

System dynamic model on cost-time-material waste analysis for supply chain management of offsite panelised systems in the housing sector

Sanaz Nesarnobari^{1b}, Wajiha Shahzad^{1b}, Mostafa Babaeian Jelodar^{1b}
and Monty Sutrisna
College of Sciences, Massey University, Auckland, New Zealand

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Abstract

Purpose – To effectively support the housing sector, the offsite construction (OSC) supply chain (SC) requires strengthened skills, expanded operational capacity and improved organisational capabilities. However, ongoing SC management (SCM) issues, such as cost overruns, inefficient processes and material waste, continue to limit the housing sector's adoption of OSC. By addressing these barriers, this study aims to improve OSC-SCM processes while expanding the talent and capability base needed for construction ecosystems.

Design/methodology/approach – A system dynamics (SD) modelling approach is used to analyse cost and time dynamics under multiple disruption scenarios quantitatively. The model incorporates key barriers, like design inefficiencies, labour shortages, equipment delays and logistical constraints, while also simulating the potential performance gains achievable through skill development, capacity expansion and capability upgrading.

Findings – The simulation results demonstrate the complex relationships among SC performance, operational capacity and personnel capability in OSC. The findings point to key areas for leverage where focused interventions, such as digital design integration, improved worker training and rapid logistics planning, can increase productivity, cut waste and improve preparedness simultaneously.

Originality/value – In the OSC context, this research presents a novel integration of SD modelling, showing how digitally driven skill enhancement and capacity building can serve as catalysts for attaining next-generation construction performance and overcoming enduring SCM barriers.

Keywords Supply chain management, Offsite construction, Housing sector, Panelised system, System dynamics, Barriers

Paper type Research paper

1. Introduction

The global construction sector continues to face persistent challenges related to productivity stagnation, cost overruns and schedule delays, particularly in the housing sector. Recent studies indicate that construction projects experience cost overruns and delays, with supply chain (SC) barriers identified as a primary contributing factor (Stephens, 2022; Wang *et al.*,



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2019a). Offsite construction (OSC) has emerged as a promising solution to address these challenges by improving construction speed, ensuring consistent quality and controlling costs. Globally, OSC adoption rates are high in advanced economies, while New Zealand's adoption remains comparatively limited, constrained by SC fragmentation, geographic isolation and labour shortages (Carradine, 2020; Shahzad *et al.*, 2023). Although cost and time performance in OSC-SC have been investigated, existing studies predominantly rely on static estimation methods or isolated factor analyses, offering limited insight into the dynamic, interdependent nature of SC barriers. In contrast, this study advances the literature by developing a system dynamics (SD) based cost, time and material waste analysis framework that explicitly captures endogenous interactions, feedback loops and the propagation of barriers across multiple SC stages in panelised offsite housing systems. Rather than examining individual barriers in isolation, the proposed approach enables a system-level understanding of how labour, material, logistics and operational barriers jointly influence project cost, delivery over time and material waste.

Building on earlier conceptual and empirical work on OSC-SCM challenges (Nesarnobari *et al.*, 2024b, 2024d), this study extends prior findings by operationalising these challenges within a dynamic simulation framework tailored to the New Zealand housing context.

The aim of this study is to develop and operationalise a SD-based cost, time and material waste analysis framework that quantifies the dynamic impacts of SC barriers in offsite panelised housing systems.

To achieve this aim, the study addresses the following research questions:

- RQ1. What are the key SC barriers influencing cost, time and material waste in offsite panelised housing systems?
- RQ2. How do these barriers interact dynamically across different SC stages to influence project cost, time and material waste over time?
- RQ3. How can SD modelling improve the estimation and management of cost, time and material waste trade-offs under SC barriers in OSC?

The scope of the study focuses on panelised offsite housing systems, with particular attention to cost, time and material waste dynamics and SC barriers relevant to the New Zealand context. By integrating SCM principles with SD modelling, this research develops a structured and framework for informed decision-making in OSC projects. The framework captures endogenous interactions, feedback propagation and dynamic trade-offs across multiple SC stages, thereby extending existing OSC-SCM research beyond static or stage-specific modelling approaches.

2. Literature review

All facets of the OSC-SC management (OSC-SCM) were thoroughly examined using Scopus databases by investigating a decade of studies. Subsequently, a comprehensive review was undertaken to delve deeper into the barriers impacting the OSC global implementation.

SCM involves collaborating and integrating various businesses' value chains, primarily enhancing customer value and profitability (Speller T, 2007). SCM aims to streamline processes and optimise the flow of materials and components throughout the SC, from the source to the end user (Nkolika *et al.*, 2020). Multiple business entities, such as manufacturers, suppliers, developers, contractors and distributors, are directly and indirectly involved in the SC of the OSC. They facilitate the forward movement of materials and the

backward exchange of information (Mostafa *et al.*, 2014). Early studies (2008–2016) primarily addressed foundational challenges in OSC-SC. However, from 2018 onwards, research shifted towards leveraging computational and simulation models to tackle inefficiencies and mitigate risks more effectively. In recent years (2021–2023), studies have increasingly focused on advanced technologies, including the Internet of Things (IoT), blockchain and simulations, to enhance decision-making and address complex SC barriers (Castelblanco, 2016; Nesarnobari *et al.*, 2024b; Zhang *et al.*, 2025). This progression highlights the strategies' evolution from addressing basic coordination issues to adopting sophisticated, technology-driven solutions to optimise OSC-SC performance (Alhawamdeh and Lee, 2024; Clyde Zhengdao Li *et al.*, 2024). These theoretical foundations collectively shape the study's SD modelling approach, ensuring it captures the complexity and dynamic interactions within OSC-SC, thereby bridging theoretical insights with practical applications (Yuan, 2024).

Earlier OSC studies primarily focused on foundational coordination and productivity issues within fragmented SCs. These studies highlighted problems related to material flow, communication inefficiencies and project coordination; however, they generally relied on static or descriptive analytical approaches. Later research increasingly adopted simulation and computational techniques, including SD, optimisation and digital technologies, to improve forecasting and operational efficiency. Although these approaches improved understanding of dynamic project behaviour, many studies remained limited to isolated stages of the SC or focused predominantly on either cost or scheduling. More recent studies have further integrated digital technologies such as IoT and blockchain into OSC-SCM research. Nevertheless, limited research simultaneously captures endogenous interactions, disruption propagation and multi-stage cost–time–material waste dynamics within panelised OSC systems. Therefore, a gap remains in developing integrated system-level modelling frameworks capable of analysing interconnected SC barriers dynamically across OSC project stages.

Recent studies consistently indicate that OSC-SC continue to face structural constraints, including fragmentation, coordination difficulties and inefficient information exchange, despite increasing global adoption. Contemporary reviews further highlight ongoing challenges in planning, scheduling and logistics, underscoring the absence of fully integrated OSC-SCM frameworks (Clyde Zhengdao Li *et al.*, 2024; Masood *et al.*, 2022). Panelised OSC systems differ from volumetric and modular systems in their reliance on distributed manufacturing, component-level logistics and sequential on-site integration. Unlike fully volumetric modules, panelised systems require tighter coordination between design precision, material procurement, manufacturing tolerances and transportation scheduling. These interdependencies intensify SC sensitivity, making cost and time performance particularly vulnerable to upstream barriers. Therefore, understanding dynamic cost–time–material waste behaviour within panelised OSC-SCs is critical for improving system-level efficiency (Nesarnobari *et al.*, 2026). While cost–time analysis in construction has been examined, many existing approaches rely on deterministic, factor-based, or stage-isolated models that do not fully capture interdependencies across SC processes (Marzouk and Azab, 2014). Within the OSC domain, cost research has predominantly focused on comparative assessments between traditional and prefabricated systems, emphasising cost differentials and productivity gains rather than dynamic cost propagation mechanisms (Arashpour *et al.*, 2018). Moreover, limited studies explicitly model time-dependent disruption effects and multi-stage feedback interactions within panelised SCs under barriers (Marzouk and Azab, 2014; Zhao *et al.*, 2022). Consequently, there remains a need for modelling approaches capable of capturing feedback loops, time delays and interconnected

cost behaviours across OSC-SC stages. Furthermore, the unpredictability of import material costs might pressure financial planning and budgetary restrictions. Inadequate quality checks or machine errors may result in component defects during manufacturing (Li *et al.*, 2018). Factory equipment needs to be maintained, but malfunctions can cause delays and higher costs (Chen *et al.*, 2023). Keeping a trained crew capable of operating complex equipment and meeting stringent quality control requirements is also critical. Skill gaps or labour shortages can disrupt production schedules and lower final product quality (Chen, 2020). There are unique challenges when moving large components from the production plant to the building site. Ensuring compliance with transportation standards, obtaining the necessary permissions and organising logistics are crucial to enabling seamless and timely deliveries (Arashpour *et al.*, 2018). Unexpected events, such as road closures, bad weather, or mechanical failures, can disrupt transportation plans and lead to costly delays. In addition, delays may result from logistical issues, including traffic, weather and road limitations (Hsu *et al.*, 2018). The weather, site conditions and labour constraints all affect assembly procedures, further complicating the production process. It takes careful planning and coordination to modify assembly processes to account for these circumstances while upholding efficiency and safety requirements (Anvari *et al.*, 2016). All parties involved must work together effectively, pay close attention to detail and solve problems proactively to successfully navigate the complexity of the OSC-SC.

An SD-based neural network model was used to predict delays in OSC projects, highlighting the importance of dynamic modelling in mitigating project risks (Zhao *et al.*, 2022). The following year, SD was used to plan, forecast and manage cash flow in construction projects, demonstrating their versatility in addressing financial complexities (Dabirian *et al.*, 2023). Furthermore, SD applied to improve the accuracy of total project cost estimation for general contractors, ultimately enhancing profitability (Liu and Luo, 2023). Similarly, improved construction accuracy for precast components by identifying causal relationships and pinpointing the most sensitive factors affecting outcomes done by 2024 (Yuan, 2024).

Examining stakeholder interactions reveals that SC are considerably more complex than traditional construction (Ikonen *et al.*, 2013). Various barriers, such as delays, increased costs (Bello *et al.*, 2023) and environmental impacts such as global warming (Wasim *et al.*, 2020), complicate SC integration, mainly because of an insufficient understanding of these challenges (Wang *et al.*, 2019b). SD are designed to analyse and manage such intricate feedback systems by viewing a system as a network of interdependent elements (Marzouk and Azab, 2014). This approach, widely applied across diverse fields to capture internal feedback loops and time delays, enhances decision-making and is increasingly popular in modelling construction project management (Marzouk and Azab, 2014). SD offers a framework for examining dynamic interactions, feedback mechanisms and evolving behaviours within the OSC-SC. At the same time, SCM principles provide a foundation for identifying and implementing strategies to enhance efficiency and address challenges. Together, these frameworks enable the development of practical insights and solutions tailored to the specific complexities and barriers of OSC (Shahzad *et al.*, 2022). Table 1 summarises the key SC challenges identified across the main stages of the OSC-SC, including raw material sourcing, design and planning, manufacturing, transportation and on-site assembly. These challenges were synthesised through a systematic literature review, reflecting both upstream and downstream barriers that influence cost, time and operational performance in OSC projects.

As shown in Table 1, material-related and labour-related challenges emerge consistently across multiple SC stages, indicating their systemic influence on OSC performance. Issues

Table 1. Supply chain challenges based on literature review

Supply chain processes	Challenges	References
Raw material sourcing	Material quality Material supply	[28], [29], [30]
Design and planning	Material importing issues Lack of design standards & codes Poor design flexibility Complications on seismic performance Complications on fire-resistant performance Lack of experienced designer The limited size of elements Longer duration (design phase) Lack of innovation Resistance to change Construction consent	[14, 17, 24, 31–35]
Manufacturing	Lack of manufacturing capacity Lack of skilled labourers Higher manufacturing cost Incompetence of manufacturers Defects Loss of productivity Quality control Increased risk due to uncertainties Escalated in the deficiency of labour training	[14, 24, 36–40]
Transportation	Poor road condition Higher transportation cost Lack of suitable vehicle Potential damage Delay due to logistic issues Incompetence of suppliers Traffic conditions Products size Cost of labour	[14, 32, 38, 41–46]
Assembling	Lack of technician on-site Complexity of connection Assembly limitations Floor area conditions Production size Cost of labour Limited site space	[25, 32, 33, 36, 38, 47]

such as material quality, importing constraints and price volatility originate in the raw material sourcing stage but propagate downstream to manufacturing and assembly. Similarly, skill shortages and limited technical expertise recur across design, manufacturing, transportation and assembly phases, underscoring their role as persistent drivers of cost escalation and schedule disruption. In contrast, design-related barriers tend to be concentrated in earlier stages but can cascade, affecting manufacturing efficiency and on-site assembly. This research also bridges global challenges with localised applications in New Zealand. The country's unique context, characterised by geographic isolation, a limited skilled workforce and a growing demand for affordable housing, amplifies SC barriers commonly observed worldwide. For example, transportation delays because of long

distances and regulatory compliance requirements present distinct challenges in the New Zealand OSC industry. By tailoring SD models to reflect these localised factors, the research provides context-specific strategies to mitigate delays, improve cost efficiency and enhance resource utilisation. Furthermore, adopting global best practices in SCM, such as lean construction principles and advanced forecasting tools, ensures that solutions are not only innovative but also adaptable to the unique dynamics of New Zealand's construction sector. This approach aligns with global efforts to optimise OSC-SCs while addressing the specific needs of local markets (Nesarnobari *et al.*, 2024d). Although substantial research has examined SC challenges, cost overruns and performance inefficiencies in OSC, much of the existing work adopts static, factor-based or stage-specific approaches. Foundational studies in construction cost management highlight the persistent issue of cost escalation and estimation inaccuracy; however, limited research integrates these insights within a dynamic, system-level modelling framework tailored to panelised offsite housing systems. Consequently, there remains a gap in understanding how interconnected SC barriers propagate over time and collectively influence project outcomes. This study addresses this gap by developing a SD-based framework that captures multi-stage interactions and disruption feedback mechanisms.

Methodologically, earlier OSC-SCM studies relied predominantly on qualitative case studies, interviews, surveys and descriptive analyses to identify SC challenges and operational constraints. While these approaches provided valuable contextual understanding and industry insights, they were inherently limited in their ability to capture dynamic interactions, feedback relationships and temporal changes across SC stages. Subsequent research increasingly adopted simulation-based methods, including discrete-event simulation, SD and optimisation models, to investigate operational performance, resource allocation and scheduling efficiency. Although these approaches enhanced analytical capabilities and forecasting accuracy, many remained focused on isolated SC processes or single performance dimensions such as cost, time or productivity. More recently, studies have incorporated digital technologies, including building information modeling (BIM), internet of thing (IoT), blockchain and digital twins, to enhance information visibility, traceability and stakeholder coordination. Nevertheless, the majority of these studies continue to examine specific aspects of OSC-SCs independently, with limited consideration of disruption propagation, multi-stage interactions and the simultaneous dynamics of cost, time and material waste across panelised OSC systems. The reviewed literature indicates that upstream barriers are primarily associated with raw material procurement, import dependency and design coordination, whereas midstream barriers are strongly linked to manufacturing reliability, labour availability and equipment performance. Downstream barriers mainly involve transportation restrictions, weather-related disruptions and assembly constraints. Importantly, these barriers do not operate independently. Delays or disruptions originating in upstream stages frequently propagate downstream, amplifying project cost escalation, schedule overruns and material waste accumulation across multiple OSC processes. This dynamic interdependence highlights the need for system-level modelling approaches capable of capturing feedback loops and mechanisms for the propagation of disruption.

The challenges identified in Table 1 serve as the basis for selecting key variables, feedback loops and barrier scenarios to be incorporated into the SD model developed in this study. Previous studies have identified a range of cost, time and resource-related variables influencing OSC-SC (Clyde Zhengdao Li *et al.*, 2024). For example, material supply uncertainty, labour availability, equipment reliability and transportation constraints have been reported as key drivers of cost escalation and schedule disruption. These variables form

the foundational structure of the SD model developed in this research. While some of the model variables are grounded in existing literature, several variables were refined or contextualised based on primary data collected through expert interviews and case insights, particularly to reflect the specific characteristics of the New Zealand OSC context. A complete list of the variables used in the SD model, along with their definitions and sources, is provided in the [Appendix](#).

2.1 Theoretical foundation of the study

This study is grounded in systems theory and SCM principles, which conceptualise construction SCs as interconnected, feedback-driven systems characterised by non-linearity and time delays. OSC-SCs exhibit multi-stage interdependencies, where disruptions in upstream activities propagate dynamically to downstream manufacturing and assembly processes. SD provides an appropriate methodological foundation for modelling such behaviour, as it enables the representation of feedback loops, accumulation processes and endogenous cost propagation mechanisms. By integrating SCM concepts with SD modelling principles, this research establishes a system-level analytical framework for examining cost–time interactions in offsite panelised housing systems.

Previous studies have examined costs, time, performance and SC within OSC. However, much of this work has relied on static analytical approaches or factor-based analyses that evaluate these elements independently. Such approaches often overlook the dynamic interdependencies between SC stages and the cumulative effects of disruptions across the construction process. In contrast, this research adopts a dynamic system perspective to capture how disturbances in manufacturing, logistics and coordination processes propagate throughout the SC and influence overall project performance. Furthermore, the study situates this analysis specifically within panelised offsite housing systems, thereby linking SC dynamics to the broader context of housing delivery. These distinctions and contributions have now been clarified in the revised introduction and literature review sections.

3. Research method

The research method comprises five main stages. In the first stage, a literature review was conducted to identify the aim and objectives, and in the second step, a triangulation methodology was used to identify and evaluate barriers. This methodology involved a comprehensive literature review, semi-structured interviews and case studies to refine the identified factors specific to the residential sector. In the third stage, a causal loop diagram was developed based on the evaluated factors to recognise their effect on the SC process. Subsequently, for stage four, the SD approach was applied to develop a cost–time–material waste model tailored for offsite panelised systems in the housing sector. The last stage involved validating the model using a real case study and discussing the results to inform future research directions.

3.1 Triangulation methodology

Triangulation methodology entails using several approaches, data sources, ideas or researchers to examine a single topic to increase the validity and reliability of research findings ([Jonsen and Jehn, 2009](#)). This method can enhance the validity and reliability of the findings by using multiple methods and data sources ([Andújar-Montoya *et al.*, 2020](#)). Researchers can reduce bias, cross-verify data and develop a more thorough understanding of the subject by combining various methodologies ([Sepasgozar and Davis, 2018](#)). For example, integrating case study validation with qualitative methods, such as literature reviews and interviews, enables a more thorough analysis, as the strengths of one approach

can offset the weaknesses of the other. This study adopted methodological triangulation by integrating a systematic literature review to identify key SC barriers, semi-structured expert interviews to validate and contextualise these factors and case study analysis to examine their manifestation in real project settings. The combination of theoretical synthesis, practitioner insight and empirical case evidence enhances the robustness, credibility and contextual relevance of the findings. Semi-structured interviews provided a balanced approach between structured and open-ended questioning, enabling in-depth exploration of complex SC challenges (Vernikos, 2013). A total of 29 open-ended questions were developed to gather data, focusing on the current state and challenges of the OSC for about 60 min. Given the specialised nature of the field and potential constraints on participants' availability, purposive sampling was combined with "snowball sampling" techniques (Dawson, 2009) to identify qualified interviewees. A total of 15 industry professionals participated in the interviews, including senior managers, directors, engineers and executives across manufacturing, design, logistics and project delivery. Participants had professional experience ranging from 10 to over 20 years in offsite panelised construction. The study adopted a theory-informed qualitative design, with interview questions structured around SC barriers identified in the literature. As such, the interviews were not exploratory in nature but were conducted to validate, contextualise and refine pre-identified variables within the New Zealand OSC context. A purposive sampling strategy targeted senior professional with extensive cross-stage SC experience (A. Mohammadi, 2018; Dalton *et al.*, 2013; K. Manley, 2019; Zolghadr *et al.*, 2022). Data saturation was systematically assessed during analysis; no new barrier categories or causal mechanisms emerged after the 13th interview, and the final two interviews confirmed thematic consistency. Given the study's focused scope and participants' high level of expertise (10–20+ years), 15 interviews were deemed methodologically sufficient. This approach is consistent with qualitative research practice, in which additional interviews are often conducted beyond saturation to verify thematic consistency.

The final sample size also aligns with previous qualitative studies in construction management, where expert-based interviews commonly involve 8–15 participants (Godoyon Wusu *et al.*, 2025; Laura Kauppinen *et al.*, 2025). Then, qualitative data were analysed using content analysis, and case studies were analysed to verify the findings. A total of two offsite panelised housing projects in Auckland were selected based on predefined criteria, including high OSC integration, incorporation of sustainable or low-carbon materials, accessibility of project data and stakeholders, comparable building typology and project initiation within the past five years.

The boundaries of each case were defined at the project level, focusing specifically on SC processes related to design, manufacturing, logistics and on-site assembly. The unit of analysis was the SC performance within each project, particularly cost, time, material waste-related barriers and operational constraints. A case analysis was conducted to assess the consistency of the identified barriers and the dynamic behaviour of cost, time and material waste with empirical project evidence.

3.2 System dynamics

SD was introduced in 1958 as a tool for visualising and analysing dynamic feedback systems, facilitating comprehension of complex challenges (Ding *et al.*, 2016). Its advantage lies in examining the dynamics of complex systems, emphasising collaboration and interaction among elements (Yuan, 2014). Additionally, it is described as a computer simulation technique (Vensim-PLE software) for studying the dynamic behaviour of social and economic systems (Liu *et al.*, 2020). SD has been used in various fields, such as project

cost, resilience, policies, uptake, waste management and the potential of OSC, for the past few years. The barriers to OSC-SCM are explained as a complex, open information feedback system involving many information, material and economic flows among parameters (Maqsoom *et al.*, 2019). A comprehensive information feedback system for all-encompassing barriers of OSC-SCM can be built with SD. This system makes logical linkages between the system parameters more evident (Ajayi, 2016; Li *et al.*, 2014). It gathers information and visually represents the flow between the system's internal and external environments while precisely describing the system's evolutionary law. This method can also model interdependencies and identify how changes in one area impact others through feedback loops. Additionally, a thorough framework for understanding how various elements, including standardisation, logistics and regulatory compliance, interact and influence one another over time is crucial for understanding the long-term effects of SCM decisions. Furthermore, this technique enables the simulation of multiple scenarios, which aids in forecasting the effects of alternative tactics and locating any potential flaws or inefficiencies, as well as optimal management for managers to assess the potential impacts of changes in SC strategies without disrupting actual operations. Also, it can model cost structures over time, identifying cost-saving opportunities and understanding the contribution of different factors to overall expenses. By integrating empirical data from several case studies, the SD model provides a significant understanding of SCs' dynamic behaviour, facilitating the creation of resilient and flexible solutions. This strategy improves theoretical knowledge while giving industry participants valuable tools to maximise SC efficiency and reduce risks (Nesarnobari *et al.*, 2024a). The objective of this research is to create an SD model to analyse the comprehensive barriers of OSC-SCM, investigate the major variables influencing OSC delivery, forecast the model for OSC delivery and create an OSC delivery strategy based on research findings as a guide for the advancement in the residential sector. Reviewing the latest papers of OSC research indicates that SD is highly significant in OSC due to its ability to manage the intricate interconnections and dynamics within the SC (Ekanayake *et al.*, 2021). It divides the research subject into different subsystems and creates a causal relationship among each subsystem to analyse both the entirety and the relationships within it (Song *et al.*, 2019). The SD research methodology is outlined in Figure 1.

3.3 System boundary

The system boundary is defined to prevent unnecessary analysis and enable the identification of the system's functionality through comprehensive integration. For this purpose, it delineates and segregates influencing factors into inner and outer systems (Li *et al.*, 2017). To enhance profitability, industries must strive for minimal costs and expedited delivery without compromising on meeting mandated reductions in material waste through optimisation strategies. Nevertheless, for many businesses, the escalating uncertainty surrounding the influence of environmental policies on profits remains a pressing concern. This underscores the imperative for proactive adaptation and strategic planning to navigate these evolving regulatory landscapes and sustain economic viability (Yu *et al.*, 2020). The OSC-SCM process lies within the system boundary and includes building design, manufacturing, transportation and assembly. Project costs and additional expenses are accounted for within these processes.

The study uses the SD model to explicitly incorporate indicators across project costs, delivery times and material waste. The SC for the panelised system in OSC comprises five primary stages: design, raw material procurement, manufacturing, transportation and assembly. Within the delivery time framework, the design phase involves measurement,

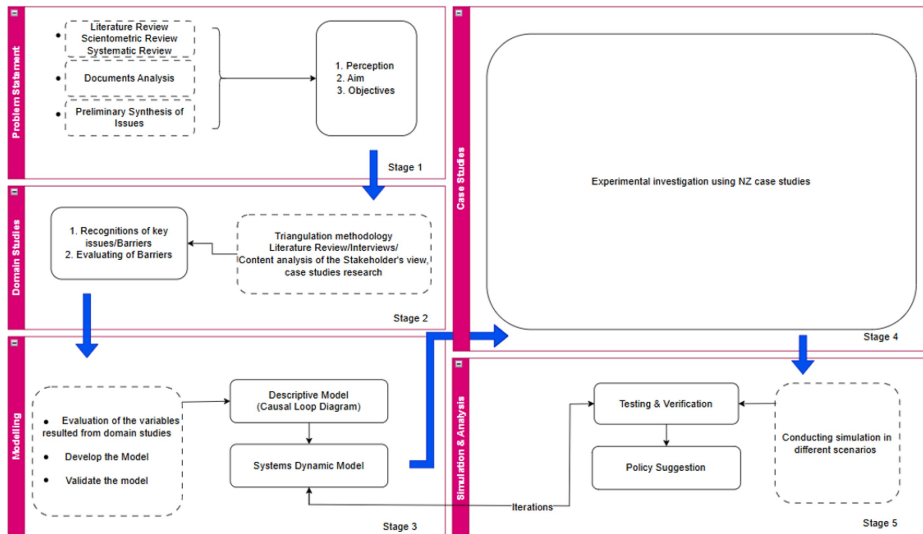


Figure 1. Methodology framework

design preparation and consent acquisition. The procurement phase includes planning, material ordering and quality checking. Manufacturing time is then allocated for production activities, followed by the transportation phase, which involves packing or storing, lifting and transporting the components to the site. Finally, the assembly phase covers site preparation/installation activities.

In terms of project cost, the design stage incurs expenses for design fees and quantity surveying. Procurement costs include raw material expenses, transportation of materials to the factory and storage. Manufacturing costs include machinery and labour, while logistics costs include equipment, labour and crane or lifting operations. Assembly costs similarly include installation, labour, crane/lifting requirements.

Additionally, the process generates solid waste at multiple stages: manufacturing waste during production, transportation waste during delivery and assembly waste.

This section presents the findings structured in alignment with the research objectives. The results are organised to demonstrate how SC barriers dynamically influence cost–time behaviour within panelised offsite systems.

4. Results

4.1 Challenges in supply chain management

To achieve the research objective (Vernikos, 2013), 15 qualitative semi-structured interviews were conducted to identify specific challenges within the OSC-SCM framework. A prevalent issue highlighted during the design stages is the lack of expertise among designers, leading to multiple complications. The scarcity of skilled labour extends beyond design and manufacturing to material handling and equipment maintenance. For instance, poor material quality control, defects in components and equipment failures highlight the critical need for skilled professionals to ensure the smooth progression of OSC. Respondents emphasised the adverse impact of lead times and inflation on material preparation, particularly citing fluctuations in fuel prices and transport levies as significant concerns. Respondents pointed

to the compounding effects of raw material import delays and machine part shortages, further emphasising SC's vulnerabilities.

The interplay between logistical challenges and regulatory barriers is evident in the transportation phase. Factors such as road restrictions, vehicle suitability and logistics inefficiencies compound the problem of transportation. Moreover, crane failures and a lack of competent transport suppliers significantly intensify delays and cost escalations when weather conditions or regional geography exacerbate these barriers. The assembly stage faces significant limitations because of site conditions, including floor area constraints, adverse weather and space limitations, all of which hinder the effective deployment of cranes. The unavailability of suitable cranes and skilled operators leads to cost increases and schedule overruns. Additionally, delays in construction arise from challenges in labour availability, which is crucial for on-site assembly processes, particularly when combined with fluctuations in crane rental prices.

Furthermore, the absence of standardised design codes and a lack of experienced design coordination hinders project initiation. Interviews revealed a recurring theme: clients' comprehension of design regulations and limitations on flexibility. The demand for prefabricated elements in most countries is low, attributed to clients' reluctance to adopt such methods. Moreover, the geographical location poses challenges for transporting equipment, such as CNC machines, and for servicing and repairs, which are expensive and time-consuming because of a lack of local expertise. Figure 2 illustrates how barriers feed into broader systemic inefficiencies.

4.2 Model development

4.2.1 Causal loop diagram. Critical factors influencing the SC were identified using a triangulation methodology to develop the causal loop diagram. The causal loop diagrams (CLD), which depict the main feedback mechanisms, emphasise the structure of an SD model (Ding et al., 2016). A CLD is a crucial tool in SD that helps explain the sources of dynamism inside a system by articulating the linkages among the diverse components that make up the system (Ajayi, 2016). It achieves this by visualising a model's cause-and-effect relationships among variables. The CLD may demonstrate how each variable interacts to dynamically affect the system. The feedback loop indicates the model's dynamic behaviour (Hongping, 2011). In a CLD, variables and inter-variables are connected by causal chains, where arrows represent positive and negative causal links. A closed system, known as a feedback loop, is created when several causal chains combine, and it can be either positive or negative. It is termed a negative feedback loop when it includes an odd number of negative causal chains. Conversely, if it consists of an even number of negative causal chains, it is

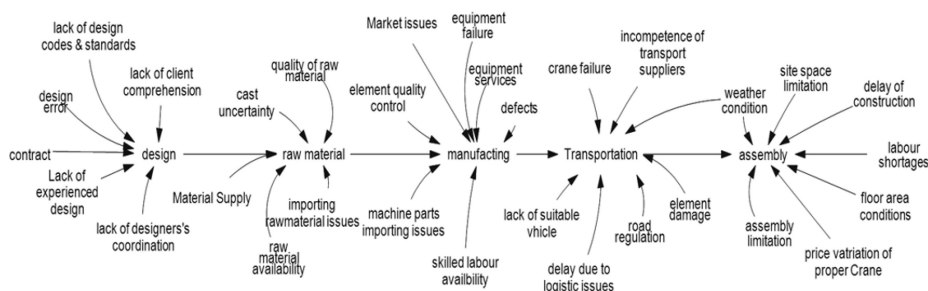
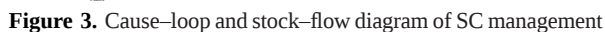


Figure 2. Mapping the challenges of the SC of OSC from triangulation methodology

Feedback Loop 1 (R1) involves the correlation among design changes, expenses, duration, adherence to design codes and standards and design errors. When errors occur in the design process, they trigger adjustments, leading to longer design durations and higher costs. Consequently, this loop is expected to exhibit negative feedback.



Feedback Loop 2 (R2) involves the interplay among material demand, availability, overdue issues, quality checks, costs and time. This also includes the impact of manufacturing costs, production time, errors, labour availability, labour costs and element failures. When an element fails, it disrupts manufacturing and drives up material costs, extending the time required for each step. This reduces labour availability, thereby raising labour costs. Ultimately, this loop escalates the project cost and is classified as a positive feedback loop.

Feedback Loop 3 (R3) encompasses transportation time, costs, crane availability, crane failures and weather conditions. Adverse weather conditions reduce crane availability and lengthen transportation times, increasing costs. This loop is also considered a positive feedback loop.

Feedback Loop 4 (R4) involves installation costs (IC), time, installed components, labour costs, labour availability and element damage. Installing components increases labour availability and reduces element damage. Consequently, this loop is considered a negative feedback loop. The interdependence of these elements underscores the importance of tackling feedback loops holistically to improve SC efficiency and project performance, as inefficiencies in one stage of the OSC process can spread.

4.2.2 Stock-flow diagram. Coyle states that the stock and flow diagram is a technique used in SD modelling to show causal links between variables (Coyle, 1997). This method improves how feedback mechanisms and the rules governing how system components interact are visualised. As a computational algebraic representation (Ajayi, 2016), a stock–flow diagram enables quantitative analysis and mathematical simulation of a model, expanding beyond mere evaluation through causal analysis and use of trees (Wang *et al.*, 2018).

A diagram is used to assess the possible effects of the project by examining the interconnectedness depicted in Figure 3. This diagram offers a detailed model illustrating the processes and structure related to costs. The extended time and material waste lead to increased costs; hence, cost is represented as a flow. The stock–flow diagram has level, rate, auxiliary, constant and shadow variables. The level variable accumulates alongside a rate variable, which governs the rate of change. The auxiliary variable influences the rate variable. Specifically, there are seven variables directly associated with the overall construction cost. The model incorporates all quantifiable factors and provides a comprehensive framework for analysing cost, time and material waste in OSC-SCs. It integrates 74 variables categorised into stocks-flows and auxiliary variables to capture the dynamic interactions and feedback loops across key processes, including material procurement, manufacturing, transportation, installation and design. Stocks, such as Material Cost (MaC), Manufacturing Labour Cost (MLC) and Factory Cost (FC), represent accumulated costs, while flows, such as Material Usage Change Rate (MUCHR) and Transportation Cost Change Rate (TCCHR), reflect changes over time. Auxiliary variables, including Weather Impact (WI), Labour Availability (LAA) and Material Quality Check (MQCH), provide critical inputs for evaluating risks, constraints and performance metrics. The model also incorporates external factors such as delays, equipment failures and design errors to simulate real-world complexities and challenges. Through its interconnected structure, the model facilitates scenario analysis and optimisation strategies, enabling decision-makers to enhance efficiency, reduce waste and improve overall project performance. Brief variable descriptions are in the Appendix.

4.3 Data collection

Case studies for data collection were selected using predefined criteria. First, projects were required to use panelised OSC systems to reflect contemporary OSC practices. Second,

diversity in project size, scope and complexity was considered to ensure the model could capture a range of operational conditions and SC constraints. Third, detailed information on project duration, cost structures and SC processes was required to support model verification.

Based on these criteria, two residential housing projects were selected. Case Study A involved approximately 150 medium-density residential houses located in Ohakune, while Case Study B comprised approximately 250 residential units in Auckland. Both projects adopted panelised OSC systems, in which structural components were manufactured off-site and transported for on-site assembly.

The two cases represent different SC contexts within offsite housing delivery. Case Study A reflects logistical challenges associated with remote project locations, including transportation lead times and coordination constraints, whereas Case Study B represents a high-density urban development environment characterised by complex project coordination and installation sequencing. These contrasting contexts enabled the examination of how SC disruptions and operational constraints influence cost, time and material waste dynamics across different OSC environments.

It is important to note that the purpose of the case studies was to empirically verify the behavioural patterns generated by the SD model. The cases, therefore, serve as practical references to assess whether the simulated SC dynamics, such as delay propagation, cost escalation and material waste generation, are consistent with observed project experiences.

The case studies were selected to provide empirical contexts for verifying the behavioural patterns produced by the SD model. Both projects involve medium-density residential developments employing panelised OSC systems and share comparable SC structures. However, they represent different operational environments within offsite housing delivery, including remote logistics conditions and high-density urban construction contexts. This variation enables the examination of how SC constraints influence cost, time and material waste dynamics across different OSC settings. Data collection primarily occurred through two primary sources. The first involved gathering information from diverse literature, internet sources and reports pertinent to the subject matter by [Zhang et al. \(2020\)](#). Second, to understand this potential, this paper uses data from medium-density OSC in New Zealand to conduct simulations. Data for each stage were collected through site visits over the project time and interviews with relevant managers. The chosen case studies span a range of initiatives in terms of size, scope and complexity. Because of its diversity, the model can handle a wide range of variables and scenarios commonly encountered in OSC. The case studies also offer practical illustrations of SCM barriers, enriching the model with actual situations and decision-making procedures. Furthermore, the case studies cover a range of regulatory frameworks and technical implementations, highlighting the model's adaptability and practicality across various scenarios. In alignment with the production cycle, the time unit "Month" is used in the SD model, with a simulation period of 12 months from 2024 to 2025. Detailed project and progress updates were analysed to calibrate and validate the SD model. A sensitivity analysis, inspired by [Sterman \(1992\)](#), was conducted to identify critical factors influencing SC performance.

4.4 Model validation

Following the creation of stock and flow diagrams, two case studies were chosen to undergo a comparative analysis and simulation input. Each case study pertained to residential housing projects in New Zealand. Verification of SD is essential to ensuring scenario correctness ([Richardson, 1981](#); [Sterman, 1992](#)). The model was validated using seven tests ([Barlas, 1996](#)).

- (1) Boundary adequacy: This test assures that important and significant factors and concepts are sufficiently taken into account (Qudrat-Ullah and Seong, 2010). In Test 1, validation was done by conducting interviews with representatives from the literature review (Nesarnobari *et al.*, 2024c), and the focus group contained one industry and two academic experts who had previously assisted in collecting data.
- (2) Structural verification: This test determines if the links and interconnections in the model accurately match those in real-world (Ding *et al.*, 2016). In Test 2, all causal and feedback loops outlined in this paper are based on empirical research, literature review, interviews and verifiable factual data.
- (3) Parameter test: This test verifies parameter values using real-world descriptive and numerical data (Ajayi, 2016). In Test 3, the constants used in the model are sourced from an actual project carried out in New Zealand, literature review findings and interviews. Consequently, all these constants meet the criteria for a parameter verification test.
- (4) Dimensional consistency test: This test verifies that all variables' unit dimensions are accurate and consistent (Du *et al.*, 2024; Sterman, 1992). In test 4, Vensim conducted the unit check to ensure that each parameter adheres to its designated unit and that all equations maintain dimensional consistency.
- (5) Extreme condition test: This test shows that the model is still valid in extreme situations, like when all strategies are implemented 100% of the time or 0% (Ajayi, 2016). In Test 5, Material Cost (MaC), Manufacturing Labour Cost (MLC), Element Cost (EC) and Manufacturing Equipment Cost (MEC) demonstrate a substantial impact on the Manufacturing Cost (MC) during extreme condition testing. Setting these costs to zero reduces the Construction Cost (CC) by approximately 54%. The influence of quality checks on material costs (MaC) is analysed by adjusting the Material Quality Check (MQCH) values to 0, 0.5 and 1. The MC is nearly 1.5 times higher when MQCH is zero than when it is 1. Additionally, when MQCH is set to 0.95, the MC rises to approximately 1.337×10^6 NZD, as lower MQCH values result in greater panel damage and, consequently, higher material demand costs. This observation underscores the model's consistent responsiveness and suggests the potential for verification with additional variables.
- (6) Behaviour sensitivity test: This test looks for significant model structural errors (Barlas, 1996). In Test 6, for instance, modifying the duration of lifter hours onsite enables an evaluation of its effect on the project cost. The lifter hours vary between 8 and 48 hours, with increments of [1,8,24,32,48]. These variations arise from delays attributed to weather conditions, site accessibility issues and equipment malfunctions. The graph demonstrates higher lifter hours significantly increase costs, emphasising the impact of prolonged equipment usage on overall expenses. It highlights the importance of efficient assembly management in accurately assessing the project cost associated with panel delivery. Similarly, other critical variables undergo sensitivity analysis and successfully pass test.
- (7) Model behaviour verification: This test verifies model behaviours by comparing simulation results with accurate data (Barlas, 1996). Test 7 focuses on validating the simulation results by comparing them with real-world project data. Key factors influencing project construction costs (CC) include delivery time, transportation duration, labour productivity, prefab damage, material quality, design flaws,

resource availability and manufacturing efficiency. The model was validated using two real-world case studies, Case Study A (Ohakune) corresponds to EXC1 and Case Study B (Auckland) corresponds to EXC2 in Figure 4. The projected costs closely align with the actual construction costs. For case studies, the projects experienced smooth progress without encountering significant barriers during months 5–7. As a result, the project costs either increased slightly or remained stable. Notably, the cost–time graph exhibits a steeper gradient during the initial months of the project, suggesting that major cost impacts, such as design modifications and raw material issues, predominantly arise early in the timeline. In contrast, the gradient flattens after approximately the ninth month, indicating more stable costs in later stages. For further insights, a detailed analysis was presented in Figure 4.

5. Results of simulation and discussion

5.1 Basic simulation

As outlined, the critical barriers influencing the cost and time required to deliver the offsite panelised system were identified, including material quality control, manufacturing labour availability, equipment failures, transportation limitations, weather impacts and labour shortages (Appendix). These barriers were integrated into the SD model to comprehensively evaluate and analyse their effects on construction and manufacturing costs. The model underwent rigorous structural and behavioural tests, confirming its alignment with real-world observations. This validation builds confidence in the model’s capacity to represent the complexities of OSC projects. Assumptions such as the absence of material quality issues, a project volume under 150 cubic metres and a design duration of 12 working days were used to reflect typical project conditions in Auckland. The analysis further assumed that pilot studies were unnecessary for this medium-density townhouse project, located 231 kilometres from the manufacturing facility. The scenario analysis results are accurate and can represent the real-world circumstances surrounding the manufacture.

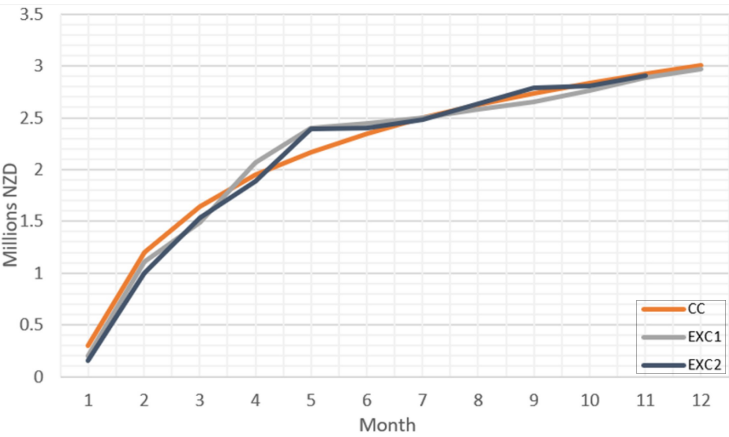


Figure 4. The model behaviour verification

The simulation results presented in Figure 5(a) demonstrate the construction cost (CC) components, including installation cost (IC), transportation cost (TC), design cost (DC) and manufacturing cost (MC). CC steadily increases over the 12-month simulation, with MC being the dominant contributor. IC and DC remain relatively similar and consistently lower than MC, while TC is the lowest-cost component throughout the timeline. Notably, all cost components exhibit a slow increase in the initial two months, suggesting initial project ramp-up effects before costs stabilise into predictable growth trends. In Figure 5(b), the breakdown of MC reveals its components: Material Cost (MaC), Factory Cost (FC) and Manufacturing Labour Cost (MLC). FC is comparable to other cost components during the first month, but its growth stabilises after the second month. By contrast, MC sees a substantial surge in the second month, driven primarily by material and labour costs. A pivotal shift occurs by the fifth month, where MaC falls below MLC, highlighting the increasing influence of labour costs on manufacturing expenses over time. This fluctuation emphasises the dynamic interplay between material supply, labour availability and production efficiency. The significant rise in MC in the early months aligns with increased demand for labour and materials as manufacturing scales up, while FC stabilises due to fixed infrastructure costs. These trends underscore the importance of optimising labour and material SCs to manage cost volatility effectively.

5.2 Scenario discussion

5.2.1 Project cost. The simulation findings, which shed light on construction project cost (CC) across four scenarios [Figure 6(a)] show how important barriers are in shaping the project's overall cost. These scenarios provide a thorough understanding of the project's cost behaviour by capturing the dynamic relationships among essential variables, including weather, design flaws, equipment availability and production disruptions. Costs rise more sharply in the CC2 scenario, which assesses the effects of design mistakes brought on by inexperienced designers. By the halfway point of the project, CC2 had surpassed CC1, demonstrating the substantial impact of design-related inefficiencies on project costs. This emphasises the importance of improving design processes through standardisation and improved designer training to reduce mistakes. The scenario with the sharpest cost curve is CC3, which looks at assembly delays caused by lifter unavailability. According to the chart, CC3 costs increase quickly, surpassing CC1 and CC2 prices early in the project schedule and remain the highest construction project cost. This highlights the importance of equipment availability for managing project budgets and schedules. In addition to directly affecting expenses, assembly delays brought on by equipment limitations also spread to later project stages, increasing the overall financial burden. The cost trend in the CC4 scenario, which focuses on CNC and other manufacturing equipment repairs and maintenance, is less steep than in CC3, but it is still much higher than in CC1. The findings demonstrate how the

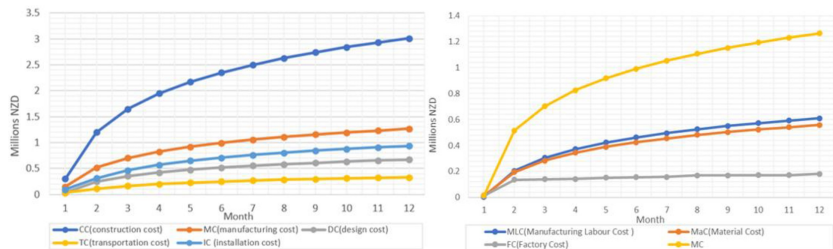
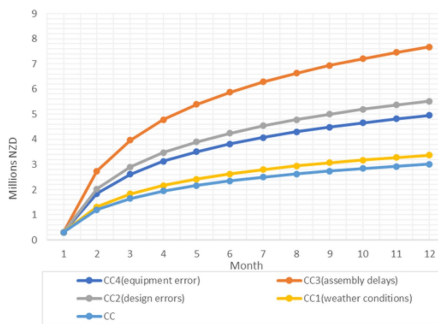
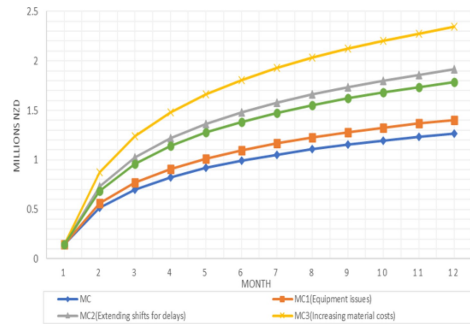


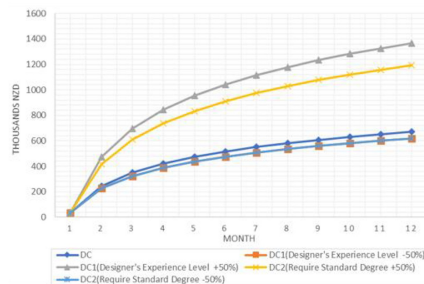
Figure 5. a: The CC simulation results, b: The MC simulation results



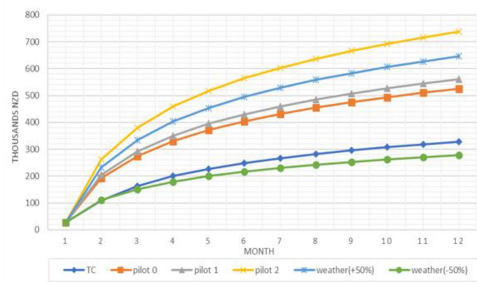
(a) The result of scenarios for project cost.



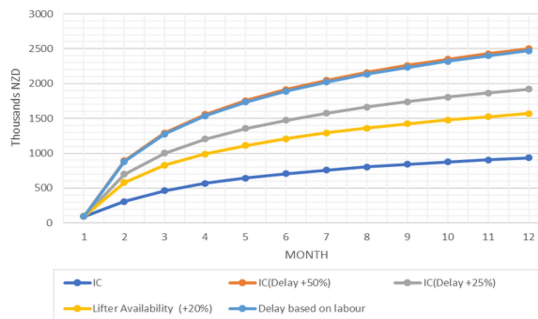
(b) Simulation result of manufacturing cost



(c) The result of the scenarios for the design level.



(d) Different scenarios of transportation cost



(e) Results of different scenarios for assembly cost

Figure 6. Result of different scenarios

dependability of manufacturing equipment impacts project costs. Early maintenance problems lead to significant cost increases, especially during the first few months of the project. This suggests that proactive equipment maintenance and robust repair practices are crucial for reducing manufacturing delays and the associated costs [Figure 6(a)].

5.2.2 Manufacturing cost. As illustrated in Figure 6(b), the simulation results compare the cumulative manufacturing cost (MC) trajectories over a 12-month period under four

significant disruption scenarios, enabling a direct assessment of their relative cost impacts and temporal behaviour. Every scenario depicts significant barriers faced throughout the construction process and their effects on rising project costs.

Delays in CNC equipment maintenance caused by a lack of skilled workers in MC1 result in longer downtime, lower production and higher costs. Compared to the baseline (MC), the scenario exhibits a consistent rise in building costs, reflecting the ongoing financial strain from equipment failures. To avoid costly delays, this highlights the need for preventive service plans, easily accessible repair staff and investments in dependable equipment. The extra expenses spent by extending work shifts to recover from process delays are simulated by the MC2 scenario. The cost increase shown in [Figure 6b](#) is mild and remains above the baseline throughout the project's duration. The trade-off between time recovery and financial impact is illustrated by the fact that, although extending shifts might aid in schedule maintenance, this strategy significantly increases labour costs, thereby offsetting the entire project cost. Stricter quality checks are the driving force behind MC3, which shows the largest cost escalation of all the scenarios. The dramatic rise in project expenses, evident early in the schedule and sustained throughout the year, underscores the crucial impact of raw material price swings on overall project costs. This scenario emphasises the need for efficient procurement plans, supplier agreements and inventory management to mitigate the effects of rising material prices. Finally, MC4 (Manufacturing Errors), which considers rework caused by manufacturing flaws and unsuccessful quality tests, raises prices above MC1 but remains below MC3. To prevent costly rework during construction, this scenario emphasises the importance of robust quality assurance procedures, skilled workers and early problem detection.

The most important factor influencing construction project expenses overall is MC3 (increasing material costs), followed by MC4 (manufacturing errors), MC2 (extending shifts due to delays) and MC1 (equipment issues). To effectively control construction project costs, these findings highlight the importance of managing material pricing volatility, ensuring equipment reliability and implementing effective labour and quality management measures.

5.2.3 Design cost. The simulation findings show how design costs (DC) in OSC projects are affected by the designer's experience level (DEL) and compliance with standard degree requirements (RSD) [[Figure 6\(c\)](#)]. The four scenarios modelled were 50% increase in DEL, 50% drop in DEL, 50% increase in RSD and 50% decrease in RSD. These situations shed light on how differences in designer skill and clarity of standards affect project budgets, schedules and design effectiveness. Because fewer mistakes and redesigns were needed in scenarios with DEL variability, 50% increase in designer experience dramatically decreased design expenses throughout the 12-month simulation. Otherwise, frequent mistakes caused by a reduction in designer expertise (–50%) led to a sharp increase in design costs, extending the redesign process and postponing further project phases. This demonstrates the precise relationship between designer proficiency and design process efficiency, highlighting the value of hiring qualified experts to reduce errors and related costs [[Figure 6\(c\)](#)].

Compared to the baseline scenario, the 50% improvement in adherence to standard degree requirements across scenarios, including RSD changes, decreased ambiguities in design rules and resulted in a progressive decrease in design expenses. However, the lack of universality and clarity in codes and standards led to a significant increase in design costs, with adherence to standards dropping by 50%. Owing to unclear criteria, mistakes were made at the initial design stage, resulting in costly redesigns and manufacturing delays. The simulations highlight how important it is for designers to be proficient and to follow explicit design guidelines to reduce design costs and ensure the effectiveness of the design process. Raising DEL and RSD speeds up project development, lowers redesign work and reduces the

chance of mistakes. These results imply that organisations had to prioritise professional training and the development of uniform design codes.

5.2.4 Transportation cost. The findings in [Figure 6\(d\)](#) show the total transportation costs (TC) under five scenarios that examine how weather and pilot vehicles affect OSC. As baseline conditions for transportation, the scenarios include “Pilot Zero”, with no pilot vehicles; “Pilot 1”, with one pilot vehicle; and “Pilot 2”, with two pilot vehicles. Two weather-related scenarios also examine 50% increases and decreases in unfavourable weather impacts on transportation operations. Because there are no additional expenditures related to pilot vehicles, the Pilot Zero scenario continues to have the lowest costs of any simulation. However, adding one or two pilot vehicles raises expenses by about 1.5% in the Pilot 1 and 2 scenarios, indicating a gradual increase in expenditures. This demonstrates the cost of maintaining operational safety and compliance, especially for large or specialised shipments that require a pilot truck to navigate correctly [[Figure 6\(d\)](#)]. The weather-related scenarios demonstrate how weather significantly influences transportation costs. The cost trajectory is steepest when unfavourable weather conditions increase by 50%, as they reduce operational efficiency, cause delays and increase the risk of damage to the materials being carried. The need for remanufacturing and retransportation further increases costs because of these damages. On the other hand, the scenario highlighting the advantages of good weather in preserving efficiency and reducing risks shows the lowest costs among the weather-related scenarios, with a 50% reduction in the costs of unfavourable weather conditions. Overall, the analysis highlights two crucial aspects that affect transportation costs: the unpredictability of weather conditions and the operational and safety requirements for pilot vehicles. Pilot vehicle safety is an actual expense, even if it is required for compliance and accident prevention. Similarly, unfavourable weather has direct financial repercussions (delays) and indirect ones (damage and rework), underscoring the need for backup plans, continuous monitoring and robust logistics to mitigate its effects.

5.2.5 Assembly cost. Four scenarios are examined in the IC analysis: two that address assembly delays (with increases of 50% and 25%, respectively) and two that address lifter availability and labour-related delays [[Figure 6\(e\)](#)]. A 50% increase in assembly delays results in the most significant increase in IC, followed by the 25% delay scenario. These findings suggest that assembly delays play a significant role in cost increases. Project timetables are frequently thrown off, labour and equipment standby costs rise and delays impact later project phases. Strategic scheduling and effective assembly resource management are crucial to reducing interruptions, as seen by the sharp cost increase in these cases. Delays caused by labour shortages have the same effect on IC as those caused by other factors, such as bad weather or difficulties at the job site. This result emphasises labour availability is important to preserving project budgets and schedules. To lessen these effects, it also underscores the need for effective staff planning, training and retention initiatives.

In contrast, lifter availability has a comparatively smaller influence on IC than in the other cases. This implies that the region’s lifter supply is usually enough and does not present a significant challenge to project operations. Lifters’ dependability and accessibility allow stakeholders to focus on more urgent issues, such as labour management, and to reduce delays caused by external factors [[Figure 6\(e\)](#)]. The analysis emphasises that the leading causes of increased IC are delays, particularly those because of personnel availability and assembly interruptions. Optimising IC and improving overall project performance will require addressing these delays by better scheduling, resource allocation and labour management. The results imply that to successfully lower cost escalations, the focus should be on addressing labour shortages and external delay factors, even though lifter availability remains stable.

5.3 Management discussion

The proposed model holds significant managerial implications for construction and project managers. Firstly, with appropriate modifications, this model can be adapted to evaluate other project elements, thereby enhancing its versatility and applicability across various contexts. For example, studies by [Nesarnobari et al. \(2024a\)](#) and [Liu and Luo \(2023\)](#) emphasise the importance of context-specific adaptations in OSC models to address unique logistical, regulatory and operational challenges. This adaptability empowers contractors to use the model as a decision-support tool to evaluate project expenses and delivery timelines under varying conditions. By leveraging simulations, stakeholders can anticipate and mitigate potential challenges, such as assembly delays or material shortages, aligning with broader SCM discussions on proactive barrier management ([Zhao et al., 2022](#)). Moreover, the model enables contractors to compare transportation, assembly and manufacturing companies to identify cost-effective and time-efficient options. However, there are some restrictions on how broadly the concept may be applied. For example, its usefulness may be affected by cultural differences in project management practices and by geographic limitations, such as transportation issues in remote areas. Additionally, the model's applicability in less developed OSC markets may be constrained by industry-specific characteristics such as the adoption of modern manufacturing technology or the availability of skilled personnel. These limitations are consistent with research by Sterman, who emphasised necessity of considering systemic variations when using dynamic models in various contexts ([Sterman, 1992](#)).

From a theoretical perspective, this study contributes to the broader literature by integrating SD into SCM for OSC, providing a comprehensive framework for evaluating interdependencies among project elements, such as design, manufacturing and assembly. It extends existing theories on dynamic modelling in construction (e.g. [MacAskill et al.](#) & [Liu et al.](#)) by addressing real-world scenarios, such as equipment delays and material waste, offering nuanced insights into cost and time optimisation ([Liu and Luo, 2023](#); [MacAskill et al., 2021](#)). Practically, the model emphasises actionable strategies, such as workforce training, advanced barrier management protocols and the recruitment of experienced panel designers. These recommendations resonate with the findings of [Hussein et al. \(2021\)](#) on the importance of capacity building and process standardisation in OSC for enhancing project efficiency and profitability ([Hussein et al., 2021](#)).

The discussion further underscores the cascading effects of assembly delays, which extend beyond project costs to impact client satisfaction, reputation and future business opportunities. As suggested by [Ajayi \(2019\)](#), investing in workforce training programs to improve skills and implementing robust risk management systems are critical for long-term competitiveness. Addressing these delays also aligns with global efforts to standardise OSC practices, reducing inefficiencies and improving predictability. Moreover, the study emphasises the value of experienced panel designers in minimising design errors, a finding supported by [Gusmao Brissi et al. \(2021\)](#), who identified design inefficiencies as a major contributor to cost and schedule overruns. Skilled designers reduce the need for rework in manufacturing and transportation, enabling projects to progress smoothly and efficiently. Similarly, workforce training for operating new manufacturing equipment emerges as a key recommendation, echoing [Ajayi \(2019\)](#) on the benefits of investing in human capital to enhance operational efficiency. By reducing equipment repair delays and minimising reliance on foreign technicians, projects can lower secondary costs, such as travel and accommodation, further optimising operational expenditure. The findings of this study have direct implications for housing affordability. By identifying material price volatility and manufacturing errors as the dominant cost drivers, the results highlight leverage points for

targeted interventions that could reduce overall construction costs. In the context of affordable housing delivery, even marginal improvements in cost control at the manufacturing stage can significantly influence final unit prices. The findings also reveal important implications for housing delivery time and material efficiency, both of which are critical factors influencing housing affordability. Time delays within OSC-SCM, particularly those related to manufacturing errors, transportation disruptions and coordination inefficiencies, can significantly extend project delivery timelines. In housing projects, prolonged construction durations increase financing costs, labour expenditures and overhead expenses, which are ultimately reflected in higher housing prices. Therefore, improving SC coordination and reducing production-related delays contribute to faster housing delivery and improved affordability outcomes.

Similarly, material waste imposes an additional economic burden, directly affecting the cost structure of residential construction. Inefficient material utilisation in panelised manufacturing processes leads to unnecessary consumption of raw materials, higher procurement costs and increased disposal expenses. In large-scale housing developments, cumulative waste across multiple projects can substantially elevate total construction costs. By identifying waste-generating processes within offsite manufacturing and SC operations, this study highlights opportunities for improving resource efficiency. Reducing material waste not only lowers construction costs but also supports more economically sustainable housing delivery, which is essential for addressing housing affordability challenges.

Finally, the study highlights the critical link between project errors and material waste generation, aligning with global sustainability debates. Damage to materials during transportation or fluctuations in moisture levels can result in significant waste, as [Zhang et al. \(2020\)](#) identified. Effective management strategies for delivering elements, from raw materials to the production site, are essential to minimise waste and optimise resource utilisation. This aligns with the broader SCM emphasis on lean construction and waste reduction to achieve sustainable project outcomes ([Peng, 2021](#)).

In conclusion, while the study's findings provide valuable insights for theory and practice, they must be contextualised within specific cultural, geographic and industry-specific factors. Future research could explore how the proposed model can be adapted to diverse OSC markets and integrated with emerging technologies, such as Industry 5.0, to enhance SC and efficiency further.

5.3.1 Implications for research, industry practice, housing policy and society. From a research perspective, this study extends OSC-SCM scholarship beyond static, factor-based and stage-specific assessments by representing cost, time and material waste as mutually dependent outcomes of one supply chain system. The model shows how upstream design, procurement and manufacturing disruptions can propagate into transportation and assembly rather than remaining confined to the stage in which they originate. Its added value is therefore not simply another catalogue of OSC barriers, but an empirically verified explanation of when and through which feedback mechanisms those barriers accumulate. This provides a reusable basis for future comparative studies, model refinement and hypothesis testing across panelised housing markets.

For industry practice, the scenario results provide a defensible order of managerial attention. Manufacturing should be treated as the primary cost-control point because it was the dominant component of construction costs, with material price volatility and manufacturing errors producing the strongest manufacturing cost effects. Procurement teams can use the model to stress-test price and supply assumptions; manufacturers can evaluate quality-control intensity, preventive maintenance and workforce arrangements; designers can test the consequences of experience levels and compliance with standardised design

requirements; and project managers can assess weather, transport, labour and assembly contingencies before committing to a delivery plan. Used at project gateways, the model can supplement conventional estimates with scenario ranges and reveal where a local saving may transfer cost, delay or waste to a later supply chain stage.

The commercial implication is improved risk visibility, not a guaranteed percentage saving. Developers, contractors and panel manufacturers can compare alternative suppliers, production plans, maintenance schedules, logistics arrangements and workforce investments under a common cost–time–waste framework. This can support more realistic contingencies, clearer allocation of disruption risk in contracts and earlier intervention where the simulated exposure is highest. In particular, the findings support prioritising design competence, material prices and supply controls, manufacturing quality, equipment reliability and labour continuity over lower-impact cost items. These applications may reduce rework, standby expenditure, financing exposure and programme uncertainty, but the magnitude of any benefit must be recalibrated using project-specific data.

At the housing-sector level, the study provides a means to link project-level operational decisions to aggregate delivery performance. If repeatedly applied across a programme or portfolio, the model can help housing providers and public procurers identify recurring bottlenecks that constrain panelised housing capacity, including scarce design and manufacturing skills, import exposure, factory reliability and logistics vulnerability. This evidence can inform pipeline sequencing, supplier development initiatives, workforce training, procurement, packaging and investment in domestic manufacturing capability. It can also help distinguish barriers that require firm level management from systemic constraints that may justify coordinated industry or government action. In this respect, the framework adds to existing practice by shifting attention from retrospective cost reporting to prospective testing of supply chain resilience before disruptions are embedded across multiple projects.

For public policy, the model should be used as a decision-support and policy-testing instrument, not as a direct prediction of national housing outcomes. Central and local government agencies could adapt it to examine how procurement rules, standardisation initiatives, training support, transport constraints or measures addressing material supply exposure might influence the reliability of offsite housing programmes. The model may also support evaluation of whether interventions improve delivery capacity without creating offsetting costs, delays or waste elsewhere in the SC. Because the present validation is based on two New Zealand residential cases, broader policy use requires calibration with data from additional regions, housing typologies, suppliers and market conditions.

The societal relevance arises through the pathways linking supply chain performance to housing delivery. Fewer design and manufacturing errors, more reliable scheduling and lower material waste may reduce avoidable project expenditure and improve the timeliness and environmental performance of residential development. At scale, these improvements could support housing affordability, supply reliability and residential quality of life; however, they should not be presented as automatic reductions in house prices. Land costs, finance, regulation, market structure and developer pricing also shape affordability, and the model does not estimate the pass-through of construction savings to purchasers or tenants. The defensible societal claim is therefore that the framework identifies controllable production and supply chain conditions that can support, but cannot alone secure, better housing outcomes.

The framework also has teaching value in construction management, SC and housing policy courses. Its causal-loop and stock-flow structures can be used to demonstrate feedback, delay propagation and trade-offs, while scenario exercises can train students and

practitioners to test interventions before implementation. Future research should develop portfolio- and sector-level versions of the model, quantify the pass-through from project efficiencies to dwelling prices and rents and evaluate implementation outcomes longitudinally. These extensions would test whether the project-level mechanisms identified here translate into sustained commercial and social benefits.

Collectively, the findings reveal that cost escalation, time delay and material waste patterns are structurally embedded within SC interdependencies (Sanaz [Nesarnobari, 2026](#)). This integrated understanding connects the literature-derived barriers, empirical validation and dynamic modelling outcomes into a unified analytical framework.

6. Conclusion

The developed SD model addresses key shortcomings in prior research by providing a practical and effective tool for evaluating the impact of various barriers on cost and schedule performance in panelised projects. The SD approach facilitates system-wide dynamic flow analysis, supporting managerial decision-making by enabling comprehensive modelling and simulation of interconnected activities and variables. The model's robustness and applicability were validated through rigorous testing, demonstrating its utility as an experimental platform for simulating diverse scenarios. This capability enables stakeholders to model and test the effects of various technical and managerial interventions, thereby identifying optimal solutions in advance. This study developed and validated a SD-based framework for analysing cost, time and material waste behaviour within panelised OSC-SCs under disruption conditions. Unlike static or stage-specific estimation approaches, the proposed framework captures dynamic interactions, feedback mechanisms and disruption propagation across interconnected SC stages, enabling a system-level understanding of OSC performance within the New Zealand housing context.

The study significantly contributes to the theoretical understanding of OSC-SCM. Through validating the SD model using real-world data, the research provides a robust framework for analysing the complexities of SCM in OSC. The findings deepen the theoretical debate by showcasing how barriers, such as logistics, regulatory compliance and quality control, interact to impact SC efficiency. The study also highlights the model's flexibility and adaptability across diverse settings, offering valuable insights for advancing its application in future research. The simulation findings demonstrated that material price volatility, manufacturing errors, labour shortages, transportation disruptions, weather conditions and assembly delays were among the most influential barriers affecting project performance. The results further revealed that upstream disruptions associated with design coordination, procurement and manufacturing reliability frequently propagated downstream, contributing to cumulative cost escalation, schedule overruns and material waste generation. These findings highlight the interconnected nature of OSC-SC behaviour and the importance of proactive coordination across design, manufacturing, logistics and assembly processes.

The study further demonstrates the practical value of SD modelling as a scenario-based decision-support tool for OSC stakeholders. At the project level, it enables testing of alternative disruption conditions and interventions relating to design capability, material procurement, manufacturing quality, equipment maintenance, workforce continuity, logistics and assembly planning. At programme and housing-sector levels, repeated application can reveal common capacity constraints, inform supplier and workforce development and support more resilient procurement and investment decisions. These uses can improve cost predictability, delivery reliability and resource efficiency, although any affordability or policy effects depend on project-specific calibration and on wider land, finance, regulatory and market conditions.

From a theoretical perspective, the study advances OSC-SCM research by integrating dynamic SC interactions, feedback structures and multi-stage cost–time–material waste analysis within a unified modelling framework. Practically, the findings provide actionable insights for improving SC resilience, reducing operational inefficiencies, strengthening workforce capability and enhancing decision-making in panelised housing delivery.

Future research may extend the model by incorporating additional operational variables, hybrid OSC systems and emerging digital technologies associated with Industry 5.0 environments, including AI-supported forecasting, digital twins and augmented decision-support systems. Such extensions could further improve the adaptability and robustness of OSC-SC planning under increasingly complex construction environments.

The originality of this research lies not merely in applying SD to OSC, but in integrating dynamic SC interactions, disruption propagation and multi-stage cost–time–material waste analysis within a panelised OSC context supported by empirical industry validation.

Data availability

Some or all data and models that support the findings of this study are available from the corresponding author upon reasonable request.

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Table A1. Variables and their classifications in the system dynamics model

No.	Variables	Abbrev.	Variable type
1	Material cost	MaC	Stock
2	Material usage change rate	MUCHR	Flow
3	Unit price of material	UPM	Auxiliary variable
4	Increased percentage unit price of material	IUPM	Auxiliary variable
5	Material quality check	MQCH	Auxiliary variable
6	Material error quantity	MEQ	Auxiliary variable
7	Material overdue quantity	MODQ	Auxiliary variable
8	Material usage quantity	MUQ	Auxiliary variable
9	Material supply quantity	MSQ	Auxiliary variable
10	Material demand quantity	MDQ	Auxiliary variable
11	Manufacturing labour cost	MLC	Stock
12	Manufacturing labour cost change rate	MLCCHR	Flow
13	Unit price of labour per month	UPLPM	Auxiliary variable
14	Manufacturing labour hours per month	MLHPM	Auxiliary variable
15	Manufacturing labour quantity	MLQ	Auxiliary variable
16	Manufacturing labour availability	MLA	Auxiliary variable
17	Manufacturing labour actual hours per month	MLAHPM	Auxiliary variable
18	Manufacturing equipment cost	MEC	Stock
19	Manufacturing equipment cost change rate	MECCHR	Flow
20	Equipment repair cost per month	ERCPM	Auxiliary variable
21	Equipment repair time	ERC	Auxiliary variable
22	Equipment repair quantity	ERQ	Auxiliary variable
23	Factory cost	FC	Stock
24	Element cost change rate	ECCHR	Flow
25	Unit price of element	UPE	Auxiliary variable
26	Element quantity demand	EQD	Auxiliary variable
27	Element quantity supply	EQS	Auxiliary variable
28	Element failure	EF	Auxiliary variable
29	Material waste increase	MWI	Auxiliary variable
30	Manufacturing regular cost	MRC	Auxiliary variable
31	Element damage	ED	Auxiliary variable
32	Design cost	DC	Stock
33	Design cost change rate	DCCHR	Flow
34	Unit design cost	UDC	Auxiliary variable
35	Project volume	PV	Auxiliary variable
36	Design required change	DRCH	Auxiliary variable
37	Design error	DE	Auxiliary variable
38	Design duration	DD	Auxiliary variable
39	Designer's experience level	DEL	Auxiliary variable
40	Require standard degree	RSD	Auxiliary variable
41	Transportation cost	TC	Stock
42	Transportation cost change rate	TCCHR	Flow
43	Unit price of transport for each KM	UPTKEM	Auxiliary variable
44	Transport time	TT	Auxiliary variable
45	Each crane time	ECT	Auxiliary variable
46	Road limitation	RL	Auxiliary variable
47	Pilot	Pilot	Auxiliary variable

(continued)

Table A1. Continued

No.	Variables	Abbrev.	Variable type
48	Pilot cost	PC	Auxiliary variable
49	Speed of pilot	SP	Auxiliary variable
50	Crane number	CN	Auxiliary variable
51	Transporting labour availability impact	TLA	Auxiliary variable
52	Speed of crane	SC	Auxiliary variable
53	Crane maximum tone	CMT	Auxiliary variable
54	Element tone	ET	Auxiliary variable
55	Road traffic	RT	Auxiliary variable
56	Transporting crane availability impact	TCA	Auxiliary variable
57	Weather impact	WI	Auxiliary variable
58	Installation cost	IC	Stock
59	Installation cost change rate	ICCHR	Flow
60	Lifter hours	LH	Auxiliary variable
61	Lifter quantity	LQ	Auxiliary variable
62	Lifter availability	LA	Auxiliary variable
63	Lifter failure	LF	Auxiliary variable
64	Unit price of lifter per hour	UPLPH	Auxiliary variable
65	Extra labour quantity needed due to delay	ELQN	Auxiliary variable
66	Labour availability	LAA	Auxiliary variable
67	Assembly labour quantity	ALQ	Auxiliary variable
68	Assembly labour hour	ALH	Auxiliary variable
69	Unit price of assembly labour per Hour	UPALPH	Auxiliary variable
70	DELAY	D	Auxiliary variable
71	Unit price of lifter due to delay	UPLD	Auxiliary variable
72	Construction cost	CC	Auxiliary variable
73	Manufacturing cost	MC	Auxiliary variable
74	EXPECTED COST	ExC	Auxiliary variable

Corresponding author

Sanaz Nesarnobari can be contacted at: s.nesarnobari@massey.ac.nz