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# Using Building Information Modeling to Enhance Supply Chain Resilience in Prefabricated Buildings: A Conceptual Framework

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**Abstract:** Prefabricated buildings usually involve various project participants and complicated processes of design, manufacturing, transport, assembly, and construction, which means they constantly face supply chain disruptions. As a tool to realize information integration and facilitate communication among project participants in the supply chain, building information modeling (BIM) is widely recognized as an important technology to foster supply chain resilience. However, it is unclear how BIM can facilitate supply chain resilience in prefabricated buildings. This study aims to construct a conceptual framework to better understand the influencing paths of BIM on supply chain resilience in the context of prefabricated buildings. It employs an integrative review method to identify key factors influencing the resilience of the prefabricated building supply chain and explore the effects of BIM on these factors. The role of BIM in linking these factors was verified through an empirical case. The results show that BIM resources and capabilities can enhance supply chain resilience by influencing participant factors (assembly construction capability, design capability) and partnership factors (information sharing, cooperation, coordination, and trust). This study incorporates supply chain resilience and BIM technology into a conceptual framework in the context of prefabricated buildings, providing new theoretical insights for future supply chain management.

**Keywords:** prefabricated buildings; supply chain resilience; BIM



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## 1. Introduction

The broad construction sector is transforming from high consumption, low output, and low productivity to a stage with high-quality products and advanced techniques, addressing sustainable development concerns. Following this trend, prefabricated buildings have been considered as a sustainable and efficient form of construction as an alternative to traditional building methods [1,2]. The prefabricated building is described as a series of construction procedures in which building components are produced and manufactured in a factory, delivered to construction sites, and finally assembled on the spot into a final product [3]. In this way, prefabricated buildings have the advantages of reducing environmental burden [4], saving on-site construction labor [5], and improving productivity and project quality [6]. They are widely recognized as conscious efforts to reduce climate change and improve resource efficiency, contributing to sustainable development [2]. Such advantages have become the driving force behind the rapid growth of assembly construction. Hence, various countries all over the world are increasingly using modular construction techniques to transform residential buildings, schools, and hospitals [7].

In the context of prefabricated buildings, the supply chain is a contractor-centered construction network consisting of the owner, the designer, the contractor, the component manufacturing manufacturers, the logistics companies, and other stakeholders involved during the whole project, starting from the procurement of prefabricated components to the delivery of the completed project [8]. Unfavorable weather or sudden natural disasters, such as heavy rain or frost, can increase the difficulty of transport and assembly, leading to the risk of disruption or breakage in the prefabricated building supply chain [9]. At the same time, internal factors such as complicated links in the supply chain, a low level of cooperation among participants, and poor information sharing can also bring additional risks to the supply chain [10]. This not only threatens the continuity of business operations but also negatively impacts the general competitiveness of involved construction organizations [11].

Prefabricated building supply chain resilience represents the ability of organizations associated with the project to survive, adapt, and thrive in risky, uncertain, and changing situations [12]. The ability of a supply chain to recover quickly from a risky situation depends on its level of resilience [13]. Therefore, for prefabricated building projects to run smoothly, the supply chain needs to be strengthened. In other words, more efforts are required to enhance the supply chain resilience of prefabricated buildings.

Along with the construction industry's digital transformation progress, building information modeling (BIM) has gradually increased as the core driving technology for the digital development of modular construction [14]. BIM technology is able to connect information related to building design, procurement, and construction, and hence promote coordination, cooperation, information sharing, and integration among various project participants in the supply chain [15]. BIM can not only facilitate the digitalization of supply chains and help automate decision making for business operations, but it can also enhance supply chain efficiency [15]. BIM maturity reflects the degree of BIM technology use [16]. There are variations in BIM maturity in prefabricated building projects due to factors such as organizational culture, resources, technological tools, personnel skills, project size, and project complexity [17]. In practice, supply chain resilience varies when it comes to different levels of BIM application [18]. Although some studies have suggested that BIM can promote supply chain resilience, the pathways of such influences are far from clear. Thus, this study aims to explore the impact of BIM technology on supply chain resilience in prefabricated buildings.

To address the above research aim, this study will conduct an integrative review analysis, followed by an empirical case study. Based on the integrative review, a conceptual framework for BIM and supply chain resilience was first established. Then, we used an empirical case in the context of prefabricated buildings to validate and refine the framework. This study attempts to open the "black box" between BIM and prefabricated building supply chain resilience and lays a theoretical foundation for future empirical research. It also provides insights for practitioners on how to enhance the supply chain resilience of prefabricated building projects through BIM application.

## 2. Prefabricated Building Supply Chain

The supply chain concept originated in the manufacturing industry. A supply chain is a network of organizations working together and encompasses a combination of different processes and activities that produce value in the form of products and services from upstream to downstream [19]. Vrijhoef and Koskela integrated the manufacturing supply chain management model with the construction industry and argued that a construction supply chain is a network structure that exchanges and controls the flow of capital, logistics, and information in projects with the goal of fulfilling the owner's requirements, linking multiple project parties [20]. The management mode of prefabricated buildings is different from that of the traditional construction industry. Materials and equipment are supplied to component factories for processing, and then third-party logistics enterprises transport finished and semi-finished products to the site for installation. The supply chain management process for prefabricated buildings involves multiple phases, various stakeholders, and complex operational nodes. As such, the supply chain faces numerous risks that cannot be ignored during the whole life cycle [21]. Unforeseen risk events can lead to labor shortages, material supply disruptions, order backlogs, and delivery delays, increasing the uncertainty of supply chain disruptions [9]. These risk factors in the implementation of supply chain management in prefabricated buildings are well summarized in previous research [22]. Zhang et al. pointed out that early or delayed delivery of prefabricated components is one of the main factors hindering the smooth operation of the supply chain management process, and that efficient production scheduling can reduce the risk of supply delays and transport delays [23]. The development and use of advanced information technologies such as BIM, RFID, and blockchain can coordinate the management of the various parties involved and improve the transparency, visibility, and security of the supply chain management process [24]. In summary, the supply chain of prefabricated buildings is exposed to risks such as disruption, component crushing, and transport delays. It is important to improve the resilience of the supply chain to guarantee the smooth execution of prefabricated buildings.

## 3. Prefabricated Building Supply Chain Resilience

Definitions of supply chain resilience based on the existing literature are not consistent. Ponomarov and Holcomb proposed that supply chain resilience refers to the ability to foresee risks, react to disruptions, and recover [25]. Supply chain resilience is the ability of an enterprise to maintain, adjust, and thrive in dynamic change [26]. Tukamuhabwa defined supply chain resilience as the ability to actively organize and construct a network of supply chains to prevent accidental disruptions [27]. Rajesh and Ravi described supply chain resilience as the ability to flexibly handle various variations in the supply chain [28]. Resilience is generally considered as the capacity of organizations to organize themselves in a variety of contexts, including interruptions in the form of disturbances and pressures, and to adapt to changing circumstances [29]. As the definition of supply chain resilience continues to evolve, scholars have viewed it from three dimensions: the ability to resist risk and preserve stability; the ability to restore itself from risky shocks; and the ability to adapt to changing environments. Considering the three aspects, the supply chain resilience of prefabricated buildings in this study is defined as the supply chain's ability to maintain stability during normal operations, recover quickly in response to risks, and adapt to changes in a dynamic environment [29,30].

Prefabricated assembly building products involve the supply and installation of a wide range of prefabricated components, requiring multiple levels of business units to coordinate and cooperate. Therefore, its supply chain network system is complex, risky, and uncertain in nature. This calls for supply chain resilience. Scholars have begun to focus on the influencing factors of supply chain resilience in prefabricated buildings. Zhu et al. screened 15 key influencing factors on the resilience of the supply chain of prefabricated buildings from six perspectives: supply chain level, design units, component manufacturers, logistics companies, contractors, and supervisory units [8]. Zhang et al. summarized five dimensions of prefabricated building supply chain resilience as influencing factors from the perspective of risk tolerance [10]. These factors include prefabricated component manufacturing, transportation and warehousing, assembly and construction, information, and partnership. In addition, Zhang et al. found that the manufacturing of components and the assembly construction have a remarkable impact on prefabricated building supply chain resilience, whereas the transportation and storage of components had a lesser impact, and the information and partner factors had a strong moderating effect on the above processes [10]. Lu et al. summarized 15 key impact factors of supply chain resilience for assembly building supply chain, and 6 highly concentrated factors were identified: risk management, inventory management, contingency planning, visibility, environmental risk, and information technology [31]. Wang et al. explored 18 crucial factors on the resilience of the assembly building supply chain in terms of external and internal environments [13].

These studies provide solid foundations for understanding the influencing factors of prefabricated building supply chain resilience.

## 4. BIM and Prefabricated Building Supply Chain

BIM is recognized as an important strategic and digital tool to improve production and management efficiency in the architectural, engineering, and building sectors. Widely promoted as an information integration platform, BIM can help visualize and simulate construction processes using three-dimensional geometric information models, thus facilitating communication between participants [32]. With proper implementation, BIM can efficiently address many issues, including numerous changes at various phases of construction, a lack of coordination among project parties, and schedule and cost management [14]. BIM is now widely employed across the different stages of the prefabricated building life cycle [33]. The implementation of BIM in prefabricated building design can enable collaborative design optimization, component deepening, schematic design, and pre-planning [30], assessing component usage schedules and scenarios in advance, and quickly responding to the risk of disruptions in the supply chain. BIM can help support the flow of materials or building products, automatically generate the bill of quantities, and dynamically enrich the bill of quantities with model attributes. BIM can also help realize information sharing and integration, throughout the whole building lifecycle [34], addressing the problem of process fragmentation. Additionally, BIM helps to resolve issues with disconnected information transfer during the design, production, and building processes, as well as a lack of cooperation across different specialties [35]. Project participants can better understand each other's expectations and anticipate actions with a high level of information sharing. This is the key to effectively avoiding disruptions in the prefabricated building supply chain, improving supply chain resilience, and achieving effective project outcomes.

BIM is increasingly integrated with other digital tools to produce benefits in the construction supply chain. For example, the combination of BIM and GIS can create a model of the visual building supply chain so that the actual materials at each point in the chain can be monitored and analyzed. Based on logistics situations, status of resource availability, and internal supply chain maps generated from the model, managers can send warning signals about materials when necessary. Managers can quickly determine root causes of delayed deliveries, achieving improved monitoring and management abilities in the construction supply chain [36]. To produce the best assembly sequences, the combined use of BIM and the Improved Genetic Algorithm (IGA) may graphically simulate and draw the prefabricated building models in a parametric manner. Additionally, it can minimize assembly sequence errors during construction by providing pre-construction training for professionals [37]. The combination of BIM with the Internet of Things (IoT) has resulted in the development of an intelligent BIM platform that enhances data collection and progress tracking while facilitating automated decision making. BIM paired with IoT with sensors can facilitate flexible sharing and transmission of information between various stakeholders, improving visibility and traceability of the entire process of prefabricated buildings. This help decision-makers develop awareness of unexpected situations and respond appropriately to the dynamic environment [38]. In summary, the use of BIM can realize prefabricated building design optimization, scheme design, and visualization of the entire building process; build a communication network among stakeholders to facilitate the openness, sharing, and integration of information; and provide timely risk warnings. Therefore, BIM plays an essential role in preserving supply chain stability for prefabricated buildings and lowering the disruption risk. It is a key tool to enhance the resilience of prefabricated building supply chains.

## 5. Research Design

To depict the links between BIM use and the supply chain resilience of prefabricated buildings, this study mainly relied on an integrative review analysis, followed by an empirical case study. This study was organized in the following steps: (1) sorting out and identifying the influencing factors on the supply chain resilience of prefabricated buildings; (2) screening evaluation indicators for BIM maturity; (3) identifying key elements of supply chain resilience that relate to BIM use; (4) establishing a conceptual framework of BIM and supply chain resilience in the context of prefabricated buildings; and (5) validating the framework through an empirical case.

Snyder (2019) divided the methods of the literature review into three types: systematic review, semi-systematic review, and integrative review [39]. This study mainly relies on an integrative review to unpack the relationship between BIM and supply chain resilience in prefabricated buildings. Integrative review is the process of evaluating, criticizing, and synthesizing the literature on a research topic to form new theoretical frameworks and perspectives [40]. This approach usually requires creative data collection, combining ideas and perspectives from different domains or research streams. Using this method, this study first identified an ensemble of influencing factors based on the previous literature on the supply chain resilience of prefabricated buildings. Secondly, it identified evaluation metrics for the degree of BIM technology adoption by synthesizing typical BIM maturity evaluation frameworks. Then, the influencing factors that are related to BIM implementation are analyzed in detail. We subsequently constructed a conceptual model to link BIM implementation to supply chain resilience. The research design process diagram is shown in Figure 1.

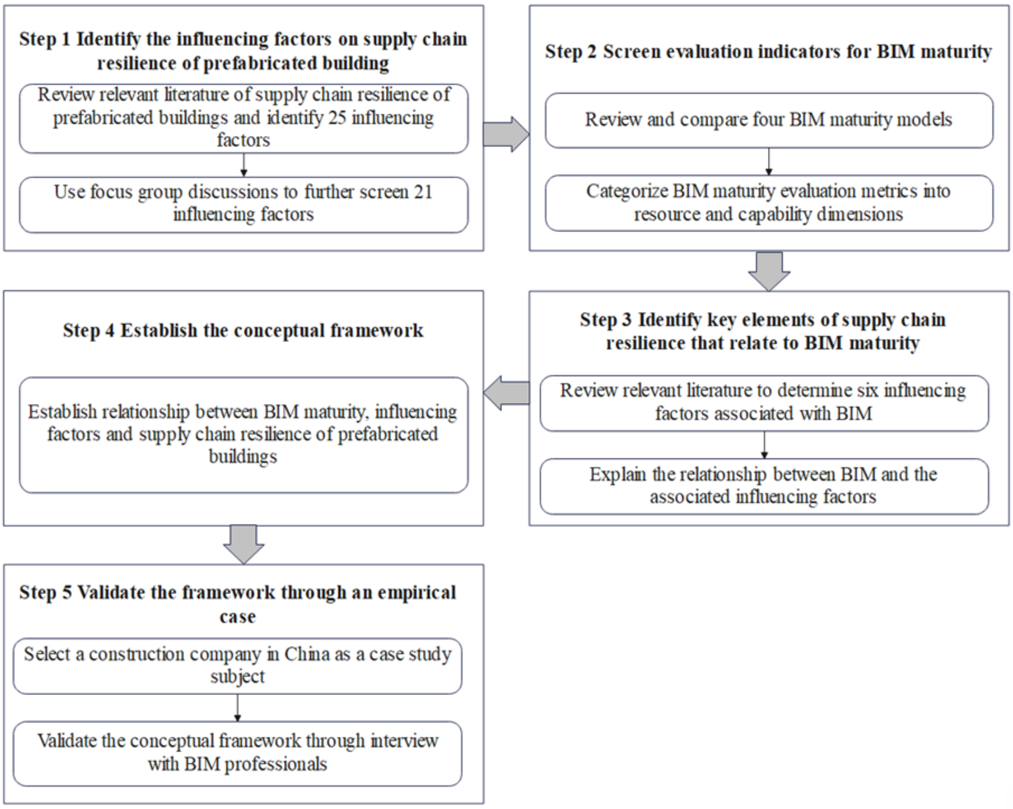


**Figure 1.** Research design process.

### *5.1. Influencing Factors on Supply Chain Resilience of Prefabricated Buildings*

The influencing factors on the supply chain resilience of prefabricated buildings were extracted mainly from the existing literature. The relevant literature was collected and screened using a top-down approach: a literature search was conducted using specific keywords, followed by a manual review to exclude the literature that did not fit within the scope (see Figure 2). The Web of Science database was selected as the data source, with "prefabricated building", "prefabricated construction", and "supply chain" as key terms search within titles, abstracts, and keywords. The first relevant article was published in

2012, so the time frame was defined as 2012 to 2023. Initially, 122 documents were retrieved. Subsequently, the relevant articles collected from the search results were screened. During this process, we mainly used a manual review method. Focusing on the dilemma challenges, risk response, and resilience enhancement of the prefabricated building supply chain, we analyzed the retrieved literature, excluded articles that were not within the scope of the target research area, and finally identified 13 valid papers (Figure 2).

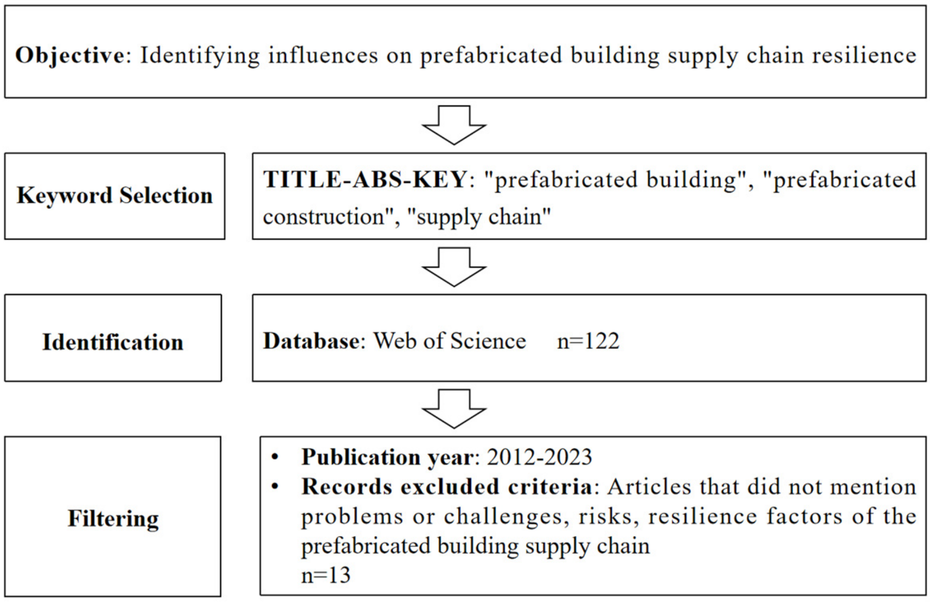


**Figure 2.** Steps to select records.

The influencing factors were extracted from the selected 13 references. We further summarized 25 influencing factors for the supply chain resilience of prefabricated buildings from four perspectives, namely external, partnership, participants, and supply chain (Table 1).

Subsequently, a focus group interview was used to further screen the key influencing factors of supply chain resilience in prefabricated buildings. We have invited six experts to score the 25 identified factors. The experts' work units covered the important nodes in the assembly building supply chain, and they had more than three years of experience in prefabricated buildings. Two of the experts were from universities, two of them from construction companies, one from a design firm, one from a component production company, and one from a government agency. Among the 25 factors identified, experts considered the overlap between the concepts of manufacturer management and component manufacturing capacity, as well as between response speed and risk awareness. The connotation of supply chain complexity was considered to overlap with the category of supply chain factors. In addition, funding status and market price change both represent changes in funding under market volatility. Experts suggested these two factors be combined into a new factor named market price changes and cash flow. Therefore, manufacturer management, capital position, supply chain complexity, and responsiveness were excluded. Focus group discussions then led to the identification of 21 key influencing factors (see Table 2).

**Table 1.** Factors influencing prefabricated building supply chain resilience.

| No. | Influencing Factors | Explanation | Literature |
|---|---|---|---|
| | | External Factors | |
| E1 | Environment | Natural weather such as typhoons, rainstorms, and floods will affect transportation and assembly. | [9] |
| E2 | Market Price Changes | Degree of price volatility in the materials market such as price increases, decreases, stabilizes, etc. | [41] |
| E3 | Policy Regulation | Progress in the implementation of relevant preferential policy documents and level of support. | [9] |
| | | Partnership Factors | |
| PS1 | Information Sharing | Including the level of enterprise information construction, the effect of information sharing in the supply chain, the degree of interactive platform construction, the accuracy and timeliness of information transmission, etc. | [42–45] |
| PS2 | Collaboration | Including the partnership with the owner (which should be consistent with the objectives of the owner's covenants) and the partnership with component manufacturers, stability, and longevity. | [42,43] |
| PS3 | Coordination | Timely detection of supply chain problems, rapid traceability of causes, and reassignment of responsibilities. | [46] |
| PS4 | Trust | Relationships of trust among supply chain parties. | [28] |
| | | Participants Factors | |
| P1 | Transport Capability | Including logistics company reliability, transportation costs, traffic accidents, alternative transportation routes, transportation accuracy, transportation visibility, transportation distance, etc. | [8,42,44,47] |
| P2 | Design Capability | Including the ability to control design changes, design correctness, completeness, and accuracy, etc. | [42–44] |
| P3 | Assembly Construction Capability | Including prefabricated building construction organization design, technical program development, process arrangement, etc. | [48] |
| P4 | Supervisory Capacity | Factory or construction site monitoring of supervision methods and execution. | [43] |
| P5 | Professionals and Labor Training | Including on-site personnel's experience in prefabricated building construction, costing, safety, etc., and construction safety education for employees, innovative concept development, and practical skills enhancement. | [49] |
| P6 | Subcontractor Management Capability | Including the general contractor's management of subcontractors, specialized subcontractors' management ability, and technical level. | [43] |
| P7 | Component Manufacturing Capacity | Including the degree of production integration, quality of components, technical capabilities, and manufacturing costs of manufacturers, and manufacturing quantities. | [45] |
| P8 | Manufacturer Management | Including supplier management maturity, supply plan, factory standardization, professionalism, and normative degree. | [50] |
| | | Supply Chain Factors | |
| SC1 | Risk Awareness | Including preset resilience in the decision-making phase, setting up contingency plans, disaster recovery plans, etc. | [42] |
| SC2 | Degree of Redundancy of Components | Including product inventory levels, contingency storage levels, production overcapacity capacity, and the capacity to replace parts of defective quality promptly. | [42,43] |
| SC3 | Supply Chain Structure | Including supply chain complexity and number of firms at supply chain nodes. | [46] |
| SC4 | Flexibility in the Supply of Raw Materials | Speed of response, on-time completion to schedule, quantity of components, and machinery held in reserve. | [43] |
| SC5 | Product Variety | Diversity of product range. | [43] |
| SC6 | Number of Manufacturers | Including the number of suppliers available in the supply chain and flexible supply base. | [44] |
| SC7 | Stock Capacity | Spare means of production in stockpiles. | [28] |
| SC8 | Funding Status | Including proportion of funds used, timing of funds deployment, and ability to finance. | [46] |
| SC9 | Response Speed | The speed at which risk control measures are carried out when a risk event occurs. | [42] |
| SC10 | Supply Chain Complexity | Including supply chain costs, product quality, scheduling efficiency, and delivery efficiency. | [51] |

### 5.2. BIM Maturity

BIM maturity reflects the extent of its application. BIM maturity is often used to measure the degree of development and level of competence of project teams, organizations, or the industry in applying BIM technologies and methodologies [16]. A number of BIM maturity models and evaluation systems have been proposed by scholars or institutions. For instance, Succar established the BIM Maturity Matrix (BIMMM) in 2009 as a tool to assess the extent to which BIM is being used in organizations (designers and contractors) and extended the scope of measurement to include the non-technical aspects of BIM use [52]. The BIMMM looks at three dimensions of process, technology, and policy and measures an organization's technology and resources as well as the ability to share information and collaborate across different organizations. The CIC Research Program's Owner Matrix, published by the 2013 Building Information Modeling Facility Owner Planning Guide V2.0, assesses project owners in terms of goals, uses, processes, information, facilities, and individuals. This model measures a wide range of topics, from macro goals and strategic planning levels to micro levels of human resources and training and is considered one of the most comprehensive assessment models for evaluating an organization's BIM maturity [53]. Owner's BIMCAT, a project owner's BIM competency framework developed by Giel and Isaa in 2016, contains three measurement dimensions: operational, strategic, and administrative, covering almost the full lifecycle view [54]. Developed by TNO, the Netherlands Organization for Applied Scientific Research, the BIM Quick Scan tool is divided into four chapters: organization and management, mindset and culture, information structures and information flows, and tools and applications [55].

**Table 2.** Refined factors influencing supply chain resilience in prefabricated buildings.

| No. | Influencing Factors |
|---|---|
| External Factors | |
| E1 | Environment |
| E2 | Market Price Changes and Cash Flow |
| E3 | Policy Regulation |
| Partnership Factors | |
| PS1 | Information Sharing |
| PS2 | Collaboration |
| PS3 | Coordination |
| PS4 | Trust |
| Participants Factors | |
| P1 | Transport Capability |
| P2 | Design Capability |
| P3 | Assembly Construction Capability |
| P4 | Supervisory Capacity |
| P5 | Professionals and Labor Training |
| P6 | Subcontractor Management Capability |
| P7 | Component Manufacturing Capacity |
| Supply Chain Factors | |
| SC1 | Risk Awareness |
| SC2 | Degree of Redundancy of Components |
| SC3 | Supply Chain Structure |
| SC4 | Flexibility in the Supply of Raw Materials |
| SC5 | Product Variety |
| SC6 | Number of Manufacturers |
| SC7 | Stock Capacity |

Comparing the above BIM maturity models, the key difference is the setup of their respective measurement metrics. The indicators from these models can be broadly categorized into six themes: staff, facilities, technology, information data, strategy, process, and technology. In terms of assessment, BIMMM, CIC Research Program's Owner Matrix, and Owner's BIMCAT all use a qualitative rating method with sequential ratings, while BIM QuickScan uses a quantitative assessment method, usually with the rating scale ranging from five to ten. In addition, all four maturity models assess the level of BIM adoption from an organizational perspective. The CIC Research Program's Owner Matrix and Owner's BIMCAT are aimed at owners. The BIMMM and BIM Quick Scan assess the level of BIM maturity from the perspective of designers and contractors.

Moreover, these models often do not differentiate resources and capabilities. According to the resource-based view (RBV), the diversity, scarcity, irreplaceability, and inimitability of resources are critical to organizations' competitive advantages. These resource characteristics drive organizations to develop and accumulate specific capabilities to make better use of resources [56]. In this sense, capabilities are considered as the application of available resources to achieve certain outcomes, and its qualitative assessment can enable organizations to utilize the resources efficiently [57]. Separating resources and capabilities will help organizations be prepared for BIM use step by step. Therefore, based on the RBV and capability research, we divided BIM maturity indicators from the aspects of resource and capability.

The above four BIM maturity models are screened as references, namely BIMMM [52], CIC Research Program's Owner Matrix [53], Owner's BIMCAT [54], and BIM Quick Scan [55]. Initial indicators of BIM maturity were identified according to the number of times the metrics appeared in previous models. Meanwhile, we also considered the BIM practice to retain certain indicators. For instance, the indicator of selecting competent project participants was rarely mentioned in previous models, but it was retained in this study because it helps to ensure the transmission of information among all project parties. Finally, BIM maturity indicators consist of personnel, facilities, and data at the resource level and strategic, process, and technical capabilities at the capability level, as Table 3 illustrates.

**Table 3.** BIM maturity evaluation indicators.

| Metrics | | | Definition | CIC | BIMCAT | BIMMM | BIM Quick Scan |
|---|---|---|---|---|---|---|---|
| Resources | Personnel | Training | Training of staff on BIM competencies | √ | | | √ |
| | | Employee Talent | Employee BIM experience level | | √ | √ | √ |
| | | Culture | Level of employee acceptance of BIM applications | | √ | | √ |
| | | Roles and Responsibilities | Division of labor and responsibilities of personnel | √ | | √ | |
| | Facilities | Software | Equipped with software related to BIM application | √ | | √ | √ |
| | | Hardware | Equipped with hardware for BIM applications | √ | | √ | √ |
| | | Physical Space | Physical conditions of the enterprise for BIM applications | √ | | √ | √ |
| | Data | Data Richness | The extent of available data | √ | √ | | √ |
| | | Data Accuracy | How much information reflects the actual situation | √ | | | |
| | | Data Timeliness | Up-to-date BIM information | √ | | | |
| | | Data Availability | Stability and ease of access to data | | | | √ |
| Capabilities | Strategic Capability | Goal Planning Capability | BIM vision and work goal planning | √ | √ | | √ |
| | | Standards Development Capability | Development of BIM standards and specifications | | √ | | |
| | | Management Support | Level of management support for BIM | √ | √ | | √ |
| | Process Capability | Execution Capability | Execution of BIM objectives | | | √ | |
| | | The Ability to Se-lect Capable Project Participants | Selection of purchasers, contractors, etc. with the ability to use BIM | | | √ | |
| | | Supervision Mechanism | Supervision of the degree of BIM use and standardization | | √ | √ | |
| | Technical Capability | Research and Development Capability | BIM-related software development | | √ | | |
| | | Software Use Ability | Ability to operate software during the whole process | √ | √ | | √ |
| | | Integration and Expansion Capability | Integration and expansion of software functions | | √ | | |

Note: "√" means that the indicator is mentioned in previous BIM maturity models.

### 5.2.1. Resource Level

Personnel:

(1) Training: to improve the technical level of existing BIM technicians and relevant personnel, the organization should carry out trainings, including inviting professionals to give lectures, e-learning, internal staff training;
(2) Employee talent: this mainly refers to the BIM experience of employees and whether employees can skillfully apply the technology of BIM at their work;
(3) Culture: this mainly refers to the organization's BIM culture and employees' recognition of BIM application. The organization's innovation culture and environmental rendering for BIM can promote development of BIM;
(4) Roles and responsibilities: this mainly refers to division of roles and the responsibilities of personnel related with BIM. Such as whether the organization has a reasonable division of roles for BIM managers and technicians, whether there is goal planning and behavioral norms for BIM positions, whether the BIM personnel can reasonably adapt to the positions.

Facilities:

(1) Software: this mainly refers to software resources involved in BIM application, and the criteria includes the completeness of the functions, operability of the selected software, degree of localization of foreign software, and popularity of the software among BIM personnel;

(2) Hardware: hardware resources include electronic equipment and other related hardware facilities to satisfy the requirement to run BIM-related software;
(3) Physical space: This reflects the physical conditions in which the organization operates the BIM application by technical personnel.

Data:

(1) Data richness: construction projects continuously generate all kinds of data in the whole life cycle, such as contract data, design data, and on-site construction information;
(2) Data accuracy: it is the degree of authenticity of the data and the extent to which it reflects the actual situation. It ensures that the decisions based on the data are consistent with reality;
(3) Data timeliness: this mainly refers to the timely update of BIM data and information. BIM information changes at any time with the advancement of the project, and organizations should interact with the upstream and downstream units to ensure that the information they receive is current;
(4) Data availability: this refers to the accessibility of data related to the project. Organizations should ensure that the data have a stable source is stable and easy to obtain when necessary.

### 5.2.2. Competency Level

Strategic Capability:

(1) Goal planning capability: it represents the BIM vision and target planning of the organization in adopting and implementing BIM;
(2) Standard development capability: this refers to whether organizations develop BIM standards and specifications to standardize the use of BIM. This ability is also evaluated by the level of detail and operability of the standards;
(3) Management support: it represents the degree of management support for BIM, which is in terms of capital investment and organizational policy planning.

Process Capability:

(1) Execution capability: it is manifested in the implementation of the above target planning and standard development by the organization;
(2) The ability to select capable project participants: it refers to the organization's ability to choose upstream and downstream partners such as purchasers, subcontractors, etc., who are capable to deliver BIM projects;
(3) Supervision mechanism: this refers to the organization's ability to supervise whether the staff completes the corresponding BIM tasks, such as designating BIM personnel in charge of supervision, implementing monthly scoring and evaluation of staff, and setting up relevant reward and punishment systems.

Technical Capability:

(1) Research and development capability: it refers to the organization's ability to innovatively develop and expand the functions of BIM-related software. This includes whether it has technical personnel for BIM software development, whether it can achieve software localization, and whether it can develop BIM-related plug-ins;
(2) Software use ability: this refers to the ability of the organization to use various kinds of BIM software for projects. The ability to use BIM tools includes the following ten applications: (1) survey analysis and feasibility study; (2) visual model design; (3) simulation and conflict detection; (4) bidding management; (5) construction progress management; (6) construction quality management; (7) project investment and cost management; (8) risk identification and problem pre-control; (9) collaborative operations management; (10) completion acceptance and post-evaluation;

(3) Integration and expansion capability: This refers to the ability of the organization to integrate and expand the software functions and promote the application of BIM in information processing, cost control, and others fields. It is manifested in that how. BIM is integrated with GIS, the Internet of Things, cloud computing, and other technologies.

### *5.3. Relationship between BIM and Factors Influencing Supply Chain Resilience in Prefabricated Buildings*

This research reflects the level of BIM application through BIM (capability) maturity. The relationship between BIM use and influencing factors on prefabricated building supply chain resilience was investigated by analyzing the identified literature (Table 4).

**Table 4.** Relationship between BIM and factors influencing supply chain resilience.

| No. | Influencing Factors | BIM Maturity | References |
|---|---|---|---|
| | External Factors | | |
| E1 | Environment | ○ | Nil |
| E2 | Market Price Changes and Cash Flow | ○ | Nil |
| E3 | Policy Regulation | ○ | Nil |
| | Partnership Factors | | |
| PS1 | Information Sharing | √ | [18] |
| PS2 | Collaboration | √ | [15,58] |
| PS3 | Coordination | √ | [59] |
| PS4 | Trust | √ | [18] |
| | Participants Factors | | |
| P1 | Transport Capability | ○ | Nil |
| P2 | Design Capability | √ | [29,60] |
| P3 | Assembly Construction Capability | √ | [61,62] |
| P4 | Supervisory Capacity | ○ | Nil |
| P5 | Professionals and Labor Training | ○ | Nil |
| P6 | Subcontractor Management Capability | ○ | Nil |
| P7 | Component Manufacturing Capacity | ○ | Nil |
| | Supply Chain Factors | | |
| SC1 | Risk Awareness | ○ | Nil |
| SC2 | Degree of Redundancy of Components | ○ | Nil |
| SC3 | Supply Chain Structure | ○ | Nil |
| SC4 | Flexibility in the Supply of Raw Materials | ○ | Nil |
| SC5 | Product Variety | ○ | Nil |
| SC6 | Number of Manufacturers | ○ | Nil |
| SC7 | Stock Capacity | ○ | Nil |

Note: If BIM use is related to the influencing factors, marked with a "√": If BIM use is irrelevant with the influencing factors, marked with a "○".

The integrative review is aimed at exploring how BIM implementation facilitates prefabricated building supply chain resilience. According to Table 4, among the 21 factors on the resilience of the prefabricated building supply chain, BIM use has an impact on six of them, including the design capability, assembly capability, and construction capability at the level of participating entities and cooperation, information sharing, coordination, and trust at the level of partnership.

## 6. Conceptual Framework

Based on the integrated review, this study establishes a preliminary conceptual framework to illustrate the role of BIM technology implementation in influencing prefabricated building supply chain resilience. BIM implementation can impact the supply chain resilience of prefabricated buildings by influencing participant factors (design capabilities, assembly capabilities, and construction capabilities) and partnership factors (collaboration, information sharing, coordination, and trust), as shown in the conceptual framework in Figure 3.

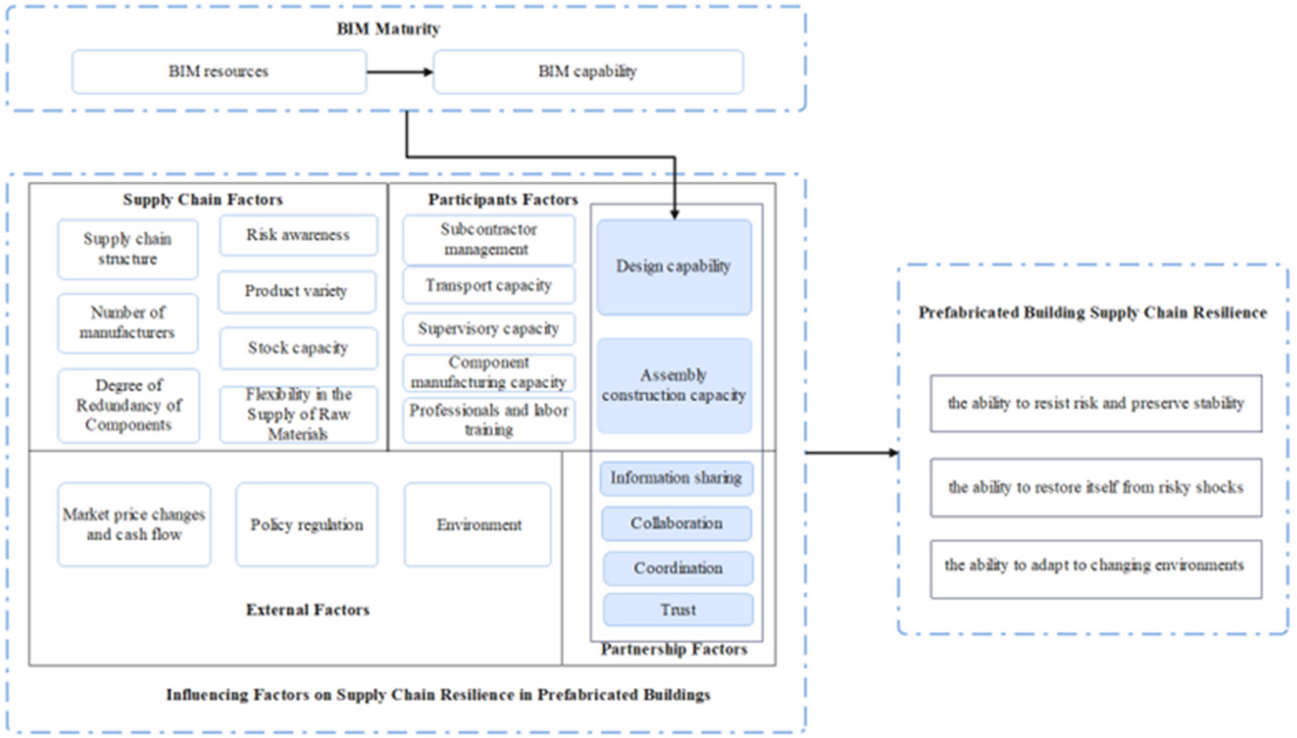


**Figure 3.** The conceptual framework for BIM and prefabricated building supply chain resilience. Note: The blue color highlights the influencing factors that are related to BIM use.

BIM maturity is divided into two key dimensions: BIM capability and BIM resources. BIM resources are the foundation of BIM capability [57,63]. BIM resources have a direct impact on BIM capability, and resource-rich organizations are more likely to achieve effective application of BIM technology. The link between resources and capabilities further supports the role of BIM in supply chain resilience. The role of BIM is manifested by direct and indirect mechanisms. BIM resources can play indispensable roles by influencing BIM-related capabilities and further fostering supply chain resilience. In addition, BIM effectively enhances prefabricated building supply chain resilience by influencing design capability, assembly and construction capability, collaboration, information sharing, coordination, and trust. Their relationships are illustrated as follows.

BIM and design capability: Prefabricated buildings require highly accurate components and modules to ensure that they fit seamlessly when assembled on-site. Using BIM, designers can achieve a higher level of visualization and improve the quality of the design [64]. BIM technology has the capability of collision checking, which intelligently detects clashes present in the design model and helps to reduce design errors [65]. In addition, BIM technology can assist in design change management through its parametric modeling solutions [66]. This helps to improve supply chain efficiency as well as resilience.

BIM and assembly construction capability: Construction simulation using BIM technology can determine a reasonable construction plan to guide the construction, thus reducing the risk of construction errors and guaranteeing the quality and efficiency of the assembly [62]. BIM provides workers with more intuitive information about the installation of components, which helps to improve the workers' operation skills and work efficiency [67]. Meanwhile, the 3D modeling function of BIM helps to better plan the construction site and optimize the use of materials and human resources. Such optimization improves the smoothness of site operations and reduces conflicts between materials and personnel, thus improving overall site management [68]. This is essential to keep the supply chain functioning properly.

BIM and collaboration. BIM applications provide an efficient and trustworthy communication channel between the participants of a prefabricated building project, which has a facilitating effect on the collaborative relationship between the project participants [18,69]. By sharing models and data, participants can work more closely together in planning and decision making [70]. BIM should be deployed beyond the design and construction phases of a project, and effective collaboration in BIM can lead to more efficient buildings and better management. As a result, BIM presents some important changes in the traditional build and delivery process [71]. This technology can integrate the needs of stakeholders in a project, work together to solve problems, and ultimately promote greater efficiency and cooperation between participants [72].

BIM and information sharing: The application of BIM in prefabricated building supply chain information management has changed the phenomenon of "information islands" caused by backward information sharing, scattered information storage, and serious information loss. BIM provides a collaborative platform for storing, transmitting, and sharing information and runs through the whole process of the building supply chain [73]. Each participant provides data that can be compatible based on a unified interaction platform, making the information flow smoother [67]. BIM provides highly transparent information, allowing real-time access, reducing information asymmetry, and enhancing the visualization of supply chain status [74]. BIM facilitates the exchange and sharing of information among various participants, which plays an important role in speeding up the decision-making process for managers [75].

BIM and coordination: BIM can improve coordination in the organization of prefabricated building projects [76]. The relative fragmentation of the various segments and processes in the prefabricated building supply chain hinders the effective integration of materials, components, and on-site services [77]. BIM communication is seen as central to enhance operational planning through visualization and virtual modeling [78]. This motivates participating entities to utilize BIM to coordinate with each other to ensure the proper functioning of the supply chain.

BIM and trust: BIM-based management is beneficial for building trusting relationships among project participants, thus enhancing the integration efficiency of the project [79]. BIM enables project participants to interact with resources on the same digital platform. All parties can access and understand comprehensive information about the project on the same platform, which helps to build consensus among the participants, reduces disputes that may arise from information asymmetry, and maintains the trust relationship among the participants in the supply chain [18]. When organizations in a supply chain trust each other, they can help each other in times of need, increasing the resilience of the supply chain.

To sum up, the conceptual framework provides an integrated view to link BIM use and supply chain resilience, establishing the relationship between the impact of BIM technology on prefabricated building supply chain resilience.

## 7. An Empirical Case

Finally, this study used an empirical case to validate the conceptual framework linking BIM and prefabricated building supply chain resilience. A general building construction contractor in China, hereinafter named Company A, is selected as the object of study. Company A is a qualified enterprise with a complete assembly of the whole industry chain, often engaged in the supply chain network as an Engineering Procurement Construction (EPC) general contractor. It is committed to becoming a first-class green building integrated service provider. As a market leader in terms of size and competitive strength, the organization has applied BIM technology to build an integrated intelligent construction information system and constructed a "design-production-construction-maintenance" value chain based on an integrated operation platform. Over the years, it has relied on BIM to assist in the construction of several of its prefabricated building projects.

The case information was mainly collected based on existing documents about the organization and internet-based information. In addition, we conducted an in-depth interview with a key informant from the organization, who not only has experience in managing and operating BIM projects but also acts as a consultant responsible for developing BIM target work plans, BIM standards and specifications, etc. The interviewee has more than 3 years of working experience in BIM use and is able to provide sufficient information about the application of BIM in the assembly building supply chain of the case organization. The interview questions were designed based on the conceptual framework for BIM and prefabricated building supply chain resilience. We mainly asked the key informant how BIM affected prefabricated building supply chain management. Sample questions include: (1) How does BIM affect design capability and assembly construction capability? (2) Does BIM promote collaboration, information sharing, coordination, and trust among participants in the prefabricated building supply chain?

According to the collected information about the case organization, it can be seen that BIM plays an important role in improving design and assembly capabilities and facilitating collaboration, information sharing, coordination, and trust. As mentioned by the interviewee, "We often use the parametric function of the BIM software to create standardized "family" libraries of various prefabricated components. As the number, types, and specifications of components increase, we gradually build up a standardized prefabricated component library, which improves design efficiency and quality". In the construction stage, "using BIM to simulate the real construction environment and construction process, we can predict in advance whether the construction arrangement of the project is balanced, whether the site layout is reasonable, and whether the lifting process is correct". BIM can also be used to optimize the spatial operation and installation sequence of prefabricated components during lifting.

For the role of BIM in collaboration, the interviewee supported that "the design team and the supply chain can share the BIM model to ensure that all parties involved have a consistent understanding of the project", "the designer delivers the drawings to the component manufacturers, who can use the BIM platform to disassemble the components, achieving a closer collaboration and docking with vendors" and "construction sites may communicate directly with the design team through BIM to provide feedback on the actual construction situation in order to make timely adjustments to the design and solve construction problems".

The case also supported the role of BIM in information sharing: "when changes are made by the design team, these changes can be updated directly into the BIM model for all relevant teams to view, which ensures that we get synchronized and accurate information" and "marking up the BIM model and sharing special requirements and suggestions for the manufacturing process in the BIM model enables a smoother flow of information between design and manufacturing". Regarding the role of BIM in coordination, the case suggested that the team can correlate the construction plan with the BIM model and use BIM to simulate the assembly process. In this sense, the simulation of BIM is beneficial for coordinating problems that might arise.

In terms of the link between BIM and trust, the interviewee mentioned that "the sharing of the BIM model between the design team and the manufacturer helps the manufacturer to be able to produce high-quality modules in accordance with the design specifications, which enhances trust". The case indicates that BIM provides a repository of information that enables the various parties involved to share, update, and maintain information. This sharing process helps to build trust because they know that the project information is accurate and up-to-date.

## 8. Conclusions

The study aims to investigate the impact of BIM on the supply chain resilience of prefabricated buildings and construct a comprehensive conceptual framework to link BIM and supply chain resilience. It defines prefabricated building supply chain resilience and synthesizes previous critical studies on the factors influencing prefabricated building supply chain resilience. It further emphasizes the key role of BIM in facilitating supply chain management. The integrated review summarizes 25 important factors influencing the supply chain resilience of prefabricated buildings at the external, partnership, participant, and supply chain levels. Then, 21 key factors affecting resilience were further identified. Secondly, this study selects the evaluation indicators of BIM maturity and categorizes them into two dimensions: BIM resources and capabilities. Finally, it is proposed that BIM technology, reflected through resources and capabilities, enhances the supply chain resilience of prefabricated buildings by influencing the design capability, assembly capability, and construction capability at the participant level and the cooperation, information sharing, coordination, and trust at the partnership level.

This study provides important theoretical contributions in understanding how digital tools enhance resilience. It unpacks the underlying mechanisms between BIM application and supply chain resilience in the context of prefabricated buildings. A conceptual framework linking BIM and supply chain resilience is established. Few studies have examined the role of BIM from the standpoint of supply chain management in prefabricated buildings, even though BIM is widely utilized in the architectural, engineering, construction, and operation sectors. The conceptual framework proposed emphasizes that BIM as a technology and management tool improves supply chain resilience and identifies six key mediators, including design capability, assembly and construction capability, cooperation, information sharing, coordination, and trust. The framework hence suggests more precise directions for future research.

This study provides guidance to practitioners and project managers engaged in prefabricated buildings by highlighting the roles of BIM resources and capabilities. They can optimize their supply chain management strategies by focusing on key aspects of design, assembly construction, collaboration, information sharing, coordination, and trust through BIM use. This can help them better adapt to supply chain uncertainty, reduce risk, and improve management efficiency. It is also important for them to distinguish between BIM resources and capabilities. Resources are the foundation of BIM capabilities, and they can play indirect but indispensable roles in influencing supply chain resilience. The conceptual framework can inspire managers to provide resources such as training, software, and hardware for BIM use, as well as data and information to strengthen the competence of their staff in the utilization of BIM tools and techniques. Managers in construction organizations can optimize BIM capabilities by developing BIM work objectives, implementing standard BIM processes, mastering and innovating BIM technologies, building effective implementation teams, setting up effective monitoring mechanisms, and selecting partners with BIM experience and capabilities.

There are still a few limitations. First, this study only examined the impact of BIM on supply chain resilience. Future research could extend to other related digital technologies and examine their possible effects on supply chain resilience. For example, the role of radio frequency identification (RFID) technology for tracking components in the prefabricated building supply chain can be further explored. Second, this study mainly conducts an integrated review. Future research could rely on a broader review to identify more elements that may impact supply chain resilience. The conceptual framework in this study can be further validated with more empirical cases. Specifically, longitudinal case studies are promising avenues for further validation. Last but not least, the digitalization of the construction industry is considered to offers a more sustainable approach in addressing climate change. Future research could link more emerging digitalization methods and digital tools, providing additional insights into the relationships among digitalization, resilience, and sustainable development.

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