Digital Collaboration and Supply Chain Resilience in Prefabricated Construction: A System Dynamics Case Study

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Abstract. Prefabricated construction changes not the need for construction work, but the place and timing of much of that work. A considerable number of operations once completed on site are now organised through factory production. Taking the CSCEC Technology Shenzhen Changzhen Public Housing Project as the case, this paper studies the relationship among digital collaboration, supply chain resilience, and delivery stability in prefabricated building projects. Case evidence and system dynamics are used together. BIM application, smart construction platforms, component traceability, intelligent factories, and smart construction sites are first treated as observable practices in the project. They are then transformed into variables such as Digital Collaboration Level, Supply Chain Visibility, Cross-Stakeholder Collaborative Response Capability, Assembly Backlog, Cumulative Delay, and Supply Chain Resilience. Based on these variables, the paper develops causal loop diagrams and a stock-and-flow diagram. The results show that digital collaboration does not work as a simple, independent factor that raises delivery performance immediately. Its influence is first reflected in the information structure of the supply chain. When component status is easier to identify, stakeholders can respond more quickly, backlog can be controlled more effectively, and delay recovery can be shortened. In this way, digital collaboration contributes to stronger supply chain resilience and more stable project delivery. The paper explains this dynamic mechanism in the context of a large prefabricated housing project and provides a reference for collaborative supply chain management.

Keywords: Digital Collaboration, Prefabricated Construction, Supply Chain Resilience, Project Delivery Stability, System Dynamics

1. Introduction

Prefabricated building delivery is a chain of connected activities rather than a single site operation. Detailed design, component decomposition, procurement and scheduling, factory production, transportation and distribution, and on-site installation all have to be linked. In actual projects, however, these activities are often handled by different organisations. A small information gap created in design or production may later appear on site as a delay, a quality issue, or an installation mismatch. Construction supply chains are temporary and inter-organisational in nature. For this reason, problems found during installation are often related to differences between earlier plans and the actual needs of the project [1]. BIM can support data exchange and the representation of construction sequences for off-site manufacturing [2]. Even so, the presence of digital tools alone is not enough to ensure stable delivery. Their value depends on whether project data are actually used for collaborative planning, anomaly detection, and resource adjustment.

Supply chain resilience is about whether a system can identify disruptions, absorb their effects, respond to them, and recover afterwards. For a complex supply network under continuous uncertainty, resilience is more than returning to the original schedule. It also means adapting while the main operation continues [3]. Existing studies on prefabricated construction have discussed resilience through BIM, structural equation modelling, and system dynamics [4-6]. What is still not fully explained is the engineering-level pathway: through which project processes digital collaboration affect delivery, and what roles visualisation and cross-stakeholder response play in that process [7]. To answer this question, this paper uses the Changzhen Public Housing Project as the case. The case study is used to organise project facts and derive research variables [8]. System dynamics is then used to describe feedback, accumulation, and time-lag relationships [9]. The purpose is to identify where

digital collaboration enters the prefabricated supply chain and how it influences coordination and recovery after disruptions.

2. Case Overview and Analytical Framework

2.1. Case Selection and Supply Chain Characteristics

The Shenzhen Changzhen Public Housing Project, also known as Fenghuang Yinghui City, is a large prefabricated public housing project. Public information shows that its construction area is about 1.15 million square metres and that it contains 9,672 housing units. The first 7,056 units have already been delivered for occupation [10]. Under the EPC delivery model, design, component manufacturing, logistics, on-site installation, inspection, and handover are closely connected. The project is also delivered in phases and depends on a strict hoisting sequence. Because of these characteristics, it is suitable for analysing planning alignment in prefabricated construction supply chains.

For this project, the supply chain can be described as follows: detailed design → component coding → procurement and scheduling → component production → transportation and site entry → on-site stacking and hoisting → acceptance and handover. A design change may require changes in component fabrication, while production progress must fit the installation windows on site. If components arrive before they are needed, they may occupy limited yard space and cause additional handling. Therefore, project performance cannot be evaluated only by on-site construction efficiency. It also depends on timely information, transparent component status, and the capacity of the participating organisations to adjust their plans around a common delivery objective.

2.2. Digitalization Practices and Variable Transformation

Table 1. Case Data, Analytical Dimensions, and Transformation of Research Variables

Case material / public evidence	Analytical dimension	Research variable	Reason for inclusion
BIM-supported integration of design, procurement, production, construction, operation, and maintenance	Digital collaboration foundation	Digital Collaboration Level	To judge whether digital technologies cover the major supply chain stages
Smart commerce, intelligent factories, smart construction sites, and smart operation and maintenance systems	Digital collaboration foundation	Platform Integration Level	To examine the strength of information connection across project stages
Component identification coding and QR-code tracking	Supply chain visibility	Component Status Tracking Accuracy	To assess whether component status can be traced from design to acceptance
Records on component production, transportation, site arrival, and installation	Supply chain visibility	Status Visualization Level	To observe information delay and changes in component status
Information links among design, procurement, production, and construction participants	Multi-entity collaborative response	Collaborative Response Capability	To analyze schedule adjustment and resource coordination after disruptions
Mechanism variables such as Assembly Backlog, Cumulative Delay, and Recovery Rate	Supply chain recovery capability	Supply Chain Resilience	To support the following system dynamics feedback-loop analysis
Public outcomes such as delivered units, construction rhythm, and quality performance	Project delivery stability	Project Delivery Performance	To provide an observation dimension for case outcomes

The digital practices used in the Changzhen project cover design, procurement, manufacturing, construction, operation, and maintenance. BIM supports model and data integration. Smart commerce and intelligent factory systems link procurement with production. Smart construction sites feed progress and quality information back to the management side. Component coding makes it possible to trace status during production, transportation, site arrival, installation, and acceptance [11,12]. These practices correspond to the visualisation and information-sharing mechanisms discussed in existing research on prefabricated construction [2,4].

Table 1 converts the case evidence into research variables. This step is needed because the public information available for the project is scattered across different types of evidence. Once the evidence is reorganised into analyzable units, the discussion can focus more directly on how digital collaboration affects supply chain resilience and project delivery performance.

3. Case Analysis and Research Findings

3.1. BIM-Driven Information System and Process Integration

In the Changzhen case, digital collaboration first changes the organisation of project information. In a conventional prefabricated supply chain, design information, component production records, transport information, and site installation data are often kept by different organisations or in different systems. This separation can easily create information asymmetry, which then leads to planning mismatch. In Changzhen, BIM, the digital twin information-sharing platform, and QR-code-based component tracking made component status from design to acceptance easier to identify and trace.

This process can be understood as a move from digital collaboration to status visualization. BIM links component information with construction sequences. QR-code traceability records component location and status. Smart construction site technologies send field progress and quality information back to the management system. Studies of prefabricated construction and BIM-based virtual assembly also show that prefabrication requires a clear understanding of construction sequence and schedule, and that virtual assembly helps contractors understand the assembly process and reduce rework risk [13]. Therefore, in this case, digital collaboration first improves the visibility of supply chain status. Performance improvement is achieved later through the use of that visibility.

3.2. Enhancing Collaborative Response Efficiency across Stakeholders

Visualization alone does not automatically create better performance. It becomes useful only when visible information is used to revise plans and coordinate resources. If site installation is delayed, production batches, transport arrangements, and hoisting plans need to be adjusted together. If component production is delayed, the site team has to revise the installation sequence and resource allocation in time; otherwise, labour and equipment may remain idle.

In the Changzhen project, smart business systems, intelligent factories, and smart construction site systems connect demand lists, procurement scheduling, component production, and site installation more closely than a fragmented process would allow. Problems can therefore be found earlier, and information can move more quickly among participants. Cross-stakeholder collaborative response is the mechanism that links digital collaboration with supply chain resilience.

3.3. Enhancing Supply Chain Resilience and Delivery Stability

Disruptions are difficult to avoid in prefabricated construction projects. What matters more is whether the project can return to its planned construction rhythm after a disruption. When collaborative response capability is stronger, the project is better able to reduce the number of components waiting for assembly and to limit cumulative delay. The adjustment may involve production schedules, transport plans, installation sequences, and resource allocation.

The Changzhen case suggests three related mechanisms through which digital collaboration affects delivery performance. The first is reduced information transmission lag, which allows stakeholders to obtain updated information about design, production, transportation, and site installation. The

second is improved supply chain visibility, through which component status and site progress become clearer. The third is stronger cross-stakeholder collaborative response, which enables the project team to revise plans and restore progress after disruptions. Together, these mechanisms affect supply chain resilience and project delivery stability.

Overall, the case analysis identifies the digital practices involved, defines the main variables, and clarifies the mechanism pathways. These results provide the variable basis and case context for the following system dynamics analysis, where the feedback relationships among variables are examined in greater detail.

4. Analysis of System Dynamics Mechanisms

4.1. System Boundaries and Variable Definitions

The system boundary is drawn around the prefabricated building supply chain before project delivery. It covers detailed design, component decomposition, procurement and production scheduling, precast component manufacturing, transportation, on-site storage, hoisting and installation, quality acceptance, and delivery feedback. Factors such as macro-level policy, real estate market changes, enterprise financial capacity, regional labour markets, and long-term operation and maintenance performance are treated as contextual conditions rather than variables in the core feedback structure in Figure 1. The time boundary starts at the production-transportation-installation coordination stage after detailed design and component decomposition and ends when delivery stability is formed. A variable is included only if it falls within this boundary, changes over time, and has an explainable influence on backlog, delay, recovery, or delivery stability. The variables are derived from the case workflow, public project information, and previous studies on system dynamics and prefabricated supply chains [6,7,9].

The variables are divided into four groups. Group A refers to the digital collaboration foundation, including Digital Collaboration Level, Information Transmission Delay, and Component Status Tracking Accuracy. Group B refers to the collaborative response process, including Supply Chain Visibility, Cross-Organizational Collaborative Responsiveness, and Scheduling-Delivery Alignment. Group C includes disruption and process-status variables: Disruption Intensity, Assembly Backlog, Issue-Resolution Pressure, Cumulative Delay, On-Site Inventory and Yard Pressure, and Hoisting Operation Efficiency. Group D includes performance and feedback variables, namely Recovery Rate, Supply Chain Resilience, Project Delivery Stability, and Willingness to Invest in Digitalisation.

4.2. Causal Loop Diagram and Feedback Mechanisms

For reading Figure 1, the signs on the arrows should be understood as relationship directions rather than value judgments. A “+” sign means that the two connected variables tend to move in the same direction, while a “-” sign means that a rise in one variable is associated with a fall in the other. The symbol “||” is used where the effect is not immediate, for example when information has to be transmitted, decisions have to be made, or actions need time to take effect. The labels “R” and “B” are used to distinguish reinforcing and balancing feedback loops.

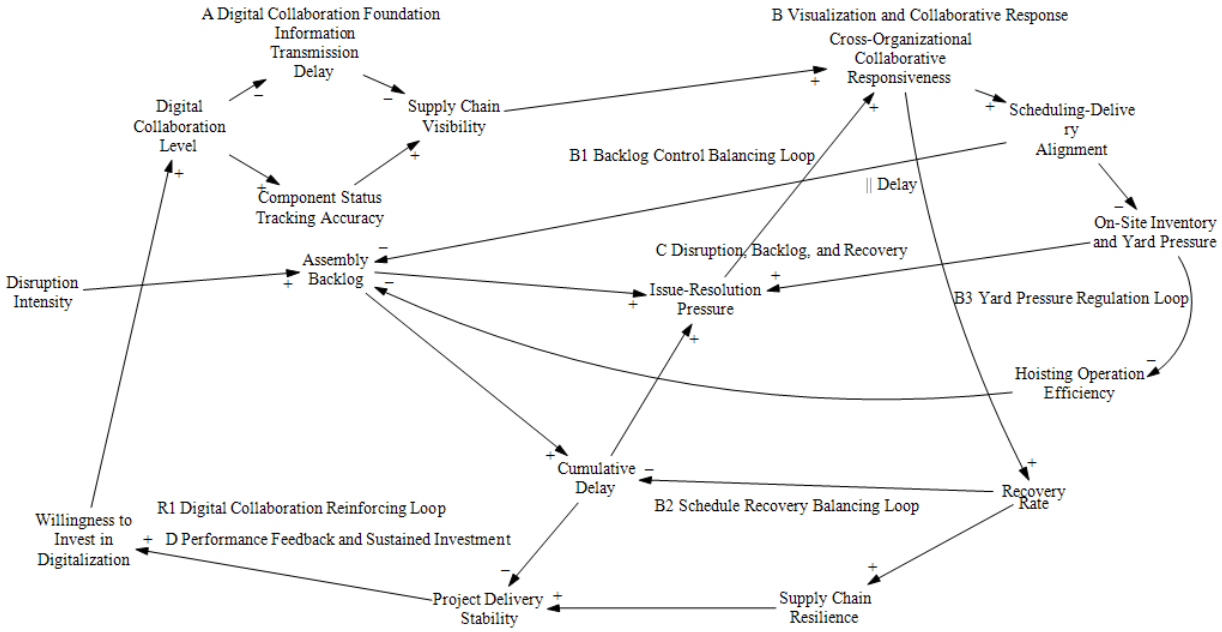


Figure 1. Causal Loop Diagram of the Impact of Digital Collaboration on the Resilience and Delivery Stability of the Prefabricated Building Supply Chain.

Digital Collaboration Dimension: R1 describes the reinforcing process related to digital collaboration. When the Digital Collaboration Level improves, information can be passed among participants with less delay, and the accuracy of Component Status Tracking also becomes higher. These two changes make the supply chain more visible. With clearer visibility, the organizations involved in design, production, transportation, and site installation are more likely to work from the same understanding of component status and project progress. This improves Cross-Organizational Collaborative Responsiveness, helps increase the Recovery Rate, and further supports Supply Chain Resilience. Once Project Delivery Stability becomes stronger, the project organization has more reason to continue investing in digitalization. This investment willingness then becomes a feedback force that further raises the Digital Collaboration Level.

Causal Loop: Digital Collaboration Level → Information Transmission Delay / Component Status Tracking Accuracy → Supply Chain Visibility → Cross-Organizational Collaborative Responsiveness → Recovery Rate → Supply Chain Resilience → Project Delivery Stability → Willingness to Invest in Digitalization → Digital Collaboration Level

Supply Chain Resilience Dimension:

B1 represents the balancing process for backlog control. When Disruption Intensity rises, more components may wait for assembly, so Assembly Backlog increases. A larger backlog then adds to Cumulative Delay and creates stronger Issue-Resolution Pressure. If Supply Chain Visibility is relatively high, the project team can locate the source of the backlog earlier instead of reacting only after the delay has already expanded. Through Cross-Organizational Collaborative Responsiveness, the team can adjust production schedules, transportation arrangements, and site resources. These adjustments improve Scheduling-Delivery Alignment and help limit the further growth of Assembly Backlog.

Causal Loop: Disruption Intensity → Assembly Backlog → Issue-Resolution Pressure → Cross-Organizational Collaborative Responsiveness → Scheduling-Delivery Alignment → Assembly Backlog

B2 is the Schedule Recovery Balancing Loop. When Cumulative Delay increases, Issue-Resolution Pressure also increases. This pressure pushes the project team to reallocate resources, change hoisting sequences, and optimize installation plans. Stronger Cross-Organizational Collaborative Responsiveness improves the Recovery Rate. As the Recovery Rate increases,

Cumulative Delay is gradually reduced, and the system moves back toward a more stable delivery state.

Causal Loop: Cumulative Delay → Issue-Resolution Pressure → Cross-Organizational Collaborative Responsiveness → Recovery Rate → Cumulative Delay

B3 is the Yard Pressure Regulation Loop. In prefabricated construction, early component arrival is not always helpful. When Scheduling-Delivery Alignment is weak, early arrivals may increase On-Site Inventory and Yard Pressure. This may cause disordered stacking, repeated handling, and waiting time before hoisting. Hoisting Operation Efficiency is then reduced, and Assembly Backlog may increase. A digital platform can coordinate production schedules, delivery windows, and installation plans, so unnecessary early arrivals are reduced, and delivery matches hoisting operations more closely.

Causal loops: Scheduling-Delivery Alignment → On-Site Inventory and Yard Pressure → Hoisting Operation Efficiency → Assembly Backlog. On-Site Inventory and Yard Pressure → Issue-Resolution Pressure → Cross-Organizational Collaborative Responsiveness.

Delivery Stability Dimension:

Under the combined action of these loops, Digital Collaboration Level, Supply Chain Visibility, Cross-Organizational Collaborative Responsiveness, and Recovery Rate form a connected mechanism chain. The expected results are lower Assembly Backlog, reduced Cumulative Delay, and more controllable On-Site Inventory and Yard Pressure. These results further support Supply Chain Resilience and Project Delivery Stability.

4.3. Transformation and Mechanism Representation of the Stock-and-Flow Diagram

In system dynamics analysis, the causal loop diagram is usually used first to identify feedback structures among variables. The stock-and-flow diagram then separates state variables, rate variables, and auxiliary variables. To show how the causal relationships in Figure 1 work through accumulation, depletion, and adjustment, this study develops the stock-and-flow diagram in Figure 2 based on the causal loop diagram and Table 2. Figure 2 also converts the four variable groups from the case analysis into stocks, flows, and auxiliary variables.

Table 2: Relationships between Key Stock Variables and Corresponding Flow Variables

Stock variable	Inflow variable	Outflow variable	Qualitative expression
Digital Collaboration Level	Digital Investment Formation Rate	Digital Collaboration Capability Decay Rate	INTEG (Digital Investment Formation Rate - Digital Collaboration Capability Decay Rate)
Assembly Backlog	Backlog Formation Rate	Backlog Clearance Rate	INTEG (Backlog Formation Rate - Backlog Clearance Rate)
Cumulative Delay	Delay Accumulation Rate	Delay Recovery Rate	INTEG (Delay Accumulation Rate - Delay Recovery Rate)
Supply Chain Resilience	Resilience Enhancement Rate	Resilience Loss Rate	INTEG (Resilience Enhancement Rate - Resilience Loss Rate)

Auxiliary variables include Information Transmission Delay, Component Status Tracking Accuracy, Supply Chain Visibility, Cross-Organizational Collaborative Responsiveness, Scheduling-Delivery Alignment, Issue-Resolution Pressure, On-Site Inventory and Yard Pressure, Hoisting Operation Efficiency, Recovery Rate, Project Delivery Stability, and Willingness to Invest in Digitalization. These variables are not stocks and do not accumulate directly. Instead, they affect the system state by changing formation, clearance, recovery, enhancement, or loss rates. For example, stronger Supply Chain Visibility and Cross-Organizational Collaborative Responsiveness can improve Scheduling-Delivery Alignment and Recovery Rate. This slows the formation of Assembly Backlog, supports backlog clearance, and accelerates recovery from Cumulative Delay. At the same time, Disruption Intensity, On-Site Inventory and Yard Pressure, and Issue-Resolution Pressure influence Assembly Backlog, Cumulative Delay, and the loss of Supply Chain Resilience.

In Figure 2, rectangles represent stock variables, valves and thick pipes represent flow variables, plain text represents auxiliary variables, clouds indicate sources or sinks outside the system boundary, and grey angle brackets indicate shadow variables.

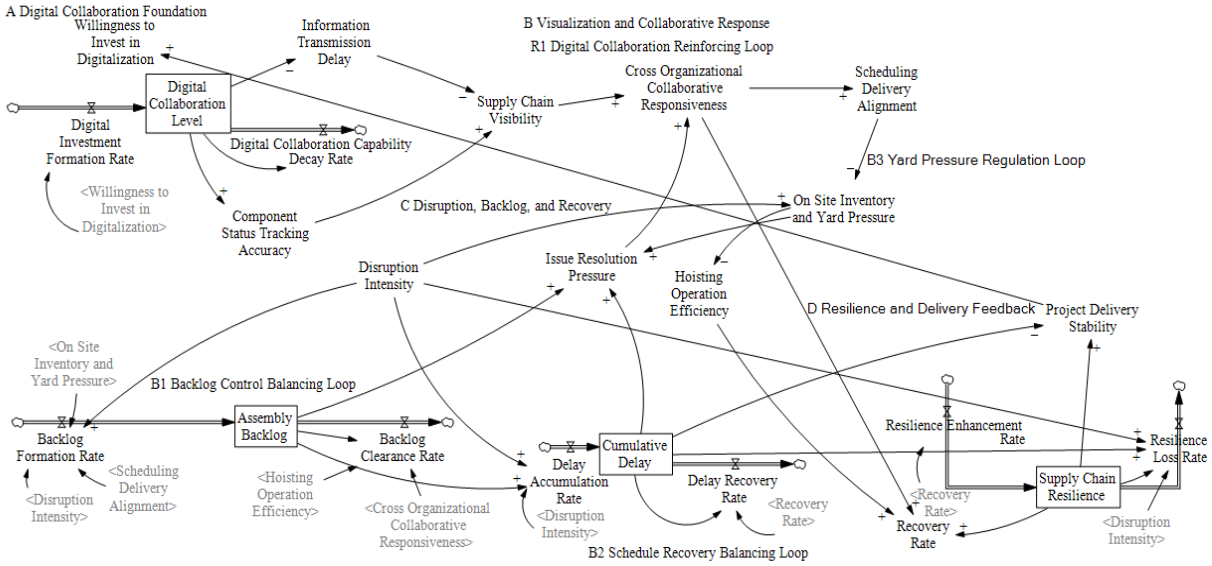


Figure 2: Stock and Flow Diagram of the Impact of Digital Collaboration on the Resilience and Delivery Stability of the Prefabricated Building Supply Chain.

Based on the structural model, digital collaborative management in prefabricated construction can be improved from three aspects. First, project teams should build a full-lifecycle data record for prefabricated components. Information on component coding, design confirmation, production, quality inspection, transportation, site arrival, hoisting, and acceptance should be updated continuously so that stakeholders can understand component status in real time. This can reduce repeated communication and scheduling errors caused by unclear information. Second, digital platforms should not be used only to improve efficiency in separate stages. They should also support workflow synchronization across design, production, transportation, and installation. This helps avoid storage yard congestion caused by premature upstream production and reduces disruptions caused by last-minute site adjustments. Third, projects should set up early-warning and closed-loop resolution mechanisms for supply delays, transport deviations, design changes, quality issues, and changing site requirements. When responsibilities are clearly assigned, visual component data can be converted into Cross-Organizational Collaborative Responsiveness, which then improves Supply Chain Resilience and Project Delivery Stability.

5. Conclusion

Using the Shenzhen Changzhen Public Housing Project as the case, this study converts BIM application, smart construction platforms, component traceability, intelligent factories, and smart construction sites into variables such as Digital Collaboration Level, Supply Chain Visibility, Cross-Stakeholder Collaborative Response, Assembly Backlog, Cumulative Delay, and Recovery Rate. The case analysis and the system dynamics model both show that digital collaboration mainly works by improving the information structure of the supply chain. Clearer component status and shorter information lag help design, production, logistics, and site teams align scheduling, delivery, and hoisting with a common progress baseline. This collaboration helps control backlog and yard storage pressure, speeds up delay recovery, and improves Supply Chain Resilience and Project Delivery Stability. The study also indicates that the value of digital management should not be limited to maximising efficiency within separate stages. Its greater value lies in coordinating production, transportation, and installation as an integrated process.

This study still has several limitations. First, the data mainly comes from public reports. Internal project metrics, such as component production cycles, delivery time deviations, on-site inventory levels, and anomaly resolution time, were not available. The model therefore explains structural relationships rather than producing precise simulation results. Second, the case is a single public housing project with its own organizational capacity and policy context, so the findings cannot be directly generalized to quantify effects across all prefabricated construction projects. Third, delivery stability is also affected by EPC organizational capacity, policy support, corporate resources, project management experience, and site conditions. Future studies could estimate parameters through interviews and project records, compare scenarios with different disruption levels, yard capacities, and collaboration levels in Vensim, and conduct multi-case comparisons across projects with different scales, regions, and organizational models. In practice, attention should be paid to unique component coding, cross-stakeholder data access rights, early-warning thresholds, and accountability mechanisms for anomaly resolution, so that digital platforms can support practical collaborative decision-making.

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