

Article

Simulation Analysis of Supply Chain Resilience of Prefabricated Building Projects Based on System Dynamics

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Abstract: In light of the intricate dynamics and uncertain risk parameters inherent in the supply chains of prefabricated building projects, bolstering the resilience of these supply chains can substantially mitigate disruption risks and facilitate superior operational outcomes for involved enterprises. This study identifies key metrics emblematic of supply chain resilience within prefabricated building projects, spanning five critical resilience dimensions: predictive prowess, absorptive potential, adaptability, inherent resilience, and growth capability. Employing the Analytic Hierarchy Process (AHP) and system dynamics (SD), we formulate a resilience simulation model specific to these supply chains. Utilizing the Nanchang Yinwang Village Comprehensive Housing Community Project as a case study, we forecast the trajectory of supply chain resilience over a five-year span and simulate the resilience variations in response to diverse variable magnitudes. Our findings reveal a consistent upward resilience trend over the five-year period. Moreover, the resilience stature of the prefabricated building project supply chain exhibits variability under distinct variable shifts. Of all the subsystems, the most reactive secondary factors encompass risk cognizance, logistics support level, collaboration intensity, supply chain reconfiguration aptitude, and managerial strategic decision-making prowess. Notably, amplifying the absorptive potential of resilience yields the most profound enhancement in overall resilience.

Keywords: prefabricated building; supply chain resilience; AHP; system dynamics; simulation



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1. Introduction

Prefabricated buildings represent a novel paradigm in environmentally responsible construction. They not only mitigate construction waste and emissions but also transform traditional manufacturing processes in the construction sector, streamlining intermediate steps, optimizing resource utilization, and enhancing both production efficiency and building quality [1]. These benefits, such as component standardization, functional diversification, and green construction, align with China's vision for a sustainable and health-focused construction industry. Indeed, China's "14th Five-Year Plan for Construction Industry Development", endorsed by the Ministry of Housing and Urban–Rural Development, emphasizes the importance of these buildings, advocating for their enhanced benefits, and fostering a synergistic policy and industrial framework [2]. The life cycle of a prefabricated building encompasses pre-design, factory production, logistics, on-site assembly, and post-operational maintenance. Each stage is interdependent, and disruptions at any point jeopardize the project's timeline, budget, and safety. Viewed as a functional network, the supply chain encapsulates the project's entire life cycle, consolidating each phase into an integrated system.

However, recent global challenges, particularly the COVID-19 pandemic, have strained this supply chain. Lockdown measures have impeded international production, logistics, and labor services, inducing significant economic stagnation [3]. Coupled with international economic volatility and escalating talent and technological costs, the resilience of the prefabricated building supply chain against uncertainties has been compromised [4].

Despite these adversities, the concept of supply chain resilience has gained traction in academic research. The supply chain for prefabricated buildings confronts multifaceted challenges, including technological advancements, organizational dynamics, cost management, and external factors like natural disasters and governmental regulations [5]. In the face of unforeseen emergencies, the supply chain for prefabricated building projects may experience disruptions or even complete breaks. Such disruptions can impede the seamless progression of these projects and potentially diminish the overall competitiveness of pivotal enterprises within the supply chain [6]. Though resilience does not negate the risks, it facilitates prompt risk responses and restores the supply chain to its pre-disturbance state. Analyzing this resilience can bolster the supply chain's risk response and fortify collaborative risk management across entities.

To fortify the resilience of individual participants in prefabricated building projects and ensure the enduring stability of the entire supply chain, we synergistically employ the Analytic Hierarchy Process (AHP) and the system dynamics (SD) model to probe into the supply chain resilience inherent to these projects. Initially, we identify a gamut of determinants influencing the robustness of the prefabricated building supply chain. Utilizing the AHP, we compute the relative significance of these determinants. Subsequently, an SD simulation model encapsulating this robustness is devised. To elucidate its dynamic behavior, we integrate an empirical case study from a prefabricated building project in Nanchang City, shedding light on its inherent resilience trajectory.

2. Literature Review

2.1. Prefabricated Building

Prefabricated building systems originated in Europe and North America during the 17th century, but gained significant traction after World War II. This surge in popularity can be attributed to the extensive war damages, post-war labor shortages, and a scarcity of production means. Western European nations, driven by the pressing need to address housing shortages, undertook comprehensive research into assembly-based construction, igniting an industrialization wave in the sector. By the 1960s, the environmentally friendly and sustainable attributes of prefabricated construction aligned well with the sustainable development goals of developed nations, leading to its widespread adoption. With the dawn of the 21st century and the enactment of supportive policies, China witnessed a rapid growth in the prefabricated building sector. By 2019, China accounted for 42.75% of the global prefabricated building market share [7].

The growing emphasis on prefabricated construction has spurred scholarly interest. Kamali, for instance, devised a sustainable performance evaluation model comparing the sustainability of prefabricated and traditional buildings from economic, environmental, and social perspectives. This study found economic sustainability as the predominant concern for construction firms [8]. Similarly, Gan introduced an automated BIM-based tool that leverages a BIM object library to extract material information and fetch carbon emission factors and cost coefficients, thereby facilitating sustainability analysis of prefabricated construction projects [9]. Lee proposed a digital twin framework employing IoT and BIM for real-time logistics simulation, which identifies potential logistics risks and ensures timely delivery of prefabricated components, enhancing construction efficiency [10].

The promotion of prefabricated buildings aligns seamlessly with China's vision for green, healthy, and sustainable development. It plays a pivotal role in revolutionizing the construction industry. However, while construction techniques and costs related to prefabricated buildings are well-researched, studies delving into their supply chain and its resilience are scant.

2.2. Supply Chain Resilience

Supply chain resilience is an emergent research domain that underscores the intricate adaptability of organizations within supply networks to maintain equilibrium, particularly when faced with disruptions [11]. Current international investigations spotlight three

primary facets: integration with supply chain risk management, resilience quantification, and enhancement strategies.

In the realm of integration with supply chain risk management: Koronis et al. methodically reviewed and structured supply chain resilience literature, advocating for an adaptive, swift response to unforeseen supply chain threats, with an emphasis on restoring pre-disruption structures and functions [12]. Holcomb and colleagues postulate that while the idea of supply chain resilience remains nebulous within risk management, its incorporation can adeptly counterbalance post-disruption revenue and cost disparities, ultimately reverting the network to its optimal state [13]. Aldrighetti et al. introduced a pioneering mathematical model—a risk-averse mixed-integer nonlinear problem—for sculpting a bi-level resilient supply chain network. Their computational experiments underscored recovery actions as paramount in counteracting short-lived risk disruptions [14]. Kong Fanhui and team delved into supply chain resilience operations under supply disruption risks in the Original Entrusted Manufacture (OEM) framework. Their multivariate model and resilience interaction mechanisms revealed that advanced deep learning algorithms can significantly bolster supply chain resilience, thereby curtailing corporate losses [15].

Regarding the quantification of supply chain resilience: Xu and collaborators scrutinized the interplay and significance of resilience indicators, amalgamating fuzzy decision tests, decision lab analyses, and network analytics (fuzzy-DEMATEL-ANP), enriched by literature reviews and expert insights [16]. Moosavi and Hosseini pioneered a simulation-based quantitative method for assessing supply chain resilience across diverse disruption scenarios [17]. Chen and associates contrived a disruptive environment-based resilience measurement model, centered on supply chain cost constituents, facilitating an exploration of the nexus between unit capital investments and their efficacy in diminishing order deficits [18]. Pavlov and team, building on qualitative resilience evaluations, conceived a hybrid fuzzy–probabilistic approach to amalgamate customer expectations, thereby formulating a dual (quantitative and qualitative) supply chain resilience assessment model [19]. Qian Cunhua’s study established a resilience metric system tailored to prefabricated building supply chains, integrating interval intuition fuzzy quantitative indexes and the AHP for weight determination, further enriched by the pinch angle vector cosine and barrier degree methods for resilience level discernment [20]. Yu Jinyan’s research, harnessing global pandemic and cross-border e-commerce logistics data, explored logistical timeliness’s spatial–temporal heterogeneity, melding quantitative analysis of influential factors with an examination of spatial resilience patterns and temporal trajectories [21].

In the realm of supply chain resilience augmentation: Rice and Caniato underscored the efficacy of amalgamating supply chain flexibility with redundancy to bolster resilience [22]. Brandon et al. gathered data from 264 UK-based manufacturing facilities, establishing a correlation between supply chain connectivity, information-sharing resources, and enhanced supply chain visibility, consequently amplifying resilience and robustness [23]. Drawing from various supply chain management viewpoints, Colicchia employed empirical research to holistically dissect the determinants of supply chain resilience. The findings reaffirmed the pivotal roles of leadership’s organizational prowess, efficient information dissemination, customer relations, inter-enterprise collaboration, and the overarching capability to boost supply chain resilience [24]. Shang Jing and Chen Ming, through an information technology lens, examined its influence on supply chain resilience, proposing targeted strategies to elevate resilience levels [25]. Wang Yuqi and colleagues, while scrutinizing the imported crude oil supply chain network amidst environmental perturbations, harnessed a system dynamics methodology to simulate disruptions, aiming to fortify the network’s resilience [26]. Li Weian, integrating a dynamic capacity perspective and corporate risk mitigation strategies, employed Necessary Condition Analysis (NCA) and Qualitative Comparative Analysis (QCA). This synthesis, encompassing six antecedent conditions spanning dynamic capability and organizational initiative, illuminated the synergistic impact model, positing it as an optimal pathway for businesses to attain peak supply chain resilience [27].

Upon reviewing global research findings on supply chain resilience, several observations emerge. Firstly, current scholarly endeavors predominantly target the manufacturing sector, while industries like construction, particularly prefabricated building projects, remain underexplored. Secondly, the majority of investigations are qualitative, often rooted in theory with a dearth of tangible case studies, rendering their practical applicability questionable. Lastly, many studies adopt a static vantage point on supply chain resilience, overlooking its dynamic nature influenced by evolving internal and external conditions.

2.3. Supply Chain Resilience of Prefabricated Building Project

Distinct from traditional construction and manufacturing supply chains, the operational process within the prefabricated building supply chain garners distinctiveness from its specialized production mode, eliciting scholarly attention. Ji executed a qualitative analysis on the factors influencing the resilience of the prefabricated building supply chain, segregated by various stages. Initiating from supply chain nodes, he proffered influences such as the design adaptability of components, managerial proficiency of component factories, reliability of logistics firms in transportation, and the expertise of on-site construction personnel [28]. Kabirifar, employing the TOPSIS method, prioritized factors affecting supply chain resilience in large-scale residential construction projects in Iran, within the integrated model of Engineering, Procurement, and Construction (EPC) [29]. Zhu Lei investigated the factors influencing the resilience of the prefabricated building supply chain from both the perspective of node enterprises and the overall supply chain, establishing the ISM model to discern the interrelationships amongst the influencing factors [30]. Li Yao, grounding his work in risk management and life cycle theories, scrutinized both internal and external risk factors of prefabricated residential supply chain operations, and posited that ineffective inter-enterprise communication catalyzed supply chain instability [31]. Chen Chao attributed the suboptimal risk resistance of the prefabricated building supply chain to inefficiencies in production, transportation, prefabrication, and related organizational decision making, with prefabricated components as the core [32].

Amidst the robust promotion of prefabricated building development in China, scholarly exploration into the supply chain of prefabricated building projects has incrementally drawn attention. Nonetheless, studies focusing on the resilience of the supply chain in prefabricated building projects remain scant, predominantly approaching from a risk management perspective, lacking consensus on the resilient supply chain and its influential factors. A majority of extant studies engage in single-dimensional and qualitative methodologies, devoid of a diversified viewpoint and multi-dimensional comprehensive induction.

3. Materials and Methods

This section initially delineates the establishment of a supply chain resilience evaluation framework tailored for prefabricated building projects, subsequently elucidating the application of the Analytic Hierarchy Process (AHP) and system dynamics (SD) models within this research context.

3.1. Supply Chain Resilience Evaluation System for Prefabricated Building Project

Resilience in the context of the supply chain for prefabricated building projects pertains to its intrinsic ability to mitigate risk and disruption. This ability, reflecting a specific dimension of risk disturbance resistance within the supply chain, is compartmentalized into five discernible subsystems: forecasting capacity, absorption capacity, adaptive capacity, recovery capacity, and growth capacity. Following a comprehensive review and synthesis of a multitude of both domestic and international literature, this study identifies representative factors from these subsystems, which resonate with the unique attributes of prefabricated building projects and their supply chain management characteristics, to formulate a resilience evaluation index system, as depicted in Table 1.

Table 1. Evaluation index of supply chain resilience of prefabricated building project.

First Grade Indexes	Second Index	Reference
Forecast capacity	Supply chain structure (FC ₁)	[3,33,34]
	Supply chain complexity (FC ₂)	[35,36]
	Risk awareness (FC ₃)	[3]
Uptake capacity	Prefabricated construction level (UC ₁)	[3,33]
	Logistics support level (UC ₂)	[3,33,37]
	Supplier management (UC ₃)	[34,36]
	Components production flexibility (UC ₄)	[34,36,37]
Adapt capacity	Information management capability (AC ₁)	[11,37,38]
	The degree of collaboration (AC ₂)	[11,26]
	Inventory redundancy (AC ₃)	[35,36,38]
	Risk management level (AC ₄)	[38–40]
Recovery capacity	Funds scheduling capacity (RC ₁)	[20,37]
	Emergency response capability (RC ₂)	[20,38]
	Resource reengineering capability (RC ₃)	[37,38]
	Supply chain reconfiguration capability (RC ₄)	[37,39]
Growth capacity	Organizational learning ability (GC ₁)	[36,38]
	Assembly technology innovation investment (GC ₂)	[3,37,39]
	Management strategic decision-making ability (GC ₃)	[16,38,40]

3.2. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) epitomizes a robust analytical and evaluative methodology, offering noteworthy applicative benefits within the realm of scientific analyses and system evaluations. It meticulously constructs a hierarchical measurement index system, aligning with the decision-making objectives inherent to complex systems, and ascertains weight values through an appraisal of the relative significance of indicators across disparate hierarchical levels. The methodology encompasses several critical steps:

(1) Judgment matrix construction and weight value calculation

Experts are convened to form a decision-making assembly, tasked with constructing a judgment matrix (A) utilizing the 1–9 scale method (refer to Table 2) [41].

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}$$

Here: a_{ij} denotes the importance of X_i to X_j to a , and $a_{ij} \times a_{ji} = 1$.

Table 2. Scale and meaning of hierarchical analysis.

Scale	Explanation
1	The two factors are equally important when compared
3	Comparing the two factors, the former is slightly more important than the latter
5	Comparing the two factors, the former is significantly more important than the latter
7	Comparing the two factors, the former is very important than the latter
9	Comparing the two factors, the former is extremely more important than the latter
2, 4, 6, 8	The median value of the above neighboring judgments

(2) Weight vector calculation

The judgment matrix facilitates the determination of the pertinence of subsequent level indices relative to preceding ones. Through sequential computation of the weights of various level indicators, the weight of the lowest level index within the overarching objective is ultimately derived. Weight calculation methodologies encompass the sum

product method, root mean square method, and the eigenvalue method, among others, with the square root method employed in the current study. The procedural steps are delineated as follows:

First, the geometric mean of each row element of the judgment matrix $A = (a_{ij})_{n \times n}$ is

$$\bar{a}_i = \left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}}, i = 1, 2, \dots, n \quad (1)$$

Then \bar{a}_i is normalized to a weight vector.

$$\omega'_i = \frac{\left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}}}{\sum_{k=1}^n \left(\prod_{j=1}^n a_{kj} \right)^{\frac{1}{n}}} \quad (2)$$

The weight obtained by the AHP is: $W' = (\omega'_1, \omega'_2, \dots, \omega'_n)$.

(3) Consistency test

To evaluate the logical coherence of the judgment matrix, the consistency index (CI) is employed to assess matrix consistency, while the consistency ratio (CR) is utilized to determine whether the matrix adheres to consistency standards. A CR value below 0.1 indicates satisfactory matrix consistency; otherwise, matrix reconstruction is necessitated to ensure consistency. The consistency ratio (CR) is computed by employing the average random consistency index (RI) (values are provided in Table 3) [42]. The pertinent computational formula is detailed as follows:

$$CI = \frac{\mu_{\max} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

Table 3. Average random consistency index.

Order	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.38	1.41	1.46

3.3. System Dynamics Model

System dynamics (SD), initially introduced by Professor J.W. Forrester from the Massachusetts Institute of Technology, USA, represents a methodological approach to the systematic analysis of socio-economic issues, amalgamating both qualitative and quantitative analytical methods [43]. This model, known for its aptitude in developing high-order, nonlinear, time-dynamic, and multi-feedback mechanism models, has found applicability across various fields for simulation and predictive research [44]. The application of system dynamics typically encompasses three modeling phases: problem articulation and conceptualization, formulation of a dynamic hypothesis equation model, and model testing and analysis, as depicted in Figure 1. These phases facilitate a comprehensive understanding for decision makers regarding the procedural adherence required for model construction, articulation and conceptualization, formulation of a dynamic hypothesis equation model, and model testing and analysis.

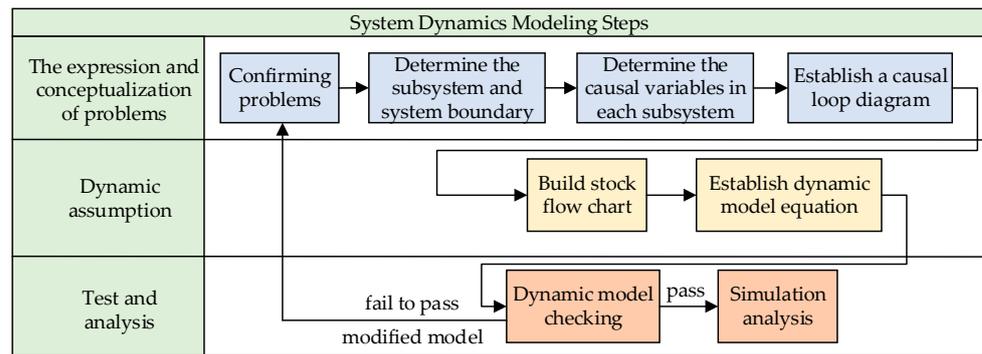


Figure 1. System dynamics modeling process.

In the present study, an Analytical Hierarchy Process (AHP) structure model is developed to evaluate the resilience of the supply chain within prefabricated building projects. Subsequent to determining the weight of each index within the system, the Vensim PLE (7.3.5) software, a system dynamics simulation platform, is utilized to construct and analyze a simulation model of the supply chain resilience specific to prefabricated building projects.

(1) Causal loop diagram

A Causal Loop Diagram (CLD) delineates the causal interconnections among system elements, serving as a pivotal tool in system dynamics to elucidate the origins of dynamism within a system. Variables and inter-variables in a CLD are interconnected through causal chains, with arrows symbolizing positive and negative causal relationships. Multiple causal chains coalesce to form a closed circuit, termed a feedback loop, which is classified as either positive or negative. A loop is identified as a negative feedback loop when it encompasses an odd number of negative causal chains; conversely, it is designated a positive feedback loop when an even number of negative causal chains are present. The causality diagram is instrumental in the preliminary phase of system dynamics modeling, laying a theoretical groundwork for subsequent modeling endeavors.

(2) System stock-flow diagram

To elucidate the logical interplay among the system components, we constructed a stock-flow diagram grounded on the causal loop representation. This approach enhances the visualization of feedback mechanisms and the regulatory principles governing the interactions between system constituents. The stock-flow diagram serves to distinctly categorize the attributes of each system variable. Primarily, the diagram encompasses state variables, rate variables, auxiliary variables, and constants.

(1) State variables

Often referred to as ‘flow’, the state variable captures the cumulative dynamics within the system. It epitomizes the stability and flux of materials and resources therein. Within the stock-flow schematic, state variables are conventionally denoted by rectangular boxes. The current state variable can be mathematically expressed as the sum of its preceding value and the net difference between the inflows and outflows:

$$Q_t = Q_{t-\Delta t} + \Delta t \times (V_1 - V_2) \quad (5)$$

Among them, Q_t is the state variable at time t , $Q_{t-\Delta t}$ is the state variable lagging one period, Δt is the time interval, and V_1 and V_2 are the inflow and outflow rates, respectively.

(2) Rate variable

Rate variables quantify the velocity of alterations in the system’s cumulative dynamics. Within the system framework, the rate variable significantly influences the evolution of the

state variable. By imposing constraints on the rate equation, one can delineate the modality and magnitude of such control. The mathematical expression of the velocity variable is:

$$Q_t = Q_{t-\Delta t} + \Delta t \times R_{t-\Delta t} \quad (6)$$

Here, $R_{t-\Delta t}$ denotes the velocity variable at time $t - \Delta t$.

(3) Auxiliary variables and constants

The auxiliary variable acts as an intermediary between the information source and the decision-making process, facilitating the articulation of feedback in information-driven decisions. In contrast, constants remain invariant over time, maintaining consistent values irrespective of temporal shifts.

4. Case Analysis and Results

4.1. Project Overview

The Yinwang Village Comprehensive Housing Community Project (hereafter referred to as the YWC Project), situated in Luojia Town, Qingshan Lake District, Nanchang City, epitomizes a pivotal venture in the realm of resettlement housing communities, employing prefabricated building methodologies within the urban confines of Nanchang City. Encompassing a substantial investment approximating CNY 1.2 billion, the YWC Project spans an extensive land area of approximately 184 acres, translating into a total construction expanse of about 400,000 square meters. The project heralds the establishment of twenty new structures, comprising seventeen high-rise residential and podium buildings, augmented by a three-tier kindergarten, a two-tier vegetable market, and a four-tier supporting commercial building.

4.2. Data Processing

(1) Determination of evaluation index weight

This investigation solicited the expertise of eight senior personnel, integrally involved in the project, to constitute an expert decision-making consortium. Employing the 1–9 scale methodology, an evaluative framework was crafted, wherein interacting factors and the significance of the factor groups were systematically scored, thereby facilitating the formation of a judicious matrix and substantiating the subsequent computations. Consequently, the weight of the supply chain resilience evaluation index for the YWC Project was ascertained, with the resultant data encapsulated in Table 4.

Table 4. Weight value of supply chain resilience evaluation index of YWC project.

First Grade Indexes	Weight	Second Index	Weight
Forecast capacity	0.1207	Supply chain structure (FC ₁)	0.1834
		Supply chain complexity (FC ₂)	0.1652
		Risk awareness (FC ₃)	0.6514
Uptake capacity	0.3525	Assembly construction level (UC ₁)	0.1365
		Logistics support level (UC ₂)	0.3378
		Supplier management (UC ₃)	0.2994
		Components production flexibility (UC ₄)	0.2263
Adapt capacity	0.2153	Information management capability (AC ₁)	0.1911
		The degree of collaboration (AC ₂)	0.2671
		Inventory redundancy (AC ₃)	0.1072
		Risk management level (AC ₄)	0.4346
Recovery capacity	0.0968	Funds scheduling capacity (RC ₁)	0.1073
		Emergency response capacity (RC ₂)	0.3412
		Resource reengineering capacity (RC ₃)	0.1791
		Supply chain reconfiguration capacity (RC ₄)	0.3724

Table 4. Cont.

First Grade Indexes	Weight	Second Index	Weight
Growth capacity	0.2148	Organizational learning capacity (GC ₁)	0.2535
		Assembly technology innovation investment (GC ₂)	0.2193
		Management strategic decision-making capacity (GC ₃)	0.5272

(2) Constructing a cause and effect diagram

The intricacies of assembly construction project supply chain resilience arise from a constellation of variables. To dissect the interconnected roles these variables play in the overarching resilience of the supply chain, we undertook a rigorous analysis of their causal interplay. As a culmination of this investigation, we present a causal diagram that delineates the dynamic interactions underpinning the resilience of assembly construction project supply chains. This diagram serves as a visual conduit, encapsulating the feedback mechanisms intrinsic to the system (refer to Figure 2 for details).

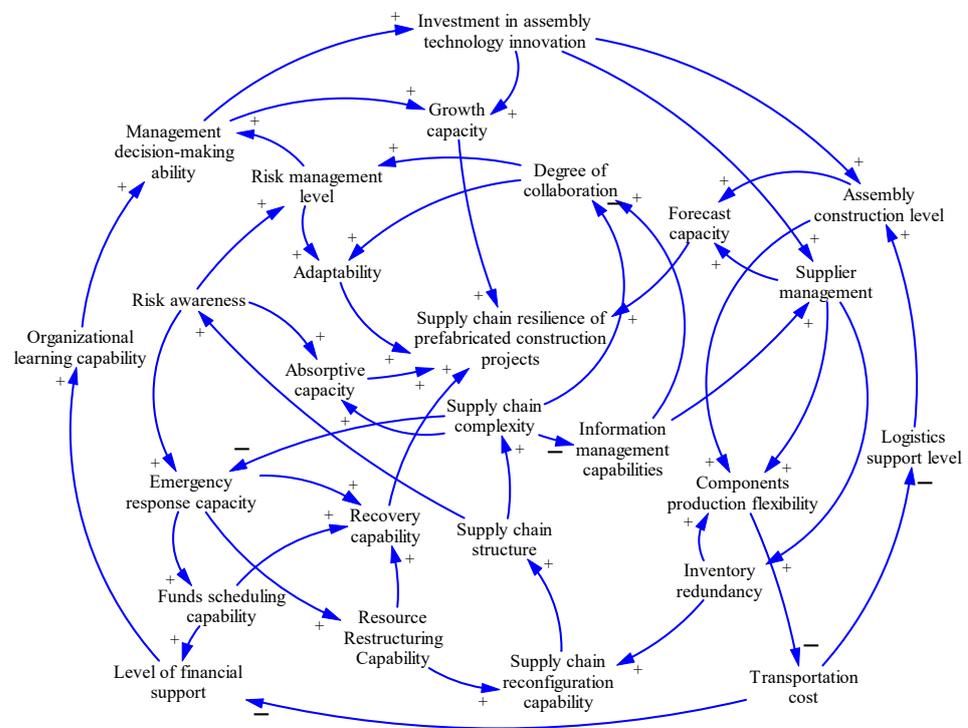


Figure 2. Causal loop diagram of supply chain resilience subsystem of prefabricated building project.

(3) Constructing stock flow diagrams

The resilience framework for prefabricated building supply chains is stratified into five distinct subsystems: predictive capacity, absorptive strength, adaptive prowess, recuperative capability, and growth potential. We embarked on an in-depth exploration of the interrelations among the indices within these subsystems. Emerging from this exploration is a comprehensive stock flow diagram, which captures the essence of the resilience system for prefabricated building supply chains (Figure 3 provides a visual representation). Within this diagram, we discern five state variables, five rate variables, twelve constants, and six auxiliary variables.

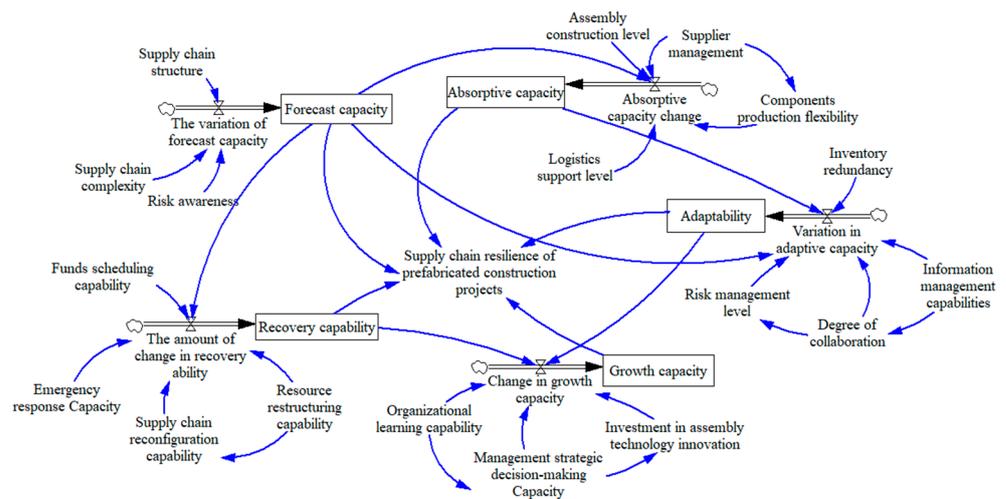


Figure 3. Stock flow diagram of supply chain resilience system of prefabricated building project.

(4) Determination of simulation model formula

Informed by the weightage assigned to each index through the Analytic Hierarchy Process (AHP), as tabulated in Table 4, we have discerned the pivotal functional interrelations that are foundational to the system dynamics (SD) stock flow diagram. Consequently, we have formulated the corresponding SD equations that encapsulate the resilience of the project’s supply chain, which are systematically laid out in Table 5.

Table 5. Project supply chain resilience system dynamics equation.

	SD Equation
The influence level of forecast ability Forecast capacity variation R_{FC}	$INTEG(\text{forecast capacity change}, 0)$ $0.1834 \times FC_1 + 0.1652 \times FC_2 + 0.6514 \times FC_3$
The influence level of uptake ability Uptake capacity variation R_{UC}	$INTEG(\text{uptake capacity change}, 0)$ $1.0875 \times \text{forecast capacity influence level} + 0.1365 \times UC_1 + 0.3378 \times UC_2 + 0.2994 \times UC_3 + 0.2263 \times 1.0375 \times UC_4$
The influence level of adapt capacity Adapt capacity variation R_{AC}	$INTEG(\text{adapt capacity change}, 0)$ $1.1875 \times \text{forecast capacity influence level} + 1.475 \times \text{uptake capacity influence level} + 0.1911 \times AC_1 + 0.2671 \times 1.4375 \times AC_2 + 0.1072 \times AC_3 + 0.4346 \times 1.4063 \times AC_4$
The influence level of recovery capacity Recovery capacity variation R_{RC}	$INTEG(\text{recovery capacity change}, 0)$ $1.3688 \times \text{adaptive capacity influence level} + 0.1073 \times RC_1 + 0.3412 \times RC_2 + 0.1791 \times RC_3 + 0.3724 \times 1.2813 \times RC_4$
The influence level of growth capacity Growth capacity variation R_{GC}	$INTEG(\text{growth capacity change}, 0)$ $1.2 \times \text{adaptability influence level} + 1.1963 \times \text{recovery capacity influence level} + 0.2535 \times GC_1 + 0.2193 \times 1.4313 \times GC_2 + 0.5272 \times 1.0125 \times GC_3$ $0.1207 \times \text{forecast capacity influence level} + 0.3525 \times \text{uptake capacity influence level} + 0.2153 \times \text{adaptability capacity influence level} + 0.0968 \times \text{recovery capacity influence level} + 0.2148 \times \text{growth capacity influence}$
Supply chain resilience of prefabricated building project	

Note: The influence coefficients between subsystems and the indirect influence coefficients of variables are determined by the expert scoring method and weighted average method.

4.3. Model Imitation and Analysis

(1) Supply chain resilience prediction analysis of YWC project

The YWC project employs a system dynamics model to simulate supply chain resilience over a designated 60-month period, initiated at $(t = 0)$ with a simulation step size

of one month. Employing the constructed system dynamics model, a trend prediction is undertaken, with the resultant prognostications delineated in Figure 4.

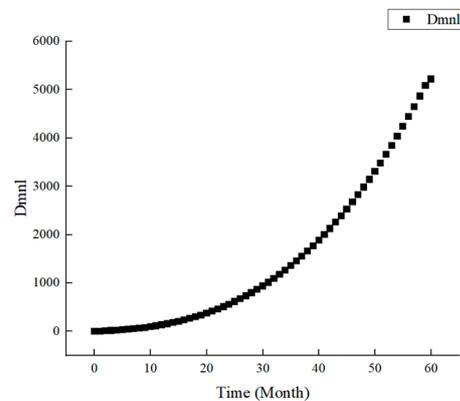


Figure 4. The development trend of supply chain resilience of YWC project.

A discernible, steady exponential enhancement in the project's supply chain resilience is observed throughout the 5-year simulation span. Given that system variables are initialized to zero, the system's initial resilience metric is equivalently zero. Particularly, during the initial phase up to month 10, the resilience remains subdued due to the nascent system's fragile foundation and a deficiency in experienced optimization of technology, management, and emergency response within the project supply chain system. However, resilience progressively augments with perpetual advancements in assembly technology, capital influx from chain participants, and a bolstering of risk perception and mitigation capabilities across nodal enterprises, enhancing prediction, absorption, adaptation, recovery, and growth capabilities of the supply chain resilience. Post the 20-month mark, the YWC project's supply chain resilience commences a notable, precipitous enhancement.

(2) Comparative analysis of subsystem change schemes

Various factors modulate the resilience of the prefabricated building project's supply chain. This investigation employs a controlled variable approach, altering prediction, absorption, adaptability, recovery, and growth capabilities by 30%, respectively, to simulate project supply chain resilience trends under subsystem parameter modifications. Trends under these conditions are depicted in Figure 5.

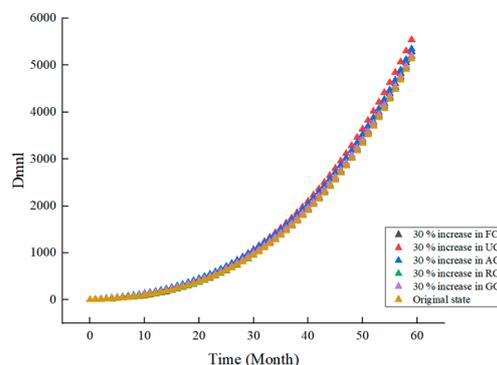


Figure 5. Simulation of project supply chain resilience subsystem change.

In the figure, "Current" denotes the initial resilience level. It becomes evident that amplifying the functionality of any subsystem bolsters the project's supply chain resilience. Furthermore, juxtaposing the resilience trajectory of the project's supply chain (Figure 5) with simulation outcomes (Table 6), it is discerned that adjusting the activity degree of individual systems via control variables (in sequence: predictive, absorptive, adaptive, recovery, and growth systems), and contrasting against the initial state resilience level of

the project's supply chain, yields resilience elevations post the 60-month simulation of 5.03%, 10.15%, 6.26%, 2.32%, and 3.55%, respectively. Remarkably, a 30% augmentation in the absorptive capacity influence level emerges as the most potent in enhancing the project's supply chain resilience, underscoring the absorptive capacity subsystem as pivotal within the project's supply chain resilience framework.

Table 6. Project supply chain resilience subsystem change simulation results.

Time (Month)	Original State	FC Increased by 30%	UC Increased by 30%	AC Increased by 30%	RC Increased by 30%	GC Increased by 30%
0	0	0	0	0	0	0
10	68.04	71.86	100.2	112.57	74.23	97.84
20	314.00	330.49	397.69	406.26	334.08	373.61
30	834.45	877.27	990.39	977.63	876.14	923.86
40	1727.52	1815.26	1977.8	1924.82	1798.53	1846.74
50	3092.93	3249.13	3460.98	3347.53	3200.96	3241.95
60	5031.96	5285.25	5542.59	5347.06	5184.73	5210.79

(3) Comparative analysis of secondary sub-factor change schemes

To evaluate the influence of individual sub-factors on the resilience of the project supply chain, we subjected each sub-factor within the five subsystems to an incremental adjustment of 0.5 (representing a single-factor alteration). The outcomes of these modifications are graphically represented in Figure 6. The data suggest a direct proportionality between the secondary sub-variables of any given subsystem and the supply chain resilience of the project. Specifically, as the value of a singular sub-factor increases, there is a corresponding enhancement in the supply chain's resilience. Upon close examination of the five subsystems, several sub-factors emerged as particularly influential on the resilience of the YWC project's supply chain. These include risk awareness (FC₃), logistics support level (UC₂), risk management level (AC₄), supply chain reconstruction capability (RC₄), and managerial strategic decision-making prowess (GC₃). Notably, this observation aligns with the hierarchical weightings determined via the Analytical Hierarchy Process (AHP).

In order to more intuitively reflect the effect of single factor changes on the supply chain resilience of YWC project, the simulation results of single factor changes of supply chain resilience of YWC project shown in Table 7 are summarized.

Within the FC subsystem, alterations in the sub-factors, namely, supply chain structure (FC₁), supply chain complexity (FC₂), and risk awareness (FC₃), yield final resilience scores of 5481.32, 5305.6, and 5915.82, respectively. Of these, the modification in risk awareness (FC₃) exerts the most pronounced positive impact on the project's supply chain resilience, boasting an augmentation of 13.32% relative to the baseline. In the context of the UC subsystem, incremental enhancements in the assembly construction level (UC₁), logistics support level (UC₂), supplier management (UC₃), and component production flexibility (UC₄) result in resilience scores of 5292.24, 6153.88, 5760.83, and 5546.93, respectively. The increments correspond to 3.12%, 19.91%, 12.25%, and 8.08%. It becomes evident that optimizing the logistics support level (UC₂) is paramount to bolstering the supply chain's resilience. Within the AC subsystem, the resilience metrics, under the influence of its four sub-variables, ascend to 5550.12, 6169.53, 5279.71, and 6547.9. Here, the degree of collaboration (AC₂) coupled with the risk management level (AC₄) emerges as pivotal in elevating resilience. Pertaining to the RC subsystem, a 0.5 increase in its single variable yields resilience values of 5297.48, 5742.69, 5551.14, and 5824.37. The most influential among these is unmistakably the supply chain reconfiguration capability (RC₄).

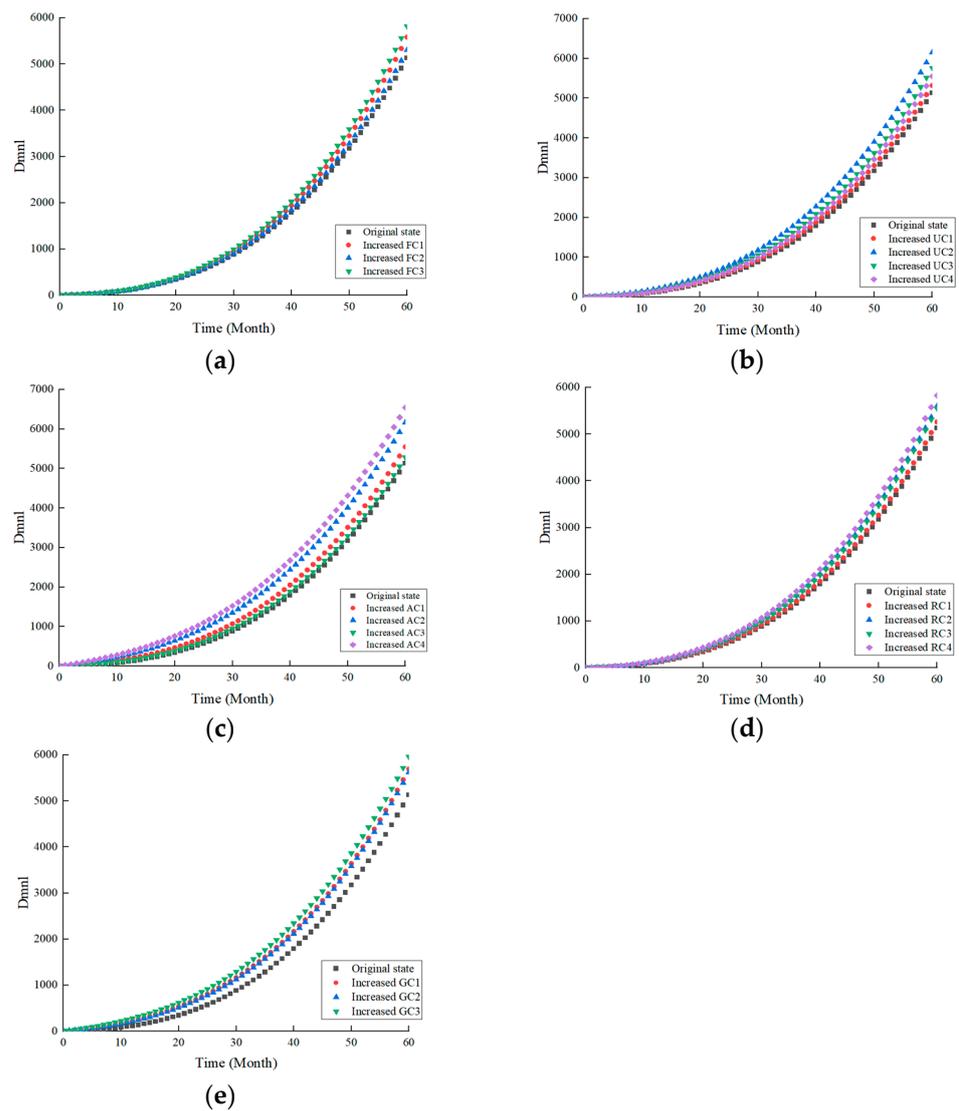


Figure 6. Simulation of single factor change of project supply chain resilience. (a) FC subsystem. (b) UC subsystem. (c) AC subsystem. (d) RC subsystem. (e) GC subsystem.

Table 7. Project supply chain resilience single factor change simulation results.

Subsystem	Factor Changes	Final Toughness Level	Subsystem	Factor Changes	Final Toughness Level
Forecast capacity	FC ₁ + 0.5	5481.32	Growth capacity	GC ₁ + 0.5	5693.52
	FC ₂ + 0.5	5305.6		GC ₂ + 0.5	5624.23
	FC ₃ + 0.5	5915.82		GC ₃ + 0.5	5956.82
Uptake capacity	UC ₁ + 0.5	5292.24		GC ₄ + 0.5	5297.48
	UC ₂ + 0.5	6153.88	Recovery capacity	RC ₁ + 0.5	5742.69
	UC ₃ + 0.5	5760.83		RC ₂ + 0.5	5551.14
	UC ₄ + 0.5	5546.93		RC ₃ + 0.5	5824.37
Adapt capacity	AC ₁ + 0.5	5550.12			
	AC ₂ + 0.5	6169.53			
	AC ₃ + 0.5	5279.71			
	AC ₄ + 0.5	6547.91			

5. Discussions and Suggestions

5.1. Discussions

The supply chain of prefabricated buildings is characterized by intricate integration, involving numerous diverse participants. With its connections extending both upstream and downstream and intertwining with other sectors, there is an inherent complexity and a heightened degree of uncertainty. Such intricacies enhance the associated risks, amplifying the potential for supply chain disruptions. In response to these challenges, our research integrates the concept of resilience into prefabricated building projects. We present a resilience simulation model that seeks to understand the dynamics of resilience within the supply chain of these projects.

The resilience of the supply chain in prefabricated building projects encompasses the capacity of the chain to withstand disturbances, retain its stability amid risks, and autonomously recover. This research incorporates five resilience dimensions: predictive capability, absorption capacity, adaptability, robustness, and growth potential. Specifically, predictive capability emphasizes the supply chain's need for accurate forecasting of potential changes and challenges, facilitating proactive preparations. Absorption capacity and adaptability ensure that the supply chain can effectively mitigate shocks during risks, adapt to evolving circumstances, and sustain its operations. Robustness and growth potential underscore the supply chain's ability to promptly recover post disturbances, reinstate stability, and capitalize on favorable scenarios to innovate and progress.

Incorporating system dynamics methodologies, we delineate the interrelations among these indicators. By deriving causal and stock-flow diagrams, we have established a dynamic simulation model that scrutinizes the resilience of the supply chain. Notably, our study addresses a gap in the existing literature, which often overlooks the variable nature of supply chain resilience in response to internal and external environmental shifts.

5.2. Suggestions

The resilience construction of supply chains is an important force to promote the further development of prefabricated building projects. To this end, this paper puts forward the following suggestions:

(1) Augment risk prevention and management awareness.

Enterprises should elevate their consciousness of supply chain vulnerabilities and enhance risk management proficiencies. Implementing robust incentive systems can galvanize employee participation in daily supply chain operations, fostering a collective risk prevention and sharing ethos. Additionally, instituting a dynamic risk early-warning system can facilitate timely responses to potential threats, thereby preserving the supply chain's resilience.

(2) Cultivate internal and external collaborative mechanisms.

Forging robust intra- and inter-enterprise collaborations can solidify supply chain resilience. Firms should prioritize personnel development, foster inter-departmental dialogues, and bolster overall competitiveness. Concurrently, routine professional dialogues can foster mutual assistance and enduring partnerships among enterprises.

(3) Enhance logistics competencies.

Given that prefabricated components predominantly rely on road transportation, refining logistics is pivotal. For instance, designing specialized vehicles for transporting bulky and weighty prefabricated components can bolster the stability and efficiency of logistics operations.

6. Conclusions

In this study, we present a novel simulation model for assessing the resilience of supply chains in prefabricated building projects. This model uniquely integrates the Analytic Hierarchy Process (AHP) with system dynamics (SD). Using the Nanchang YWC

prefabricated building project as a case study, we forecast the evolution of its supply chain resilience over a five-year horizon. Subsequent iterative adjustments of the model's subsystems and secondary sub-factors provide insights into the resilience trajectory of the project's supply chain. Empirical validation underscores the robustness and applicability of our proposed model. Key findings from our analysis include:

- (1) The supply chain within prefabricated building projects exudes complexity, entailing a myriad of participants and a tightly-knit connectivity amongst them. Consequently, the entirety of the system can be accurately characterized as an integrated, nonlinear, multi-feedback dynamic system. The deployment of System Dynamics (SD) for crafting a system dynamics model affords not only a more precise reflection of the intricate causal interrelations among factors but also a quantitative depiction of the system's lateral evolution under the influence of assorted variables.
- (2) Insights derived from simulation forecasting illuminate a notable fragility in the overall risk resilience, principally attributed to an experiential deficit in refining technology, management, and emergency response within the supply chain system of prefabricated building projects during initial phases. However, a subsequent elevation is observable in the level of assembly technology, capital allocation among chain participants, risk awareness of node enterprises, and collective risk mitigation capacities, propelling the overarching anti-risk caliber of the prefabricated assembly construction project supply chain along an exponential growth trajectory.
- (3) Perturbations in disparate subsystems give rise to divergent risk-resilience levels within the prefabricated assembly construction project supply chain. Notably, the absorptive capacity subsystem emerges as a pivotal entity, exerting a prominently amplifying effect on the risk-resilience caliber of the prefabricated building engineering supply chain, thereby situating itself as a linchpin within the entire risk-resilience framework of the prefabricated building engineering supply chain.
- (4) An examination into the modulation of single-factor variables reveals that the most sensitive secondary sub-factors within each subsystem encompass risk awareness, logistics support level, collaboration degree, supply chain reconfiguration aptitude, and management strategy decision-making capability. These elements, therefore, crystallize as paramount factors in enhancing the resilience level of the supply chain within prefabricated building projects.

Theoretically, this study advances and refines the existing body of knowledge on supply chain resilience within the realm of prefabricated building projects. By amalgamating insights from both literature reviews and empirical fieldwork, we delineate a comprehensive evaluation index system for appraising the resilience of supply chains in prefabricated building undertakings. This not only widens the applicability of pertinent theories and methodologies but also offers pivotal theoretical scaffolding for stakeholders in prefabricated building enterprises, enabling them to harness the insights gleaned from our findings both structurally and cognitively. On a practical plane, our results demystify avenues to augment supply chain resilience for prefabricated building entities. Enhancing such resilience fortifies the supply chain's capacity to adeptly navigate unforeseen challenges, thereby diminishing the susceptibility to potential disruptions.

A caveat associated with this study is the inherent subjectivity in deploying hierarchical analysis for ascertaining the weightings of the resilience evaluation indicators specific to prefabricated building projects. To address this, future investigations may contemplate the adoption of objective weight assignment strategies, or potentially, an amalgamation of both subjective and objective paradigms. Moreover, our current exploration is circumscribed to modulating a singular subsystem or variable to discern resilience trends. It would be instructive for subsequent research to simultaneously modulate multiple subsystems and variables, thereby shedding light on the resilience trajectory of supply chains in prefabricated building projects under multifaceted alterations.

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