behavioral intention. It posits that individuals' behavioral intentions are shaped by both cognitive and emotional factors. According to the theory, at the cognitive level, individuals process and evaluate information, beliefs, and knowledge, which shape their understanding and cognition of a particular situation or problem. Emotion plays a crucial role in decision-making and behavioral processes, while intentions reflect the combined influence of cognition and emotion on final behavior. The CAC model in this study offers some guidance but is insufficient to comprehensively explain consumer green stadium consumption as a tangible green consumption behavior. Therefore, by referencing the precedent of expanding the application of the CAC model in existing research [14] and integrating it with the reality of green consumption behaviors, we apply the CAC model to the field of green consumption and innovatively expand it. The cognitive component is extended to include environmental cognition and its three subsets: environmental responsibility, environmental awareness, and green self-efficacy. The affective component is expanded into two dimensions: the natural dimension, represented by the natural connection, and the consumption object dimension, represented by the perceived value of green buildings and trust. It is hypothesized that natural connection, the perceived value of green buildings, and trust function as chain mediators between environmental cognition and its subsets and the willingness to consume green sports stadiums, as illustrated in Figure 1.

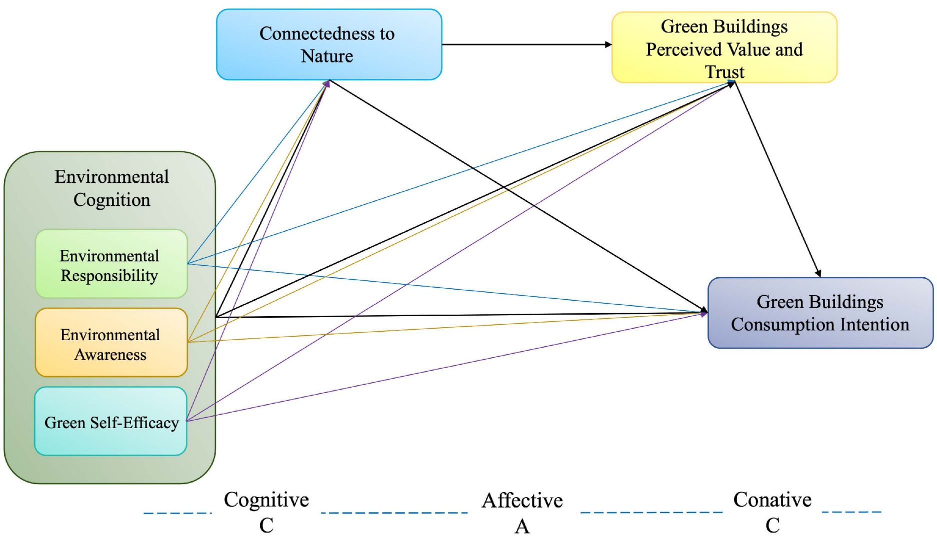


Figure 1. The conceptual diagram of the model.

2.1. Environmental Cognition and Consumption Intentions of Green Stadiums

Green consumption willingness is defined as the likelihood and willingness of an individual to prioritize products with eco-friendly features over traditional products in their consumption choices [15]. Based on this concept, this study integrates the characteristics of green buildings and defines green stadium consumption willingness as the likelihood and willingness to choose green stadiums over traditional stadiums in stadium consumption. Environmental cognition refers to the process by which individuals store, process, and recombine environmental stimuli to recognize and understand the environment [16]. Environmental cognition serves as the foundation and premise for individuals to care about environmental issues and consciously adopt environmentally friendly behaviors [17]. However, some studies have pointed out that there is no direct correlation between environmental cognition and environmental behaviors [18]. Existing research lacks a unified division of environmental cognition. For instance, some scholars divide environmental cognition into environmental protection cognition and environmental risk cognition, to explore the degree of consumer agreement with environmental protection views and their understanding of the hazards posed by environmental problems [19]. Others categorize it into three aspects: environmental knowledge, the perception of environmental problems, and the cognition of individual environmental responsibility. This categorization aims to explore the degree of individual knowledge about the environment, the awareness of existing problems and hazards to humans, and individual environmental protection behaviors [20]. Based on the above divisions and combining existing research on the drivers of green consumption and environmental protection behaviors [21–23], environmental cognition is divided into three subcategories: environmental responsibility, environmental awareness, and green self-efficacy. These correspond to the psychological aspects of environmental responsibility, environmental protection psychology, and personal green emotions, respectively. This paper innovatively splits the concept of environmental cognition and focuses on the distinct forms of these three subcategories while exploring their contribution to the intention behind green stadium consumption. In the field of green consumption, consumers with high environmental cognition are more likely to develop green consumption intentions and engage in behaviors that benefit the environment [24]. When consumers possess high environmental cognition, they become more aware of the environmental impact of their actions and tend to act in ways that are beneficial to the natural environment. Consequently, when considering their consumption choices, high environmental cognition prompts them to select green products with environmental value and sustainable functions. Therefore, based on the aforementioned hypothesis:

H1: *Environmental Cognition Positively and Significantly Influences the Consumption Intention for Green Building Stadiums.*

Environmental responsibility refers to an individual's recognition of their duty to preserve the environment. It encompasses the concept of actively taking measures to address environmental problems based on a thorough understanding of the environment's benefits [25]. The model of responsible environmental behavior posits a strong link between an individual's sense of responsibility and their environmental actions, suggesting that a higher sense of responsibility increases the likelihood of engaging in environmentally beneficial behaviors.The higher the sense of responsibility, the more likely the individual is to act in favor of the environment [26]. This study argues that in the field of green consumption, green consumption behavior is often accompanied by higher economic and time costs. When consumers are faced with a choice between individual interests and environmental interests, those with a high sense of environmental responsibility are more inclined to choose green consumption that aligns with environmental interests, thereby generating higher green consumption intentions. Therefore, based on the above proposed hypothesis:

H1a: *Environmental Responsibility Positively and Significantly Influences the Consumption Intention for Green Building Stadiums.*

Environmental awareness is defined as a conscious recognition of the impact of environmental problems and an awareness of the importance of environmental protection [27]. Ahmad [28] points out that consumers with a high level of environmental awareness are more inclined to adopt environmentally friendly measures to address and improve environmental protection issues. Compared to traditional stadiums, green stadiums have lower energy consumption and pollution emissions. When consumers possess high environmental awareness, they are more likely to focus on the green attributes of green stadiums and recognize their significant role in environmental protection, thus generating consumption intentions. Therefore, based on the above hypothesis:

H1b: *Environmental Awareness Positively and Significantly Influences the Consumption Intention for Green Building Stadiums.*

Self-efficacy refers to an individual's judgment and evaluation of their ability to perform a specific task [29]. Many scholars have introduced self-efficacy into the environmental field, defining green self-efficacy as a self-assessment of an individual's ability to achieve environmental goals [30]. According to self-consistency theory, once an individual develops a self-perception of their ability to satisfy needs, they will seek to maintain a state that aligns with this self-perception and implement consistent behaviors. In the examination of green consumption, Lin [31] asserts that green efficacy significantly enhances consumers' propensity to engage in green consumption. Moreover, Lin identifies the augmentation of green self-efficacy as a critical determinant in the decision-making process of opting for green products. Therefore, based on the above proposed hypothesis:

H1c: *Green Self-Efficacy Positively and Significantly Influences Consumption Intention for Green Building Stadiums.*

2.2. The Mediating Role of Natural Connection

Natural connection has been a prominent focus in environmental psychology research in recent years, with its conceptualization and related studies continuing to expand and deepen. The definition of natural connection is divided into two main aspects: first, the emotional dimension. Some scholars, such as Mayer [32], consider natural connection to be the emotional bond between individuals and nature, characterized by a sense of connection and unity with nature in one's emotional experience. Second, at the cognitive level, Schultz [33] views natural connection as the individual's perception of the relationship between humans and nature, emphasizing a sense of belonging. Although some scholars have subsequently expanded the idea that a connection to nature is a multidimensional psychological construct encompassing both cognition and emotion [34], the core of nature connection remains rooted in these two dimensions. Overall, despite varying conceptualizations and definitions, the notion of a connection to nature as a variable trait describing individual differences in human–nature relationships has been widely accepted by the majority of scholars. These differing definitions have also prompted scholars to develop various measurement tools. For example, in Tam's [35] study, he compared several nature connection scales and found notable differences, highlighting that the cognitive perspective of the measure was less relevant than the affective perspective concerning the variables of environmental attitudes and behaviors. He emphasized the importance of distinguishing between the cognitive and affective components of a connection to nature. In line with the purpose of this study, we primarily focus on the measurement of the emotional component of a connection to nature, referencing Mayer's definition, which posits that nature connection is the sense of connection and unity between humans and nature in terms of emotional experience.

A connection to nature holds significant value for the health, happiness, and sustainable development of individuals. Several studies have highlighted its positive effects on both physical and mental health [36], focusing primarily on direct and indirect factors. Firstly, regarding direct factors, positive experiences resulting from direct contact with nature, such as walking, exercising, or engaging in recreational activities in natural environments, strongly promote a closer human–nature relationship [37]. Secondly, indirect contact, such as learning nature-related courses to acquire environmental knowledge [38] or watching nature-themed videos [39], can help individuals build an objective, concrete, and accurate understanding of the natural world, thereby fostering the development of natural connections.

Environmental cognition is crucial in influencing consumers' green consumption behavior, yet it is insufficient on its own to fully drive such behavior. Research indicates that, compared to environmental cognition, environmental emotion has a more profound impact on individuals' environmentally friendly behavior [40]. Emotion plays a pivotal role in shaping behavior, serving as the motivation behind actions and significantly affecting individuals' decisions and actions. Yue's [41] study indicated that an individual's environmental cognition stimulates environmental emotion, which subsequently influences environmentally friendly behavior. As emotional care for the environment and nature increases, the relationship between individuals and nature strengthens, thereby enhancing the willingness to protect the natural environment. Therefore, based on the aforementioned hypothesis:

H2: *Natural connection mediates the relationship between environmental cognition and willingness to consume green building stadiums.*

Cognitive–emotional theory posits that the subject's perception of an object leads to the formation of emotions. Palmberg asserts that a sense of environmental responsibility emerges from an individual's comprehensive understanding of the environment's benefits [42]. Once this cognition is established, it subsequently leads to the development of an emotional bond between humans and nature, resulting in a natural connection. When consumers possess a heightened sense of environmental responsibility, their deepening cognition of the environment enhances their level of natural connection. This, in turn, fosters a behavioral intention to protect the environment, making them more inclined to engage in green consumption. Therefore, based on the above, the following hypothesis is proposed:

H2a: *Natural connection mediates the relationship between a sense of environmental responsibility and willingness to utilize green building stadiums.*

It has been noted that environmental awareness encompasses concern for various aspects of environmental issues [43]. This awareness may stem from indirect contact with the natural environment, such as media information and the experiences of others. Such indirect contact, including education about the natural environment, can enhance an individual's degree of natural connection [44]. It can be assumed that when consumers exhibit a high level of environmental awareness, their concern, knowledge, and understanding of the environment are significantly deepened. This heightened awareness facilitates the establishment of a strong natural connection, which in turn fosters the creation of pro-environmental behavioral intentions. Therefore, based on the above hypothesis:

H2b: *Natural connection mediates the relationship between environmental awareness and consumption intentions in green building stadiums.*

Direct exposure to the natural environment is another crucial factor in enhancing the connection to nature. In Maddock's [45] study, it was found that time spent in nature was positively correlated with self-efficacy, indicating that exposure to or participation in natural environments can significantly boost an individual's green self-efficacy level. Based on this, it can be argued that there is a facilitating relationship between green self-efficacy and nature connection. Specifically, as consumers' green self-efficacy increases, the time they spend in nature will further integrate into the emotional aspect of their connection to nature, making them more inclined to engage in environmentally protective behaviors during their consumption process. That is, as consumers' green self-efficacy increases, their accumulated time spent in contact with nature will further integrate into the affective dimension of their connection to nature, subsequently inclining them towards green consumption behaviors that protect the environment. Therefore, based on the above hypothesis:

H2c: *Natural connection mediates the relationship between green self-efficacy and willingness to utilize green building stadiums.*

2.3. Mediating Role of Perceived Value and Trust in Green Buildings

Trust is defined as the degree of willingness to rely on an object based on its competence, reliability, and expectations [46]. In the field of green research, Chen (2010) [47] introduced the concept of "green trust" in his study on the drivers of green brand equity. Green trust is defined as the willingness to rely on an object based on the beliefs or expectations generated by the object's credibility, benevolence, and environmental performance capabilities. Chen emphasized that green trust significantly influences the promotion of consumers' willingness to engage in green consumption.

Consumer-perceived value represents consumers' assessment of their own benefits and losses in consumption activities after careful consideration [48]. As society progresses, consumers increasingly prioritize the environmental protection and sustainable development aspects of their consumption choices, in addition to fulfilling their personal needs. In this context, based on consumer-perceived value, the scholar Yang [49] introduces the concept of green perceived value. He defines it as the value consumers derive from products that do not harm the natural environment or cause minimal damage, have low energy consumption, facilitate recycling and resource regeneration, and are harmless to human health.

The facilitative relationship between perceived value and trust has also been affirmed by existing research. Kim [50], in her study of the online shopping experience, notes that perceived value significantly impacts the enhancement of customer trust. In the field of green consumption, Chen (2010, 2012) and Cheung [51] explored the antecedent variables for the formation of green trust in their studies. These scholars concurred that an important antecedent variable for green trust is green perceived value. In other words, consumers form trust in green products or services based on a combined judgment of rational assessment and emotional input.

In the dimensional division of trust and perceived value, both include the factor of emotion. Augstin [52] analyzes the intrinsic mechanism of trust, highlighting its essential function in exchange behaviors between parties. Through a reciprocal mechanism, consumers develop positive emotions and reward those who trust their service providers. In the exchange behavior between two parties, trust plays an essential role. Through the mechanism of reciprocity, consumers develop positive emotions and reward those service providers who trust them. This emotional dependence based on reciprocity is referred to as emotional trust. Regarding perceived value, Kolter [53] expanded the concept in his early research, asserting that the evaluation of consumer perceived value should consider not only monetary, physical, and intangible services but also the emotional, energy, and time costs invested by the consumer. In Li's [54] research, green perceived value is further divided, where emotional value signifies that consumers not only fulfill their needs by purchasing or using green products but also experience pleasure and pride. In summary, this study extracts and integrates the emotional components of perceived value and trust, encompassing the emotional factors and the promotional relationship between them. These elements collectively support the emotional connection consumers establish with green buildings based on perceived value and trust, termed as green building perceived value and trust. In this study, green building perceived value and trust refers to consumers' or individuals' value cognition and subjective emotional trust towards green building-related products.

In sports consumption research, some scholars have verified the promotional relationship between consumer perception and their green sports consumption intention [55]. In the realm of green consumption, green perceived value and trust are crucial components of consumer perception. Wasaya's [56] study also highlights that green trust significantly impacts consumers' green consumption intention. It can be considered that there is a positive relationship between green perceived value and trust and green consumption intention. When consumers perceive that green buildings provide environmental value and protect the environment, indicating a higher level of perceived value and trust in green buildings, they are more inclined to choose green stadiums as the focus of their consumption intention to achieve the desired green value. Therefore, it can be further argued that green perceived value and trust positively influence consumers' green sports consumption intention. Based on the above hypothesis:

H3: *Green building perceived value and trust play a mediating role between environmental cognition and willingness to utilize green building stadiums.*

The sense of environmental responsibility is crucial in shaping consumers' green building perceived value and trust. It has been noted that environmental responsibility significantly promotes green perceived value and trust [57]. When consumers possess a heightened sense of environmental responsibility, they are more attentive to ecological protection and view environmental conservation as their obligation and responsibility. Consequently, they are more likely to take proactive measures to enhance the ecological environment. When consumers have a high sense of environmental responsibility, they prioritize ecological protection and regard environmental conservation as their duty and responsibility. This heightened awareness leads them to take actions to improve the ecological environment, pay greater attention to the green attributes and environmental protection aspects of their consumption, and enhance their perceived value of green products. Consequently, they are more likely to trust and prefer green products and services, thereby fostering green consumption intentions. Therefore, based on the above hypothesis:

H3a: *Green building perceived value and trust mediate the relationship between environmental responsibility and willingness to utilize green building stadiums.*

Studies have shown that although consumers may have a high level of environmental awareness, this alone is insufficient to influence their green consumption behavior [58]. The CAC model posits that emotion is the transmission of cognition and serves as a crucial driver of behavioral intentions. Punyatoya's [59] research indicates that when consumers' environmental awareness is heightened and they can better perceive the green functions and value of a brand, meeting their environmental protection expectations, their green trust in the brand will also increase. When consumers are more aware of environmental protection, they are more likely to perceive the green functions and values of a brand, fulfilling their expectations for environmental protection. With a high level of environmental awareness, consumers pay greater attention to the perceived value and trust of green buildings, establishing a strong emotional connection with green building consumption. Consequently, they are inclined to choose green buildings with environmental protection functions and sustainable development attributes when making consumption decisions. Therefore, based on the above hypothesis:

H3b: *Green building perceived value and trust mediate the relationship between environmental awareness and willingness to utilize green building stadiums.*

Consumer self-efficacy determines how product value and trust are perceived, influencing consumer behavioral intentions. In Zhu's behavioral study on consumers' use of ride-sharing, it was found that self-efficacy significantly positively contributes to perceived value [60]. However, self-efficacy does not directly affect consumers' behavioral intentions but influences them through perceived value. Therefore, this study infers that self-efficacy, perceived value, and trust also have a facilitating relationship in the field of green consumption. Green consumption can effectively promote consumers' perceived value and trust in green buildings, which in turn affects their intention to utilize green stadiums. Based on the above hypothesis:

H3c: *Green building perceived value and trust mediate the relationship between green self-efficacy and willingness to utilize green building stadiums.*

2.4. Chain-Mediated Effects of Natural Connectivity and Green Building Perceived Value and Trust

In this study, the emotional component is expanded into two parts: natural connection and green building perceived value and trust. Natural connection fosters an emotional bond between consumers and the natural environment, while green building perceived value and trust establishes an emotional connection between consumers and green building consumption. An increase in the level of natural connection is more likely to make consumers aware of the impact of their behaviors on the environment and strengthen their emotional commitment to protecting it. The latter addresses the emotional response to the environmental role and value of consumers' green consumption behavior.

Natural connection describes the relationship between humans and nature. Scholars have expanded the connotation of natural connection in existing research, highlighting that it includes the individual recognition of the value of nature [61]. Building on this, this study constructs a relationship between natural connection and green building perceived value and trust. It posits that an increase in the level of natural connection enables consumers to more deeply perceive the value of the consumer object to nature. In other words, natural connection can enhance the perceived value and trust in green buildings.

Cognition is a crucial foundation for emotion generation in the CAC model. The enhancement of environmental cognition levels promotes consumers to establish a natural connection, making it easier for them to consider the impact of their consumption behavior on the environment. This leads to increased attention toward the environmental protection, safety, and sustainable development functions of green buildings. Consequently, consumers develop trust and emotional dependence on these green attributes, further prompting them to choose green stadiums as the precedent for green buildings, to fulfill their environmental protection needs related to their consumption behavior. However, the influence of cognitive factors in this process varies between age groups. Existing research indicates that age negatively influences environmental cognition, with young people, who are more focused on their development, being more concerned about environmental damage and thus exhibiting higher environmental cognition [62]. It is necessary to consider the degree of influence of this pathway among different age groups. Therefore, based on the above hypotheses:

H4: *Natural connection and green building perceived value and trust as chain mediators between environmental cognition and consumption intentions in green building stadiums.*

H4a: *Natural connection and green building perceived value and trust as chain mediators between a sense of environmental responsibility and willingness to utilize green-built sports stadiums.*

H4b: *Natural connection and green building perceived value and trust as chain mediators between environmental awareness and consumption intentions in green building stadiums.*

H4c: *Natural connection and green building perceived value and trust as chain mediators between green self-efficacy and intention to utilize green building sports stadiums.*

3. Study Design

3.1. Research Targets

Convenient sampling was used to select diverse groups of different ages and classes in society, and data were collected through anonymous offline methods. A total of 500 questionnaires were distributed, and 492 were returned. (According to the rule of thumb by Bentler [63] and Jackson [64], for the structural equation model using the maximum likelihood method for parameter estimation, the ratio of the sample size to the estimated parameters should be at least 5:1 to ensure credible parameter estimates, and close to 10:1 to ensure the validity of the significance test. Therefore, for the 24 questions in the research questionnaire set in the model, this study, adhering to the traditional ratio of estimated parameters to the number of questions and considering the research work's complexity, aims to set the sample size to be more than 20 times the number of questions to ensure scientifically robust results). After excluding invalid questionnaires due to extensive omissions, short response times, and uniform scoring, 463 valid questionnaires were retained, resulting in a validity rate of 94.12%. (Although the sample size is not as large as the targeted 480 valid samples, the difference is minimal. The observed variables are continuously and asymptotically normally distributed, and the scale reliabilities are high, ensuring that the sample remains scientifically valid). This study obtained public consent, and the questionnaire guidance included the informed consent content, ensuring that no part of the questionnaire involved personal privacy or any interventions on the subjects, adhering to ethical requirements. Upon checking the research subjects, it was found that (as shown in Table 1): from a gender perspective, there were 219 males (47.3%) and 244 females (52.7%), indicating a balanced gender ratio. In terms of age distribution, 147 participants (31.7%) were 18–30 years old, 169 participants (36.5%) were 31–40 years old, 111 participants (24%) were 41–50 years old, and 36 participants (7.8%) were 51 years old and above. Overall, the sample in this paper has a balanced proportion across various demographics and is representative.

Table 1. Descriptive statistical analysis.

Name (of a Thing)	Options (as in Computer Software Settings)	Frequency	Percentage (%)
distinguishing between the sexes	male	219	47.3
	women	244	52.7
(a person's) age	18–30 years	147	31.7
	31–40 years	169	36.5
	41–50 years	111	24
	51 and over	36	7.8
education attainment	Bachelor's degree or above	274	59.2
	Specialized and below	189	40.8
incomes	less than 5000	189	40.8
	5000–10,000	170	36.7
	10,000 or more	104	22.5

3.2. Variable Selection

The measurement of environmental responsibility in this paper is based on the environmental responsibility scale developed by Stone [25] et al. and Jaiswal [65] et al. Their scales were adapted through a rigorous process of translation and back-translation to ensure linguistic accuracy. The questions were continuously adjusted and modified in terms of nomenclature to align with the study's theme, resulting in a four-question scale for assessing the sense of environmental responsibility. An example question would be "I will take the initiative to learn about environmental protection". The Cronbach's Alpha for the environmental responsibility scale is 0.840, which is greater than the acceptable threshold of 0.7, indicating good reliability. While numerous studies have examined the influence of consumers' environmental awareness on their consumption perceptions from an individual perspective, there is a paucity of research on their purchasing tendencies, such as the consumption of green sports buildings, from the perspective of environmental awareness. This paper integrates relevant empirical studies on environmental awareness by Eskiler [66] and others, culminating in a six-item scale suitable for this study. An example item is "I have always maintained a positive attitude towards environmental protection and green initiatives". The Cronbach's Alpha for this scale is 0.875, also exceeding 0.7, indicating high reliability. The measurement of green self-efficacy in this paper draws on the work of Chen [67] et al. and Chen [68]. The research scales from these studies were used as a foundation, and the related questions were streamlined appropriately to form a three-item scale for green self-efficacy. An example item is "I feel that I can practice environmental protection ideas successfully" (The specific question items are shown in Appendix A Table A1). The Cronbach's Alpha for this scale is 0.834, also exceeding 0.7, indicating high reliability.

The measure of natural connectedness in this paper draws on the Connectedness to Nature Scale (CNS) developed by scholars such as Mayer [32] et al. This scale has been widely used by scholars globally since its inception and is recognized for its strong scientific validity. In this paper, we condensed the original 13-item scale, retaining the more representative items, and ultimately formed a five-item scale for natural connections. An example item is "I am deeply aware of the impact of my behavior on the natural world". The test Cronbach's Alpha = 0.896 > 0.7. The measurements of perceived value and trust in green buildings, as well as the willingness to purchase green buildings in this paper, draw on the work of Chen et al. [47], Ahn et al. [69], and Manaktola et al. [70]. Based on these sources, this paper organizes 3-item and 4-item scales for perceived value and trust in green buildings and willingness to purchase green buildings by integrating the study's content with the characteristics of the target audience. Example items include "I think that the environmental protection statements of green building stadiums are usually credible", and "I tend to choose green sports stadiums for consumption due to environmental concerns". The Cronbach's Alpha coefficients for these scales are 0.884 and 0.871, respectively, both exceeding 0.7, indicating good reliability.This paper adopts a Likert 5-point scale, ranging from "strongly disagree" to "strongly agree", scored from 1 to 5 points. The higher the score, the more likely the subject is to agree with the statement, and the more pronounced the characteristics of a particular variable.

Because this paper subdivided environmental cognition into three dimensions, and given the similarity in their connotations, the measurement questionnaire for these three dimensions was adapted by drawing on the questionnaires of previous scholars. It is necessary to test the validity of this conceptualization to consider integrating the three dimensions into the overall concept of environmental cognition. Exploratory factor analysis showed that the KMO value was 0.913, and Bartlett's test of sphericity was significant ($p < 0.05$). The factor analysis extracted three factors (as shown in Table 2), each with eigenvalues greater than 1. The variance explained by the rotation of these three factors was 28.092%, 21.141%, and 17.634%, respectively, with the cumulative variance explained by the rotation totaling 66.867%.The number of factors extracted was as expected. The data of this study were rotated using the maximum variance rotation method to determine the correspondence between the factors and the study items. Table 3 demonstrates the information extraction of the factors for the research items and the correspondence between the factors and the research items. It can be seen that all the research items in this paper have a common degree value higher than 0.4, indicating a strong correlation between the research items and the factors, and that the factors can effectively extract the information. Finally, the confirmatory factor analysis of sustainable consumption motivation shows the following results: CMIN = 64.357, DF = 62, CFI = 0.999, TLI = 0.999, RMSEA = 0.009, and SRMR = 0.023. These values indicate that the conceptualization of sustainable consumption motivation is acceptable (see Table 4 for details).

Table 2. Total variance explained.

Ingredient	Initial Eigenvalue			Extract the Sum of the Squares of the Loads			Rotational Load Sum of Squares		
	(Grand) Total	Percentage of Variance	Cumulative %	(Grand) Total	Percentage of Variance	Cumulative %	(Grand) Total	Percentage of Variance	Cumulative %
1	5.731	44.082	44.082	5.731	44.082	44.082	3.652	28.092	28.092
2	1.734	13.341	57.423	1.734	13.341	57.423	2.748	21.141	49.233
3	1.228	9.444	66.867	1.228	9.444	66.867	2.292	17.634	66.867
4	0.558	4.291	71.158						
5	0.540	4.153	75.311						
6	0.483	3.712	79.023						
7	0.457	3.512	82.535						
8	0.436	3.357	85.892						
9	0.417	3.208	89.100						
10	0.400	3.073	92.173						
11	0.367	2.824	94.997						
12	0.345	2.654	97.651						
13	0.305	2.349	100.000						

Table 3. Factor load matrix.

	Ingredient			Commonality
	Environmental Awareness	A Sense of Environmental Responsibility	Green Self-Efficacy	
ER1	0.180	**0.790**	0.239	0.714
ER2	0.203	**0.734**	0.226	0.630
ER3	0.165	**0.780**	0.086	0.644
ER4	0.209	**0.802**	0.204	0.729
EA1	**0.754**	0.155	0.204	0.635
EA2	**0.748**	0.225	0.118	0.623
EA3	**0.771**	0.099	0.146	0.625
EA4	**0.731**	0.217	0.129	0.598
EA5	**0.741**	0.112	0.226	0.613
EA6	**0.757**	0.201	0.114	0.626
GSE1	0.217	0.163	**0.849**	0.794
GSE2	0.216	0.226	**0.798**	0.736
GSE3	0.185	0.267	**0.787**	0.726

Note: The bold text is the common factors; EC: Environmental Cognition; ER: Environmental Responsibility; EA: Environmental Awareness; GSE: Green Self-Efficacy; CN: Connectedness to Nature; GBPVT: Green Buildings Perceived Value and Trust; GBCI: Green Buildings Consumption Intention; same below.

Table 4. Conceptual fitting.

CMIN	DF	CFI	TLI	RMSEA	SRMR
64.357	62	0.999	0.999	0.009	0.023

4. Findings

4.1. Common Method Bias Test

The Harman one-factor test was used to test for common method bias. It was found that there were six factors with eigenvalues > 1 and the variation explained by the first factor was 39.908% and the variation explained by the rotation was 15.420%. The critical criterion of 40% was not reached, indicating that common method bias was not significant in this study. The common method bias was further examined using unmeasurable latent method factor effect controls (as shown in Table 5), where CMIN/DF is the relative ratio of the chi-square and the degrees of freedom, where less than 3 indicates a good fit, and less than 5 is acceptable. TLI, CFI is greater than 0.9, indicating that the model has a good fit. RMSEA, SRMR is less than 0.08, indicating a good fit, and all the above indicators meet the standard. Taken together, most of the model fit indicators meet the standards of the four-factor model with a good fit. The fit index of the seven-factor model with one additional methodological factor on top of the six-factor model did not improve significantly, indicating that there is indeed no common methodological bias in this study.

Table 5. Comparison of indicators between the four-factor model and the common methodological bias (five-factor) model.

Sports Event	CMIN	DF	CFI	TLI	RMSEA	SRMR
six-factor model	294.122	260	0.995	0.994	0.017	0.026
seven-factor model	245.499	236	0.999	0.998	0.009	0.023
magnitude of change Δ	48.623	24	−0.004	−0.004	0.008	0.003

4.2. Correlation Test

Pearson correlation analysis of environmental cognition and its three content perspectives with nature connection, perceived value of green building with trust and willingness to buy showed (as shown in Table 6) significant ($p < 0.05$) positive correlation of all the variables involved in this paper.

Table 6. Correlation analysis.

	M	SD	EC	ER	EA	GSE	CN	GBPVT	GBCI
EC	3.410	0.773	1						
ER	3.455	0.954	0.814 **	1					
EA	3.401	0.897	0.784 **	0.468 **	1				
GSE	3.373	1.014	0.827 **	0.506 **	0.467 **	1			
CN	3.439	0.940	0.499 **	0.345 **	0.395 **	0.468 **	1		
GBPVT	3.466	0.960	0.589 **	0.455 **	0.509 **	0.467 **	0.552 **	1	
GBCI	3.555	0.896	0.645 **	0.506 **	0.516 **	0.543 **	0.474 **	0.595 **	1

Note: ** $p < 0.01$.

4.3. Measurement Model Testing

4.3.1. Split Model Test

A structural equation model, with environmental responsibility, environmental awareness, and green self-efficacy as latent variables, green building stadium consumption intention predictor variables, gender, age and other elements as control variables, and natural connection, green building perceived value and trust as mediator variables, was tested for fit. The model fitting results show (Table 7): CMIN = 294.122, DF = 260, CMIN/DF = 1.131, CFI = 0.995, TLI = 0.994, RMSEA = 0.017, and SRMR = 0.026. All fitting indices in the model are relatively satisfactory, which indicates that the split mediator model is acceptable, and the specific path coefficients are the same as those in Table 8 and Figure 2.

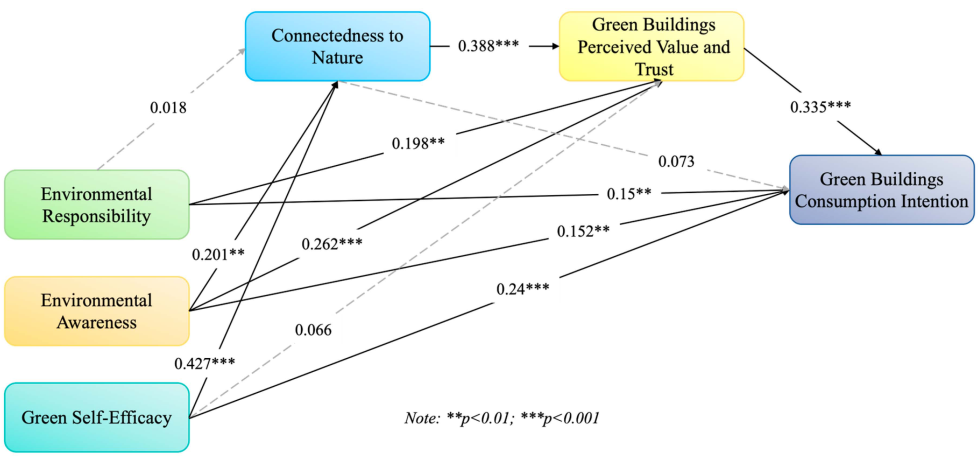


Figure 2. Diagram of split model results.

Table 7. Split model fit coefficients.

CMIN	DF	CFI	TLI	RMSEA	SRMR
294.122	260	0.995	0.994	0.017	0.026

Table 8. Split model path coefficients.

Implicit Variable	Independent Variable	β	SE	t	*p*
CN	ER	0.018	0.066	0.265	0.791
	EA	0.201	0.06	3.35	0.001
	GSE	0.427	0.064	6.689	0
GBPVT	ER	0.198	0.057	3.454	0.001
	EA	0.262	0.053	4.926	0
	GSE	0.066	0.064	1.04	0.298
	CN	0.388	0.048	8.031	0
GBCI	ER	0.15	0.057	2.639	0.008
	EA	0.152	0.055	2.778	0.005
	GSE	0.24	0.061	3.939	0
	CN	0.073	0.055	1.34	0.18
	GBPVT	0.335	0.059	5.647	0

4.3.2. Second-Order Model Test for Independent Variables

This paper proceeded to test the fit of the structural equation model with environmental cognition and the three connotations as latent variables, the consumption intention of green building stadiums as predictor variables, elements such as gender and age as control variables, and natural connection, perceived value of green stadiums, and trust as mediator variables (e.g., Table 9). The model fit indexes are CMIN = 311.538, DF = 266, CMIN/DF = 1.171, CFI = 0.993, TLI = 0.992, RMSEA = 0.019, and SRMR = 0.030, which shows that all the fit indexes in the model are relatively satisfactory, which indicates that the model is acceptable, and the specific path coefficients are as shown in Table 10 and Figure 3.

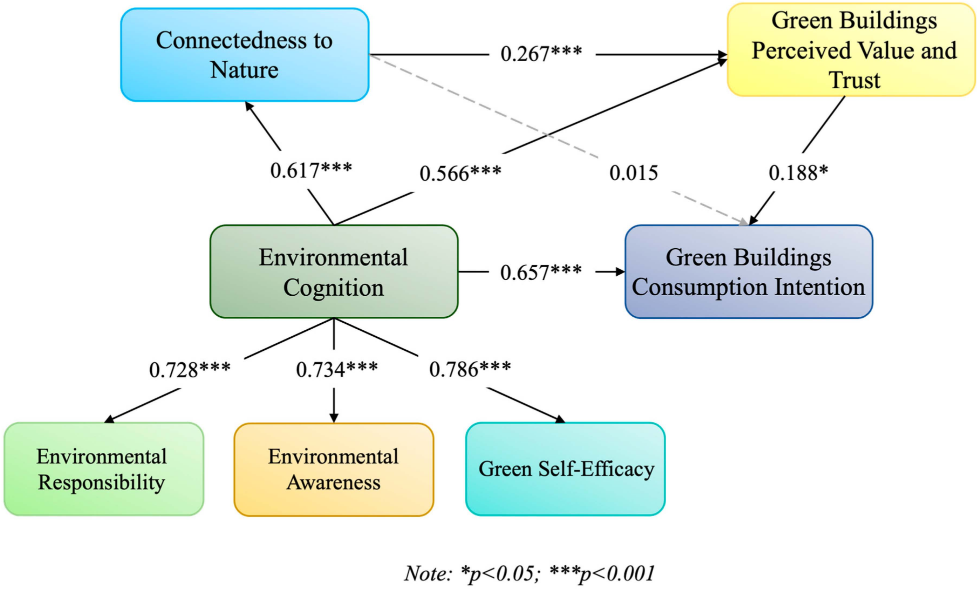


Figure 3. Graph of second-order model results.

Table 9. Second-order model fit coefficients.

CMIN	DF	CFI	TLI	RMSEA	SRMR
311.538	266	0.993	0.992	0.019	0.030

Table 10. Second-order model path coefficients.

Implicit Variable	Independent Variable	β	SE	t	p
CN	EC	0.617	0.041	15.171	0
GBPVT	EC	0.566	0.058	9.72	0
	CN	0.267	0.058	4.586	0
GBCI	EC	0.657	0.079	8.27	0
	CN	0.015	0.058	0.25	0.803
	GBPVT	0.188	0.075	2.491	0.013

4.4. Mediated Effects Test

As shown in Table 11, the test shows that environmental responsibility, environmental awareness, and green self-efficacy in environmental cognition positively predict consumption intention, respectively, with confidence intervals excluding 0, and the direct effects are all significant; the standardized coefficient of environmental responsibility→green building perceived value and trust→consumption intention is 0.066, with confidence intervals excluding 0, and the indirect effects are significant, and the indirect effects account for 30.00%; The standardized path coefficient of environmental awareness→green building perceived value and trust→willingness to buy is 0.088, the confidence interval does not include 0, the indirect effect is significant, and the indirect effect accounts for 31.32%; the standardized path coefficient of environmental awareness→natural connection→green building perceived value and trust→willingness to buy is 0.026, the confidence interval does not include 0, the indirect effect is significant, and the indirect effect accounts for 9.25%; the standardized path coefficient of green self-efficacy→natural connection→green building perceived value and trust→consumption intention is 0.056, the confidence interval does not include 0, the indirect effect is significant, and the proportion of indirect effect is 16.05%. The four statistically significant paths were tested for differences in specific mediated effects, and it was found that for diff1 (int1–int2), diff2 (int1–int3), diff3 (int1–int4), diff4 (int2–int3), diff5 (int2–int4), and diff6 (int3–int4), the t-values are −0.826, 1.077, 0.403, 1.887, 1.340, and −1.114, respectively, the *p*-value is greater than 0.05, and the difference in the effects of the four paths is not statistically significant; so far, for the hypotheses of this paper in the previous period, H1, H1a, H1b, H1c, H3, H3a, H3b, all of them are valid; the hypotheses of the chain mediation, H4, are partly valid (H4a does not hold); and hypotheses H2, H2a, H2b, H2c, and H3c do not hold.

Table 11. Descriptive statistical analysis.

Effect (Scientific Phenomenon)	Trails	Efficiency Value	Magnitude of Effect	t-Value	95% CI	
					Lower Limit	Limit
A sense of environmental responsibility						
direct effect	ER→GBCI	0.15	68.18%	2.197 *	0.0265	0.293
	ER→CN→GBCI	0.001	0.45%	0.151	−0.01	0.028
indirect effect	ER→GBPVT→GBCI (int1)	0.066	30.00%	2.089 *	0.014	0.141
	ER→CN→GBPVT →GBCI	0.002	0.91%	0.212	−0.019	0.024
Total indirect effect		0.07	31.82%	2.097 *	0.012	0.0142
aggregate effect		0.22	100.00%	2.766 **	0.066	0.375
environmental awareness						
direct effect	EA→GBCI	0.152	54.09%	2.291 *	0.03	0.291
	EA→CN→GBCI	0.015	5.34%	0.877	−0.01	0.058
indirect effect	EA→GBPVT→GBCI (int2)	0.088	31.32%	2.685 **	0.038	0.171
	EA→CN→GBPVT →GBCI (int3)	0.026	9.25%	2.188 *	0.009	0.058
Total indirect effect		0.129	45.91%	3.699 ***	0.073	0.21
aggregate effect		0.281	100.00%	4.327 ***	0.163	0.418
Green self-efficacy						
direct effect	GSE→GBCI	0.24;	68.77%	3.064 **	0.096	0.402
	GSE→CN→GBCI	0.031	8.88%	1.062	−0.025	0.093
indirect effect	GSE→GBPVT→GBCI	0.022	6.30%	0.741	−0.033	0.087
	GSE→CN→GBPVT →GBCI (int4)	0.056	16.05%	2.513 *	0.025	0.116
Total indirect effect		0.109	31.23%	2.726 *	0.04	0.201
aggregate effect		0.349	100.00%	4.478 ***	0.206	0.514

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

5. Analysis and Discussion

5.1. The Impact of Environmental Cognition (and Subcategories) on Consumption Intentions of Green Building Stadiums

This study verifies the relationship between environmental cognition and the consumption intentions for green building stadiums. It concludes that environmental cognition significantly promotes the formation of consumption intentions for green stadiums. Despite some scholars arguing that the relationship between environmental cognition and environmental behavior is not significant [71], the findings of this study align with most research in the field of green consumption [72]. The established relationship between environmental cognition and green stadium consumption intentions corroborates the CAC model, which posits that cognition is an antecedent variable of behavioral intention and plays a crucial role in driving consumer behavior. The enhancement of cognitive levels is likely to transform consumers' information, knowledge, and other factors into behavioral intentions. As environmental cognition improves, consumers become increasingly aware of the impact of their consumption behaviors. In this study, with the improvement and deepening of environmental awareness, consumers are increasingly aware of the impact of their consumption behaviors on the environment. They become more cautious in their consumption choices and ultimately select green consumption options that benefit the ecological environment to mitigate their environmental impact. Additionally, the three dimensions of environmental responsibility, environmental awareness, and green self-efficacy, which are components of environmental cognition, positively contribute to green stadium consumption intentions. This finding aligns with previous studies on each dimension [73–75]. However, this study reveals differences in the strength of these dimensions' roles. The path coefficients indicate that the sense of environmental responsibility and environmental awareness have similar path coefficients, while green self-efficacy has a significantly larger impact than the other two dimensions. The significantly greater impact of self-efficacy suggests that in the process of developing environmental cognition related to green stadium consumption, green self-efficacy plays a crucial role. Consumers with high self-efficacy exhibit greater confidence in their behavior, increasing the likelihood of specific behavior implementation [76]. When consumers possess a strong sense of green self-efficacy, they believe their actions can effectively improve the environment, thereby fostering environmental behavior. Consequently, the implementation of consumer behavior is more likely to be associated with a heightened sense of environmental responsibility and awareness. Consumption behavior is more inclined towards consumer objects with green attributes. Therefore, in the context of sports consumption, consumers will prefer environmentally friendly green stadiums, thereby generating consumption intentions. Unlike the strong influence of green self-efficacy, environmental responsibility and environmental awareness are more focused on the individual consumer's understanding of the importance of environmental protection and engaging in eco-friendly behaviors. Consequently, the roles of environmental responsibility and awareness are relatively less significant.

5.2. The Important Mediating Role of Perceived Value and Trust in Green Buildings

The data analysis in this study reveals that the perceived value and trust in green buildings plays a crucial mediating role between environmental cognition and the willingness to consume green building stadiums, consistent with related research findings [77,78]. The green transformation of stadiums offers consumers new options with environmental attributes. As consumers' environmental cognition and knowledge grow, their perception of the consumption objects strengthens. This heightened perception makes it easier for consumers to recognize the environmental protection and sustainable development value of green buildings, establish trust in them, and subsequently generate consumption intentions towards green building sports stadiums. For consumers, the enhancement of individual environmental awareness remains limited. However, for policy implementers or managers, elevating individual awareness of green buildings through the dissemination of green knowledge is a crucial strategy to foster trust and emotional connections with green buildings. This study finds that the perceived value of green buildings and trust within the environmental cognitive dimensions—specifically environmental responsibility and environmental awareness—mediate the promotion of consumers' willingness to engage with green buildings and stadiums. However, this does not hold true for green self-efficacy, diverging from existing studies [79]. This discrepancy may stem from the internalization of environmental responsibility and awareness, which augments consumers' environmental protection knowledge, thereby facilitating the perception of the environmental value of green buildings and generating the intention to engage with green buildings and stadiums. It is easier to perceive the environmental value of green buildings, establish trust, and subsequently form consumption intentions. In contrast, green self-efficacy regarding the intention behind green sports building consumption arises from the recognition and evaluation of one's own ability. Individuals believe that they can achieve the goal of environmental protection through their actions, thereby generating consumption intentions. This results in a disparity in the perceived value of green buildings and trust as mediators. This study concludes that the dimensions of environmental responsibility and environmental awareness within environmental cognition are more likely to drive emotional factors, thereby influencing behavioral intentions. When consumers possess a heightened sense of environmental responsibility and awareness, they are more inclined to recognize their own interests as intertwined with those of the environment. They integrate their personal interests with environmental interests, making them more likely to perceive the value of environmental protection and establish trust when considering green buildings as a consumption choice. Consequently, they are willing to pay a premium to protect environmental interests. This perception drives them to select environmentally friendly green stadiums as their preferred choice. Therefore, at the level of environmental cognition, environmental responsibility and awareness are more effective in driving emotional factors than green self-efficacy, facilitating the perceived value and trust in green buildings, and subsequently promoting the intention to consume green stadiums.

5.3. Differences in the Chain Path Influence of Environmental Cognition Subcategories on Consumption Intentions for Green Building Stadiums

In this study, the variable of natural connection in environmental psychology is introduced into the domain of green sports consumption, with the perceived value and trust of green buildings serving as representative emotional variables. The data analysis reveals that natural connection, along with the perceived value and trust of green buildings, acts as a chain intermediary between environmental cognition and the willingness to consume green sports stadiums. Research on natural connection within the consumer field is relatively scarce, yet it has been established that a promotional relationship exists between natural connection and pro-environmental behavior [80]. This relationship indicates that consumers' pro-environmental behaviors are driven by the environmental value and sustainable development attributes inherent in the consumption of green sports stadiums. When consumers have a high level of environmental awareness, it becomes easier to establish an emotional connection with the natural environment. This emotional connection encourages consumers to pay more attention to their own behavior and the environmental protection value of their consumption choices. As a result, they perceive a higher value in green buildings and establish trust, ultimately forming the intention to consume green stadiums. This intention aligns with their desire to fulfill their own environmental value and sustainable development needs. This research helps to promote the relationship between environmental value and pro-environmental behavior, as well as the sustainable development attributes inherent in green stadium consumption. We believe this conclusion is consistent with existing research as a whole [81].

The chain mediation path of environmental responsibility within the environmental cognition subcategory does not hold as effectively as environmental awareness and green self-efficacy, which are generated through direct or indirect contact with the environment. The development of a sense of environmental responsibility is more about recognizing environmental problems [82], viewing the environment as an entity affected by one's behavior, and considering environmental protection as a personal duty, rather than establishing a direct link with the environment. Additionally, a sense of environmental responsibility remains at the level of individual awareness and does not necessarily translate into action, with governmental environmental protection behavior often exemplifying personal action [83]. In contrast, the path involving environmental awareness and green self-efficacy plays a chain mediation role in natural connection and perceived value and trust in green buildings. According to the CAC model, intention results from the interaction of cognition and emotion, with cognitive factors positively influencing intention. However, relying solely on cognition is insufficient, as emotional factors are a crucial complement, catalyzing the cognitive impact on intention. Environmental awareness and green self-efficacy, through knowledge of environmental protection and the evaluation of self-protection behavior, respectively, establish an emotional connection with the natural environment, forming a natural link. This endows consumers with a stronger subconscious drive for environmental protection and behavioral norms, making them more likely to prioritize the environmental value of their consumption choices. Green buildings, as environmentally friendly structures, implement the principles of green, environmental protection, and sustainability from construction to operation. Consequently, consumers with a high level of natural connection pay greater attention to the environmental protection role and value provided by choosing green buildings. They trust green buildings more and are therefore more inclined to select green buildings as the preferred venue for stadiums over traditional options.

6. Summary and Outlook

In this study, a research model was constructed using the CAC model to promote green stadium consumption intention, and the relationships between variables were verified. The following conclusions were drawn from data collection and analysis: (1) Environmental cognition positively influences green stadium consumption intention. Environmental responsibility, environmental awareness, and green self-efficacy all significantly impact green stadium consumption intention. (2) The perceived value of green buildings and trust play a mediating role in the relationship between environmental cognition and its subcategories—environmental responsibility and environmental awareness—on the consumption intention of green stadiums. (3) Natural connection, along with the perceived value and trust in green buildings, acts as a chain mediator in the promotion of environmental cognition and its subcategories—environmental awareness and green self-efficacy—on the consumption intention of green stadiums.

The purpose of this paper is to provide a reference for studying the promotion of consumers' green sports consumption behavior from cognitive and affective perspectives. From a theoretical standpoint, the emotional component of the CAC model constructed in this study includes the variable of natural connection, highlighting the significant impact of consumers' connection with nature on their intention to consume green sports stadiums. Traditional Chinese cultural concepts such as Confucianism and Taoism, which emphasize the unity and coexistence of man and nature, deeply influence Chinese consumers, making them more likely to establish an emotional connection with nature and thereby promoting the consumption intention of green sports stadiums. This study also expands the CAC model to further elucidate the impact of cognition and emotion on consumer behavior, providing a theoretical reference for the future use of green buildings as a carrier of green consumer behavior and broadening the research ideas on consumer cognition and emotion in relation to green buildings. Additionally, this study identifies a psychological pathway for the government or administrators to recognize green stadiums more easily. By enhancing the public's sense of environmental responsibility, environmental awareness, and green self-efficacy, an emotional connection with nature can be established, leading to greater attention to the environmental value of green buildings, fostering trust, and inclining consumers towards choosing green stadiums in their consumption decisions.

Regarding practical significance, from an individual perspective, this study enhances the green awareness of consumers and positively influences the dissemination of green culture, the formation of green habits, and the understanding of green behaviors. It underscores the close relationship between environmental green development and the healthy coexistence of humanity. From the perspective of government or administrators, a scientific and reasonable natural resources protection policy is crucial in promoting consumers' environmental awareness. It helps the public realize that environmental protection is not solely the responsibility of the state but also a personal duty, thereby enhancing their sense of environmental responsibility. Strengthening the popularization of green knowledge is essential for consumers to acquire environmental knowledge, fostering their environmental awareness, and encouraging them to adopt green, environmentally friendly, and sustainable behaviors in the future.

The limitations of this study are detailed as follows: Firstly, while this study introduces the variable of natural connection into the exploration of green sports consumption behavior, this variable is relatively under-researched in this field. The influence of natural connection on green sports consumption is examined from a broad perspective, which holds some research significance but lacks depth. Secondly, although the study's questionnaires encompass diverse samples across various age groups and incomes, and the sample size meets research and modeling standards, it remains relatively small from a broader perspective. In terms of sample diversity, different age groups were considered, but comparative analyses focusing on environmental perceptions and the impact of factors such as different occupations and health levels were not emphasized. Thirdly, the sample country for this study is China. Given the differences in national conditions, traditional cultures, policy formulation and implementation, and green sustainable management across countries and regions, further exploration is required to incorporate these factors into studies of different countries or regions.

Author Contributions: Conceptualization: L.C. and X.S.; Methodology: L.C.; Software: Y.H.; Validation: Y.H.; Investigation: X.S. and S.F.; Data curation: L.C. and Y.H.; Writing—original draft: L.C., X.S., S.F. and C.L.; Supervision: C.L.; Project administration: Q.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data available on request from the authors.

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

Appendix A

Table A1. Questionnaire.

Variant	Subject	Score
Environmental Responsibility (ER)	I have a responsibility to do my part to protect the environment and conserve resources.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I will take the initiative to learn about environmental protection	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	Although my impact is small, I want to contribute to the protection of the environment.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I think my consumer behavior has some impact on the natural environment	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree

Table A1. *Cont.*

Variant	Subject	Score
Environmental Awareness (EA)	I will take the initiative to learn about environmental protection in my life and improve my ability to protect the environment.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I think that adopting environmentally friendly behaviors in professional life is a spontaneous choice	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I will actively encourage my family, friends and colleagues to adopt greener behaviors	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I have always had a positive attitude towards environmental protection and green initiatives	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I believe that action to protect the environment is essential for the development of future generations.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I will pay attention to environmental protection in my personal behavior, such as buying green products, insisting on waste separation, etc.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
Green Self-Efficacy (GSE)	I think I can successfully practice environmental protection	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I feel empowered to help achieve environmental goals	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I think I can actually fulfill my environmental mission.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
Connectedness to Nature (CN)	I think I'm part of the same destiny as nature.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I often feel close to the plants and animals in nature.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I am acutely aware of the impact my actions will have on the natural world.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I think people are part of nature.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I think I'm part of a natural cycle.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
Green Buildings Perceived Value and Trust (GBPVT)	I think environmental claims for green building stadiums are usually credible	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I chose green building because it's more environmentally friendly than other buildings.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	The environmental performance of green buildings meets my expectations	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
Green Buildings Consumption Intention (GBCI)	I tend to prefer green stadiums for consumption due to environmental concerns	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	The reason I choose to consume green stadiums is because of its green performance and other factors that are in line with a healthy life in sports	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree
	I would recommend my friends and family to spend money on green building stadiums.	1. strongly disagree 2. somewhat disagree 3. generally 4. somewhat agree 5. strongly agree

Note: Extraction method: Principal Component Analysis (PCA).

References

1. Huang, H.F.; Yang, J.Z.; Zheng, Z.Q. Research on the correlation between sports consumption and fiscal and tax macro incentives in public sports venues. *J. Xi'An Inst. Phys. Educ.* **2018**, *03*, 257–263.
2. Wan, L. Research on the intention of urban youth's sports consumption behavior. *J. Nanjing Inst. Phys. Educ. Nat. Sci. Ed.* **2015**, *14*, 139–144.
3. Kellison, T.; Orr, M. Climate vulnerability as a catalyst for early stadium replacement. *Int. J. Sport. Mark. Spons.* **2021**, *22*, 126–141. [CrossRef]

4. Geng, Y.; Dong, H.; Xue, B.; Fu, J. An overview of Chinese green building standards. *Sustain. Dev.* **2012**, *20*, 211–221. [CrossRef]
5. Zeng, J.M.; Ma, Y.X. Dynamic mechanism, problem review and implementation strategies of green transformation of sports venues. *J. Beijing Sport Univ.* **2023**, *9*, 24–34.
6. Kim, Y.H.; Kim, D.J.; Wachter, K. A study of mobile user engagement (MoEN): Engagement motivations, perceived value, satisfaction, and continued engagement intention. *Decis. Support Syst.* **2013**, *10*, 142–149. [CrossRef]
7. Akroush, M.N.; Mahadin, B.K. An intervariable approach to customer satisfaction and loyalty in the internet service market. *Internet Res.* **2019**, *29*, 772–798. [CrossRef]
8. Lim, S.H.; Kim, D.J. Does emotional intelligence of online shoppers affect their shopping behavior? From a cognitive-affective-conative framework perspective. *Int. J. Hum.–Comput. Interact.* **2020**, *36*, 1304–1313. [CrossRef]
9. Kwahk, K.Y.; Ahn, H.; Ryu, Y.U. Understanding mandatory IS use behavior: How outcome expectations affect conative IS use. *Int. J. Inf. Manag.* **2018**, *38*, 64–76. [CrossRef]
10. Jia, Y.; Zhang, X. The impact of environmental cognition and perceived benefits on consumers' willingness and behavioral deviation in participating in express. *Resour. Sci.* **2022**, *44*, 2060–2073.
11. Tang, M.H.; Peng, J. The impact of green transformational leadership on team green behavior: A local exploration based on a social cognitive perspective. *Psychol. Sci.* **2019**, *42*, 1478–1484.
12. Yang, X.; Jiang, J.; Chen, S.C. Achieving sustainability: Determinants of conscious green purchasing behavior during the COVID-19 pandemic. *Bus. Strategy Environ.* **2023**, *32*, 2229–2244. [CrossRef]
13. Han, S.; Lerner, J.S.; Keltner, D. Feelings and consumer decision making: The appraisal-tendency framework. *J. Consum. Psychol.* **2007**, *17*, 158–168. [CrossRef]
14. Hsiao, C.C. Understanding content sharing on the internet: Test of a cognitive-affective-conative model. *Online Inf. Rev.* **2020**, *44*, 1289–1306 . [CrossRef]
15. Rashid, N.R.N.A. Awareness of eco-label in Malaysia's green marketing initiative. *Int. J. Bus. Manag.* **2009**, *4*, 132–141. [CrossRef]
16. Arcury, T. Environmental attitude and environmental knowledge. *Hum. Organ.* **1990**, *49*, 300–304. [CrossRef]
17. Gifford, R.; Nilsson, A. Personal and social factors that influence pro-environmental concern and behavior: A review. *Int. J. Psychol.* **2014**, *49*, 141–157.
18. Frick, J.; Kaiser, F.C.; Wilson, M. Environmental knowledge and conservation behavior: Exploring prevalence and structure in a representative sample. *Personal. Individ. Differ.* **2004**, *37*, 1597–1613. [CrossRef]
19. Peng, Y.C. Analysis of the impact of urban residents' environmental cognition on environmental behavior. *J. Cent. South Univ.* **2015**, *21*, 168–174.
20. Ye, N. Research on the influence mechanism of green cognition and green emotion on green consumption behavior. *J. Nanjing Tech Univ. Soc. Sci. Ed.* **2019**, *18*, 61–74.
21. Liu, Z.L.; Anderson, T.D.; Cruz, J.M. Consumer environmental awareness and competition in two-stage supply chains. *Eur. J. Oper. Res.* **2012**, *2012*, 602–613. [CrossRef]
22. Rodrigues, J.; Domingos, T. Consumer and producer environmental responsibility: Comparing two approaches. *Ecol. Econ.* **2008**, *66*, 533–546. [CrossRef]
23. Tawde, S.; Kamath, R.; ShabbirHusain, R.V. 'Mind will not mind'-Decoding consumers' green intention-green purchase behavior gap via moderated mediation effects of implementation intentions and self-efficacy. *J. Clean. Prod.* **2023**, *383*, 135506. [CrossRef]
24. Xie, C.; Wang, R.; Gong, X. The influence of environmental cognition on green consumption behavior. *Front. Psychol.* **2022**, *13*, 988585. [CrossRef]
25. Stone, G.; Barnes, J.H.; Montgomery, C. Ecoscale: A scale for the measurement of environmentally responsible consumers. *Psychol. Mark.* **1995**, *12*, 595–612. [CrossRef]
26. Neo, S.M.; Choong, W.W.; Ahamad, R.B. Differential environmental psychological factors in determining low carbon behaviour among urban and suburban residents through responsible environmental behaviour model. *Sustain. Cities Soc.* **2017**, *31*, 225–233. [CrossRef]
27. Kollmuss, A.; Agyeman, J. Mind the gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? *Environ. Educ. Res.* **2002**, *8*, 239–260. [CrossRef]
28. Ahmad, W.; Kim, W.G. Schwartz personal values, theory of planned behavior and environmental consciousness: How tourists' visiting intentions towards eco-friendly destinations are shaped? *J. Bus. Res.* **2020**, *110*, 228–236. [CrossRef]
29. Bandura, A. *Social Foundations of Thought and Action*; Prentice-Hall, Inc.: Englewood Cliffs, NJ, USA, 1986; p. 2.
30. Roberts, J.A. Green consumers in the 1990s: Profile and implications for advertising. *J. Bus. Res.* **1996**, *36*, 217–231. [CrossRef]
31. Lin, H.Y.; Hsu, M.H. Using social cognitive theory to investigate green consumer behavior. *Bus. Strategy Environ.* **2015**, *24*, 326–343. [CrossRef]
32. Mayer, F.S.; Frantz, C.M.; Bruehlman-Senecal, E.; Dolliver, K. Why is nature beneficial? The role of connectedness to nature. *Environ. Behav.* **2009**, *41*, 607–643. [CrossRef]
33. Schultz, P.W.; Shriver, C.; Tabanico, J.J.; Khazian, A.M. Implicit connections with nature. *J. Environ. Psychol.* **2004**, *24*, 31–42. [CrossRef]
34. Nisbet, E.K.; Zelenski, J.M.; Murphy, S.A. The nature relatedness scale: Linking individuals' connection with nature to environmental concern and behavior. *Environ. Behav.* **2009**, *41*, 715–740. [CrossRef]

35. Tam, K.P.; Lee, S.L.; Chao, M.M. Saving Mr. Nature: Anthropomorphism enhances connectedness to and protectiveness toward nature. *J. Exp. Soc. Psychol.* **2013**, *49*, 514–521. [CrossRef]
36. Richardson, M.; Cormack, A.; McRobert, L.; Underhill, R. 30 days wild: Development and evaluation of a large-scale nature engagement campaign to improve well-being. *PLoS ONE* **2016**, *11*, e0149777. [CrossRef]
37. Nisbet, E.K.; Zelenski, J.M. Underestimating nearby nature: Affective forecasting errors obscure the happy path to sustainability. *Psychol. Sci.* **2011**, *22*, 1101–1106. [CrossRef]
38. Cheng, J.C.H.; Monroe, M.C. Connection to nature: Children's affective attitude toward nature. *Environ. Behav.* **2012**, *44*, 31–49. [CrossRef]
39. Soga, M.; Gaston, K.J.; Yamaura, Y.; Kurisu, K.; Hanaki, K. Both direct and vicarious experiences of nature affect children's willingness to conserve biodiversity. *Int. J. Environ. Res. Public Health* **2016**, *13*, 529. [CrossRef] [PubMed]
40. Kanchanapibul, M.; Lacka, E.; Wang, X.; Chan, H.K. An empirical investigation of green purchase behavior among the young generation. *J. Clean. Prod.* **2014**, *66* 528–536.
41. Yue, T.; Wang, Q.; Long, R.; Chen, H.; Li, M.; Liu, H. Impact of Urban Residents' Environmental Cognition on Voluntary Carbon-Reduction Behavior: The Mediating Role of Environmental Emotion. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15710. [CrossRef]
42. Palmberg, I.E.; Kuru, J. Outdoor activities as a basis for environmental responsibility. *J. Environ. Educ.* **2000**, *31*, 32–36. [CrossRef]
43. Do Paco, A.; Raposo, M. "Green" segmentation: An application to the Portuguese consumer market. *Mark. Intell. Plan.* **2009**, *27*, 364–379. [CrossRef]
44. Liefländer, A.K.; Fröhlich, G.; Bogner, F.X.; Schultz, P.W. Promoting connectedness with nature through environmental education. *Environ. Educ. Res.* **2013**, *19*, 370–384. [CrossRef]
45. Maddock, J.E.; Suess, C.; Bratman, G.N.; Smock, C.; Kellstedt, D.; Gustat, J.; Perry, C.K.; Kaczynski, A.T. Development and validation of self-efficacy and intention measures for spending time in nature. *BMC Psychol.* **2022**, *10*, 51. [CrossRef]
46. Hart, P.; Saunders, C. Power and trust: Critical factors in the adoption and use of electronic data interchange. *Organ. Sci.* **1997**, *8*, 23–42. [CrossRef]
47. Chen, Y.S. The drivers of green brand equity: Green brand image, green satisfaction, and green trust. *J. Bus. Ethics* **2010**, *93*, 307–319. [CrossRef]
48. Zeithaml, V.A. Consumer perceptions of price, quality, and value: A means-end model and synthesis of evidence. *J. Mark.* **1988**, *52*, 2–22. [CrossRef]
49. Yang X.Y.; Zhou Y.J. Green value: A new dimension of customer perceived value. *China Ind. Econ.* **2006**, *7*, 110–116.
50. Kim, C.; Zhao, W.; Yang, K.H. An empirical study on the integrated framework of e-CRM in online shopping: Evaluating the relationships among perceived value, satisfaction, and trust based on customers' perspectives. trust based on customers' perspectives. *J. Electron. Commer. Organ. (JECO)* **2008**, *6*, 1–19. [CrossRef]
51. Cheung, R.; Lam, A.Y.; Lau, M.M. Drivers of green product adoption: The role of green perceived value, green trust and perceived quality. *J. Glob. Sch. Mark. Sci.* **2015**, *25*, 232–245. [CrossRef]
52. Agustin, C.; Singh, J. Curvilinear effects of consumer loyalty determinants in relational exchanges. *J. Mark. Res.* **2005**, *42*, 96–108. [CrossRef]
53. Kotler, P. A generic concept of marketing. *J. Mark.* **1972**, *36*, 46–54. [CrossRef]
54. Li, J.X.; Liu, D.; Liu, L. The effect of environmental awareness on consumers' green purchasing: Mediating role of green perceived value. In *The 19th International Conference on Industrial Engineering and Engineering Management*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 767–776.
55. Nam, C.; Dong, H.; Lee, Y.A. Factors influencing consumers' purchase intention of green sportswear. *Fash. Text.* **2017**, *4*, 1–17. [CrossRef]
56. Wasaya, A.; Saleem, M.A.; Ahmad, J.; Nazam, M.; Khan, M.M.A.; Ishfaq, M. Impact of green trust and green perceived quality on green purchase intentions: A moderation study. *Environ. Dev. Sustain.* **2021**, *23*, 13418–13435. [CrossRef]
57. Saif, S.; Zameer, H.; Wang, Y.; Ali, Q. The effect of retailer CSR and consumer environmental responsibility on green consumption behaviors: Mediation of environmental concern and customer trust. *Mark. Intell. Plan.* **2024**, *42*, 149–167. [CrossRef]
58. Jackson, T. Live better by consuming less?: Is there a "double dividend" in sustainable consumption? *J. Ind. Ecol.* **2005**, *9*, 19–36. [CrossRef]
59. Punyatoya, P. Linking environmental awareness and perceived brand eco-friendliness to brand trust and purchase intention. *Glob. Bus. Rev.* **2014**, *15*, 279–289. [CrossRef]
60. Zhu, G.; So, K.K.F.; Hudson, S. Inside the sharing economy. *Int. J. Contemp. Hosp. Manag.* **2017**, *29*, 2218–2239. [CrossRef]
61. Perkins, H.E. Measuring love and care for nature. *J. Environ. Psychol.* **2010**, *30*, 455–463. [CrossRef]
62. Chen, X.; Peterson, M.N.; Hull, V.; Lu, C.; Lee, G.D.; Hong, D.; Liu, J. Effects of attitudinal and sociodemographic factors on pro-environmental behaviour in urban China. *Environ. Conserv.* **2011**, *38*, 45–52. [CrossRef]
63. Bentler, P.M.; Chou, C.P. Practical issues in structural modeling. *Sociol. Methods Res.* **1987**, *16*, 78–117. [CrossRef]
64. Jackson, D.L. Revisiting sample size and number of parameter estimates: Some support for the N: Q hypothesis. *Struct. Equ. Model.* **2003**, *10*, 128–141. [CrossRef]
65. Jaiswal, J.; Bihari, S. Role of connectedness to nature and perceived environmental responsibility on green purchase behavior. *Asian J. Bus. Res.* **2020**, *10*, 65–84. [CrossRef]

66. Eskiler, E.; Altunışık, R. The moderating effect of involvement in the relationship between customer behavioral intentions and its antecedents. *Sage Open* **2021**, *11*, 21582440211014495. [CrossRef]
67. Chen, Y.S.; Chang, C.H. Enhancing green purchase intentions: The roles of green perceived value, green perceived risk, and green trust. *Manag. Decis.* **2012**, *50*, 502–520. [CrossRef]
68. Chen, G.; Gully, S.M.; Eden, D. Validation of a new general self-efficacy scale. *Organ. Res. Methods* **2001**, *4*, 62–83. [CrossRef]
69. Ahn, Y.H.; Pearce, A.R.; Wang, Y.; Wang, G. Drivers and barriers of sustainable design and construction: The perception of green building experience. *Int. J. Sustain. Build. Technol. Urban Dev.* **2013**, *4*, 35–45. [CrossRef]
70. Manaktola, K.; Jauhari, V. Exploring consumer attitude and behavior towards green practices in the lodging industry in India. *Int. J. Contemp. Hosp. Manag.* **2007**, *19*, 364–377. [CrossRef]
71. Almeida, C.; Altintzoglou, T.; Cabral, H.; Vaz, S. Does seafood knowledge relate to more sustainable consumption? *Br. Food J.* **2015**, *117*, 894–914. [CrossRef]
72. Wang, J.H.; Yan, L.L. The impact of multi-dimensional environmental cognition on consumers' environmentally friendly behavior. *J. Nanjing Tech Univ. (Soc. Sci. Ed.)* **2021**, *20*, 78–94.
73. Sharma, N.; Dayal, R. Drivers of green purchase intentions: Green self-efficacy and perceived consumer effectiveness. *Glob. J. Enterp. Inf. Syst.* **2016**, *8*, 27–32. [CrossRef]
74. Hou, Y.; Chen, S.; Yao, Z.; Huang, Q.; Shen, X.; Cao, L.; Cheng, J.; Gui, F.; Zhang, Y.; Wang, X. Green Building Consumption Perception and Its Impact on Fitness Service Purchasing Intentions: An Extended Institutional Analysis and Development Decision-Making Model Analysis. *Buildings* **2023**, *13*, 2536. [CrossRef]
75. Kautish, P.; Paul, J.; Sharma, R. The moderating influence of environmental consciousness and recycling intentions on green purchase behavior. *J. Clean. Prod.* **2019**, *228*, 1425–1436. [CrossRef]
76. Bandura, A. Self-efficacy: Toward a unifying theory of behavioral change. *Psychol. Rev.* **1977**, *84*, 191. [CrossRef]
77. Zulfanizy, K.; Wahyono, W. The influence of green perceived value, risk and quality toward green purchase intention through green trust. *Manag. Anal. J.* **2019**, *8*, 79–89.
78. Aprianti, V.; Hurriyati, R.; Gaffar, V.; Wibowo, L.A. The effect of green trust and attitude toward purchasing intention of green products: A case study of the green apparel industry in Indonesia. *J. Asian Financ. Econ. Bus.* **2021**, *8*, 235–244.
79. Sh. Ahmad, F.; Rosli, N.T.; Quoquab, F. Environmental quality awareness, green trust, green self-efficacy and environmental attitude in influencing green purchase behavior. *Int. J. Ethics Syst.* **2022**, *38*, 68–90. [CrossRef]
80. Martin, L.; White, M.P.; Hunt, A.; Richardson, M.; Pahl, S.; Burt, J. Nature contact, nature connectedness and associations with health, wellbeing and pro-environmental behaviours. *J. Environ. Psychol.* **2020**, *68*, 101389. [CrossRef]
81. de Miranda Coelho, J.A.P.; Gouveia, V.V.; de Souza, G.H.S.; Milfont, T.L.; Barros, B.N.R. Emotions toward water consumption: Conservation and wastage. *Rev. Latinoam. Psicol.* **2016**, *48*, 117–126. [CrossRef]
82. Knopman, D.S.; Susman, M.M.; Landy, M.K. Civic environmentalism: Tackling tough land-use problems with innovative governance. environment: Science and policy for sustainable development. *Environ. Sci. Policy Sustain. Dev.* **1999**, *41*, 24–32. [CrossRef]
83. Lee, K. Gender differences in Hong Kong adolescent consumers' green purchasing behavior. *J. Consum. Mark.* **2009**, *26*, 87–96. [CrossRef]

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

Buildings Editorial Office
E-mail: buildings@mdpi.com
www.mdpi.com/journal/buildings

MDPI

Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-4576-7