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Panelised Offsite Construction Supply Chains in New Zealand Residential Sector: An Integrated System Dynamics and Multi-Objective Optimisation Framework

A thesis submitted in partial fulfilment of the requirements for the degree of

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Abstract

The New Zealand residential construction sector faces persistent capacity and productivity constraints, necessitating the adoption of practical solutions to meet growing housing demand. Offsite Construction (OSC) presents considerable potential to address residential delivery challenges; however, it has not yet been widely adopted within New Zealand. Therefore, their full potential for integration and widespread adoption remains unrealised. OSC performance is fundamentally shaped by Supply Chain Management (SCM) effectiveness, where Offsite Construction-Supply Chain Management (OSC-SCM) performance can be systematically measured through operational efficiency and the ability to withstand and resolve supply chain-related challenges. There is a lack of an integrated and dynamic framework that explicitly models and optimises panelised OSC-SCM performance by capturing the impact of supply chain barriers on cost, time, and material waste. To increase OSC acceptance and performance, this study assesses and examines the significance of aligning OSC procedures with SCM. To unlock the full benefits of offsite methods, organisations must prioritise aligning OSC strategies with robust supply chain management (SCM) practices, thereby improving operational efficiency and overcoming the challenges constraining their broader adoption. A deeper investigation into this matter, along with the underlying factors influencing OSC's performance, is therefore critical. Building on the findings of the literature review, this study develops a comprehensive framework for panelised OSC-SCM to enable a more rigorous examination of the critical factors impacting this effective integration. By addressing both project-level performance outcomes and higher-level management alignment, the research seeks to identify the underlying mechanisms through which these barriers contribute to the underperformance of residential OSC projects. The empirical findings from semi-structured interviews with key stakeholders highlighted several critical barriers to OSC adoption in New Zealand (NZ), including labour shortages, design modifications, crane and transport limitations, and weather-induced delays. To strengthen the credibility of these qualitative insights, a triangulation approach was employed, whereby interview evidence was systematically compared with system dynamics modelling outputs. This methodological integration revealed strong alignment between perceived and simulated disruptions, confirming that small but recurring schedule interruptions can escalate into significant project-level overruns through feedback loops. The system dynamics model further illuminated the complex interdependencies across cost, time, and material waste, demonstrating how isolated

inefficiencies within the OSC supply chain can trigger cumulative and non-linear effects on residential project performance.

This research proposes strategies for optimising panelised OSC–SCM and offers actionable guidance for construction firms and policymakers seeking to enhance capability, capacity, and overall performance in the residential sector. This study emphasises the material dimension of OSC, specifically the use of engineered panelised systems, alongside supply chain and project management factors. Depending on the system's design and use, each material makes a distinct contribution to improving OSC performance, whether through lower embodied impacts, greater precision, or reduced waste. The OSC-SCM framework's integration of sustainable material choices aligns construction performance objectives with broader environmental goals, positioning OSC as a key pathway for delivering low-carbon housing in NZ and internationally. In line with the boundary of this thesis, the environmental performance is considered as an embedded supply-chain outcome of OSC-SCM, focusing on embodied impacts rather than operational energy performance. This study emphasises how supply chain optimisation and the adoption of sustainable materials can work together to decarbonise the housing sector by integrating material choices within the OSC-SCM framework.

The study identifies and critically analyses the factors most influential in shaping OSC adoption and integration, considering not only its role within the housing industry but also its underlying operational processes and the decision-making resources required for effective implementation. Building on these insights, the multi-objective optimisation models created with the Genetic Algorithm (GA) and the Grey Wolf Optimisation (GWO) included the validated barriers. To identify feasible options under the stochastic conditions of OSC supply chains, each algorithm facilitated the investigation of trade-offs among time, cost, and material waste reduction. Together, the optimisation results provide a rigorous quantitative foundation for decision support, enabling practitioners to identify high-impact constraints, evaluate trade-offs, and configure supply chains more effectively.

The findings demonstrate how an optimal supply chain configuration can be achieved by systematically incorporating multiple schedule variabilities, thereby reflecting the stochastic realities of panelised OSC projects. Beyond improving predictive accuracy, the proposed model constitutes a foundational framework for a decision-support system specifically tailored to practitioners operating in OSC-SCM. Its application enables the quantitative identification and prioritisation of critical factors driving variations in both schedule and budget, providing a

transparent mechanism for risk-informed decision-making. The robustness of the framework was confirmed through rigorous quantitative validation, which illustrates its capacity to address the inherent complexity and uncertainty of supply chain scheduling in residential construction. These results underscore not only the model's practical utility for enhancing project-level performance and achieving measurable cost efficiencies but also its broader potential to inform strategic supply chain management practices and policy frameworks that support the scaling of OSC adoption in New Zealand's housing sector. These findings are equally applicable to international construction markets dealing with comparable issues.

Keywords: Offsite Construction, Panellised System, Supply Chain Management, Barriers, Optimisation, System Dynamics, Grey Wolf, Genetic Algorithm, Medium Density Houses, New Zealand.

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Table of Contents

1	Introduction.....	1
1.2	An Overview of Offsite Construction and Supply Chain Management	1
1.3	Panelised Offsite Construction in the Context of Residential Construction	5
1.4	Research Problem.....	7
1.5	Research Scope	10
1.6	Research Methodology	12
1.7	Reliability and Validity.....	14
1.8	Research Ethics	16
1.9	Research Significance	17
1.10	Thesis Organisation	18
2	Comprehensive Literature Review of Offsite Construction Supply Chain Management	20
2.1	Offsite Construction Supply Chain Management: A Scientometric Analysis and Systematic Literature Review.....	22
2.1.1	Introduction.....	23
2.1.2	Background	23
2.1.3	Research Methodology	24
2.1.4	Bibliometric Analysis.....	25
2.1.5	Scientometric Review.....	26
2.1.6	Systematic Analysis	27
2.1.7	Profile of Publication	27
2.1.8	Discussion.....	31
2.1.9	Discussion of Results	44
2.1.10	Conclusion	47
2.2	Investigation of the Effects of Supply Chain Disruptions on Offsite Construction Projects	49
2.2.1	Introduction.....	50
2.2.2	Methodology.....	51
2.2.3	Findings.....	53

2.2.4	Discussion.....	56
2.2.5	Conclusion	58
2.3	Mapping Supply Chain to Enhance Capability and Capacity of Prefabricated Housing Supply in New Zealand.....	60
2.3.1	Introduction.....	61
2.3.2	Literature Review.....	62
2.3.3	Research Methodology	67
2.3.4	Findings and Discussion	68
2.3.5	Conclusion	76
2.4	The Impact of Timber Offsite Construction on Global Warming.....	78
2.4.1	Introduction.....	79
2.4.2	Literature Review.....	80
2.4.3	Research Methodology	83
2.4.4	Results	83
2.4.5	Conclusion and Further Research	88
3	Research Methodology.....	90
3.1	Introduction.....	90
3.2	Research Philosophy and Paradigm	90
3.3	Research Philosophy Adopted for this Study	93
3.4	Research Conceptual Framework.....	95
3.5	Research Approach	98
3.6	Research Design	99
3.6.1	Data Collection & Analysis	101
3.6.2	Literature Review.....	102
3.6.3	Scientometric Review Method.....	102
3.6.4	Systematic Review Method	103
3.6.5	Semi-structured Interview Method	104
3.6.6	Triangulation Approach.....	105
3.6.7	Data Analysis	105
4	Toward Seamless Delivery: Qualitative Unravelling of Supply Chain Constraints in Offsite Construction.....	110
4.1	Introduction.....	111

4.2	Literature Review	113
4.3	Research Method	116
4.4	Expert Interviews.....	118
4.4.1	Case Studies.....	119
4.5	Findings.....	121
4.5.1	Interview Analysis	122
4.5.2	Material Sourcing Stage	122
4.5.3	Design Stage.....	123
4.5.4	Manufacturing Stage.....	124
4.5.5	Transportation Stage.....	125
4.5.6	Onsite Assembly Stage	126
4.5.7	Barriers Impact of Project Construction Cost of Delivery	126
4.5.8	Barriers Impact on Time of Delivery	127
4.5.9	Barriers Impact on Waste of Materials.....	128
4.6	Case Study Results	129
4.7	Discussion.....	133
4.7.1	Proposed Framework.....	136
4.8	Conclusion	140
5	System Dynamic Model on Cost-Time Estimation for Supply Chain Management of Offsite Panelised Systems in the Housing Sector.....	144
5.1	Introduction.....	145
5.2	Background	146
5.2.1	Barriers to SCM	146
5.3	Research Method	149
5.3.1	Triangulation Methodology	149
5.3.2	System Dynamics.....	150
5.3.3	System Boundary	152
5.4	Results	153
5.4.1	Challenges in SCM	153
5.4.2	Model Development	154
5.4.3	Data Collection	157
5.4.4	Model Validation	158

5.5	Results of Simulation and Discussion	160
5.5.1	Basic Simulation	160
5.5.2	Scenarios Discussions	162
5.6	Management Discussions.....	167
5.7	Conclusion	168
6	Unlocking the Full Potentials of Offsite Construction (OSC) by Optimising Its Procurement and Delivery	171
6.1	Introduction.....	172
6.2	Literature Review	174
6.2.1	Procuring Offsite Construction Projects	174
6.2.2	Delivering Offsite Construction Projects	177
6.3	Proposed Optimisation Framework.....	180
6.4	Research Method	182
6.4.1	Mathematical Modelling	183
6.4.2	Implementing the Framework: A Case Study Project	187
6.5	Discussion.....	194
6.5.1	Limitations and Recommendations for Future Studies	195
6.6	Conclusion	195
7	Time–Cost–Waste Trade-offs in Panelised Offsite Construction Supply Chain Management	197
7.1	Introduction.....	198
7.2	Background	200
7.2.1	Barriers to Supply Chain Management	200
7.3	Offsite Construction Supply Chains.....	201
7.4	Methodology.....	204
7.4.1	Notations	206
7.4.2	Problem Description.....	208
7.4.3	Problem Assumptions	209
7.4.4	Problem Formulation.....	209
7.4.5	Model output	214
7.4.6	Method GWO & Surrogate Machine Learning.....	214
7.5	Supply Chain Barriers	219

7.6	Case study: Offsite Panelised System for the Residential Sector	221
7.6.1	Case Background and Parameters	221
7.6.2	Quantifying the Barriers in the Panelised Supply Chain Process	223
7.7	Result Analysis	230
7.7.1	Cost Result Analysis	232
7.7.2	Time Result Analysis.....	232
7.7.3	Material Waste Analysis	233
7.7.4	Pareto Front Analysis	234
7.7.5	Sensitivity Analysis	235
7.8	Conclusion and Recommendations	237
8	Conclusion	240
8.1	Research Overview.....	240
8.2	Research Objectives and Key Outcomes	242
8.3	Integrated Decision-Oriented OSC-SCM Framework.....	244
8.4	Integrated Synthesis of Empirical Findings	247
8.4.1	Alignment with Research Objectives and Research Questions.....	247
8.4.2	Triangulation and Methodological Integration	249
8.4.3	Development of the Integrated OSC-SCM Framework	250
8.5	Theoretical Contribution and Recommendation	251
8.6	Methodological Contribution	251
8.7	Practical Contribution and Recommendation.....	252
8.8	Research Limitations.....	253
8.9	Future Research.....	254
9	References	256
10	Appendix A: Stock and Flow abbreviations.....	289
11	Appendix B: Ethics Approval	291
12	Appendix C: List of Questions	292
13	Appendix D : Author Contribution Forms	294

List of Tables

Table 1.1: Research questions and objectives.....	10
Table 2.1: Summary of the most explored keywords in OSC-SCM.....	28
Table 2.2: Design Stage-related Challenges and Strategies	34
Table 2.3: Challenges and Strategies related to Manufacturing process	36
Table 2.4: Challenges and Strategies Related to the Transportation Stage	39
Table 2.5: Challenges and Strategies related to the assembly part.	40
Table 2.6: Summarize of optimisation methods and objectives.....	42
Table 2.7: Supply Chain related Challenges in OSC	43
Table 2.8: Summary of mostly studied keywords.....	54
Table 2.9: Country active analysis	56
Table 2.10: List of disruptions adopted from recent works.....	58
Table 2.11: The carbon footprint of transporting each element	84
Table 2.12: Building Detail with Timber Element	84
Table 2.13: Building Detail with Steel Element	85
Table 2.14: Building Detail with Concrete Element	85
Table 3.1: Research objectives, methods and analysis.....	102
Table 4.1: Barriers of OSC-SCM based on the literature review over a decade	114
Table 4.2: Summary of case studies	130
Table 4.3: Comparison results for case studies	131
Table 4.4: Perceived Barriers to OSC-SCM in Prevalence Order.....	135
Table 5.1: Supply Chain based on literature review	148
Table 6.1: Dataset from the case study	189
Table 6.2: Crossover Operator	191
Table 7.1: Input parameters of the model.....	223
Table 7.2: Raw material-related barriers.....	225
Table 7.3: Probability of route segmentations and weather impact on transportation	227
Table 7.4: Probability of traffic impact on transportation	227
Table 7.5a: Probability of rainfall amounts across different intervals and factors affecting transportation rates	228
Table 7.6: Crane and labour availability impact on assembly	229
Table 7.7a: Probability of rainfall amounts across different intervals and factors affecting assembly rates.....	230
Table 7.8: Summary of Results	232

List of Figures

Figure 2-1: Methodology Framework	25
Figure 2-2: PRISMA flow diagram.....	27
Figure 2-3:Keywords co-occurrence map of reference.....	28
Figure 2-4:a. Visual network map of timber in OSC-SCM. Figure 2.4 b. Visual network map of SCM in OSC-SCM.	29
Figure 2-5: The OSC-SCM published study 2003-2023.....	30
Figure 2-6: Influential countries for OSC-SCM research	31
Figure 2-7: Gaps and Directions	32
Figure 2-8: Evaluation based on Literature Reviews.....	32
Figure 2-9: Proposed Framework for Supply Chain	33
Figure 2-10: Proposed framework for delivery of OSC-SCM barriers.....	46
Figure 2-11: Scientometric Approach.....	52
Figure 2-12: Keywords co-occurrence map of references.....	53
Figure 2-13: Country active analysis.....	55
Figure 2-14: The manufacturing process of Prefabrication in NZ (Sooriyamudalige et al., 2020).....	66
Figure 2-15: Research processes	83
Figure 2-16:Global Warming Potential for Timber, Steel, Concrete	86
Figure 3-1: Research Onion (Saunders et al. (2007)).....	93
Figure 3-2: Research onion adopted for this research Saunders et al. (2007)	94
Figure 3-3: Conceptual Framework.....	95
Figure 3-4: Research Framework	97
Figure 3-5: Research Design	100
Figure 3-6 : Whole process of thesis	101
Figure 4-1: Concept visualisation.....	116
Figure 4-2: Case Study Framework	120
Figure 4-3: Proposed Framework	138
Figure 5-1: Methodology Framework for System Dynamics	152
Figure 5-2: Mapping the challenges of the supply chain of OSC from triangulation methodology.....	154
Figure 5-3:Causal-loop and stock-flow diagrams of supply chain management	157
Figure 5-4: The model behaviour verification	160
Figure 5-5: The Construction Cost simulation results, b: The Manufacturing Cost simulation results.....	161
Figure 5-6: Result of different scenarios.....	166
Figure 6-1: Factors affecting OSC delivery.....	180
Figure 6-2:Flow Chart of Model Based on Case Study	190
Figure 6-3:Schematic Illustration of the Solution Approach based on GA Optimisation....	193
Figure 6-4:Diagram of the pareto front of the GA optimisation.....	193

Figure 7-1: Mapping the supply chain for OSC adopted from literature review	201
Figure 7-2: Methodology of the Research Paper	206
Figure 7-3: Framework of GWO	217
Figure 7-4: Flowchart of Optimisation	219
Figure 7-5: Causal-Loop diagram for OSC-SCM	220
Figure 7-6: Production, Transportation and Assembly Schematics of the Panelised System	222
Figure 7-7: The construction site of the project	223
Figure 7-8: Relationship between weather conditions and the impacting factors	228
Figure 7-9: Cost-iteration Diagram	231
Figure 7-10: Pareto Front for Objectives	235
Figure 7-11: Sensitive Analysis	237
Figure 8-1: Integrated decision-oriented framework linking dynamic barrier propagation, system behaviour, and optimisation-based decision regimes in OSC-SCM	246

Glossary

BIM - Building Information Modelling

CLD - Causal Loop Diagram

CLT - Cross-Laminated Timber

CM - Construction Management

CSCM - Construction Supply Chain Management

DB - Design and Build

DBB - Design-Bit-Build

DfMA - Design for Manufacturing and Assembly

GA - Genetic Algorithm

GDP - Gross Domestic Product

GHG - Greenhouse Gas

GWO - Grey Wolf Optimiser

JIT - Just-In-Time

LVL - Laminated Veneer Lumber

MC - Management Contracting

MDH - Medium Density Housing

ML - Machine Learning

MOGWO - Multi-Objective Grey Wolf Optimiser

NZ - New Zealand

NZD - New Zealand Dollar

OSC - Offsite Construction

OSC-SCM - Offsite Construction Supply Chain Management

PC - Precast Concrete

PBP - Prefabricated Building Project

PHB - Prefabricated Housing Building

PMSC - Prefabricated Manufacturing Supply Chain

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PM - Prefabricated Manufactured

RBV - Resource-Based View
SC - Supply Chain
SCI - Supply Chain Integration
SCM - Supply Chain Management
SCR - Supply Chain Risk
SCD - Supply Chain Disruption
SD - System Dynamics
SIP - Structural Insulated Panels
SLR - Systematic Literature Review
UK - United Kingdom
US - United States

List of Peer-reviewed Publications

Journal Articles

1. Chapter 2. Nesarnobari, S., Shahzad, W. M., Babaeian Jelodar, M., & Sutrisna, M. (2025). Offsite construction supply chain management: a scientometric analysis and systematic literature review. *Architectural Engineering and Design Management*, 21(3), 467-490.
2. Chapter 4. Nesarnobari. S., Shahzad. W., Jelodar. M. B., Sutrisna. M., (2026) “Toward Seamless Delivery: Qualitative Unravelling of Supply Chain Constraints in Offsite Construction”, *Journal of architectural engineering* 32(2), 05026003.
3. Chapter 5. Nesarnobari. S., Shahzad. W., Jelodar. M. B., Sutrisna. M., “System Dynamic Model on Cost-Time Estimation for Supply Chain Management of Offsite Panelised Systems in the Housing Sector”, 2025, Journal Paper Submitted (Under review).
4. Chapter 7. Nesarnobari. S., Shahzad. W., Jelodar. M. B., Sutrisna. M., (2026) “Time–Cost–Waste Trade-offs in Panelised Offsite Construction Supply Chain Management”, *Journal of Results in Engineering*, 30, 2590-1230.

Conference Papers

5. Chapter 2. Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Investigation of the effects of supply chain disruptions on offsite construction projects. In *International Conference on Engineering, Project, and Production Management* (pp. 161-172). Springer, Cham.
6. Chapter 2. Nesarnobari, S., Shahzad, W., & Jelodar, M. B. (2022, February). Mapping supply chain to enhance capability and capacity of prefabricated housing supply in New Zealand. In *7th New Zealand Built Environment research symposium* (p. 178).
7. Chapter 2. Nesarnobari, S., Shahzad, W. M., Jelodar, M. B., & Sutrisna, M. (2025). Impact of timber offsite construction on global warming. 47th Australian Universities Building Education Association (AUBEA2024) Conference.

Book Chapter

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1 Introduction

1.2 An Overview of Offsite Construction and Supply Chain Management

The construction sector is one of the most important investment areas worldwide, propelling infrastructure advancement and economic growth. In New Zealand, this sector is the fifth-largest industry, contributing around 6.3% of real GDP and employing over 300,000 people (MBIE, 2023). In 2023, it was valued at approximately NZ\$60.8 billion, with residential building alone accounting for NZ\$32.9 billion of work (MBIE, 2024). Notwithstanding its significant size, the sector faces persistent problems like low productivity, high employee turnover and broad skill shortages (Allison & Parker, 2013; Curtis, 2018; PWC, 2016). Maintaining efficiency and cost-effectiveness across projects becomes more challenging due to these operational constraints.

These difficulties are made worse by the widening gap between the supply and demand of affordable housing. The demand for housing has increased dramatically in recent decades due to a growing population, but the supply of available homes has not kept pace (Fitchett, 2022; Zhao et al., 2019). For many New Zealanders, this deficit has resulted in an increasing affordability dilemma and an increase in home prices (Treasury, 2024). Concerns about housing quality, price, and development speed have surfaced as persistent gaps in the current system, in addition to the acute lack of available dwellings (Charlotte Brown. et al., 2020). In order to improve profits and overall project viability, it is imperative to reduce costs and expedite construction processes, in addition to building more units, in order to address the housing problem. These problems are made worse by the industry's persistent skill shortages, which frequently result in poorer construction quality and a higher chance of reworks, which raises costs and delays even more (BDO, 2019; Gordon & Curtis, 2018; Rotimi, 2015). Recognising these challenges, there is a significant opportunity within New Zealand's residential sector to elevate industry standards. Establishing higher quality benchmarks and certification schemes could improve consumer confidence and drive overall improvements in construction quality (Buckett et al., 2014).

Researchers and business experts are increasingly looking for creative ways to address these systemic problems and mounting market pressures (Goulding & Arif, 2013). One approach that has shown significant promise is OSC. Many of the inefficiencies present in conventional onsite building techniques can be addressed by OSC by moving a sizable amount of the

construction process to controlled factory-based environments. According to construction professionals, this technique offers a convincing way to address the pressing need for affordable housing, in addition to promising to increase productivity and lower costs (Brandon, 2004; Tam et al., 2007).

However, persistent systemic issues may restrict the potential of OSC and other cutting-edge techniques. The industry's capacity to innovate and adjust to new approaches is nonetheless hampered by old housing regulations and rigid contracting procurement procedures (Brown et al., 2019; PWC, 2016). There is a strong financial incentive to get past these obstacles. According to study, the New Zealand economy could save over \$1.5 billion a year if construction productivity were to increase by just 5% (Construction Strategy Group, 2017). Additionally, it is estimated that OSC adoption will add about 1% to the country's GDP while providing substantial cost savings of up to 15% and a noteworthy 10% boost in productivity (Prefab NZ, 2019). These upgrades could finance a large number of projects without the need for extra government money, which would encourage more economic activity.

The industry can enhance OSC performance and substantially contributing to the country's larger economic and social development objectives by adopting these contemporary techniques and resolving conventional practices (Bakhtiarizadeh E et al., 2021). Offsite Construction (OSC) methods, mainly offsite panelised systems, are increasingly being adopted in the construction industry to enhance overall quality, reduce costs, and boost efficiency. These systems involve prefabricating building components in a controlled factory environment, which are then transported to the construction site for final assembly (Shahzad & Mbachu, 2012). This approach contrasts sharply with traditional construction methods that rely heavily on onsite work, where variables such as weather conditions, inconsistent workmanship, and limited control over materials can impede project timelines and quality (Nesarnobari S. et al., 2022a; Shahzad & Mbachu, 2012).

The controlled factory setting inherent in OSC provides several notable advantages, for instance, it allows for a more streamlined construction process that can significantly improve speed and efficiency. By manufacturing components in a standardised environment, there is a reduction in material waste and enhanced safety, as the risks associated with onsite hazards are minimised (Tsz Wai et al., 2021). Additionally, the systematic nature of factory production can enable better sustainability management practices, contributing to more environmentally friendly building processes through effective waste reduction and energy use control.

Numerous studies have highlighted the multifaceted benefits of OSC. Previous research reported its positive impact on sustainability (Hu et al., 2019) as well as on improving safety outcomes as one of the key advantages (Li et al., 2015). The cost-effectiveness of OSC is supported by further findings, which suggest that offsite methods can significantly reduce construction expenses (Khalili & Chua, 2013). Furthermore, the panelised systems have been documented as a prefabrication technique that leads to more precise and consistent construction outcomes (Nesarnobari S. et al., 2022c). Regarding environmental impact, it has been demonstrated that OSC methods can lead to reduced carbon emissions, an increasingly important consideration in modern construction (Nesarnobari S. et al., 2022a). The potential advantage of shortening production times was also reported, further enhancing the appeal of OSC (Taghaddos et al., 2014).

Despite these clear benefits, the widespread adoption of OSC, especially offsite panelised systems, faces several long-term barriers. One of the primary challenges lies in the need for effective collaboration across various phases of the construction process, including design, preparation, production, logistics, and assembly. The integration of these phases can be complex and requires a high degree of coordination among diverse stakeholders (Shahzad et al., 2023). These challenges are compounded by the fact that existing systems and practices are often deeply entrenched in traditional construction methods, making it difficult to shift towards more innovative approaches. As a result, while the demand for offsite construction methods is growing, their market penetration remains relatively limited, with adoption rates for such construction elements still accounting for less than 20% of the overall industry.(Broadhead, 2023; Nesarnobari S. et al., 2022a). Overcoming these systemic challenges is crucial to unlocking the full potential of OSC. Only through enhanced collaboration, modernisation of industry practices, and overcoming logistical challenges can the construction sector fully capitalise on the numerous benefits of offsite construction methods (Nesarnobari S. et al., 2022b; Zohourian et al., 2025).

These challenges of OSC can be strongly related to the efficiency of its supply chain management (SCM). SCM involves a product transformation process where items are converted from raw materials to inventory, then work-in-progress, and ultimately into completed goods, thereby creating a comprehensive supply chain (Mostafa, Dumrak, et al., 2014). This process, when applied to OSC, referred to as OSC-SC, exhibits unique characteristics that set it apart from traditional construction supply chains. In the OSC supply chain, various stakeholders play crucial roles. This network includes manufacturers who

produce the prefabricated components, suppliers who provide the necessary raw materials, developers who conceptualise and finance projects, contractors who manage onsite assembly, and distributors who coordinate the delivery of components to the construction site (Mostafa, Chileshe, & Zuo, 2014). However, the integration of these diverse entities into a cohesive supply chain is not without its challenges. Several barriers hinder the seamless integration of OSC within traditional construction supply chains. These include the fragmentation of roles and responsibilities among stakeholders, logistical challenges in transporting prefabricated modules, a lack of standardisation across components and processes, and varying regulatory requirements that differ by region or project type (Nesarnobari et al., 2024d; Zhang, Jiang, et al., 2024). These challenges can significantly disrupt the smooth flow of resources, information, and supplies throughout the supply chain. The resulting disruptions often lead to delays, increased costs, and compromised quality in the final construction projects. For instance, inconsistent information flow can lead to procurement errors, while logistical misalignments might delay the delivery of critical components, necessitating costly reworks. To overcome these issues, strategic SCM practices become essential. Practices such as fostering collaboration among stakeholders, implementing effective management protocols, and committing to continuous improvement can mitigate many of these challenges. By optimising the supply chain, stakeholders can unlock OSC's full potential, delivering faster, more affordable, and higher-quality housing solutions to meet the increasing market demand (Wang, Hu, H., et al., 2019). Furthermore, the gaps identified in current OSC supply chains often necessitate the development of tailored SCM models that address every aspect of the process. Given the complexity, large scale, and relatively brief duration of construction projects, especially those involving OSC, any proposed models must be capable of managing myriad of interactions. This includes ensuring seamless information flow, streamlining procurement processes, and optimising logistics operations. Such measures are critical to minimising the financial repercussions of reworks and ensuring the overall efficiency and reliability of the supply chain (Peter et al., 2020).

This research contributes by developing an integrated and dynamic panelised OSC-SCM framework that combines system dynamics modelling and optimisation techniques to support decision-making under uncertainty. The framework enables stakeholders to evaluate cost, time, and material waste trade-offs and improve supply chain performance in panelised construction. The framework is designed as a decision-support framework for practitioners involved in planning, scheduling, and managing supply chain risks in panelised OSC projects.

1.3 Panelised Offsite Construction in the Context of Residential Construction

OSC emerged in the 1800s and has since been known by various terms, including manufactured construction, Offsite Production (OSP), Offsite Manufacturing (OSM), and prefabricated construction. It refers to a construction method that relocates the majority of construction activities from the project site to a controlled environment, typically a manufacturing or factory facility (Prefab NZ., 2014). OSC's ability to enhance efficiency and precision, incorporate environmental features, better utilise the shrinking workforce, and shorten construction timelines has sparked growing interest (Goulding et al., 2014; Smith, 2010). The construction industry has been adapting OSC to address the increasing demand for quicker delivery of higher-quality housing (Gibb, 1999; Smith, 2010). Different variations of this method have been applied across various projects, including in the housing sector. OSC is particularly well-suited for housing, as work is carried out in a safe, controlled environment shielded from weather disruptions (Sutrisna & Goulding, 2019). Offsite construction is generally categorised into five types. (I) Component, (II) Panel, (III) Volume (3D module), (IV) Hybrid (volume + panel) and (V) Complete Building (Prefab NZ, 2018b).

According to the research, in New Zealand, the most common form of OSC is panelised OSC, consist of concrete-based and offsite timber (Moradibistouni & Gjerde, 2017). Timber offsite components are in high demand at various stages of construction, like walls, floors, roofs, precast beams and façades, tunnel linings, bridge girders, sewage discharge units, underground facilities, etc. A robust adoption necessitates a thorough knowledge of industrial technology, collaboration among SC stakeholders and complete government support (Samarasinghe. & Wood., 2021). The more offsite elements, the less time required for onsite work, and the better the quality, but extra complex transport problems.

Cost advantages, reduced construction time (Chen & Samarasinghe, 2020), eco-friendliness, safety, greater flexibility in techniques, lower waste (Mendoza, 2018), fewer defects (Cook B, 2005; Hashemi A & Hadjri K, 2014) and raised levels of health and safety (Chen & Samarasinghe, 2020; Moradibistouni et al., 2017) lessen the possibility of construction delays due to weather problems such as rainfall and wind and site exposure (Hu et al., 2024) for New Zealand projects led by offsite and assembly technology development. Eliminating dependency on the weather for site-based construction, more effective coordination of sub-trades in-house, reduced transportation, and bulk procurement price advantages can help cut timeframes and costs. Tighter quality controls and the capacity to test systems and prototypes within the factory

are merits of offsite. It can reduce the number of errors and subsequent repair work during the defect's liability period after occupancy. There will likely be less noise and neighbourhood risks on-site. They can differ in appearance and are frequently indistinguishable from conventionally built dwellings, have a lower carbon footprint due to less transportation and lower energy consumption over their lifetime (Gorgolewski, 2005). An offsite can be less expensive than a site-built building of precisely the same specs, configuration, and quality, due to the cost reductions inherent in the construction technique if the process completed without errors (Buchanan M, 2004), through efficient ordering, indoor protection, pre-planning, and cutting, able to eliminate material waste. Offsite construction can help address challenges in the building sector, including rising market expectations for higher-quality housing and the increasing stringency and expanding scope of regulatory requirements for building design, construction quality, and compliance processes. This technology is utilised in constructing houses, multi-storey buildings, roads, and bridges (Ngowi et al., 2005). The use of offsite simplifies construction activities and can decrease the need for external contractors and plastering and tiling (Poon et al., 2003). This could result in a reduction in the responsibility of staff management (R Roy, 2003) and a significant increase in total speed (Lu N & Korman T, 2010). Also, a reduction in the responsibility of staff management (Britto, 2008; Moradibistouni & Gjerde, 2017). The savings in onsite time can help balance the higher costs of new material development or pre-construction planning processes involving large offsite components (Aburas, 2011; Bildsten, 2011; Prefab NZ., 2014)

OSC has been routinely promoted to develop residential construction efficiency, quality and environmental performance (Steinhardt & Manley, 2016). However, several factors have been recognised as barriers that hinder the uptake of this method, like supply chain, procurement and knowledge (Becker, 2005; Blismas, 2006), negative perception, shortage of skills/experience, finance, lack of coordination and communication, site operations, design shortage, lack of ability to alter designs to respond to site context, lack of government support, transportation due to limited size for transferring (Gibb, 1999; Smith, 2010). Furthermore, from societal perspective, offsite buildings are low-quality buildings without aesthetic value, with the output of a repetitive, fully standardised and non-creative mechanical process (Jabar, 2014). Market failures have affected offsite construction sector (Prefab NZ, 2018b). The offsite industry is relatively new, and because of that, rules and standards have not yet been fully developed (Noktehdan et al., 2015). These challenges have contributed to the slower acceptance and hence the adoption of the offsite building system.

Unlike existing studies, this research integrates system dynamics and optimisation within a unified OSC-SCM framework, explicitly capturing the impact of supply chain barriers on cost, time, and material waste.

1.4 Research Problem

New Zealand is currently confronted with a significant housing shortage, driven by accelerated population growth and persistent issues. This situation necessitates immediate and effective interventions to enhance the provision of affordable housing (Allison & Parker, 2013; Curtis, 2018; PWC, 2016). OSC is a natural synergy of the manufacturing and construction sectors, employing techniques that exhibit significant overlap (Gann, 1996). It serves as an effective approach for offsite manufacturing and production in both mature and emerging markets (Goulding & Arif, 2013). OSC, particularly through offsite panelised systems, represents a promising innovation that integrates manufacturing principles with traditional construction practices by prefabricating building components within controlled factory environments prior to on-site assembly.

This approach offers demonstrable advantages over conventional construction methods, including improved quality control, cost reduction, accelerated construction schedules, enhanced occupational safety, superior sustainability management, and notable waste reduction (Tsz Wai et al., 2021). Despite these benefits and the increasing adoption of OSC in both mature and emerging markets internationally, its penetration in New Zealand's housing sector remains marginal, accounting for less than 20% of housing production (Linner & Bock, 2012; OffsiteNZ., 2021). This low adoption rate signals substantial opportunities for growth and underscores the necessity for targeted market interventions (Nesarnobari S. et al., 2022c; Zohourian et al., 2025).

The supply chain underpinning OSC diverges markedly from that of traditional construction, characterised by distinct stages encompassing design development, factory-based manufacturing, inventory management at both factory and site, logistics, and on-site assembly (Ikonen et al., 2013). This complex network necessitates collaboration among a heterogeneous array of stakeholders, including manufacturers, suppliers, developers, contractors, and distributors, each operating according to their own protocols, schedules, and quality standards (Mostafa, Dumrak, et al., 2014). The resultant interdependencies introduce significant complexity and issues; inefficiencies or challenges at any point within the supply chain can

propagate downstream, adversely affecting subsequent stages and undermining overall project performance (Gan et al., 2004; Said, 2015).

Effective SCM is therefore recognised as pivotal for the successful deployment and scalability of OSC within New Zealand (Nesarnobari et al., 2024b; Wang, Hu, H., & Gong, J., Ma, X., & Xiong, W., 2019). However, integrating OSC processes into extant conventional supply chains presents formidable challenges, primarily attributable to a limited understanding of the specific barriers involved (Wang Z.-L. et al., 2019). These challenges are exacerbated by the imperative for enhanced collaboration and transparent communication across the supply chain network (Mostafa, Chileshe, & Zuo, 2014). The dynamic nature of OSC demands robust, concurrent management strategies capable of handling real-time information and material flows, promptly adapting to client-driven design changes and evolving project requirements and relying on supply chain partners with sufficient flexibility to ensure seamless integration and operational continuity (Gibb & Isack, 2010; Mostafa, Dumrak, et al., 2014).

For instance, client-initiated design modifications frequently precipitate delays during the onsite assembly phase, resulting in cost escalations and schedule overruns. Moreover, suboptimal factory and site layout management often leads to inventory imbalances, causing downstream installation delays and logistical bottlenecks. Although international research has shed light on these supply chain complexities, recent studies within the New Zealand context indicate that, despite improvements in OSC performance in residential construction, SCM remains an intricate and under-explored domain that constrains broader adoption.

There exists a critical need for comprehensive research to clarify the key factors influencing OSC supply chain performance and to develop targeted optimisation strategies that accommodate the unique characteristics of this sector. Particular attention should be directed towards timber-based panelised systems, which align with New Zealand's sustainability objectives. Panelised systems are particularly relevant within the New Zealand context due to their alignment with national sustainability objectives and increasing emphasis on reducing embodied carbon emissions in the built environment. As a renewable and locally available material, timber has the potential to support both environmental performance improvements and supply chain efficiency within OSC systems. This makes panelised systems a strategically relevant focus for improving both environmental performance and supply chain efficiency in New Zealand. Enhancing SCM efficiency in OSC will not only improve productivity and cost-effectiveness but also contribute significantly to alleviating the country's housing affordability

crisis by facilitating the delivery of high-quality, affordable homes (Bakhtiarizadeh E et al., 2021; Nesarnobari et al., 2024b).

Although previous studies have examined individual OSC-SCM barriers and performance factors, existing research remains fragmented and lacks an integrated dynamic and optimisation-based framework capable of systematically analysing their interdependencies within the New Zealand residential construction context.(Clyde Zhengdao Li et al., 2024; Nesarnobari et al., 2024b). Consequently, construction practitioners face difficulties making informed decisions that can optimise project outcomes in panelised OSC supply chains. This research addresses this gap by developing a robust framework that integrates critical OSC-SCM barriers into a system dynamics model and a multi-objective optimisation algorithm to enhance project performance through improved alignment and decision making. There is a lack of an integrated, dynamic, and optimisation-based framework for panelised offsite construction supply chain management in New Zealand capable of systematically modelling the impacts of supply chain barriers on project cost, time, and material waste performance. Research Aim, Questions and Objectives

This thesis aims to develop and evaluate an integrated dynamic and optimisation-based framework for improving panelised offsite construction supply chain management performance in New Zealand's residential sector through the modelling of supply chain barriers, system interactions, and multi-objective optimisation of project cost, time, and material waste. In order to effectively achieve this aim, the following research questions and objectives have been developed (Table 1.1)

Table 1.1: Research questions and objectives

Research Objectives (RO)	Research Questions (RQ)	Covered in
	Main Research Question: How can an integrated, dynamic, and optimisation-based framework improve the performance of panelised offsite construction supply chain management in New Zealand's residential sector under supply chain barriers and uncertainties?	All chapters
1. To systematically examine and synthesise the literature related to panelised OSC-SCM.	1. What are the critical barriers, enabling factors, and supply chain characteristics influencing panelised offsite construction supply chain management in New Zealand's residential sector? 2. What strategies have been identified in the literature to mitigate OSC-SCM barriers and improve cost-time-material waste performance?	Chapters 2
2. To empirically identify and critically analyse the key factors impacting the implementation of panelised OSC-SCM in residential projects in New Zealand.	1. What are the critical barriers, enabling factors, and supply chain characteristics influencing panelised offsite construction supply chain management in New Zealand's residential sector?	Chapter 4
3. To develop and evaluate a robust model to capture the dynamic interactions between cost and time in OSC-SCM in residential projects in New Zealand.	How do dynamic interactions among supply chain variables influence project cost, time, and material waste in panelised offsite construction systems?	Chapter 5
4. To optimise the performance of panelised offsite construction supply chain systems using metaheuristic optimisation techniques to minimise project cost, time, and material waste under supply chain uncertainties.	How can metaheuristic optimisation techniques improve the performance of panelised offsite construction supply chains under uncertainty conditions?	Chapters 6 and 7

1.5 Research Scope

This study examines the supply chain management of offsite construction in New Zealand's residential sector, with a specific focus on panelised systems, given their extensive use in New Zealand (Helm, 2025; Masood et al., 2023; Nesarnobari et al., 2024b). The OSC supply chain includes five key stages: (I) raw material preparation, (II) design, (III) manufacturing, (IV) transportation, and (V) on-site assembly. Each stage is interdependent, and challenges at one stage can generate issue effects across the entire system, influencing cost, schedule, and

material efficiency. The significance of investigating these stages lies in their collective role in determining the overall performance of OSC projects (Masood et al., 2022; Nesarnobari S. et al., 2022c; Salari et al., 2022). Within the context of New Zealand, where a rapidly growing population over the past decades has intensified the demand for affordable and sustainable housing (Finnie et al., 2018), optimising each of these stages is critical. A robust understanding of this five-stage framework not only supports the wider adoption of OSC and therefore addresses pressing national priorities, including reducing construction costs, minimising delays, cutting material waste, and lowering the sector's carbon footprint (Kiernan, 2019). The escalating demand for residential housing in New Zealand has exposed significant limitations within traditional construction methods, which increasingly struggle to deliver projects efficiently (MBIE, 2020; Mitchell. et al., 2023). This situation necessitates exploring innovative construction techniques capable of addressing these challenges more effectively (Shahzad et al., 2023). OSC is one such technique that has been widely embraced in international markets such as Sweden, the United Kingdom, and Japan, where it has demonstrated considerable benefits in terms of construction speed, cost efficiency, and quality control (Brown et al., 2020). Research by Building Research Association of New Zealand (BRANZ) highlights that the current annual output of OSC within the country is estimated at approximately 2.95 billion NZD. However, this figure represents only a part of the industry's full potential, as capacity assessments suggest that the sector could feasibly support production levels approaching 5 billion NZD annually (Page, 2014). It demonstrated low uptake of OSC in New Zealand. This gap indicates a significant underutilisation of existing resources and capabilities within the OSC industry. However, these capacity gaps cannot be effectively addressed without understanding and optimising the underlying supply chain mechanisms that govern OSC performance. Moreover, based on the successful delivery of OSC projects in other countries and the capacity of the New Zealand market, it can be inferred that substantial opportunities exist to increase efficiency and expand production through better resource allocation and process optimisation (Prefab NZ, 2018a). Addressing these gaps is critical for leveraging OSC's full potential to contribute to resolving New Zealand's housing shortage through scalable and sustainable construction practices.

Construction projects are inherently complex systems involving multiple interdependent processes and stakeholders. Offsite construction has been introduced as a strategy to improve efficiency and productivity; however, within this domain, panelised systems present both opportunities and operational challenges. Despite these advancements, supply chain

inefficiencies continue to affect cost, time, and material waste performance. Therefore, there is a need to develop an integrated modelling and optimisation framework to address these challenges.

This study focuses on modelling and optimising the five key stages of the OSC supply chain to improve cost, time, and material waste performance. These stages are examined to understand their interactions and the challenges they pose to efficient supply chain operation. The study applies both process optimisation techniques and system dynamics modelling to analyse and improve the time and cost performance within the OSC supply chain. By integrating these approaches, the research has captured the dynamic and complex nature of supply chain activities and provide actionable strategies for reducing delays and costs. Particular attention is given to identifying critical barriers, including material delays, design modifications, labour availability fluctuations, and logistics constraints, which significantly impact supply chain efficiency.

This research focus on residential construction projects of Medium-Density Houses (MDH) using panelised timber OSC methods in New Zealand. Furthermore, the study addresses supply chain impacts on project time and cost. The developed optimisation framework is validated through simulation and modelling, utilising real or representative data from New Zealand offsite construction projects to ensure practical relevance. The framework employs empirical or representative case data derived from New Zealand housing projects, with data sources comprehensively described in Chapters 4–6.

1.6 Research Methodology

This research adopted an integrated mixed-methods methodology to investigate and optimise panelised offsite construction supply chain management (OSC-SCM) within New Zealand's residential construction sector. The methodological design was developed to address the complex, dynamic, and interdisciplinary nature of OSC-SCM by combining qualitative inquiry, system dynamics modelling, probabilistic simulation, and multi-objective optimisation techniques within a unified analytical framework. The research process was structured across several interconnected stages, enabling both exploratory and analytical examination of supply chain barriers, system behaviours, and optimisation opportunities influencing project performance.

The study commenced with a comprehensive literature review comprising systematic and scientometric review approaches to critically examine existing knowledge related to offsite

construction, supply chain management, supply chain disruptions, environmental sustainability, and optimisation methods within OSC environments. The literature review also examined the New Zealand residential construction context and identified critical knowledge gaps associated with fragmented supply chain practices, dynamic operational uncertainties, and the limited integration of optimisation techniques within OSC-SCM research. The findings of the literature review informed the conceptual foundation of the study and supported the identification of key variables, barriers, and system components relevant to panelised OSC-SCM.

Following the literature review stage, a qualitative investigation was undertaken through semi-structured interviews with fifteen key stakeholders involved in New Zealand's panelised offsite construction sector, including manufacturers, contractors, consultants, engineers, and supply chain participants. The qualitative phase aimed to explore the critical barriers, operational constraints, enabling factors, and interrelationships affecting OSC-SCM performance across different stages of the supply chain. The interview data were analysed using thematic analysis techniques to identify recurring patterns, causal relationships, and system-level interactions influencing project cost, time, material waste, coordination efficiency, and supply chain responsiveness. The findings from the qualitative stage subsequently informed the development of the causal structure underpinning the system dynamics model.

A system dynamics (SD) modelling approach was subsequently employed to capture the complex feedback relationships, interdependencies, delays, and nonlinear interactions characterising panelised OSC supply chains. The SD model was developed using causal loop diagrams and stock-and-flow structures to simulate the dynamic behaviour of key supply chain variables and evaluate their impacts on project cost, construction time, and material waste performance. The modelling process enabled the investigation of both reinforcing and balancing mechanisms affecting OSC-SCM performance under varying operational conditions. To further represent uncertainty and variability within the supply chain environment, Monte Carlo simulation techniques were integrated into the modelling framework to generate probabilistic scenarios associated with factors such as labour availability, weather conditions, material supply disruptions, transportation delays, design changes, and operational variability.

To enhance supply chain performance and identify optimal operational strategies, the research further applied metaheuristic optimisation techniques, including Genetic Algorithm (GA) and Multi-Objective Grey Wolf Optimiser (MOGWO). These optimisation methods were utilised

to minimise project cost, construction time, and material waste simultaneously while accounting for the dynamic interactions and uncertainty conditions identified throughout the earlier stages of the research. In addition, surrogate modelling techniques using Random Forest algorithms were incorporated to improve computational efficiency and support the optimisation process. The integration of simulation-based modelling with optimisation approaches enabled the identification of optimal trade-offs and operational scenarios across multiple supply chain performance objectives.

Finally, the findings from the literature review, qualitative investigation, system dynamics modelling, probabilistic simulation, and optimisation analyses were synthesised into an integrated conceptual framework to improve panelised OSC-SCM performance in New Zealand's residential construction sector. The overall methodological approach enabled the research to investigate OSC-SCM from strategic, systemic, and operational perspectives while providing a comprehensive understanding of the complex interactions influencing supply chain performance, resilience, and optimisation opportunities in panelised offsite construction systems.

1.7 Reliability and Validity

The quality of research must be assessed before it can be applied in practice (Noble & Smith, 2015). Validity and reliability are two critical metrics for assessing the credibility of research. The degree of credibility of research instruments is known as validity. On the other hand, reliability measures the credibility of the data collected using a valid research instrument (Creswell John W., 2016).

A study's validity is determined by how well it measures or depicts the ideas it aims to investigate, guaranteeing that the findings are reliable and relevant to actual situations. Measurement of validity, internal validity, and external validity are the three main components of validity, according to Saunders et al. (2016). While internal validity refers to whether the research instruments accurately assess what they are supposed to measure, external validity deals with how well the instruments of the study can be applied to other comparable contexts. On the other hand, reliability refers to how consistently and steadily study findings hold up over time, under various circumstances, or among observers.

By using techniques like triangulating data sources and methods, using systematic data collection procedures, and carrying out thorough data analysis, researchers can improve

validity and dependability. While statistical methods are frequently employed to support dependability in quantitative studies, rigour, transparency and reflexivity further strengthen validity in qualitative research. These components work together to reflect reliable, repeatable, and strong study results.

The OSC supply chain was analysed and improved in this study using a combination of optimisation techniques and system dynamics modelling. A more in-depth comprehension of the underlying processes and behaviours across time is made possible by system dynamics, which makes it easier to simulate intricate interactions and feedback loops inside the supply chain. In order to achieve more effective, economical, and timely project delivery, optimisation techniques were then used to enhance decision-making and resource allocation. The study effectively captured the dynamic nature of the system and offers practical ideas for improving performance by combining these two approaches.

Since case studies provide a thorough analysis of actual OSC projects, they were essential to guaranteeing the validity of this research. By enabling the investigation of causal links within the context of SCM, they supported internal validity and raised the findings' trustworthiness. In order to ensure that the concepts being studied are adequately portrayed, case studies employed a variety of data sources, including observations, documentation, and interviews. through a structured, multi-layered methodological design. For the SD component, structural validity was established by grounding causal relationships, feedback loops, and time delays in empirical evidence derived from case studies, semi-structured interviews, and project documentation within real-world Offsite Construction (OSC) supply chains. This ensured that the model structure reflected observed decision-making behaviour and operational constraints rather than abstract or assumed dynamics.

Behavioural validity of the SD model was evaluated by examining whether simulated system behaviour reproduced plausible patterns observed in practice, including delay propagation, cost escalation under disruption, and resource bottlenecks across design, manufacturing, logistics, and on-site assembly stages. Sensitivity analyses were conducted to assess the robustness of model behaviour under variations in key parameters, thereby enhancing confidence in the model's explanatory capacity under uncertainty.

The credibility of the optimisation component was ensured by embedding the optimisation process within the SD simulation environment rather than applying it to a static or deterministic formulation. Outputs from the SD model, capturing time-dependent interactions, barrier propagation, and feedback effects, were used to define the optimisation search space, constraints, and performance measures. A multi-objective Grey Wolf Optimiser (MOGWO)

was employed to identify Pareto-optimal trade-offs between time, cost, and waste, enabling transparent evaluation of competing objectives rather than reliance on a single optimal solution. To address uncertainty, probabilistic inputs and Monte Carlo simulation were incorporated prior to optimisation, enabling robustness of the solution to be assessed across a range of disruption scenarios. This approach strengthened the decision credibility of the optimisation results by ensuring that identified solutions remained effective under realistic variability rather than idealised conditions. Collectively, the integration of empirically grounded SD modelling with uncertainty-aware multi-objective optimisation ensured that the findings are methodologically valid, analytically robust, and suitable for informing decision-making in OSC supply chain practice. Furthermore, by choosing a variety of situations, the study improved external validity and the results' applicability to comparable OSC environments. This methodological approach guarantees that the results are reliable, grounded in context, and useful for industry practice.

1.8 Research Ethics

Ethical considerations have become increasingly significant in research, particularly during the data collection phase. It is imperative for researchers to conduct their studies in an ethical manner, ensuring respect and protection for all participants involved. Research ethics refer to the set of behavioural guidelines that govern interactions with participants throughout the data-gathering process (Saunders et al., 2016). These guidelines are grounded in societal norms and the philosophical foundations of ethical conduct. Given that individual behaviours and ethical perspectives can vary depending on context and philosophical stance, differing interpretations of ethical practices exist. To address these variations, formal codes of ethics have been developed to provide clear frameworks for ethical research conduct.

For this study, the code of ethics established by the Massey University Human Ethics Committee (MUHEC) was strictly adhered to. Ethical principles were observed consistently from the outset to the conclusion of the research. The ethical framework guiding this research is informed by the principles set out by the MUHEC. These principles include respect for individuals and their autonomy; the minimisation of potential harm to participants, researchers, institutions, and affected groups; the requirement for informed and voluntary participation; the protection of privacy and confidentiality; the avoidance of unnecessary deception; the management and avoidance of conflicts of interest; sensitivity to social and cultural factors such as age, gender, culture, religion, and social background; and the fair and just treatment of

all participants (Shahzad, 2011). Since the data collection involved human participants, an application for ethical approval was submitted to MUHEC and subsequently granted. The approval, categorised under low-risk research, was valid for three years, with the assigned ethics notification number 4000026647.

1.9 Research Significance

The results of this study are expected to bridge the existing knowledge gaps between offsite housing projects and its supply chain management. Despite increased focus on construction supply chain strategies in recent years, the offsite construction sector continues to face significant challenges, largely due to broader industry fragmentation (Sayed, 2019). Moreover, the successful adoption of offsite methods requires effective solutions to upstream supply chain management issues (Sayed, 2019). Since operations across different stages are interconnected, optimising the supply chain is essential. Therefore, a comprehensive review of the literature is needed to enhance performance by gaining a deeper insight into the current supply chain status and its underlying problems. This research will serve as a foundation for further investigations into the barriers faced by offsite projects and will establish an evaluation framework to explore the links between challenges, supply chain processes, procurement, and delivery.

This study explores local experiences with OSC and SCM for its implementation, and the relevant regulatory framework. Together, these elements aim to make a significant contribution to the existing knowledge on SCM for OSC, while also offering practical recommendations. The initial focus is on optimising the potential of OSC in New Zealand through improved delivery and procurement strategies. The primary objective is to identify and clearly define the main challenges and barriers faced in offsite construction projects, along with their origins within the supply chain. The first phase of the research will compile a comprehensive list of project-related issues, challenges, and root causes. By classifying and mapping these factors, project execution can be streamlined. Consequently, this research will help address the knowledge gap concerning the underlying causes of the housing shortage in New Zealand and provide valuable insights to meet the current needs of the construction industry.

Since this research centres on the connection between OSC and supply chain challenges, the ultimate goal is to develop a framework for supply chain operations that embraces an optimisation mindset through the analysis of issues and challenges. By enabling project stakeholders to identify the root causes of supply chain challenges during project execution, the traditionally low adoption of offsite methods can be better managed, thereby enhancing

capability and capacity. Categorising disruptions at each project phase will provide supply chain management with the means to address potential risks and issues comprehensively. As stakeholders become aware of the advantages of this approach, SCM can be tailored to meet industry demands, leading to improved project performance. The critical relationships can be uncovered by analysing disruptions and their interconnections through a questionnaire focused on categorised risk factors. From this viewpoint, refining and adjusting these relational elements within the SCM process will contribute to higher construction project outcomes such as enhanced performance and productivity.

Furthermore, by creating an optimised supply chain model based on system dynamics and sophisticated optimisation techniques, this study advances both academic understanding and real-world applications. In OSC projects, the model is intended to assist practitioners in making better choices about scheduling, management, and resource allocation. In the end, the results will help researchers, construction firms, and governments remove obstacles to the adoption of offsite construction, promote innovation, and boost industry competitiveness. This double influence on theory and practice emphasises how crucial the research is to the advancement of effective and sustainable building practices.

1.10 Thesis Organisation

This doctoral dissertation is structured around nine research outputs including journal, conference articles and book chapter, each of which has been submitted to, accepted by, or published in international peer-reviewed forums at the time of writing. Each published or submitted article is incorporated within the most relevant thesis chapter, ensuring that the content aligns with a distinct research objective. The thesis comprises seven chapters in total, integrating nine articles within Massey University's format for publication-based dissertations. Below is a concise overview of each chapter, including its introduction, validation, and conclusion.

Chapter 1 Introduces the study by establishing offsite construction supply chain management (OSC-SCM) within its scholarly and practical context. It outlines the research problem, formulates the aim and objectives, presents the guiding research questions, defines the scope, and provides an overview of the methodological approach.

Chapter 2 Presents a comprehensive literature review by systematically examining and synthesising the literature on panelised OSC-SCM. It defines the key concepts underpinning the thesis, including panelised systems, OSC supply chain management, procurement,

logistics, barriers, and environmental performance. This chapter establishes the theoretical and contextual basis for the empirical investigation.

Chapter 3 Research methodology explains how the research objectives are achieved through an integrated mixed-methods design. It defines the methodological logic of the study and explains how literature review, interviews, content analysis, triangulation, system dynamics, Monte Carlo simulation, and optimisation methods are connected.

Chapter 4 Qualitative Investigation of OSC-SCM Constraints addresses objective 2 by critically examining the barriers, enabling factors, and supply chain interrelationships influencing panelised OSC-SCM in New Zealand. It provides the empirical foundation for identifying the variables and causal relationships later used in the modelling stage.

Chapter 5 System Dynamics Modelling addresses objective 3 by developing and evaluating a dynamic model of panelised OSC-SCM. It explains how feedback loops, delays, and interdependencies influence project cost, time, and material waste.

Chapter 6 Focuses on optimising procurement and delivery strategies in offsite construction, examining how managerial and operational interventions can enhance OSC performance.

Chapter 7 Presents Grey Wolf Optimisation that further addresses objective 4 by applying MOGWO to evaluate multi-objective optimisation trade-offs. It extends the optimisation analysis by identifying improved solution sets for balancing cost, time, and material waste performance.

Chapter 8 Synthesis, Discussion, and Conclusions address all objectives by integrating the qualitative findings, system dynamics outputs, and optimisation results into a unified conceptual framework. It presents the overall synthesis, knowledge contributions, limitations, and future research directions

2 Comprehensive Literature Review of Offsite Construction Supply Chain Management

This chapter is based on four published research outputs:

First publication: Journal paper “Nesarnobari, S., Shahzad, W. M., Babaeian Jelodar, M., & Sutrisna, M. (2025). Offsite construction supply chain management: a scientometric analysis and systematic literature review. *Architectural Engineering and Design Management*, 21(3), 467-490.”

Second Publication: Conference paper “Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Investigation of the effects of supply chain disruptions on offsite construction projects. In *International Conference on Engineering, Project, and Production Management* (pp. 161-172). Springer, Cham.

Third Publication: Nesarnobari, S., Shahzad, W., & Jelodar, M. B. (2022, February). Mapping supply chain to enhance capability and capacity of prefabricated housing supply in New Zealand. In *7th New Zealand Built Environment Research Symposium* (P. 178).

Fourth Publication: Nesarnobari, S., Shahzad, W., Jelodar, M. B., Sutrisna, M., “Impact of timber offsite construction on global warming” published in 47th Australian Universities Building Education Association (AUBEA2024) Conference.

This chapter addresses Research Objective 1 by systematically examining and synthesising the literature on panelised Offsite Construction Supply Chain Management (OSC-SCM). Drawing on international literature through scientometric and systematic review methods, it identifies recurring issues and challenges affecting project time and cost performance. Key themes include supply chain fragmentation, limited stakeholder integration, and the lack of optimisation models, alongside enabling factors such as digital technologies and collaborative delivery frameworks.

The review further highlights how global disruptions, particularly those associated with the COVID-19 pandemic, have intensified existing vulnerabilities within OSC supply chains. These findings underscore the growing importance of resilience planning, risk management, and adaptive supply chain strategies in improving OSC project outcomes. By identifying critical knowledge gaps and defining the principal challenges and enabling factors, this chapter establishes the theoretical basis for the empirical investigation of New Zealand's OSC sector presented in subsequent chapters.

In alignment with Research Objective 1, the chapter also examines supply chain disruptions and barriers affecting New Zealand's residential OSC industry. Particular attention is given to the adoption of cross-laminated timber (CLT), laminated veneer lumber (LVL), and other prefabricated building systems, while highlighting key constraints related to market scale, regulatory requirements, logistics, and industry capability. The findings provide a sector-specific response to the question of which factors most significantly influence OSC adoption in New Zealand housing.

The analysis further incorporates insights from timber-focused environmental studies to evaluate broader sustainability and climate-related considerations. It examines the potential contribution of offsite timber systems to carbon-reduction objectives while addressing market reluctance driven by technical, financial, and regulatory uncertainties. By integrating findings across the three studies, the chapter identifies significant challenges, including limited scale, skills shortages, and supply instability, while also highlighting opportunities associated with sustainability drivers, government support mechanisms, and advances in design and manufacturing innovation. Collectively, these findings provide a contextualised foundation for the more detailed investigation of OSC implementation challenges and opportunities undertaken in the following chapters.

2.1 Offsite Construction Supply Chain Management: A Scientometric Analysis and Systematic Literature Review

The current section is based on the following article:

Nesarnobari, S., Shahzad, W. M., Babaeian Jelodar, M., & Sutrisna, M. (2025). Offsite construction supply chain management: a scientometric analysis and systematic literature review. *Architectural Engineering and Design Management*, 21(3), 467-490.

Abstract

Offsite construction (OSC) stands as a contemporary and eco-friendly construction method that holds the potential to alleviate housing shortages by increasing housing availability. Consequently, OSC needs to improve its supply chain (SC) to enhance its performance and sustainability. Hence, this study aims to perform a comprehensive review of offsite construction supply chain management (OSC-SCM), particularly in the context of the challenges. In response, this research contributes by conducting a thorough and holistic mapping of supply chain management through the analysis of 102 journal articles. The objectives of this study include first identifying challenges and gaps in the supply chain management of OSC and proposing avenues for future research. The study employs a mixed methodology to achieve these objectives, combining scientometric and systematic reviews. Through scientometric review, prominent journals, researchers, and co-occurrence networks of keywords were investigated. The in-depth findings highlight the critical challenges encompassing design, manufacturing, transportation, and onsite assembly within the OSC's supply chain. Additionally, an evident gap in the field can be addressed by strategically employing optimisation techniques. Thus, the OSC sector can surmount barriers and achieve improved project outcomes by enhancing SC efficiency. The result has significant ramifications for academic and corporate stakeholders. The construction industry may foster collaboration, creativity, and global problem-solving by utilising OSC practices since the clarity they provide on the procedures makes it easier to apply best practices.

Keywords: Scientometric Analysis, Offsite Construction, Supply Chain Management, Supply Chain Barriers, Systematic Literature Review.

2.1.1 Introduction

For any nation, the construction industry is a critical economic sector. Efficient operation of the construction industry is vital, and to ensure efficient operation, it is important to recognise and address any barriers within the construction process (Varsei & Polyakovskiy, 2017). After the COVID-19 pandemic, OSC attracted more attention due to border closure, labour shortage, site limitations, etc. (Assaad et al., 2022). OSC is one of the developments in the construction sector that has been acknowledged for enhancing industry procedures (Kamaruddin et al., 2013). Various terms, such as modularisation (Keith Fox, 2011), modern method of construction (Rahman, 2014) and prefabrication (Jaillon & Poon, 2010) can be interchangeably used to refer to OSC. It represents an innovative building approach that divides an entire structure into numerous prefabricated components. These components are fabricated within controlled factory conditions and transported to the construction site for efficient assembly. OSC offers a range of benefits, such as a reduction in construction time by up to 60% (Tsz Wai et al., 2021), an increase in safety and a rise in quality (Shahzad et al., 2023) due to its streamlined and offsite manufacturing approach (Adekitan, 2018; Ahmad, 2018). OSC challenges and limitations still exist in its uptake which has led to underdevelopment, immaturity, and stagnation (Agapiou, 2022). Managing OSC projects has reached a plateau as they get more complex over time and as the projects become more complicated (Nkolika J. Peter et al., 2020), leading to low uptake (Nesarnobari S. et al., 2022a). Therefore, the outstanding hurdle to gaining successful OSC projects is SCM issues (Wang, Hu, H., et al., 2019). For this matter, it is essential to recognise the challenges through the SCM (Nesarnobari et al., 2024d). The objectives of this study are: 1) To find a recent gap in OSC-SCM. 2) Recognise the elements which have received less attention, and 3) Map challenges and strategies for each step involved in OSC projects (design, manufacturing, etc.). For this purpose, the mixed method (systematic literature review and scientometric analysis) was adopted in order to perform a deep analysis, fully capturing the critical parameters involved. The importance of this study is in addressing these objectives to increase the adoption of OSC, which has not improved as expected in recent years (Hussein et al., 2023).

2.1.2 Background

Due to reasons such as SC fragmentation in the UK, high-efficiency demands in China, the absence of design rules in Hong Kong, and the geographic isolation of places like Australia and New Zealand, implementing OSC has become a strategic choice (Masood et al., 2016). The SC is a web of interconnected firms and supplier-distributor connections (Mostafa,

Dumrak, et al., 2014) that convert raw resources to inventories, work-in-progress and finished goods (Nesarnobari et al., 2024d). Lack of trust and knowledge throughout the SC, cumbersome tracking of the origin of a product, and difficulty in planning are all frequent issues in the construction SC (Nanayakkara, 2013). Due to the variations between OSC and traditional supply chain networks, managing the SC to ensure sustainability is complex and challenging (Wang Z.-L. et al., 2019) and requires improved collaboration and transparent communication among stakeholders (Mostafa, Chileshe, & Zuo, 2014). They must be adaptable, and dynamic concurrent management solutions must be implemented. For example, in Australia and New Zealand, the hurdles to poor process adoption that affect OSC's supply chain value include procurement, logistics, and site operations (Sahin et al., 2016). Sweden has long lead times and a scarcity of suppliers (Larsson, 2014).

Due to the correlation of SC stages, any disruption at the top of this chain affects the downstairs, potentially leading to an inefficient SC. Thus, researchers examining and enhancing the OSC-SCM performance and sustainability delved into various modelling techniques (Mostafa, Dumrak, et al., 2014; Nkolika J. Peter et al., 2020; Said, 2015).

2.1.3 Research Methodology

A two-stage scientometric and systematic review approach was adopted to understand challenges and their influence deeply (Tariq et al., 2021). Science mapping acts as a descriptive and diagnostic tool, efficiently processing vast bibliometric data to reveal systematic patterns in literature (Cobo et al., 2011) (Tijssen & Van Raan, 1994). It helps researchers uncover insights and identify connections among concepts that might be missed in manual reviews and removes subjective and biased conclusions (Su & Lee, 2010). Moreover, a systematic literature review provides a comprehensive framework for theory development, bridges gaps, and identifies areas for further investigation (Webster, 2002). Also, it is employed in construction engineering and management (Newaz, 2018; Osei-Kyei, 2015; Saieg, 2018). This approach entails an in-depth literature examination and the conceptualisation of principal research themes (Cavalieri et al., 2019; Davis et al., 2014; Razkenari et al., 2018). By applying both analyses, any inconsistencies in their conclusions could be identified by contrasting the outcomes of the two review procedures (Onwuegbuzie, 2004). Hence, a mixed-methods approach combining scientometric and systematic methods has been used in this study. Accordingly, the following sequential steps have been undertaken in the research process as in Figure 2-1.

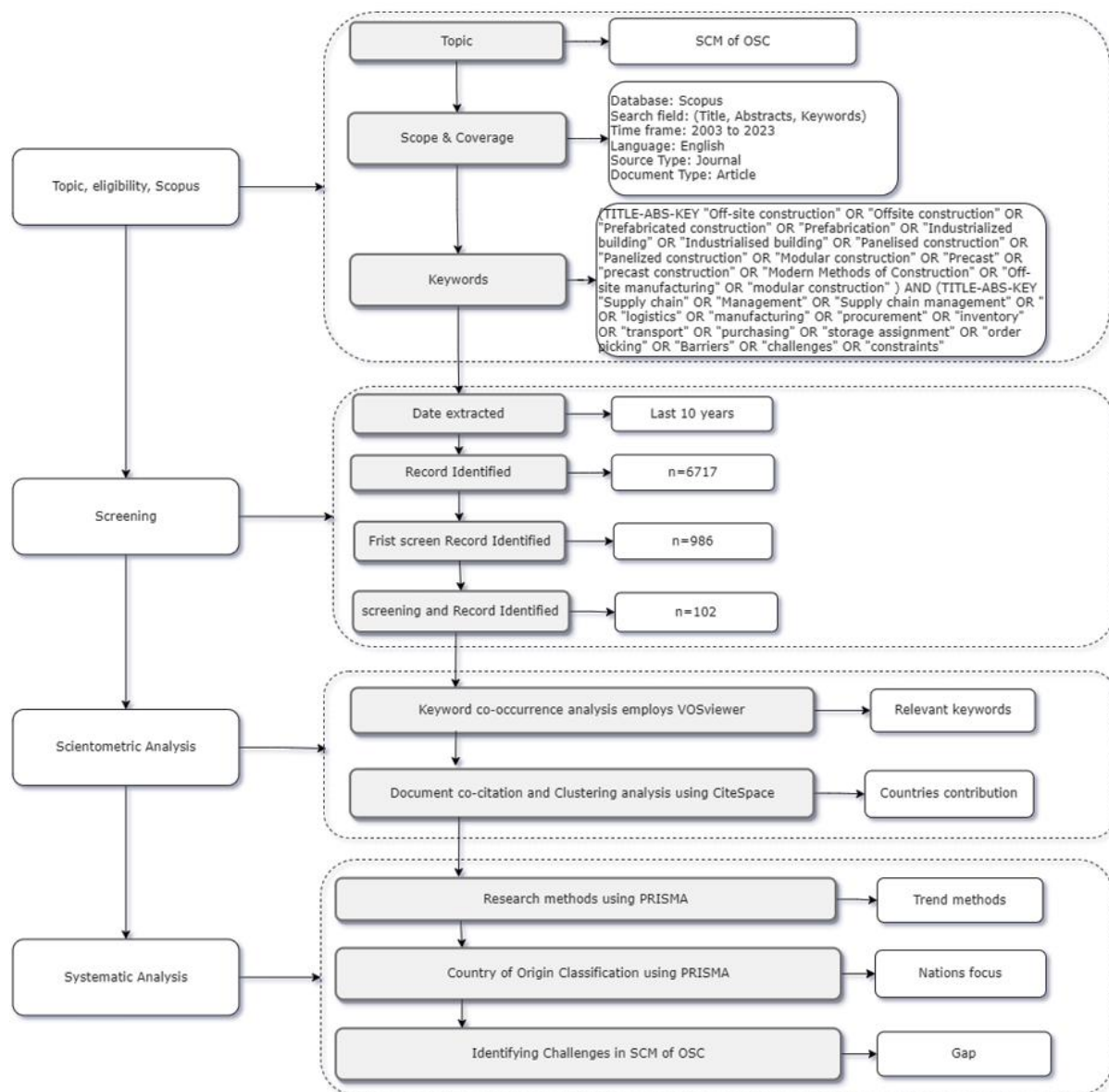


Figure 2-1: Methodology Framework

2.1.4 Bibliometric Analysis

The bibliometric search for the OSC-SCM domain was executed within the Scopus database due to its extensive source coverage (Bakkalbasi et al., 2006), comprehensive document inclusion (Al-Sharafi et al., 2021) and robust collection of academic literature related to construction topics, surpassing other databases (Cardenas et al., 2024; Falagas et al., 2008; Mongeon & Paul-Hus, 2015). Scopus was chosen because it offers a vast selection of scholarly works from over 5,000 worldwide publishers (Burnham, 2006) and a crucial repository of peer-reviewed literature, boasting high citation analysis and abstract coverage (Arpaci et al., 2020; Bakkalbasi et al., 2006) and an extensive array of peer-reviewed journals (Mok et al., 2015). In addition, according to the latest literature in construction management, Scopus is very

comprehensive, covering the most related papers to the construction field (Masood et al., 2022; Nguyen et al., 2021).

Bibliometric searches offer valuable data within an academic context (Baarimah et al., 2021; Ravindra S Bankar, 2019). To conduct a thorough literature review, articles linked to OSC sector were retrieved using the keywords:

(TITLE-ABS-KEY "Off-site construction" OR "Offsite construction" OR "Prefabricated construction" OR "Prefabrication" OR "Industrialized building" OR "Industrialised building" OR "Panelised construction" OR "Panelized construction" OR "Modular construction" OR "Precast" OR "precast construction" OR "Modern Methods of Construction" OR "Off-site manufacturing") AND (TITLE-ABS-KEY "Supply chain" OR "Management" OR "Supply chain management" OR "logistics" OR "manufacturing" OR "procurement" OR "inventory" OR "transport" OR "purchasing" OR "storage assignment" OR "order picking" OR "Barriers" OR "challenges" OR "constraints").

The search was conducted on July 29, 2023, within the titles, abstracts, keywords sections and only English journal papers were considered.

2.1.5 Scientometric Review

The scientometric review is a science mapping methodology that illustrates the interconnections and associations among pertinent studies, countries, and co-occurring keywords (Jin et al., 2019; Saad et al., 2021). Consequently, it has found applications across diverse research domains, encompassing subjects like OSC management (Li, Shen, & Xue, 2014) and SC dynamics (Darko et al., 2020). A comprehensive evaluation was conducted to determine the appropriate tools for this study (Cobo et al., 2011), leading to selection of VOSviewer & CiteSpace to generate the visualised map in this domain (chen c., 2020; G. Chen & L. Xiao, 2016). The growing adoption of both is evident in their contributions to literature reviews within the field of construction engineering and management, spanning areas like OSC (sustainability) (Wuni et al., 2020), OSC (BIM) (He et al., 2017), and building control (J. Y. Park and Z. Nagy, 2018). VOSviewer furnishes the fundamental capability required for visualizing scientometric and bibliometric networks (van Eck & Waltman, 2010; van Eck & Waltman, 2014). Also, CiteSpace can visualise diverse network architectures, identify clusters and emerging trends and generate cluster and time-zone views (chen c., 2020).

2.1.6 Systematic Analysis

The revised Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) were followed. It has developed a systematic approach to mitigating bias and enhancing clarity (Cavalieri et al., 2019; Razkenari et al., 2018) and common usability for classifying research articles like OSC-SCM (Liu Y. et al., 2020; Wang Z.-L. et al., 2019). The 198 papers were shortlisted to 102 based on specific criteria, excluding literature reviews, emphasising the OSC potential and similar themes (Figure 2-2). The inclusion criteria focused on selecting increased adoption of offsite elements, uncertainties, barriers, challenges, and related topics.

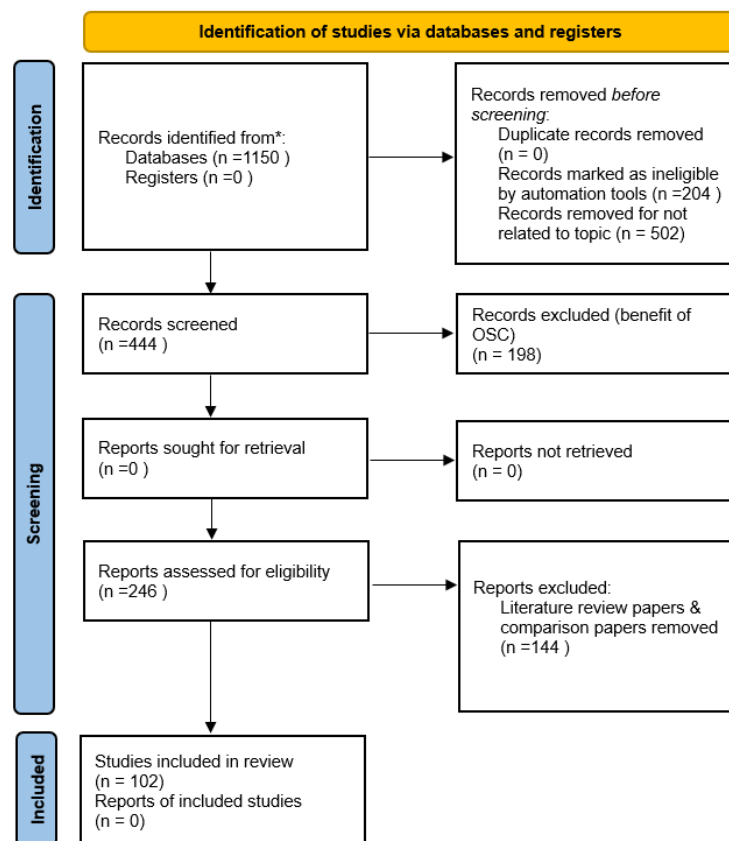


Figure 2-2: PRISMA flow diagram

2.1.7 Profile of Publication

2.1.7.1 Co-occurrence Analysis

Keywords can potentially reflect the subject of literature research (Jin et al., 2018) and the research focus in specific areas (Liu Y. et al., 2020). The visual analysis of term co-occurrence provides a rough idea of the present research hotspots. The all-keyword co-occurrence is selected, and the time parameter is set to 3 (Jin et al., 2018; Liu Y. et al., 2020). Consequently,

from a total of 955 meeting the minimum threshold, 89 were selected, forming the basis for the scientific map displayed in Figure 2-3 for visual analysis. The size of legend nodes corresponds to the frequency of keyword citations, while the distance between nodes reflects the association's strength. A greater distance indicates a weaker cross-reference link, whereas shorter distances facilitate the clustering of co-occurring phrases.

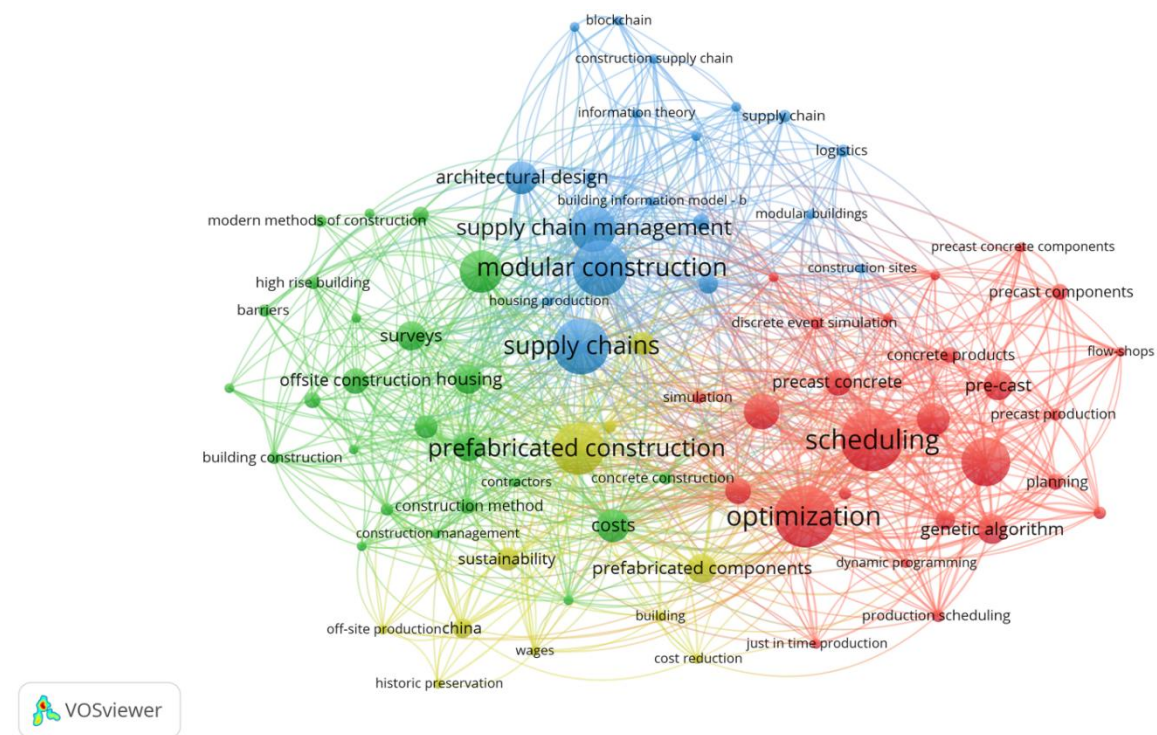


Figure 2-3:Keywords co-occurrence map of reference

Table 2.1: Summary of the most explored keywords in OSC-SCM.

keyword	Occurrence	Total link strength
Scheduling	19	135
Optimization	19	128
Supply chains	17	98
Modular construction	17	89
Prefabricated construction	16	86
GA	15	89
SCM	14	79
Prefabrication	13	70
Decision making	11	72
Costs	10	80
Production control	10	80

Since keywords can provide insights into the core content of publications, conducting keyword analysis proves valuable in pinpointing pivotal research themes. As indicated in Table 2.1 Besides "scheduling," other frequently mentioned keywords encompass "optimisation," "supply chains," "modular construction," "supply chain management," and "prefabrication," with occurrence frequencies of 19, 17, 17, 14, and 13, respectively.

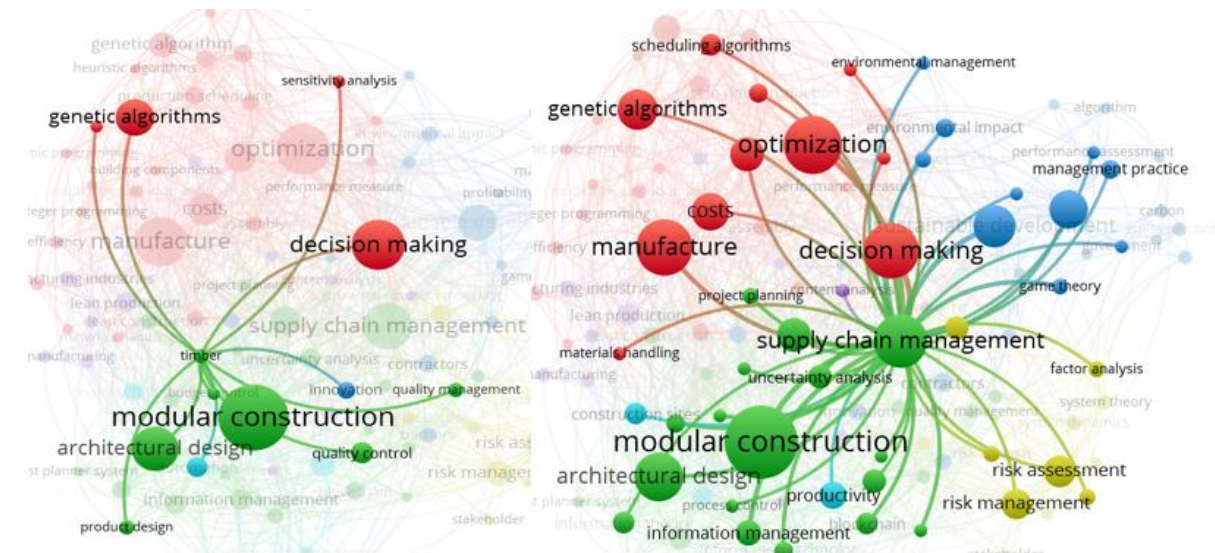


Figure 2-4:a. Visual network map of timber in OSC-SCM. Figure 2.4 b. Visual network map of SCM in OSC-SCM.

SCM is organising, carrying out, and directing the flow of products and services from their origin to the end of consumption or processing (Nkolika J. Peter et al., 2020). Timber is described as a material that can reduce greenhouse gases and material waste, and increase sustainability within the OSC to optimise efficiency and minimise costs (Carradine, 2020). Therefore, SCM and timber are considered for analysis. Figure 2-4 showcases the most related keywords associated with "timber" and "supply chain management," respectively. Fig. 2.4(a) shows that "timber" is closely connected to various construction stages, such as modular construction, decision-making, quality control, and scheduling. Notably, "optimisation" signifies a solution to the encountered barriers, given its pivotal role in addressing challenges. In Fig. 2.4(b), "supply chain management" is linked to keywords like "cost," "optimisation," "risk assessment," and "productivity." This highlights the essential role of SC and SCM in OSC, underscoring their increased significance. Numerous optimisation-related papers aiming at diverse objectives point to substantial persisting challenges throughout the SC.

Figure 2.3 represents the mapping analysis results performed in VOSviewer. Based on the obtained results using the current keywords and a total of 986 papers identified, which were

subsequently shortlisted to 102 as elaborated on, ‘optimisation’ and ‘scheduling’ along with a few more were identified as more influential parameters while ‘sustainability’, ‘risk management’ and ‘stakeholders/contractors’ are also observed and identified as influential parameters in the mappings in Figure 2.3 or 2.4 but to a lesser degree. This may also suggest that the existing literature lacks sufficient research on such important parameters, and more investigations are required to study their effect in the future. However, it is also worth mentioning that ‘optimization’ is a broad and comprehensive parameter which inherently includes and, upon successful implementation, will facilitate many other critical aspects such as ‘sustainability’, ‘risk management’ and ‘stakeholder engagement’ (Du et al., 2023; Nesarnobari et al., 2024d; Wasim et al., 2020).

2.1.7.2 Number of Publications per Year

The annual publication count, as in Figure 2-5, indicates a fluctuating pattern. However, the projection based on the polynomial trend line suggests that the number of papers in 2023 will likely surpass 2019 emphasising the growing significance of SCM. The active involvement of researchers in devising efficient SCM strategies for the successful implementation of OSC is apparent.

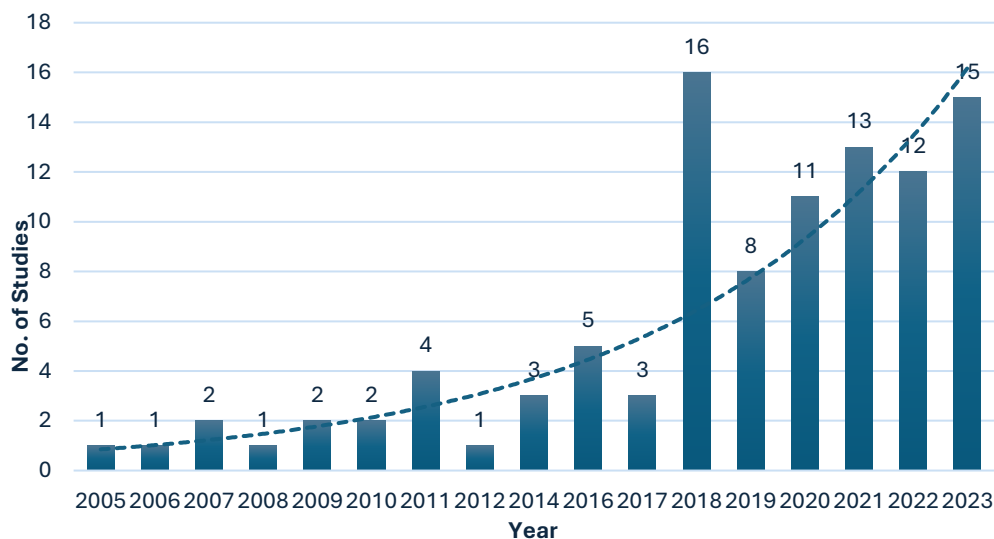


Figure 2-5: The OSC-SCM published study 2003-2023

2.1.7.3 Citespace

Utilising the CiteSpace software (Chen, 2005), a network encompassing ten nodes and 39 links was generated to explore countries' level of contribution as in Figure 2-6. In the visual representation, each node corresponds to a country, and each link signifies collaborative relationships between two nations. These prominent links hold dominant positions, signifying

the advancement of OSC-related research within their respective contexts. High betweenness centrality nodes are highlighted with pink outlines. The thickness of pink centrality outline reflects the strength of centrality; the thicker the outline, the more influential the country. Notably, China (centrality = 0.22), the United States (centrality = 0.12), Hong Kong (centrality = 0.34), Australia (centrality = 0.27), and the United Kingdom (centrality = 0.27) emerge as pivotal players in fostering research connections among nations.



Figure 2-6: Influential countries for OSC-SCM research

2.1.8 Discussion

The steps of observed gaps and directions are demonstrated in Figure 2-7. The initial focus of this section centres on addressing the barriers associated with each stage of OSC, and the specific outcomes are presented. Subsequently, strategies implemented to enhance the efficiency of SCM are discussed. The evaluations span 2016-2023, highlighting the strategies/techniques. The period 2014-2023 underscores the identified barriers. Few articles explore the entire SC, particularly from 2018 to 2023 (Figure 2-8). Longitudinal perspective presented that, from 2018 to 2023, researchers focused on addressing the barriers to manufacturing OSC elements. However, from 2014 to 2023, efforts were made to implement OSC in countries such as China, Australia, the UK, India, and Nigeria. Due to the complexity of designing offsite elements, standards or routines needed to be added; therefore, research in this field started in 2018. Consequently, many papers concentrated on increasing profit and productivity. Manufacturing analysis began in 2007 and has been in progress, revealing ongoing challenges in producing these elements. Transportation has been problematic from the early years of OSC implementation (2007-2023) due to oversized elements and specific transportation requirements. The assembly stage is more recent (2019-2023), leading to the introduction of massive OSC elements.

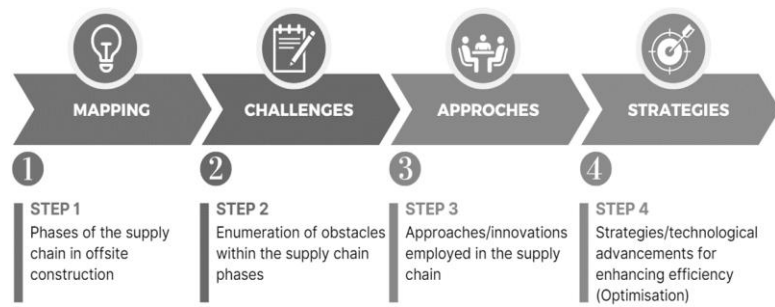


Figure 2-7: Gaps and Directions

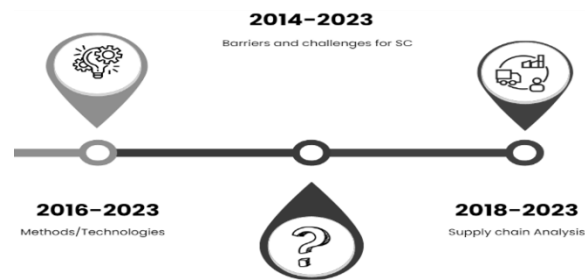


Figure 2-8: Evaluation based on Literature Reviews.

The framework (Figure 2-9) provides a comprehensive approach to understanding and navigating the complexity of SCM, inviting further examination and implementation. Encompassing the intricate network of processes, entities, and actions involved in product development and production, this framework acknowledges the inherent complexities within SC dynamics. Recognising stakeholders' diverse roles and interests promotes collaborative endeavours to optimise processes and achieve mutual benefits. It attempts to reduce these complexities by including several stakeholders and acts as a guide for the coordination and strategic alignment of all operational aspects. Through its structured methodology, the framework ensures effectiveness, efficiency, and heightened competitiveness across the SC landscape.

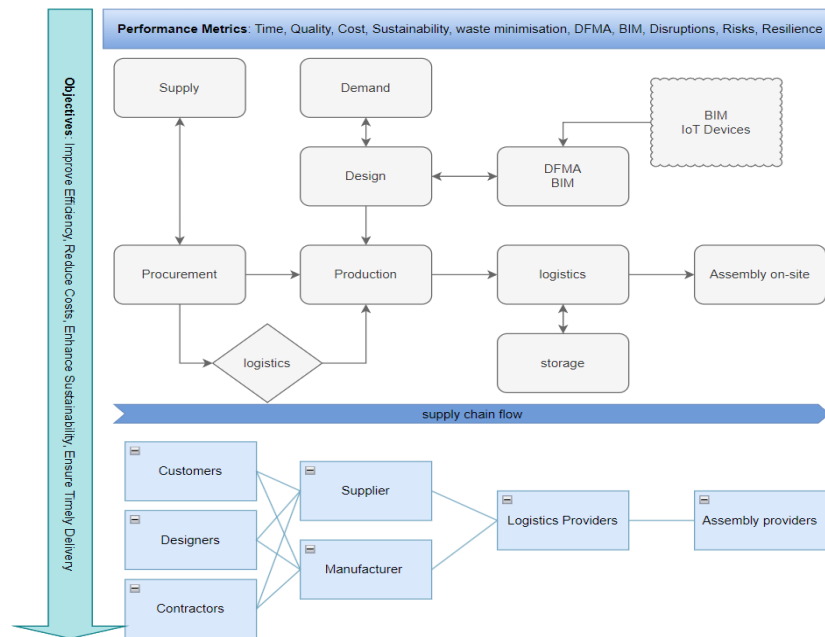


Figure 2-9: Proposed Framework for Supply Chain

2.1.8.1 Design Stage Challenges and Strategies

The systematic review emphasised the critical role of the design stage and methodologies. Abundant evidence underscores that any complications arising during the design phase can have far-reaching implications, potentially disrupting the entire OSC process and creating many challenges. Notably, all the papers in this context are recent, evidencing the contemporary significance of this issue. Effective management and resolution of design-related concerns emerge as critical factors in ensuring the smooth progression.

Table 2.2: Design Stage-related Challenges and Strategies

Stage	Challenges	Strategies/Ref
Design and Planning	Lack of standards & codes	(Bello et al., 2023; Chen et al., 2023; Choi et al., 2017; Hsu et al., 2018a; Hwang et al., 2018; Jalali Yazdi et al., 2021; Li et al., 2022; Xu et al., 2022)
	Poor design flexibility	
	Complexity on seismic performance	
	Limitation of weight and dimensions	
	Lack of experienced designer	
	Limited size of elements	
	Longer design duration	
	Lack of innovation	
	Resistance to change	
	Construction consent	
BIM (Xu Z, 2022)	IKEA model (Li H, 2011)	
BIM, Block Chain (Li X, 2022)	Design science research (Wesz J.G.B., 2018)	
	DFMA (Jalali Yazdi A, 2021; Gbadamosi A.-Q. 2020)	

Projects require different criteria due to safety, location, and building occupancy; therefore, a lack of standards and codes leads to more complexity and less flexibility in the design stages (Ferdous et al., 2019). This constraint frequently results in less-than-ideal designs that are difficult to modify in response to shifting project specifications or customer preferences, thus harming functionality and visual appeal (Bello et al., 2023). Lacking planning with precision and specific knowledge to ensure that prefabricated pieces comply with earthquake requirements affects the time and then more expenses after construction by leading the design to complexity (Jalali Yazdi et al., 2021). Transportation restrictions, among other factors, frequently restrict OSC elements, limiting their maximum permitted weight and dimensions (Jalali Yazdi et al., 2021). These constraints may limit design options and require standard equipment. This may result in more intricate assembly procedures and possible structural constraints that need to be considered in the design stage. As noted in several studies, designing prefabricated elements to create compelling and creative designs may demand specialised expertise, contributing to a shortage of skilled designers in this field (Luo et al., 2015). Experienced designers are essential to effectively navigate the distinct problems associated with prefabrication and ensure that designs are optimised for offsite manufacturing. This lack of ability may lead to longer design times, more expensive projects, and lower-quality results since less experienced designers may find it challenging to implement OSC principles.

Moreover, commencing manufacturing prematurely locks in the design, resulting in potential budgetary losses if design errors or alterations arise during production. Many clients lack awareness of these challenges and may seek modifications after starting manufacturing (Luo L-Z, 2015). Insufficient design flexibility limits the ability to make changes after the production process starts.

Certain studies have proposed using advanced technologies such as Building Information Modeling (BIM), Design for Manufacturing and Assembly (DfMA), and blockchain to surmount these barriers. BIM can improve collaboration between engineers, architects, and construction specialists by providing a building schematic. Additionally, by adjusting any aspect of the design, the designer can observe how the modification affects other phases, potentially reducing errors (Xu et al., 2022). By considering early in the design process and encouraging standardised components and procedures, DFMA can optimise the design and manufacturing stage. This simplifies designs, making them simpler to change and adapt to various regulatory environments (Jalali Yazdi et al., 2021). It can maximise the construction efficiency and cost-effectiveness (Xu et al., 2022). Blockchain technology can be utilised to monitor design updates and ensure that only allowed changes are made (Li X, 2022). Additionally, SCs can benefit from increased traceability and trust due to blockchain technology, reducing the risk of manufacturing errors and design modifications. By utilising these cutting-edge technologies, professionals may optimise OSC procedures, enhance design adaptability, and tackle the barriers presented by conventional design guidelines and specifications.

2.1.8.2 Manufacturing Stage Challenges and Strategies

The systematic review has produced unambiguous evidence (Table 2.3) that the production process has multiple challenges, including equipment faults and component deficiencies.

Table 2.3: Challenges and Strategies related to Manufacturing process

Stage	Challenges					Strategies/Ref				
Manufacturing						Artificial intelligence (Benjaoran V, 2006)				
						Automating (Nasereddin M, 2007)				
						IKEA model (Li H, 2011)				
						Metaheuristics (Arashpour M,2016)				
						Genetic Algorithm (GA) (Liu W,2023; Hyun H, 2021; Chen C,2019; Altaf M.S, 2018)				
					Lack of manufacturing capacity					
					Lack of skilled labours					
					Higher construction cost					
					Incompetence of manufacturers					
					Defects					
				Loss of productivity						
				Quality control						
				Increased risk						
				Escalated in the labour training deficiency						
	(Bello et al., 2023; Chen et al., 2023; Hamzeh et al., 2017; Ma et al., 2018; Rahman, 2014; Wang D. et al., 2018)									

The critical importance of the timely delivery of components reveals the successful completion of OSC projects (Chen et al., 2023). Efficient production scheduling plays a significant role in ensuring timely delivery (Wang Z., Hu, H., & Gong, J., 2018). The economic and environmental effects of component production schedules should be considered, emphasising the phases preceding and after component manufacturing (Kong et al., 2018). In OSC manufacturing, meticulous preparation and highly skilled labour are imperative. However, given the novelty of this method, there is a notable shortage of skilled labour (Shahzad et al., 2023) and planning issues (Bell, 2018). The risk of errors and accidents during manufacturing (safety concerns) is increased by undertrained personnel and inexperienced producers (Shahzad et al., 2023). Ineffective manufacturing processes, often due to a lack of skilled workers and proper training, can result in significant productivity losses (Shahzad et al., 2023). This inefficiency leads to poor resource utilisation and delays in production schedules (Chen et al., 2023). Moreover, the dimensions of the elements can significantly impact machinery performance, potentially leading to failure or necessitating frequent servicing to minimise errors (Arashpour et al., 2018). Such uncertainties pose risks and disrupt preparation schedules, resulting in delays and higher costs (Liu et al., 2023). Additionally, stringent quality control measures can impede manufacturing speed. Manufacturers must ensure element quality as they

will bear loads, directly impacting safety (Liu et al., 2023). Manufacturers who are inexperienced with OSC may find it challenging to adhere to quality requirements and design parameters. This incapacity may show up as incorrect material handling and assembly procedures (Rahman, 2014). The quantity of prefabricated components can be restricted by manufacturing capacity, causing bottlenecks and delays in project completion dates (Cao et al., 2022). Increased building costs result from low productivity, high defect rates, and inefficient production methods. Reduced productivity and longer training durations may result from insufficient staff, resources, or equipment (Nesarnobari et al., 2024d). Maintaining consistent quality control during the production of prefabricated components is crucial. Poor quality control procedures can lead to variability in component quality. Defective manufacturing can result from subpar craftsmanship, inadequate training, and inadequate quality control. Surface flaws, incorrect measurements, and structural weaknesses are examples of defects.

The literature revealed that optimisation techniques can mitigate the identified barriers. They encompass a range of strategies to enhance efficiency, productivity, and cost-effectiveness in OSC practices. Optimisation is a technique that helps improve resource allocation (for determining the optimal mix/quality to reduce excess and shortages (Arashpour et al., 2018)), scheduling (minimising delay-maximising output (Liu et al., 2023)), cost reduction (introducing more economical options (Kong et al., 2017)), quality control (maintaining consistent quality (Li H, 2011)), inventory management (prevent from overstocking and stockouts), enhancement in the process (eliminating bottlenecks and streamlining operations (Hyun et al., 2021)). Notably, GA emerged as the predominant approach, yielding favourable results. Examples of such approaches may include the application of lean principles to streamline workflows, adopting advanced technologies to automate processes, or implementing performance-driven design methodologies. By leveraging these optimisation methods, researchers and practitioners seek to overcome the challenges inherent in OSC and maximise the benefits of this innovative approach to building (Hyun et al., 2021). Most research in the field predominantly concentrates on planning for precast components, with limited attention given to timber elements.

2.1.8.3 Transportation Challenges and Strategies

Transporting offsite elements presents complexities (Kim et al., 2020). Effective management of crane usage, selection of suitable vehicles, and proper wrapping techniques are crucial to ensure the elements remain in optimal condition during transportation (Shahzad et al., 2023). Weather conditions pose significant challenges during transit; high winds make lifting

oversized elements difficult, while rainy conditions in humid areas necessitate measures to keep the elements dry (Hsu et al., 2018a; Wang S. et al., 2018). This emphasises the importance of appropriate wrapping and skilled labour for handling and lifting. Unsafe driving circumstances, such as narrow roadways, can make delivering significant components difficult and cause damage during transit (Kong et al., 2018). Additionally, the cost of gasoline and vehicle upkeep brought on by deteriorating infrastructure and a poor road system can result in material transportation routes that are longer and more intricate, raising transportation expenses (Chen et al., 2023). The absence of the proper vehicle for transportation also causes an extension of the delivery time. Bottlenecks in the SC can be caused by a few manufacturers and suppliers, making it challenging to find materials and components quickly. Delivery schedule delays might result from traffic congestion, drastically slowing the shipping of prefabricated pieces (Hussein et al., 2023). When loading, unloading, and transporting prefabricated components, labour costs can increase, especially if specialised knowledge is needed. Consequently, these barriers can lead to delivery delays, increasing costs (Wuni & Shen, 2020b). Most papers focused on addressing transportation challenges through optimisation techniques to minimise errors and improve efficiency (Table 2.4). Transportation optimising techniques can help to optimise routes (implementing software to determine traffic and best route (Xiong et al., 2022), optimise load and vehicle (to maximise the capacity of vehicles and no need for pilot (Nesarnobari et al., 2024d)), mitigate risk (by recognising potential risks like weather impact and develop strategies (Mostafa et al., 2018), increase collaboration (between manufacturer and transporter), optimise cost (finding the most cost-effective transportation (Chen G, 2023; Wong C.K, 2010), and to enhance scheduling (reducing waiting time and storage issues (Kong et al., 2018). Just-in-time is one of the methods that can be utilised for transportation to manage barriers for better planning (Kong et al., 2018).

Table 2.4: Challenges and Strategies Related to the Transportation Stage

Stage	Challenges	Strategies/Ref
Transportation	Poor road condition	Iterated greedy (Xiong F, 2023)
	Higher transportation cost	Particle swarm (Zhang H, 2020)
	Inferior road network system	Stochastic Petri net method (Yang Y, 2022)
	Lack of suitable vehicle	Just-in-time strategy (Kong L, 2018)
	Potential damage	Ant Lion Optimizer (Son P.V.H, 2023)
	Delay due to logistic issues	GA (Chen G, 2023; Wong C.K, 2010)
	Lack of manufacturer and supplier	Analytic hierarchy process (Mostafa S, 2020)
	Incompetence of suppliers	Mixed integer programming (Khalili A, 2014)
	Traffic conditions	
	Production size	
	Labour Cost	
	(Akinradewo et al., 2021; Chen et al., 2023; Choi et al., 2017; Hamzeh et al., 2017; Hussein et al., 2023; Lee et al., 2021; Mostafa et al., 2018; Son & Hieu, 2021; Xiong et al., 2022)	

2.1.8.4 On-site Assembly Challenges and Strategies

The assembly stage stands out as the most distinctive aspect of OSC due to its specialised requirements, particularly concerning the handling of oversized elements (Table 2.5). This phase demands labour with unique skills and specialised equipment, including appropriate cranes for the element size (Cao et al., 2022). Additionally, the interconnection of components resembles a Lego-like process (S Lim, 2016), requiring meticulous sequencing and precision during assembly. Effective management of this process is paramount, encompassing considerations such as site logistics, weather conditions, and the availability of adequately prepared space. Challenges such as inclement weather or insufficient site preparation can delay the delivery timeline, escalating costs.

Table 2.5: Challenges and Strategies related to the assembly part.

Stage	Challenges							Strategies/Ref			
Assembly	Limited site space	(Cao et al., 2022; Choi et al., 2017; Hamzeh et al., 2017; Rahman, 2014; Wasim et al., 2020; Xu et al., 2022)									
	Labour cost										
	Production size										
	Floor area conditions										
	Assembly limitations										
	Connection complexity										
	Lack of technician on site										
									Discrete event simulation (Li X,2019)	DFMA (Wasim M, 2020)	Semantic-Based Methodology (Xu Z, 2022)

There may be limitations on the movement and storage of prefabricated components on the construction site because of space constraints. It might also reduce the accessibility of large machines and other equipment (Nesarnobari et al., 2024d). This leads to more difficulty in setting up and completing the on-site assembly. Labour costs will increase if specific workforce, machinery, equipment, and safety requirements are not met due to production growth (Cao et al., 2022). The intricacy of the connections between prefabricated components can strongly impact the simplicity of assembly and its time. Errors and inefficiencies in the assembly process can result from a lack of qualified specialists with prefabricated component assembly experience (Hamzeh et al., 2017). The factory manufactures the element, so additional tools and preparation are required on-site to ensure a flawless connection between the sections (Xu et al., 2022). Access to specific portions of the site can also be restricted, and perfect alignment and fit might be required.

To eliminate or minimise the above challenges, optimisation can enhance coordination and scheduling (by managing the delivery and assembly reducing rework and delay (Li et al., 2019)), component sequencing (reducing rework and disruptions (Wasim et al., 2020)), site layout and logistics (enhancing efficiency (Chen et al., 2023)), Technology Integration (Utilising advanced technologies like BIM, augmented reality, and robotics can optimise the assembly process by improving accuracy and coordination (Gbadamosi et al., 2019)), and cost management (control expenses and keep the project within budget (Wasim et al., 2020)).

2.1.8.5 Strategies for Optimisation

Continual research efforts have been directed towards optimising a range of objectives. The accompanying table offers an extensive overview of these papers focused on optimisation, delineating the targeted objectives and methods utilised. Among the crucial objectives highlighted, tardiness and cost are frequently mentioned as paramount. GA stands out as the predominant method for optimisation in these studies. Although much research exists on optimising OSC for individual stages, the remaining barriers in the whole process and low uptake confirm that gaps in the SC still exist, requiring further investigations considering the entire cycle.

Hong Kong and China have extensively used precast concrete in buildings, making their analysis more important than other components (Wang Z., Hu, H., et al., 2018). In contrast, timber components are the most common in Australia and New Zealand (Carradine, 2020), indicating a substantial lack of investigations in this field. This discrepancy emphasises how critical it is to handle the unique requirements and difficulties of using timber construction techniques in these areas. Therefore, further research and development is required to comprehend and improve timber construction methods in Australia and New Zealand (Mehrnaz Rohani, 2019).

Table 2.6: Summarize of optimisation methods and objectives.

Ref	Method	Objective
Yao G.(2023)	MPC-NSGA-II	Sustainable construction
Xiong F. (2023)	Treated greedy	Tardiness
Du Q. (2023)	Genetic Algorithm (GA)	Composition Selection
Liu W. (2023)	Genetic Algorithm (GA)	Efficiency/productivity
Hussein M(2023)	hybrid multi-agent simulation	Decision support systems
Son P.V.H. (2023)	Ant Lion Optimizer	Cost
Chen G. (2023)	Genetic Algorithm (GA)	Cost
Cao J. (2022)	Cloud theory-based adaptive	Material scheduling
Ho C. (2022)	Early due date	Material scheduling
Jiang W. (2021)	Iterative job insertion algorithm	Tardiness/earliness
Jalali Yazdi A. (2021)	Genetic Algorithm (GA)	Design configurations
Chang C. (2021)	Discrete differential evolution	Production costs
Yazdani M. (2021)	Genetic Algorithm (GA)	Earliness/tardiness
Hyun H. (2021)	Genetic Algorithm (GA)	Production duration
Nam S. (2020)	Dependency structure matrix	Production period
Wang Z. (2020)	Blockchain, hyperledger fabric	SCM
Wang S. (2020)	Value stream	Lean production theory
Zhang H. (2020)	Particle swarm	Transportation
Mostafa S. (2020)	Analytic hierarchy process	Delivery/cost/time
Wasim M. (2020)	DFMA	Assembly times/cost
Lee J. (2019)	Genetic Algorithm (GA)	Project schedule
Chen C. (2019)	Genetic Algorithm (GA)	Decide operation/ start time
Ma Z. (2018)	Genetic Algorithm (GA)	Rescheduling
Wang Z. (2018)	Genetic Algorithm (GA)	Scheduling of production/resource allocation
Yang H. (2018)	Genetic Algorithm (GA)	SCM of manufacturing/Materials supply
Altaf M.S. (2018)	Random Sample Consensus	Radiofrequency
Xue H. (2018)	Exploratory factor analysis	Cost management
Wang D. (2018)	Heuristic algorithm	Increase the rate of pallets
Hsu P. (2018)	Two-stage stochastic programming	Inventory; Logistics
Arashpour M. (2018)	Hybrid method	Multi-skilled resources cost
Kong L. (2017)	Dynamic programming algorithm	Scheduling problem
Arashpour M. (2016)	Metaheuristics	Changeover time
Yang Z. (2016)	Genetic Algorithm (GA)	Flowshop schedules

2.1.8.6 Offsite Construction Supply Chain Management

The summarised challenges and strategies for the SC in Table 2.7 demonstrated that just one research study is related to New Zealand in precast elements. The majority of the papers reveal a low level of SCM (Nesarnobari S. et al., 2022a). Furthermore, optimisation has emerged as an avenue of exploration, with various researchers employing diverse algorithms to enhance efficiency.

Table 2.7: Supply Chain related Challenges in OSC

Stage	Challenges	Strategies/Ref
Supply Chain	Lack of collaboration between stakeholders	IoT(Internet Of Things) (Kazmi Z.A, 2022)
	Lack of benefits awareness	Decision-making, government subsidies (Du Q.; Hao T, 2022)
	Low level of SCM	Evolutionary game model (Zhang R, 2023)
	Supply chain fragmentation	Iterated greedy algorithm (Xiong F, 2023)
	Inadequate coordination among supply chain	Blockchain (Li X, 2022; Bakhtiarizadeh E, 2021)
	Ineffective stakeholder, supply chain & execution risk management	Game-based system dynamics simulation (Wang X, 2022; Du Q, 2021)
	Under informed management	Structural Equation Model (Zhao S, 2022)
	Supply Chain and Procurement Methods	Particle swarm algorithm (Zhang H, 2020)
		Advanced simulation game (Li X, 2018)
		Computational model (Wang S, 2018)
		Priority evaluation (Wang Z, 2018)
		GA (Yang H, 2018)
		CTRAUS (Ergen E, 2008)
	(Bello et al., 2023; Choi et al., 2017; Choi et al., 2016; Harris et al., 2019; Hong et al., 2018; Hwang et al., 2018; Li et al., 2016; Li et al., 2018; Mohd Nasrun Mohd Nawi, 2018; Rahman, 2014; Wu et al., 2007)	

These interruptions in the SC lead to an ineffective SC. Additionally, research domains are examining the advantages, enhancing prefabrication, lean manufacturing, incorporating SC strategies into prefabrication, recognising the critical barriers for unique elements, integrating prefabrication stakeholders, adoption challenges, delving into concerns regarding the necessary skills, and providing a thorough overview of modular systems (Masood R. et al., 2021). Partnerships between builders and manufacturers, public perception, cost barriers, less design

flexibility and negative perceptions, fragmentation, poor traceability, extensive project planning, transportation constraints, skills shortages, the complexity of SC, and a lack of understanding of SC are some of the challenges that have been mentioned (Mostafa, Chileshe, & Zuo, 2014). Consequently, scholars have employed various modelling techniques to explore the SC (Nesarnobari S. et al., 2022c). Based on the study, the development in SCM performance in NZ's residential buildings has not been sufficiently understood. Therefore, a thorough understanding of the fundamental requirements is required to optimise obtaining consent and minimise the complexity of the building stage (Darlow et al., 2021).

2.1.9 Discussion of Results

2.1.9.1 Challenges within OSC-SCM Implementation

The domain of OSC-SCM has emerged as a prominent focus due to the diverse issues in delivery (Hsu et al., 2018b; Li et al., 2018). Thus, the SC of OSC plays a crucial role in improving productivity and efficiency (Arashpour et al., 2015; Li et al., 2018; Wang & Hu, 2017); it is vulnerable and complex compared to traditional projects (Wang, Hu, H., et al., 2019) and requires minimal variations (Arashpour et al., 2019); however, few factories follow the instructions for SCM. Weather conditions, traffic congestion, road conditions, design delays, material and labour shortages, etc., influence delivery times (Hsu et al., 2018a; Wang Z., Hu, H., & Gong, J., 2018). These delays lead to an increased cost of additional labour working hours, cost of hired equipment, and time overrun (Wuni et al., 2019).

The SC was significantly impacted by mismatches between the plan and execution, including erratic demand for precast components, excessive manufacturing and lengthy lead times in the plant, messed up transportation plans, and issues with schedule and budget (Luo et al., 2020). While precast concrete remains the preferred construction component in many countries, analyses indicate implementation challenges within the SCM. However, it is noteworthy that countries where timber elements are more commonly used have not analysed enough the SC challenges associated with timber components (Carradine, 2020).

2.1.9.2 Geographic, Cultural, and Economic Effects on OSC Adoption

Geographic considerations significantly impact logistics and manufacturing. Transportation issues may make it less viable in developing nations with less developed infrastructure. Also, in countries with particular topography like New Zealand, transporting elements and site accessibility for onsite assembly is challenging and causes different issues for SCM (Nesarnobari S. et al., 2022c). Furthermore, importing raw materials to geographically isolated

countries cause challenges for manufacturers. For instance, importing takes longer leading to the expiration or deterioration of materials.

Cultural variables influence OSC adoption, such as social views towards techniques and acceptance of new technologies. In some areas where onsite construction has a long history, there can be opposition to using OSC techniques (Han & Wang, 2018). Otherwise, countries that have a vital innovation and technology advancement culture are more inclined to use and invest in SCM, like the US, the UK, and China. It is also impacted by the regulatory environment, which includes government laws, building rules, and standards. Countries with supportive regulatory frameworks like China are more likely to embrace OSC. However, implementing it may present difficulties in areas with strict laws and a lack of standardisation (Chen et al., 2018).

Economic aspects are also essential in determining the acceptance and common usage of these elements (Han & Wang, 2018). The challenges affected by the countries' economic aspects are labour costs, market demand, and the availability of financial resources. High-income areas have easier access to capital for SC process implementation and investments in cutting-edge technologies. In contrast, low- and middle-income areas may have to make financial concessions that prevent them from investing in SC and using these techniques (Jin et al., 2018).

2.1.9.3 Strategies for OSC-SCM

Bibliometric investigations have demonstrated the state-of-the-art practices applied to SC principles, highlighting their significance in improving SC. Digital twins (Lee & Lee, 2021), blockchain (Bakhtiarizadeh E et al., 2021), BIM (Yuan, 2018), lean construction (Kong et al., 2018) and optimisation algorithms (Chang et al., 2021; Ma et al., 2018; Nesarnobari et al., 2024d; Wang D. et al., 2018) are examples of digital technologies that have demonstrated the potential to improve SC visibility, streamline logistics, and lower carbon footprints in construction projects. By facilitating real-time monitoring, data exchange, and decision-making, these technologies help create a more sustainable SC. For instance, implementing optimisation algorithms like GA reduces delivery time, costs, and carbon footprint and enhances sustainability. Such optimisation is applicable for each stage of OSC and SC (Gbadamosi et al., 2020; Yao et al., 2023). BIM and DFMA can initiate optimisation from the early design stage to reduce errors and enhance productivity (Bortolini et al., 2019; Li et al., 2022). Further, blockchain can increase the integration of SC, which leads to more data

exchanges (Wang et al., 2020). Discrete-event simulation models have shown a notable decrease in construction time and manufacturer fines (Mostafa, 2018).

2.1.9.4 Proposed Framework for OSC-SCM Challenges

Drawing from the outlined framework, barriers impacting various stages of OSC delivery are identified and acknowledged. This recognition underscores the interconnected nature of these obstacles, revealing that they often transcend individual stages. Given this, attempting to isolate these barriers proves impractical. For example, challenges like site space limitations, equipment malfunctions, and alterations in on-site requirements can significantly impact the transition from manufacturing to assembly stages.

To develop strategies that minimise obstacles and maximise efficiency, it is essential to carefully consider their effects at every level of OSC delivery. This means figuring out how certain obstacles affect operations and results at different points in the SC. Stakeholders can obtain a more comprehensive understanding of the intricate dynamics involved and pinpoint possible places of intervention leverage by implementing an integrated approach to barrier analysis. The proposed framework, as revealed in Fig. 2-10, shows the effect of the barriers on the SC.

Delivery of panelised system (OSC)								
		Design	Manufacturing	Transportation	Assembly	Floor Plan Customisation		
Internal	Client Requirments	Specific Design	Material Type					
		Change in Design	Material Related Conditions					
Internal	Project Requirements	Design Delay	Material Shortage	Traffic	Inaccurate Interfaces			
		Lack of Innovation	Lost productivity	Pilot Vehicle	Safety Concerns for the On-site Workers			
			Variation in setup Times	Restricted Movement Time				
		Design Flexibility	Material Related Conditions	Weather				
		Lack of Experience	Number of Products Under Production	Size of Product				
			Standardisation	Limited Suitable Crane				
		Size Limitation	logistic issues					
			Shortage of Labour					
		Design codes & standard	Labour Cost					
			Unexpected Work Defect					
		Design Errors	Equipment Failure				Floor Area	
			Machine service/failure	Road Conditions				
			Limited Site Space					
		Change of On-site Requirements						
		Procurement method						
		Incompetence of Supplier						
	Project Location	Uncertainties		Location				
External	Regulation	Planning Regulations		Highway Agency Requirements		Certificate of Construction Compliance		
		Building Consent						
			Quality Control					
		Health and safety						

Figure 2-10: Proposed framework for delivery of OSC-SCM barriers

2.1.9.5 Proposed Research and Industry Direction for OSC-SCM

The following future directions can be proposed based on the science mapping and qualitative analysis of the current study within OSC:

1. To achieve sustainable supply chain practices, further research may focus on creating frameworks and tools that strengthen the OSC supply chain. To reduce waste and improve resource efficiency, it is necessary to build robust procurement models, put management strategies into practice, reduce potential roadblocks, disruptions and challenges, and concentrate on establishing environmentally friendly logistics solutions and sustainable material sourcing.
2. In-depth research is required on the integration of cutting-edge digital technology. The effects of blockchain, IoT, and digital twins on supply chain transparency, efficiency, and real-time decision-making should be investigated in research. The supply chain's task and resource scheduling can be improved through optimisation. By incorporating algorithms, businesses can successfully enhance their capacity to manage stocks, estimate demand, and coordinate logistics.
3. Industry practitioners should aim to enhance stakeholder integration and cooperation. Plans for efficient coordination, collaboration, and communication between producers, contractors, suppliers, and customers should be created to improve SC performance.
4. A system dynamics approach should be utilised to match OSC supply chain policies with the need for cost-effective housing. SC capabilities and delivery must be strategically aligned to achieve efficiency in OSC projects.
5. Policymakers can apply strategies like subsidies and tax incentives to reduce some of the challenges, like developing codes and standards to accommodate modern OSC techniques. Also, public awareness campaigns should be promoted to highlight the benefits of the OSC.

2.1.10 Conclusion

The body of research reveals that SCM is a rapidly growing and substantial field within OSC. The literature centred on the topic underscores the pivotal role of this field in reshaping the construction sector. By implementing effective SC strategies, OSC can contribute to cost and time reduction, quality enhancement, and sustainability improvement. This field of study produces valuable research products for construction society by tackling critical issues facing

the construction sector. The summary of barriers includes poor management, assembly restrictions, product problems, limited transportation volume, lack of design changes, etc. Because of the capacity of OSC, it can completely transform for heightened automation and standardisation by comprehending the optimisation. Moreover, many of the investigated elements pertain to precast concrete components. However, a noteworthy observation is the limited emphasis on alternative timber structural elements such as Cross Laminated Timber and Structural Insulated Panels. Conversely, timber remains the most utilised element in Australia and New Zealand, and there is less research on it. This discrepancy highlights a discernible gap within these areas, signifying an opportunity for optimising the delivery phase processes.

The literature identifies various avenues for further research to maximise the potential of OSC-SCM. The area of research that could be explored is the integration of advanced technologies, such as optimisation, BIM, blockchain and the IoT, into OSC supply chains. Integrating cutting-edge technologies holds great potential for improving efficiency and effectiveness in OSC's supply chain. However, these technologies must be optimised for the entire SC framework. This first optimisation stage ensures that the SC runs smoothly and effectively, providing a solid basis for further improvements. After optimisation, cutting-edge technology can be included to optimise workflows further and boost output. Consequently, it becomes clear that prioritising optimisation is the first step towards realising the maximum potential of productivity and efficiency gains in OSC's supply chain operations. Additionally, the research could delve into optimising transportation logistics and formulating sustainable packaging and transportation methods to mitigate the environmental impact associated with OSC.

2.2 Investigation of the Effects of Supply Chain Disruptions on Offsite Construction Projects

The current section is based on the following Article:

Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Investigation of the effects of supply chain disruptions on offsite construction projects. In *International Conference on Engineering, Project, and Production Management* (pp. 161-172). Springer, Cham.

Abstract

Off-site construction (OSC) projects have unique features that set them apart from the traditional construction approach, particularly in supply chain management. Any disruptions at the top of the supply chain impact the subsequent stages, resulting in inefficiency. Such disruptions can affect material, data, and fund flows while negatively influencing the project performance and the client's cost, quality, and schedule advantages. Late deliveries or inappropriately supplied components, component damage - redesign, and additional fees are some problems that OSC has faced. Fragmentation in the supply chain causes uncertainties and complexities that originate from various stakeholders' interfaces, impacting project performance. Improving project performance requires a comprehensive study of the market based on the relations of multiple stages among it and the construction industry in that specific region to increase capacity and uptake. Considering that supply chain disruptions in the building industry have not been comprehensively investigated, a recent detailed study of supply chain disruptions is needed to accelerate the uptake of OSC. To improve the company's performance for future disruptions, the study attempts to better understand how disruptions affect OSC. For this purpose, a scientometric literature review study method was employed, including a recently published data analysis. In conclusion, it was calculated that the whole stage of supply chain management involved disruptions, but the most important issues are Poor understanding of process plans/system failure, Limitations of onsite space, Quality damage of components, Transportation restrictions (size & weight), weather, Poor supply chain integration and disturbances, Non-standard building material, and unsuitability of project delivery method.

Keywords: Literature Review, New Zealand, Offsite construction, Supply Chain Risk, Supply Chain Disruption.

2.2.1 Introduction

Offsite construction is described as the process of creating construction elements offsite in a specifically designed manufacturing plant, similar to a factory (Nesarnobari S. et al., 2022c; Tam, 2007; Tam et al., 2007). The numerous benefits of OSC to all industrial sectors contribute to the recent surge in interest in the usage of off-site buildings. Despite its advantages, OSC application remains restricted, undeveloped, immature and sluggish (Marjaba, 2016) owing to a lack of understanding of important problems. One of the most significant barriers to adoption is supply chain fragmentation. The supply chain is an integrated network of enterprises and supplier-distributor connections (Mostafa, Dumrak, et al., 2014). The supply chain is a product transformation mechanism that transforms raw materials into inventories, work-in-process inventory, and finished items (Nesarnobari S. et al., 2022a). Control of the supply chain is a long-term competitive advantage and one of the business's most important success criteria (Chiang et al., 2006). The supply chain has become crucial because construction activities have been decentralised (Vrijhoef, 2000). OSC works with current businesses (such as suppliers) that are moving to industrialisation and their level of engagement in the offsite housing supply chain. Controlling the supply chain to guarantee sustainability is critical and complex because of the differences between OSC and traditional supply networks (Bankvall et al., 2010).

Risk events are a continual source of frustration for supply chain and logistics management. Uncertainty impedes companies' capacity to create economic value by causing overreactions and unnecessary interventions, and increasing the likelihood of delays and quality difficulties (Davis, 1993). Furthermore, it increases supply chain complexity, which should be avoided or eliminated (Davis, 1993). The five most prevalent risk classification approaches are process, control, demand, supply, and environment (Christopher & Peck, 2004; Nesarnobari S. et al., 2022c). In 2019, Luo et al. completed the most recent SCR investigation for an offshore construction project in Hong Kong. They give a more in-depth understanding of SCRs in offsite buildings by considering linked stakeholders and dynamic risk interactions to solve the limitations of traditional static risk analysis (Luo et al., 2019). The capacity to respond to and manage these risk events puts a firm ahead of its competition and reduces long-term commercial damage. Respond, efficiency, and dependability are the essential characteristics of supply chain profitability (Hendricks, 2003). Supply networks must respond quickly to external and internal risk events while being efficient and dynamic in order to remain profitable.

Risk in the supply chain is created by uncertainty about future risk occurrences, which can occur at any point in the supply chain. Risk events occurring at various levels of the supply chain system may have a negative impact on supply chain performance. Supply chain risk management is the management of such incidents, and it has become a significant component of corporate strategy. Risks can induce unexpected changes in the supply chain's material flow, manufacture, transportation, and assembly. Recognising the many types of risks and the events and conditions that cause these risks is the first step in risk management in the supply chain. As a result, it is critical to detect various sorts of hazards along the supply chain. A thorough examination of the literature is necessary for this goal. As a result, this evaluation research aims to better understand the supply chain disruptions for offsite construction, particularly in terms of enhancing management. By evaluating Scopus database papers on offshore building supply chain hazards, this study will also help scholars propose future research recommendations. Scientometric research is characterised as a "quantitative study of science, science communication, and science policy" (Hess, 1997). This work offers a scientometric review using the scientometric technique to examine and map the literature on disruptions associated with supply chain of OSC. This paper's findings highlight the significant subjects in the gap literature and give a better knowledge of current research priorities.

2.2.2 Methodology

Conducting a scientometric review can facilitate the identification of pertinent authors and countries, thereby aiding in discovering research gaps in the field. To meet the aims of this review research, relevant scholarly papers on OSC confronted with risk/ disruptions were obtained from an online dataset. As a result, a list of scholarly papers was culled from the Scopus database. Setting research limitations is critical to circumvent the problem of scanning every related article (Van Eck, 2014). In this paper, scientometric studies are performed on data from the Scopus online database, utilising scientometric methodology and a scientific mapping technique. Figure 2-11 depicts the methodological process structure for this enquiry.

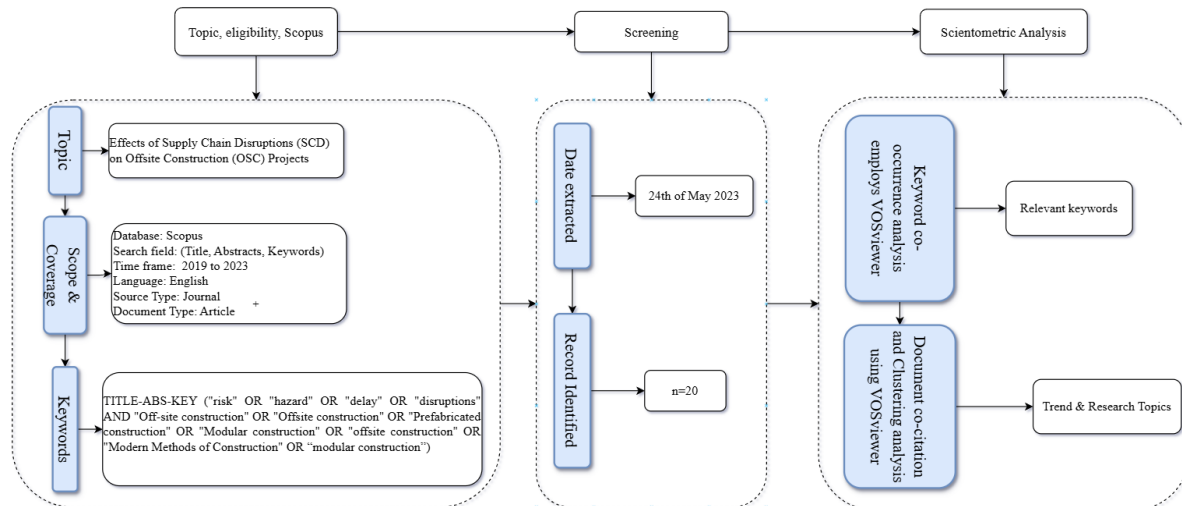


Figure 2-11: Scientometric Approach

2.2.2.1 Framework

The article's primary objective is to conduct a comprehensive scientometric analysis of how disruptions and risks impact various phases of offsite construction projects. It also aims to identify the response strategies employed by project participants thoroughly. Additionally, the paper explores strategies to promote sustainable growth in the supply and demand of offsite construction, along with the valuable management lessons the construction industry can glean from handling disruptions and risks.

The paper effectively clarifies the scientometric review methodology used to assess research related to disruptions and risks in the OSC sector. In this study, the authors utilised science mapping techniques within VOSViewer (van Eck & Waltman, 2010) to create visual representations of the offsite construction landscape. VOSViewer's growing popularity is noted for its role in facilitating literature reviews in construction engineering and project management, including fields such as public-private partnerships (Song, 2016), Building Information Modeling (BIM, as demonstrated by (He et al., 2017)), and building control (Park, 2018). Furthermore, its applicability extends to various other research domains, as indicated by (Zhao, 2017).

2.2.2.2 Screening

The Scopus database was searched by using the keyword combinations like "risk" OR "hazard" OR "delay" OR "disruptions" words. The others are: "Off-site construction" OR "Offsite construction" OR "Prefabricated construction" OR "Modular construction" OR "offsite construction" OR "Modern Methods of Construction" OR "modular construction". Finally, 20

articles were selected. Inclusion Criteria: This research investigates the impact of disruptions on offsite construction projects and the strategies to mitigate them. Therefore, this study includes papers that specifically address these subjects. Exclusion Criteria: Any literature unrelated to the offsite construction process or does not pertain to the influence of disruptions in this context will be excluded from this research.

2.2.3 Findings

2.2.3.1 Co-occurrence Analysis

A keyword co-occurrence analysis was conducted, involving a total of 791 keywords initially. After applying a predefined minimum threshold, 76 keywords were identified and screened for relevance. Duplicate and irrelevant keywords were subsequently removed from this list. Consequently, 59 valid keywords remained, forming the basis for generating the scientific map displayed in Figure 2-12. In this visualisation, the associations between keywords and clusters of phrases are colour-coded using the VOSviewer visual analysis tool. Each distinct colour corresponds to a different collection of keywords. It's important to note that the distance between two keywords on the map reflects the strength of their cross-reference link. More considerable distances indicate weaker connections, while shorter distances suggest a higher likelihood of clustering co-occurring phrases.

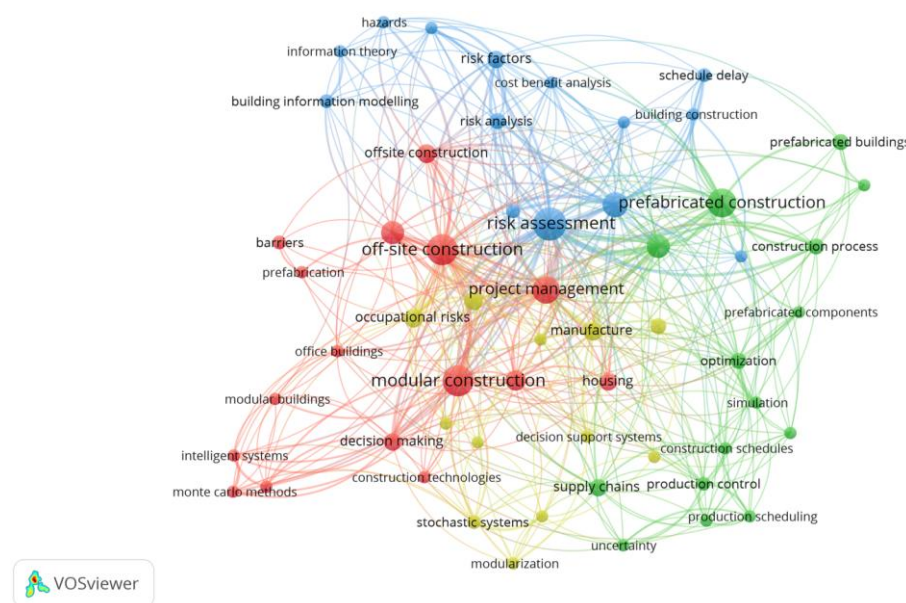


Figure 2-12: Keywords co-occurrence map of references

Figure 2-12 provides an overview of ten distinct clusters, with "risk assessment" being the most extensively researched keyword. This keyword frequently co-occurs with others such as "off-site construction," "modular construction," "risk management," "cost," and "occupational risk."

The size of each node in the figure indicates the frequency of co-occurrence of keywords. The 59 keywords are roughly categorised into four groups based on their node colours. Red Nodes: These keywords are primarily associated with decision-making, barriers, and cost research in offsite construction (OSC). They contribute significantly to understanding how OSC decisions are made, the challenges faced, and the associated costs. Green Nodes: Keywords in this category relate to optimisation techniques, risk management, production control, and genetic algorithms. These are commonly used to enhance the optimisation of offsite construction processes, focusing on efficiency and risk reduction. Purple Nodes: Simulation is a prominent keyword in this group, often employed to study ways to enhance the adoption of OSC and reduce costs related to risk management. It focuses on simulating OSC scenarios to gain insights into its potential improvements. Blue Nodes: Keywords here center around risk analysis and risk assessment, particularly concerning OSC's cost, risk, and delay. Researchers often use these terms to examine the impact of risks on OSC projects. Yellow Nodes: This category encompasses keywords related to decision support systems, supply chain management, and stochastic models, which are commonly used to manage risks in OSC. These keywords highlight strategies for effectively navigating risks within the OSC context. In summary, Figure 2-12 provides a visual representation of keyword clusters in OSC research, offering insights into the major areas of study and their interconnections, with a strong emphasis on risk assessment and management, cost analysis, and optimisation.

Table 2.8: Summary of mostly studied keywords

Number	Keyword	occurrence	Total length
1	Risk Assessment	22	140
2	Off-site construction	19	106
3	Modular Construction	19	74
4	Prefabricated Construction	17	82
5	Project management	15	91
6	Risk management	11	78
7	Costs	8	44
8	Occupational risk	7	55
9	Manufacture	7	47
10	Offsite manufacturing	7	47
11	Offsite construction	7	41
12	Risk factors	6	41
13	Supply chain	6	29
14	Risk analysis	5	21

Keyword analysis serves as a valuable tool for identifying the core content of publications, enabling us to effectively pinpoint key research topics in risk research within offsite construction (OSC). As illustrated in Table 1, aside from "risk assessment," other frequently

mentioned keywords encompass "offsite construction," "prefabrication," "risk management," "cost," and "risk factors," with 19, 17, 11, 8, and 6 occurrences, respectively. This suggests that these topics are central to the OSC risk research landscape. Furthermore, it's notable that numerous studies, particularly in China, delve into various aspects of OSC-related risks. These studies address multiple issues, such as risk identification (Zhang L., 2020) and cost management (Shujun et al., 2020). This indicates a significant interest in understanding and managing risks associated with OSC projects in China, specifically focusing on risk identification and cost control.

2.2.3.2 Countries Included in Studying Risks

This section analysed the nation or region data from the 85 articles to discover which countries are presently receiving more attention in the researched field. Table 2.9 shows that ten countries are conducting research on the subject of research. Figure 2-13 illustrates that the majority of specialists, with a total of 35 publications, have undertaken significant studies in China. China has excited international interest as the first country to announce the concerns. Scholars should look at China's contributions to risk reduction through offsite projects. There are 19 relevant studies in Australia and 9 in the United Kingdom. Apart from China, Australia, and the United Kingdom, there are eight in Hong Kong and eleven in the United States. Various countries implemented various standards for epidemic prevention policies, resulting in varying effects and techniques.

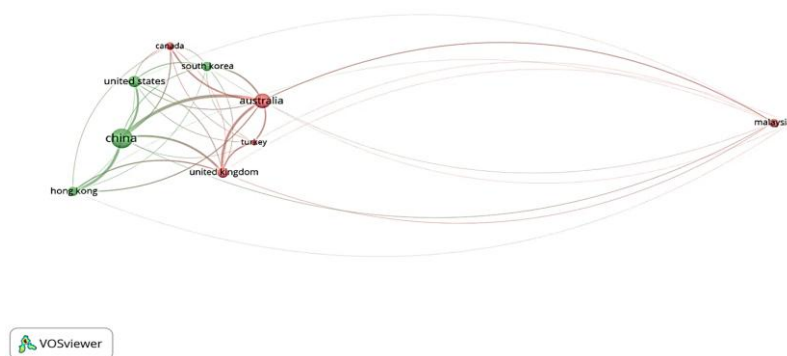


Figure 2-13: Country active analysis

Table 2.9: Country active analysis

Country	Documents	citations	Total Strength
China	35	535	1463
Australia	19	312	1357
United States	11	225	324
United Kingdom	9	213	740
Hong Kong	8	261	553
South Korea	8	131	206
Malaysia	7	35	159
Canada	6	108	219
Turkey	3	24	221
Indonesia	3	15	104

Table 2.9 shows that experts from China, Australia, and the United States rank first, second, and third in terms of the number of publications, respectively. Furthermore, China has the highest total connection strength in SCD research connected to OSC. However, China is at the forefront of global leadership in this area.

2.2.4 Discussion

During the various stages of offsite construction, including design, manufacturing, transportation, and installation, disruptions can occur. Disruptions in any stage of OSC projects affect the projects and lead to delays in the planned schedule (Hola, 2010; Kaplinski, 2008; Yang, 2011), delivery (PMI, 2013), and an increase in the total cost (Mao, 2013, 2015).

Previous research has identified various design-related risks in OSC projects, including: The absence of design codes can lead to specific concerns during the design stage, particularly regarding the performance of connections between prefabricated structural components (Vaghei, 2016). Risks associated with design uncertainty in joints between prefabricated components can subsequently impact construction (Liao, 2018). OSC designs that inadequately account for local conditions, such as supply chain management (Zhang et al., 2014; Hong et al., 2018). Insufficient knowledge or experience among industry professionals involved in the design, construction, or management of OSC projects (Luo, 2017).

Communication challenges within OSC project teams, including coordination issues between architects and contractors (Ismail, 2016; Luo, 2015; Pozin, 2017). In prefabricated building projects (PBPs), typical life-cycle stages include feasibility study, design, manufacturing and transportation, construction, and operation and maintenance (Wang & Hu, 2019; Wu et al., 2019). Eze et al. (2018) conducted a quantitative survey, identifying contractor-related and design-related causes as the primary categories of rework risk triggers, focusing on management problems and stakeholders (Eze, 2018). These risks if not addressed early will

lead to contractual risks which could be detrimental for working relationship and develop into ,or serious disputes (Jelodar, 2012). Du (2019) developed a multi-agent-based model to quantitatively assess how design change management strategies can enhance project performance. Sutrisna (2019) explored risks throughout the design stage to facilitate the adaptation of OSC (Sutrisna & Goulding, 2019). One significant factor hindering organisations from achieving value in OSC is uncertainty, which can lead to potential delays and issues due to unnecessary interventions and overreactions (Yang et al., 2022). This complexity is particularly prominent in the supply chain (Yang et al., 2022). As a result, recognising risk factors becomes crucial. Yang et al. proposed a framework for identifying uncertainties with multifaceted, interconnected, and context-specific features to address this. This framework assesses the probability and impact of these sources of uncertainty. Kim et al. (2019) proposed a dynamic model for production scheduling in precast concrete projects. They utilised discrete-time simulation and a new dispatching rule that considers the uncertainty of due dates to minimise delay in response to real-time changes (Kim et al., 2020).

Furthermore, researchers have made concerted efforts to identify and prioritise the causes of project timeline delays within the realm of offsite construction (OSC) projects. For instance, Wuni et al. (2019) undertook a comprehensive literature review to pinpoint the primary risk factors influencing modular integrated construction projects, which represent a comprehensive form of OSC (Wuni & Shen, 2019). Additionally, Wuni and Shen (2021) underscored the significant relationship between early-stage project decisions and project success in prefabricated prefinished volumetric construction projects (Shen, 2021). In a similar vein, Luo et al. (2019) conducted a meticulous investigation to uncover supply chain risks (SCRs) responsible for delays and cost overruns in precast concrete (PC) projects. Their approach involved a combination of literature analysis, interviews, focus group meetings, case studies, and social network analysis to dissect SCR-related issues tied to various stakeholders (Luo et al., 2019). Cho et al. (2021) delved into 19 instances of precast concrete (PC) construction projects in Korea during 2021. They employed fuzzy-set qualitative comparative analysis to explore the connection between early-stage PC project conditions and actual schedule delays (Cho et al., 2021). In 2020, Chang et al. developed a dual-objective optimisation model aimed at minimising security risks within systems and controlling costs to reduce the extent of construction safety risks associated with prefabricated structures (Chang et al., 2020). Additionally, in 2021, Liu et al. introduced an innovative real-time scheduling and tracking-based dynamic optimisation technique tailored for the transportation and storage of precast concrete component (Liu D. et al., 2020). Jeon et al. (2021) conducted an evaluation of

accidents related to modular construction that occurred in the United States between 2000 and 2018. Their study focused on safety risk factors, including accident types and causes (Jeong et al., 2021). Moreover, Hsu et al. proposed a mathematical model for optimising the logistics stage, encompassing manufacturing and assembly phases, to refine the risk-averse logistics configuration for modular construction projects operating under conditions of operational uncertainty (Hsu et al., 2019). The forthcoming table will present a detailed list of risks gleaned from the latest research in this field.

Table 2.10: List of disruptions adopted from recent works.

Disruptions	Sources
Material shortage Non-standard building material	Gan et al (2018) Hamdi F (2018)
Issues related to project permitting Legal and regulatory challenges Resilience performance Joint design for connecting offsite components	Hong et al. (2018), liao (2018), Chu et al. (2017), Shen et al. (2018); Xia et al. (2022)
site storage and security for off-site manufactured components safety and function of temporary structures on-site Poor understanding of process plans/system failure Lack of knowledge and expertise and low levels of skilled labour	Liao (2018), Gan et al. (2018); Gan et al. (2018); Durdyev et al. (2019); Xia et al. (2022); Wu P et al. (2019)
Inclement Weather Lateness in delivering Unsuitability of project delivery method Early arrival and wrong delivery of modules on site	Wu P et al. (2019); Ekanayake et al. (2022); Arashpour et al. (2020);
Limitation of onsite space Quality damage of components Transportation restrictions (size & weight) weather	Wu P et al. (2019); Ekanayake et al. (2022); Wuni et al. (2022); Arashpour et al. (2020);
Experience of employees in OSC projects Lack of relevant safety education Stakeholder Fragmentation and management Complexity	Wuni et al. (2022); Arashpour et al. (2020);
Poor supply chain integration and disturbances Supply chain information gap and inconsistency Poor cooperation and communication among project	Ekanayake et al. (2022); Wuni et al. (2022); Hamdi F (2018); Zhu et al. (2018); Arashpour et al. (2020);

2.2.5 Conclusion

The OSC relates to lifecycle cost reductions, decreased construction waste, increased flexibility, lower carbon emissions, and building process simplicity. However, OSC's unique design, engineering, supply chain, stakeholder mix, and management need to provide a broader range of risks and uncertainties that might jeopardise the aforementioned benefits. In response, empirical research has been conducted in several nations to investigate the numerous risks

connected with OSC. Due to the focus of more studies on distinct risk components of OSC, it is necessary to synthesise the empirical study findings in order to establish a research framework for the essential elements associated with OSC. A thorough review of 20 empirical recent research on the dangers of OSC was undertaken in this study.

The analysis of recently published articles has revealed that risk factors in offsite construction impact all supply chain stages and are not limited to a specific phase. The findings suggest that seven key factors significantly influence project timelines. These factors are: 1) Shortage of skilled and experienced laborers. 2) Late design changes. 3) Poor site attributes and logistics. 4) Unsuitability of design for modularization. 5) Contractual risks and disputes. 6) Lack of adequate collaboration and coordination. 7) Challenges related to tolerances and interfaces. These factors affect project timelines and contribute to increased project costs. While some elements may primarily impact a single stage of the construction process, others have repercussions across multiple locations. Consequently, it is crucial to analyse and identify risks associated with offsite construction thoroughly. By doing so, we can enhance the adoption of offsite construction methods over traditional in-situ construction, recognizing the benefits of the new approach.

The results of this study may significantly value and benefit academics, policymakers, and advocates in the construction industry seeking empirical quantitative proof and explanations of the recent risks repercussions needing response solutions. A comprehensive understanding of the implications of demanding response methods is critical for effectively combating the pandemic. The awareness of consequences was closely associated with reaction approaches that might enable politicians and activists to establish response plans that minimise the negative impacts of the offsite building sector.

2.3 Mapping Supply Chain to Enhance Capability and Capacity of Prefabricated Housing Supply in New Zealand

The current section is based on the following article:

Nesarnobari, S., Shahzad, W., & Jelodar, M. B. (2022, February). Mapping supply chain to enhance capability and capacity of prefabricated housing supply in New Zealand. In *7th New Zealand Built Environment Research Symposium* (p. 178).

Abstract

Long-term performance-related problems in the construction sector have caused a deficit in the housing supply in New Zealand. It is essential to enhance the capability and capacity of the residential sector of the construction industry for it to be able to tackle problems that are responsible for slow delivery of housing projects, high cost of construction, and generation of construction waste. Prefabricated construction has well-acknowledged tangible benefits, but it is relatively low in New Zealand. It is established that prefabricated housing supply chain management (SCM) in New Zealand needs improvement and integration to reap the full benefits of this technology and increase its uptake. The focus of this study is to carry out a mapping of the prefabricated housing supply chain in New Zealand and identify the disruptions in the supply chain. For this purpose, a comprehensive analytical approach is followed integrating bibliometric search and qualitative discussion by objectively investigating: 1) recent prefabricated housing research keywords, pros & cons; to identify factors that are limiting prefabricated sector to deliver New Zealand housing supply requirements 2) study gaps in combining prefabricated housing sector with other new construction concepts, 3) prefabricated construction research directions in the future There is no equivalency between the demand and supply of prefabricated housing. Trust among stakeholders, lack of workforce and a delay in the onsite assembly are significant issues in SCM. There are risks and disruptions through the whole supply chain, such as availability of imported raw material, freight delays, situations such as the Covid-19 pandemic are among other unprecedented disrupters. Moreover, the factories cannot manufacture and store bulky prefabricated components before the order and signing a contract due to lack of storage capacity. It is necessary to improve the capability and capacity of the residential sector to be able to tackle issues that are responsible for slow delivery of housing projects, high cost, and generation of construction waste.

Keywords: Supply Chain Management, Disrupters, Mapping, Prefabrication, Housing, New Zealand.

2.3.1 Introduction

Housing demand in New Zealand has risen dramatically over the last few decades. One of the primary sources of increased demand is acceleration an urbanisation plan led by a significant foreign population (Grimes et al., 2010). According to Statistics New Zealand, the country's ordinarily resident population increased by 10.8% between 2013 and 2018. However, the total number of dwellings increased by just 6.2 per cent. Between the 2013 and 2018 censuses, the population of Auckland increased by 156,168 (11%), although housing stock increased by just 6.5 per cent. (Due to migration-driven population expansion, Auckland's housing shortages have been particularly notable.) According to the most recent census statistics, developing new residences has not kept pace with population growth. Much of the new construction has not taken place where it is most needed. As a result, there was a notable housing shortage compared to population growth.

Various issues and challenges in the building industry prohibited it from keeping up with the growing demand (Finnie et al., 2018). New Zealand's construction industry productivity is lower than other nations (Allison & Parker, 2013; Curtis, 2018; PWC, 2016). The New Zealand construction sector suffers from low productivity, high staff turnover, low skills, and a lack of innovation (Sutrisna, 2020).

This demonstrates that New Zealand has to build more homes and move toward more sustainable development to ensure that future generations have access to the resources they require and the opportunity to prosper (Moradibistouni & Gjerde, 2017).

Affordability, excellent quality, and quick-build were all factors that were necessary for New Zealand homes to meet demand, but they were not provided under the existing paradigm. As previously stated, home quality has been highlighted as a data system gap in New Zealand (Charlotte Brown. et al., 2020), and it is a continuing concern in the building industry. Beyond the immediate housing crisis, it is necessary to reduce costs and move swiftly to enhance margins and reduce continuing skill shortages, contributing to lower quality and the need for rework (BDO, 2019; Gordon & Curtis, 2018; Rotimi, 2015).

Researchers and working professionals in the construction industry have been trying to develop novel ideas and approaches that meet demands and requirements to respond to the sophisticated

and growing needs to increase productivity in the industry. There were numerous options, some of which were eventually adopted. Offsite building, often known as prefabrication, has become increasingly popular (Goulding & Arif, 2013). According to construction industry practitioners, prefabrication technology is the construction industry's best hope for supplying a growing need for more affordable housing (Brandon, 2004; Tam et al., 2007). The first prefabricated house in New Zealand was received by Te Pahi, the Maori chief, in 1806. The prefabrication business began in 1833 by importing prefabricated houses for individuals as kits and pre-cut frames from the United Kingdom, the United States, and Australia (Bergdoll & Christensen, 2008; Toomath, 1996). The construction industry grew swiftly to meet the demands of a rapidly growing population and migratory population (Isaacs, 2008). In the last decade of the nineteenth century, the New Zealand Railways Department became the country's first producer of prefabricated houses (Bowron & Mace, 2007). Prefabricated building materials are divided into concrete-based and metal-based prefabricated products. Frames, partition panels, door and window frames, metallic roof systems, formwork at various stages of construction, precast beams and façades, tunnel linings, bridge girders, and platforms for meteor works, sewage discharge units, and underground facilities, among other metal prefabricated components, are in high demand. According to Prefab (Prefab NZ, 2018b), prefabrication is primarily used in the production of concrete products, prefabricated timber structures, and prefabricated metal buildings. A successful adoption requires a deep understanding of industrial ideas and technology, as well as collaboration among supply chain players and full government support (Samarasinghe. & Wood., 2021).

2.3.2 Literature Review

2.3.2.1 Prefabricated Systems

Eco-friendliness, safety, lower financial cost, faster speed, greater flexibility in construction techniques, consistent quality, lower construction waste, short construction period, fewer construction defects, and increased health and safety levels are also advantages of prefabrication-based construction (Hao and Samarasinghe, 2020; Moradibistouni et al., 2017). Houses, multi-story buildings, and highways and bridges are constructed using this method (Ngowi et al., 2005).

Prefabrication, as widely assumed, will give a more cost-effective housing alternative. However, the main advantage is that it gives you greater control over manufacturing and building circumstances, resulting in a higher-quality product. According to research literature,

the significant benefits of prefabricated techniques are higher quality and fewer flaws (Cook B, 2005; Hashemi A & Hadjri K, 2014). To achieve this increased quality, closer coordination of labour, materials, equipment, and sub-trades in controlled circumstances is employed. Quality control and any required adjustments may be made before the product leaves the production floor.

When comparing prefabrication construction to traditional methods, it is evident that the speed of building delivery has risen. The use of prefabricated panels or modules reduces the requirement for external contractors and plastering and tiling (Poon CS, 2003). This might decrease staff management responsibilities (Roy R, 2003) and considerably boost the overall construction pace (Lu N & Korman T, 2010). Prefabricated buildings can assist reduce the risk of construction delays due to poor weather in a manufacturing context. This can reduce the typical construction process's program time component by 30 to 60%. The time saved onsite can help offset the increased expenses of new material development or pre-construction planning processes that involve large, prefabricated parts (Aburas, 2011; Bildsten, 2011). Prefabrication buildings, according to BRANZ, save 27% of the material, 18% of labour, 45% of the land, and 10% of other costs (profit, plant, fees), resulting in a 15% reduction in the constructed cost of new houses (Prefab NZ., 2014).

Prefabrication also has the advantage of tight quality controls, testing systems, and prototypes within the facility. The defects liability period following occupancy can decrease the number of mistakes and subsequent repair work. Compared to typical construction, onsite noise, dust, transportation, and neighbourhood disruption will likely be reduced. Prefabricated houses can have a variety of appearances and are frequently indistinguishable from traditionally constructed homes. Cutting timelines and costs can be achieved by eliminating reliance on the weather for site-based construction, better in-house coordination of sub-trades, decreased transportation, and price advantages from bulk buying. 'Due to the cost savings inherent in the construction process, a prefabricated shell will often be less expensive than a site-built building of identical specifications, design, and quality (Buchanan M, 2004), through efficient ordering, indoor protection, pre-planning, and cutting, able to eliminate material waste. For example, in New Zealand, construction is the 'forty per cent industry,' with buildings accounting for 40% of energy consumption, 40% of the waste stream, 35% of carbon dioxide emissions, and 40% of raw material use. Because prefabricated buildings require less transportation to the job site and use less energy during their lifetime, they reduce their carbon footprint. Modular construction can reduce delivery delays by as much as 60% to the worksite. The method

provides a safe, healthy, and regulated working environment and increased worker productivity and material efficiency. Site work has previously fallen up to 50% short of its potential, and an estimated 13–18% of resources allocated have been wasted owing to inefficient use (Gorgolewski, 2005). Prefabrication technologies can also assist challenges in the construction industry, such as low-skilled labour, growing market demands for higher-quality homes, and more regulatory oversight.

2.3.2.2 Barriers to Adoption of Prefabricated Systems

Despite the significant advantages of prefabrication construction projects, prefabrication has numerous limitations in New Zealand. It is challenging to expand prefabricated building components in New Zealand since the capacity of manufacturing companies is limited. As a result, prefabricated construction elements are pretty expensive. The expense of crane logistics is a crucial barrier for prefabrication applications in New Zealand due to a lack of technology and suitably robust cranes (Shahzad, 2011).

China International Marine Containers (CIMC) Modular thinks that contemporary New Zealand modular buildings are still in the early phases of development, notably in terms of international module suppliers. According to CIMC Modular Systems (2016), the level of local acceptability and acknowledgement of modular structures is still relatively low, ranging from local governments to end-users. CIMC Modular thinks New Zealand's approval procedure is more complex and time-consuming than Australia and the United Kingdom. Second, there is a labor shortage in the building industry. The multi-domain collaborative content included in modular structures is different from traditional construction processes, according to CIMC Modular Systems (2016) (China International Marine Containers (CIMC)Group, 2016). All consultants, construction teams, and modular supply teams must collaborate to guarantee an efficient and cost-effective module design and achieve industrial factory production in modular building projects. Because there are few engineering consulting firms familiar with specific modular building systems in New Zealand, such as architectural design consultants, structural consultants, fire consultants (including fire engineers), energy efficiency consultants, sound insulation consultants, and mechanical, electrical, and public health consultants, modular construction is difficult to implement (Prefab NZ, 2018b; Shahzad, 2011). According to Scofield et al. (2009), the main obstacle in bringing modular construction to New Zealand is the lack of understanding about prefabricated building technologies among experts providing consultancy services (Scofield, 2009a). In addition to the problem of a small talent pool within the industry, no bank mortgage policy embraces prefabricated houses. Prefab NZ (2018) says

that banks have a direct system to assess the loan risk of onsite construction, but if the home is produced in advance at the factory, they need an additional assessment mechanism (Prefab NZ, 2018). At present, financial institutions have doubts about loans, which are all related to risks.

2.3.2.3 The Supply Chain Network

The supply chain (SC) is a web of interconnected companies and relationships of various suppliers and distributors (Mostafa, Chileshe, & Zuo, 2014). The SC is a product transformation method that changes items from raw materials to inventory, work-in-progress, and completed goods. To put it another way, supply chain management (SCM) is the notion of collaborating and integrating the value chains of many businesses. The strategic management of these chains has one main goal: to create value for customers and chain members in higher profitability (Speller T, 2007). These advantages would be utilised to their full extent only if growth could be generated and sustained. The SC is characterised as a "network of diverse firms and partnerships made up of several suppliers and distributors." SCM's goal is to "generate the best possible value for the whole supply chain network from the point of origin to end-user" (Gorecka M. Kacka K. Parkot L., 2008). Identifying, measuring, and modelling value across all stakeholders in the prefabrication manufactured supply chain (PM SC) is paramount to increasing the adoption of PM buildings.

There are unique features like the supply chain for offsite construction (OSC) compared to traditional supply chains. These features include design, manufacturing, factory inventory, delivery, onsite inventory, construction site, and end-project (Ikonen J. et al., 2013). The OSC-SC is a multi-tiered supply chain that begins with the creation of comprehensive design and shop drawings for structural components that will be constructed in a prefabricated factory. The components are then stored and transferred to building sites where they will be installed. These components are made to order to meet the needs of each project. As a result, prefabricators cannot manufacture certain parts before receiving orders. Contractors cannot retain huge buffer stockpiles of these components to hedge against supply delays because they are heavy and bulky (Hsu et al., 2018b).

Supply Chain Mapping (SC Mapping) refers to the systematic identification and visual representation of supply chain processes, stakeholders, and the flows of materials, information, and finances across the project lifecycle. However, supply chain performance denotes the measurable outcomes of supply chain activities, typically evaluated using indicators such as cost, time, and material efficiency. Also, supply chain efficiency refers to the optimal utilisation

of resources within the supply chain to minimise waste and cost while maintaining output. Supply Chain Effectiveness reflects the extent to which the supply chain meets project objectives, including timely delivery, quality requirements, and stakeholder expectations. In this study, SC mapping extends beyond process identification to include stakeholder interactions, communication flows, and contractual relationships that influence coordination across OSC supply chain stages.

Furthermore, the OSC-SC is rife with risks dispersed throughout its stages (design, production, logistics, and onsite building) (Wang H. et al., 2018). Any disruption at the top of the OSC-SC impacts the following stages, resulting in an inefficient SC. As a result, researchers have used a variety of modelling methodologies to investigate the OSC-SC and improve its performance and long-term viability. Compared to the manufacturing supply chain, the primary distinction is that the product is assembled onsite, and a greater portion of the supply chain is completed during production (Stroebele & Kiessling, 2017). Figure 2.14 illustrates the key stages of the panelised OSC supply chain, from initial concept development to on-site assembly. While the figure presents a sequential process flow, it is interpreted in this study as a supply chain mapping tool that captures the interdependencies between stages, as well as the flow of materials, information, and coordination requirements across the supply chain. In addition to process representation, the mapping highlights the involvement of multiple stakeholders across different stages and emphasises the importance of communication and coordination mechanisms in influencing overall supply chain performance. This mapping therefore serves as an analytical foundation for identifying potential inefficiencies, coordination gaps, and performance bottlenecks within the OSC supply chain.



Figure 2-14: The manufacturing process of Prefabrication in NZ (Sooriyamudalige et al., 2020)

According to previous research, there has been an inadequate understanding of supply chain management and its performance growth in residential construction in NZ.

Supply chain management is grounded in the principles of integration, coordination, and flow optimisation across interconnected processes (Christopher, 2016). In construction, SCM extends beyond material flow to include information exchange and stakeholder coordination,

which are critical for managing project complexity and uncertainty. In this research, supply chain mapping is not limited to a descriptive overview; rather, it serves as an analytical tool to identify process interdependencies, coordination bottlenecks, and performance drivers across OSC supply chain stages.

2.3.3 Research Methodology

The research method is based on an in-depth review of relevant literature. The research methodology for literature review is chosen from related survey studies by Chan & Yi (2014), W. Zhou et al. (2012), Hassan Ibrahim (2013), Ibem & Laryea (2014), and Guo et al. (2017). This involves the de-contextualisation and recontextualisation of the examined articles (Jelodar et al., 2016). The selection of this approach offered the benefit of bringing together proof from various research on the topic to inform practice. The analysis related to supply chain research is divided into two main perspectives: SCM for prefabricated elements and barriers to adopting prefabricated components. A three-stage literature search refined the desktop investigation to present an analysis of relevant journal papers. SCM of prefabricated elements has gained traction from practitioners over the last two decades. Hence for the study, authors selected articles published using Scopus as the primary source of literature. Scopus has a wide range of journal indexes and unique features in keyword searching and citation analysis compared to other databases like Google Scholar, Science Direct and Web of Science.

Stage 1 – Search by keywords, title, and abstract

A search criterion was designed to select emerging developments on the subject of interest, i.e., application of supply chain in NZ and links to prefabricated housing contained in article keywords, title, and abstract. Articles were searched by rearranging key phrases under the 'TITLE-ABS-KEY' menu.

Stage 2 – Selection by journal impact

This survey is based on selected top-ranked, peer-reviewed to obtain related developments.

Stage 3 – Selection by visual screening

The papers collected from stage 2 were considered to ensure that the search is concentrated on the relationship between the supply chain and prefabricated housing. This stage is designed to achieve the research objective of finding key supply chain functions and linking them to prefabricated in NZ. Screening involved reading the abstracts, findings, and conclusions. The criteria for selection were to find related work in NZ.

2.3.4 Findings and Discussion

2.3.4.1 Residential Housing in New Zealand

The residential construction sector in New Zealand is uniquely positioned to benefit from decades of international expertise and adapt knowledge and techniques to the local situation. New Zealand's home building sector has a lot of room to develop aspirational industry quality standards or labels that help customers understand the quality of what they're buying (Buckett, 2007). In New Zealand, detached housing makes up the majority of new construction (PAGE, 2013). The disparity between the rate of new house building and population growth in several of New Zealand's major cities is causing considerable worry. Auckland is particularly heavily afflicted with over a third of New Zealand's population (Quickstats, 2013). In Auckland, in particular, rising property prices and rents have become a significant source of worry (Buckett, 2007). The average business size is expected to rise, resulting in a dramatic shift in new housing features, perhaps resulting in higher quality, more affordable housing, and increased sustainability (PAGE, 2013).

Prefabricated (or industrialised) house-building (PHB) is a natural synthesis of the manufacturing and construction sectors, with techniques that overlap (Gann, 1996). However, this is a minor part of the entire house-building sector (Linner & Bock, 2012), with space to move and market intervention. A CIB report on offshore manufacturing and production (Goulding & Arif, 2013). Studies have shown that industrialising businesses may be an efficient way to increase construction capacity and capability while also increasing productivity. However, because to cost obstacles, a lack of design flexibility and opposing views, the industry's adoption of new prefabricated building technologies has been limited (Goodier C. I. & Pan, W., 2012; Mostafa, Chileshe, & Zuo, 2014; Pan, 2011). Poshdar et al. (2019) find out that most SMEs in New Zealand housing is trailing behind in new business methods (Poshdar, 2019). Building contractors also continue to be hesitant to use prefabrication, which is necessary to stay competitive and improve organisational performance.

As a result, these constraints respond slowly to the house-building supply chain, demonstrating the need of managing and improve the whole supply chain's efficiency (Bankvall et al., 2010). Supply chain management is critical for projects that employ prefabricated house-building parts to achieve sustainability. Improved prediction of under-capacity or overcapacity, as well as greater evidence-based decision-making, would eliminate waste. Furthermore, the delivery uncertainty would be reduced by prioritising the project through supply chain management.

Because offsite business is considered a specialised industry with a variety of offerings volatile, it generates a dynamic and competitive environment for firms participating in it ((Lessing, 2015). However, as the construction operations have been moved offsite, supply chains have become critical for PHB (Vrijhoef & Koskela., 2000). This contrasts with typical supply chain management techniques, which require suppliers to have previous knowledge of other parts of the supply chain (Walker, 2012, p. 137).

Regardless of the stage or phase of the house-building project, relying on supply chains is critical for achieving offsite advantages (Pan, 2012; Pan et al., 2012). PHB projects are confronting existing firms (e.g., suppliers) adjusting to industrialisation and their level of engagement in supply chains to PHB projects. Due to the unique nature of prefabricated house-building elements compared to typical supply chains, managing supply chains to achieve sustainability is a crucial topic for projects utilising prefabricated house-building parts. According to Shahzad (2011), a lack of supply chain capacity is a key obstacle to prefabrication adoption in New Zealand (Shahzad, 2011) also, Almughrabi stated that; complexity and fragmentation in New Zealand's prefabricated construction supply chain is one of the barriers to uptaking prefab in NZ (Almughrabi et al., 2021).

2.3.4.2 Residential Supply Chain

The traditional construction supply chain that developed according to relations of the construction project's participants in 2000 aligned the information and material flows among the participants within the construction process (Vrijhoef & Koskela., 2000). The other framework in 2005 considered the stages of construction from customer demand to the compilation of the project. The contractor is considered as the core of this framework and connected to the owner and designer (Xue, 2005.). This framework, despite other research, covered all the direct and indirect participants and mapped the flow of investment along the supply chain. The timeframe was developed in 2009 for a conventional industrialised house-building project to recognise the errors in the projects (Johnsson, 2009). However, because of crucial factors such as high expectancy, small economic size, and physical isolation, construction supply chain procedures in New Zealand are at a tactical level (Ying, 2015). Supply chain challenges include a lack of foreign strategic alliance partnerships, information exchange, and trade partnering (Basnet, 2003; Mollenkopf and Dapiran, 2005). Also, Interdisciplinary problems existed, such as the connection between the building supply chain and sustainability (J. E. McDevitt, 2012). The home construction supply chain is fragmented by nature, causing management issues and stifling inventiveness, so construction prices

increase and building quality decrease (NZPC, 2012). Moreover, contractors were indifferent in collaborating with other parts (Samarasinghe A, 2013). In construction, advanced technologies such as BIM software and supply chain planning and management are not taken into account (V. Tran, 2012).

Under corporate social responsibility, all stakeholders in the building supply chain are responsible for affordable housing. Still, reduced industry productivity and tight government restrictions add to the complexity (Bassett, 2015). Affordable housing is impossible without the engagement of contractors (who are the primary actors in the building supply chain) through incentive programs (Cullen, 2005). Government initiatives such as those made by the Construction Strategy Group (CSG., 2015) to decrease material and labour costs by 20% through Productivity Partnership are insufficient unless the industry is involved at both the micro and macro levels to achieve affordable housing. For this purpose, the report suggested: Introducing and integrating specialised subcontractors to increase SC flexibility, Effective subcontractor management to restrict coordination issues and rework. To minimise disputes, subcontractors should be more involved in achieving project goals, implementing standardised housing to boost scalability and production, and integrating project delivery via SC members' cooperation during the design and construction phases for the supply chain of affordable houses. Also, aspects of trade partners to achieve external emphasis (Mollenkopf and Dapiran, 2005) and effective logistics management (Fei & T. John, 2014) are suggested. Auckland council report (Parker, 2015) told factors have been considered for reforming the supply chain: 1) fewer licensed building practitioners 2) inconsistent design and manufacturing processes 3) low scale economies and limited scope economies 4) quality risk of construction and design 5) poor quality assurance 6) project management practices 7) More essential, supply chain participants should collaborate to increase overall productivity through innovative manufacturing technology. Facilitating international supply chain members will result in innovative housing solutions while also reducing market power. Affordable housing has been related to issues in building supply chain management such as alliancing, partnering, and collaboration among housing supply chain participants (Basnet, 2003; Mollenkopf and Dapiran, 2005; NZPC, 2012). These issues have to do with the relationships and coordination of supply chain participants.

Construction supply chain management needs to investigate a link between primary and particular difficulties with generic problems. Researches have explained general main barriers

to coordination, subcontractor or supplier integration, legality, stakeholder management, and corporate social responsibility.

Literature review explains specific issues: insufficient information exchange among supply chain participants, a lack of Building Information Modelling adoption by construction parties (DBHNZ, 2012), which facilitates collaboration among partners (M. Khosrow-Pour, 2013). Also, material logistic management is a critical component of supply chain management from a business viewpoint (Barriga et al., 2005). Offsite manufacturing helps customise construction elements, resulting in increased efficiency (Barriga et al., 2005). Furthermore, industrialisation can assist in integrating the construction supply chain (Dainty et al., 2001).

2.3.4.3 Construction Supply Chain Integration

Integration of the supply chain concentrates on reaching a reliable, valid, and timely flow of material, information and finance over the whole network to provide consumers value for money. Beneficiaries of reduction in cost and time for constructing order were drawn by integrating the key business functions over the supply chain (Power, 2005). Despite the manufacturing industry, the one-off product is assembled onsite through temporarily set up supply chains (Vrijhoef & Koskela., 2000). It seems that the essence of construction supply chains is far from a production viewpoint (Fearne, 2006). However, combining the processes and products in the construction sector to gain profit for the customer is suggested (Dubois, 2000; Egan, 1988). Supply chain integration has been offered for the potential to improve efficiency and effectiveness.

Nonetheless, there are barriers linked with implementation. Awad (2010) has recognised perspectives include technical, managerial, and relationship, which researchers identified to classify barriers for Supply chain integration (Awad, 2010). Technical relates to the obstacles that appear among the SCM systems and strategies; managerial refers to the restrictions that occur in planning and performance of the strategy, and relationship describes in the obstacles that influence the organisation of the whole relations (Awad, 2010). Numerous investigations like Akintoye, McIntosh & Fitzgerald, 2000; Barratt, 2004; Briscoe & Dainty, 2005; Vrijhoef, Koskela & Howell, 2001, have been carried out to recognise the obstacles to supply chain integration in the construction industry (Barratt, 2004; Briscoe, 2005; Mbachu, 2017; Vrijhoef, 2001). Results illustrate different barriers: lack of senior management responsibility, lack of understanding of supply chain management, unequal organisational structure to support the supply chain management system, low commitment of partners, uncertain strategic advantages,

and a lack of proper information technologies. The barriers of SCI were not accurately classified and discussed regarding the nature of the project.

2.3.4.4 The Supply Chain of Prefabricated Houses

Production planning and inventory control and logistics and distribution are two activities that make up a supply chain (Beamon, 1988). As discussed, the construction supply chain includes a network between participants and organisations engaged and alongside with a network of relationships and organisations together with the flow of information, the flow of materials, services or products, and the flow of funds between the owner, designer, contractor, subcontractors, and suppliers (Muya, 1999). The prefabricated housing supply chain is divided into four categories: design consent; second, manufacturing of modules/components offsite, third transportation of modules to site.

Different business entities, such as manufacturers, suppliers, developers, contractors, and distributors, are straight and indirectly involved in the prefabricated house building supply chain to deliver the house to the customer (Mostafa, Chileshe, & Zuo, 2014), processing forward flow of materials and the backward flow of information (Beamon, 1988). Prefabricated houses' supply is done in two steps: pre-assembly and onsite construction, which both have diverse demands on the supply chain. Pre-assembly includes designing, material handling, manufacturing, transportation to the place, and onsite construction involving procurement for installation and foundation (Lessing et al., 2015; Vrijhoef, 1999). The design and planning stages involve design freezes, expense planning, procurement methods, and project planning and scheduling, all of which are crucial milestones. It is essential to have an exhaustive understanding of the basic requirements to improve the design for the following consents and reduce the construction stage's complexities. Numerous studies associated with the construction supply chain have investigated and improved the supply chain's network. However, there is little investigation on the integration of supply chains of prefabricated elements. Pan et. al. explained that Prefabrication construction with various profits is one of the powerful options to conventional construction (Pan & Sidwell, 2011). The prefabrication method is one of the innovative and efficient systems of producing sustainable construction (Zhai et al., 2013). The obstacles to using this innovative method have restricted its broader uptake, individually in the housing sector. Benefits like reducing time, cost and increasing quality, productivity, health and safety, environmental impact and speed-up due to separate from weather conditions inspire the industry to use prefabrication methods in housing

construction compared to their traditional counterpart (Forum, 2002; Sparksman, 1999; Waskett, 2003).

According to the research, the prefabricated home construction process was shown to be very complicated and unique in each project. The main phases and critical stakeholders are analysed to determine the interfaces, followed by difficulties since the prefabricated home building process is not standardised. As a result, it is essential to map the exact and accurate supply chain of prefabricated housing buildings to maximise their use.

Supply chains of prefabricated housing buildings are represented in different ways in the construction and manufacturing literature and industry reports. For instance, the producers (map, 2014), manufacturers/suppliers (Liu, 2020), supply network acting as suppliers at different tiers found to be highly complex and unique to the tont tiers (Steinhardt, 2020), offsite companies in the organisational perspective (Manley, 2019), industrialised house-building companies (Lessing, 2015), or offsite manufacturing SME supply chains to PHB projects (Pablo, 2020). These supply chains are explained further by Pan and Goodier (2012) as business models based on process, risk, and financial features of offsite construction, divided by the amount of offsite work and material (Pan et al., 2012).

Also, studies have been conducted to investigate: the benefits of prefabrication (Lawson & Ogden, 2010; Pan et al., 2012; Pasquire & Gibb, 2002), the improvement of the prefabrication supply chain (Doran & Giannakis, 2011; London & Kenley, 2001; Naim & Barlow, 2003; Stroebele & Kiessling, 2017), prefabrication and lean manufacturing (Lessing et al., 2015; Mostafa, Chileshe, & Zuo, 2014; Mostafa, Dumrak, et al., 2014), the integration of supply chain strategies to prefabrication (Lessing et al., 2015; Mostafa, Chileshe, & Zuo, 2014). However, there has been little research considering the nature and the constraints in the prefabricated housing supply chain. Most of the barriers of prefabrication are aligned with the supply chain of prefabricated housing buildings. Therefore, managing and developing the performance of the complete supply chain is necessary (Bankvall et al., 2010). Shortly some of the barriers: Partnering between builders and manufacturers, public perception, cost barriers, less flexibility in design and negative perceptions (Bildsten, 2011; Goodier C. I. & Pan, W., 2012; Mostafa, Chileshe, & Zuo, 2014; Pan, 2011), extensive project planning from an early stage, lack of coordination and communication, and transportation constraints are found to be other barriers in prefabricated house building (Buckett, 2007; Kamali & Hewage, 2016). This led to low uptake of prefabricated in NZ. At the same time, nations such as the United

Kingdom, the United States, Japan, Australia, Hong Kong, Malaysia, and Singapore have recognised the benefits of offsite manufacturing processes in house building (Prefab NZ., 2014). Therefore, all these barriers affect the supply chain of housebuilding. According to previous studies, supply chain risks significantly impact (prefabricated building project) PBP performance. Enhancing PBPs' performance is critical for expanding prefabricated building use and improving capability and capacity. This demands a thorough examination of the market based on the interrelationships between the supply chain and the building industry in that particular location. Many studies have been conducted on the construction supply chain to investigate and improve networks. In the New Zealand building sector, however, such a detailed examination of different elements of prefabrication construction, including supply chain management and hazards, has not been conducted.

2.3.4.5 Shortage of Procurement Innovation in Supply Chain

Even though the construction and operation of prefabrication need considerable innovation in: resources and technical support (Tam et al., 2007), prefabrication of New Zealand lacks resources and technical assistance and lack of innovation in the supply chain leads to insufficient production potential (Konukcu, 2011; Scofield, 2009a). This causes fundamental challenges for contractors. Finnie et al. stated that traditional purchasing systems are used for imports needed for prefabrication (Finnie et al., 2018). So, this problem (lack of innovation) makes limitations to adopt prefabrication.

2.3.4.6 Prefabrication Supply Chain Integration

All the processes included in project shipment, from procuring essential components to delivering the project to the customer, are Construction Supply Chain Management (CSCM) (Behera et al., 2015). Likewise described as managing the flow of information, materials, processes, and activities between whole employees of organisations to deliver high quality and reliable products to the customer efficiently (Akintoye et al., 2000). Various authors have continuously revised the definition of CSCM in several industries and different use cases (Tan, 2001). However, the substantial premise of supply chain management can be established in systems thinking, which magnifies the significance of viewing all single parties included in the cycle of delivering a product (or service) as an essential contributor to a more robust system (Cai, 2010). Lack of collaboration and coordination amongst stakeholders is one of the barriers to the supply chain (Stadtler & Kilger, 2002). Unfit integration of all supply networks Inside an organisation prevents the adequate flow of orders and products among suppliers and end-

user (Lambert, 2000). Other challenges of supply chain management systems are low transparency, traceability, and lack of trust (Mentzer et al., 2001). Favoured supply chain management demanded a qualification from specific roles to integrate key supply chain processes (Lambert, 2000). The solution for supply chain management is Supply Chain Integration (SCI) (Konukcu, 2011). Implementing an effective and powerful SCM needs a combination of processes and flows (Cooper, 1997). The regularity of project delivery systems and collaborative relationships with sufficient flows are described as integration (Dainty et al., 2001). The complexity of suppliers in the construction industry is related to projects' size; large projects include more suppliers (Briscoe, 2001). As discussed in previous studies, there is an essential need for adopting innovation instead of traditional construction in NZ (Gordon & Curtis, 2018). As an innovative practice of construction, prefabrication technology in New Zealand is snowballing in terms of its percentage of contribution to the delivery of construction projects. Increasing demand for new houses and lack of affordable accommodations in New Zealand evolve the need for innovative and effective types of project delivery systems instead of conventional types.

The prefabrication is identified as leverage for reducing the shortcomings of traditional construction systems. Nevertheless, the construction industry is lingering in supply chain integration (Anders & T., 2010; Shahzad, 2016; Zhai et al., 2013). The complication in prefabrication supply chains is high because of broken working sites (Mostafa, Chileshe, & Zuo, 2014); this shows that better collaboration and more transparent communication is needed. Furthermore, managing the flows of information and materials and reacting speedily to any modification in customers' demands or design requires dynamic concurrent management strategies as well as the flexibility of supply chain partners to guarantee that the efficient integration of prefabrication supply chain is maintained (Gibb & Isack, 2010; Mostafa, Dumrak, et al., 2014).

A comprehensive review has been accomplished for identifying the modular barriers and enablers for supply chain integration in module manufacturing. The identified obstacles for wall panel and bathroom pods manufacturing companies in NZ are lack of trust among Stakeholders, lack of long-term Partnerships, lack of information sharing, lack of technology and automation, inadequate project planning & scheduling, lack of knowledge in consumer demand, inefficient performance measurement system, Inconsistent goals within the company, lack of clear direction and guidance, transportation of models, lack of understanding of SCM (Sooriyamudalige et al., 2020).

2.3.4.7 Supply Chain Management

A study in the supply chain of prefabricated housing buildings is rare. One of the latest researches was conducted on significant supply chain barriers for the modular component. As shown in Table, it is demonstrated that automation and trust among stakeholders are substantial barriers to the prefabrication supply chain. Prefabricated home construction is further hampered by significant project planning from the start, a lack of collaboration and communication, and transportation restrictions (Bildsten, 2011; Pan & Sidwell, 2011). Contractors may use several methods and essential aspects to reduce or remove the disadvantages while building empirical capacity and competence. These constraints respond slowly to the house-building supply chain, demonstrating the need to manage and improve the whole supply chain's efficiency (Goodier C. & Pan, W., 2012). Managing supply chains to gain sustainability due to the novel nature of prefabricated house-building elements, instead of regular supply chains, is essential for projects utilising prefabricated house-building parts. Integration of the supply chain should be from the beginning of the design phase and needs strong coordination among stakeholders to arrange labour, materials and equipment resources (Čuš-Babič et al., 2014). This coordination requires regular communication and collaboration among stakeholders to convey valuable and up-to-date information (Abedi, 2014). In this study, the latest research on the prefabricated housing supply chain in NZ has been mapped and the disruptions in the supply chain have been identified. Improved prediction of under-capacity or overcapacity, as well as more excellent evidence-based decision-making, would eliminate waste.

2.3.5 Conclusion

This research elaborated on the supply chain of the prefabricated construction sector in New Zealand. The obstacles and barriers were discussed as flawed, leading to the sector's current status. Solving offsite construction's complexity/uncertainty challenges is required to improve the industry and increase capacity and capability. This also alleviates the housing shortage. It was shown that the uptake of prefabrication was too low because of supply chain barriers.

Consequently, various influential factors from the literature that hinder its uptake were discussed, indicating the direction of future research to tackle those issues, leading to the enhancement of prefabrication. Supply chain management requires extensive investigation first to identify its barriers, disruptions and risk controls and second to employ new approaches to rectify those. Furthermore, lack of trust among stakeholders, lack of understanding of SCM,

lack of information sharing, lack of innovation (lack of technology and automation), low coordination, collaboration and partnership, transportation constraints, lack of commitment of managers and experts, vague regulations and strategic legislations, hinder building capacity and capability in the prefabricated manufacturing housing construction sector in New Zealand. There are risks throughout the entire supply chain, including the availability of imported raw materials, freight delays, and events such as the Covid-19 pandemic, among other unprecedented disruptions. Furthermore, the factories cannot manufacture and store bulky prefabricated components before an order is placed and a contract is signed due to a lack of storage capacity. Hence, future research should target supply chain management so that the housing sector will flourish and thrive gradually. A limitation of this study is that the data available is insufficient to assist in a wider analysis.

2.4 The Impact of Timber Offsite Construction on Global Warming

The current section is based on the following article:

Nesarnobari, S., Shahzad, W., & Jelodar, M. B. “Impact of timber offsite construction on global warming” published in 47th Australian Universities Building Education Association (AUBEA2024) Conference.

Abstract

Nowadays, it is crucial to discover innovative strategies to lessen global warming because of the energy consumption of the construction industry on greenhouse gas emissions. Since offsite construction (OSC) is efficient and sustainable, it has become a viable solution for this problem. This research investigates the influence of OSC on global warming, focusing on its carbon footprint and associated environmental benefits. It assesses the embodied carbon emissions related to New Zealand timber manufacturing and transportation operations while considering energy use. Comparisons are made between offsite timber, concrete and steel construction techniques to estimate the possible decrease in greenhouse gas emissions of six-storey buildings in New Zealand. The results show significant environmental benefits when comparing offsite timber construction to other materials. It is possible to achieve substantial reductions in embodied carbon emissions through efficient production techniques, reduced material waste, and the carbon-sequestering capabilities of timber. However, issues like supply chain logistics, legal frameworks, and market acceptance must be resolved to optimise the environmental benefits of offsite timber building. According to the conclusion, offsite timber construction should be encouraged as a sustainable way to lessen the negative consequences of global warming on the building sector. It offers insightful information that stakeholders, practitioners, and legislators may use to promote sustainable building practices and create a built environment that is more resilient and environmentally friendly.

Keywords: Offsite Construction, Timber, Global Warming, CO_2 emissions, Green House Gas.

2.4.1 Introduction

The contribution of the construction sector to 40% of the greenhouse gas (GHG) generation (Dolezal et al., 2021) and significant carbon dioxide emissions (Keysar & Pierce, 2007) leads to the attention of researchers to reduce the environmental impact of construction to reduce global warming. This demonstrates that the construction sector plays a significant role in the production of GHG (IEA., 2021). The benefits to the environment, economy, society, and finances will be enormous if building development is mitigated or improved in response to climate change (Wang et al., 2005).

Sustainable building practices are now essential in addressing environmental problems worldwide (Najjar et al., 2019). As a result, many sustainable building techniques are being used worldwide. Sustainable practices must be embraced as a shared duty by all parties involved in the building sector, from politicians to builders, given the growing need for resource efficiency and the need to address climate change.

New Zealand has a target to reduce the emission of GHG by 2030: *“Our first Nationally Determined Contribution (NDC1) under the Paris Agreement is to reduce net GHG emissions to 50 per cent below gross 2005 levels by 2030.”* (Environment, 2023). The goal of New Zealand and the role that building plays in global warming prompt an investigation for a means of lowering this level of greenhouse gas emissions. One technique that highlights the advantages of lower CO_2 and waste generation that reduces GHG is offsite construction (OSC). OSC is a construction carried out in a controlled environment and then transferred to the assembly site (Nesarnobari S. et al., 2022a). The most crucial benefit of offsite construction is reducing GHG by reducing construction time (Nesarnobari S. et al., 2022a). While choosing techniques helps mitigate global warming, choosing appropriate materials can also impact it (Moeck & Yoon, 2004).

The literature review indicates a gap in research focused on the effects of various materials, highlighting the necessity to understand how different materials contribute to global warming (Nesarnobari et al., 2024b). Consequently, this study aims to identify the most effective material for reducing greenhouse gas emissions from construction. To achieve this, the research will analyse three distinct buildings constructed with different materials to determine the most beneficial for this goal. By examining the environmental impact of each material throughout its lifecycle, the study seeks to provide valuable insights that can guide future construction

practices. Ultimately, the findings aim to contribute to developing more sustainable building solutions that align with global efforts to combat climate change.

Timber has long been desirable because of its natural abundance, high stiffness and strength-to-weight ratios, and ease of shaping. Over the past few decades, the government has replaced new requirements to utilise more comfortable timber. For instance, Switzerland, Italy, and Britain now allow timber structures that are six stories or higher. Four stories are the standard in North America; on rare occasions, municipal authorities may permit five or six stories. Timber buildings 20 stories or higher can be constructed using proper construction techniques (John et al., 2009). Given the natural characteristics of New Zealand, most of its residential structures are made of timber; only commercial buildings have recently begun to utilise wood, as knowledge of the material's advantages for tall buildings has grown (Nesarnobari S. et al., 2022c). Thus, there is no need to pay attention to material selection; only the methods utilised are essential. However, due to certain barriers, the uptake of timber offsite construction in New Zealand is lower than in many other countries (Nesarnobari et al., 2024b). these challenges, such as supply chain issues, market acceptance, or regulatory hurdles and increasing the awareness of people about the timber elements, optimising the supply chain, should be some solutions for the barriers (Nesarnobari et al., 2024b). For this purpose, it is essential to increase the implementation of offsite construction to reduce global warming (Nesarnobari et al., 2024a). Therefore, this research first analyses the literature review and then compares it with real case studies to emphasise the OSC projects.

2.4.2 Literature Review

Offsite construction has frequently been advocated as a method to enhance the efficiency, quality, and environmental sustainability of building construction (Steinhardt & Manley, 2016). The benefits of the prefabrication-based construction process include enhanced health and safety, reduced financial expenses, accelerated construction pace, greater flexibility in construction techniques, consistent quality, shortened construction timelines, and fewer defects during construction (Hao and Samarasinghe, 2020; Moradibistouni et al., 2017; Shahzad & Mbachu, 2012). Moreover, it offers eco-friendliness, less global warming, consistent quality, lower construction waste (Chen & Samarasinghe, 2020). It can be concluded that the main advantage is given greater control over manufacturing and building circumstances, resulting in higher quality and fewer flaws, leading to less remanufacturing and less environmental impact. This technology is expected to be more than 50% efficient in utilising energy, water, and raw

materials. This technique reduces the environmental impacts by 30-70%, decreases CO_2 emissions by 35%, and waste generation by 65% (Britto, 2008; Gorgolewski, 2005; Moradibistouni et al., 2019; Phillipson, 2001).

Mass timber is often recommended in the construction sector as a prime example of a sustainable, renewable, and circular economy resource instead of steel and concrete (Dangel, 2017). It included a variety of timber kinds, including nail-laminated wood (NLT), glue-laminated wood (Glulam), cross-laminated wood (CLT), dowel-laminated wood (DLT), laminated strand lumber (LSL), laminated veneer lumber (LVL), parallel-strand lumber (PSL), and structural insulated panels (SIP). CLT, LVL, and SIP are the more prevalent mass timber in New Zealand. In the absence of end-of-life analysis, it is imperative to consider the complete life cycle of timber products to support sustainable production and usage (Campbell, 2020).

Most of the previous research mentioned the benefit of offsite construction instead of traditional to reduce global warming (Moradibistouni et al., 2019). However, the uptake of OSC in New Zealand is low due to the economic, technological, and social barriers that New Zealand faces (Nesarnobari S. et al., 2022a).

2.4.2.1 Benefits of OSC in Reduction of Waste Generation

Construction waste is defined as solid waste; this involves wrapping new construction materials, bits and pieces of wood, plasterboard and metal, and concrete and gravel scraps (Nesarnobari S. et al., 2022b). 3.5 tons of construction waste is generated by new residential development (BRANZ, 2012), and half of the waste that goes to New Zealand landfill comes from the construction industry (Nesarnobari S. et al., 2022a). Thus, the construction industry generates 1.7 million tons of waste, which makes its way to landfills in New Zealand every year. Waste has occupied significant land areas, leading to soil contamination and air and water pollution (Jaques, 2013; Tam et al., 2007). Offsite construction has many benefits for the construction industry, such as a reduction in rework, which significantly reduces waste generation; also, improved quality workmanship offered by OSC makes the entire building life cycle more affordable (Shahzad, 2016). Moreover, this method decreases site operations and streamlines installation-related tasks on-site, permitting labours to boost productivity without interruption and preventing duplication of effort (BRANZ, 2012). Manufacturing in a controlled environment and the quality of materials away from natural disasters, such as weather conditions, improves the consistency of construction standards and quality and reduces construction defects (Shahzad W, 2018). Tam and Hao concluded that offsite construction could

reduce plastering waste by up to 100% (Vivian W. Y. Tam & Hao, 2014) and timber formwork waste by 80%. In 2015, Cao mentioned that this method could decrease the overall waste by 25 to 81.25% (Cao et al., 2015). Later, it was found that it reduced waste by 60% (Nesarnobari S. et al., 2022c). Recent research demonstrated that the implementation of this method is less than expected due to supply chain management issues for offsite construction (Nesarnobari S. et al., 2022a). This illustrates more consideration on managing these projects to use their full potential in the construction sector. For this purpose, focusing more profoundly on the issues is required.

Due to the timber-based nature of the New Zealand construction sector, different types of wood account for most construction waste (Jaques, 2013). Timber is vulnerable to moisture; weather conditions are the most common factors that increase waste generation. For example, the weather can impact the elements' quality and moisture content during raw material storage, shipping, and assembly (Nesarnobari S. et al., 2022c). Another aspect of utilising timber is reducing concrete, brick, and rebar debris. As mentioned, the moisture level of materials is essential; therefore, the strategy for keeping their quality up is often to deliver them to the site in packaging. This packaging generally does not recycle, and any errors during transportation or wrapping can increase the waste (Osmani, 2012).

Supply chain management issues lead to an increase in the waste of offsite elements, namely, manufacturing errors raised by labourers, raw material ordering issues, assembly errors raised by labourers and crane failure. This highlights the importance of a well-managed supply chain.

2.4.2.2 Benefits of OSC in the Reduction of Energy Consumption

The existing literature analysis highlights a 50% decrease in energy usage and a 35% reduction in carbon dioxide emissions associated with offsite construction compared to traditional methods (Gorgolewski, 2005; Phillipson, 2001). This suggests that the minimised material waste resulting from fewer defects and energy leaks upon completion contributes to the overall reduction in energy consumption and CO_2 emissions (Moradibistouni et al., 2019). It is evident that the choice of materials exerts a more substantial influence on life cycle energy than the selection of construction methods. Consequently, in terms of life cycle energy, timber emerges as a potentially more effective option for mitigating the impacts of global warming.

Furthermore, transporting offsite elements introduces the possibility of errors or mishandling during transit and assembly. Hence, from this standpoint, effective supply chain management is indispensable for ensuring practical and minimal transportation (Nesarnobari et al., 2024d).

This underscores the importance of implementing robust logistics strategies to optimise transportation processes and minimise environmental impact throughout the supply chain.

2.4.3 Research Methodology

This research aims to explore the benefits of Offsite Construction in the housing industry and its influence on global warming within the unique context of New Zealand. An extensive review of relevant literature was undertaken to pursue this objective, focusing on OSC within the housing sector and its implications for sustainability and greenhouse gas emissions, specifically within the New Zealand context. This literature review serves a dual purpose: it helps to identify any existing gaps in knowledge and sheds light on previously conducted studies and findings in this field (Fellows, 2021). The research methodology employed for this study is detailed in Figure 2-15, outlining the systematic approach used to collect, analyse, and synthesise relevant literature.

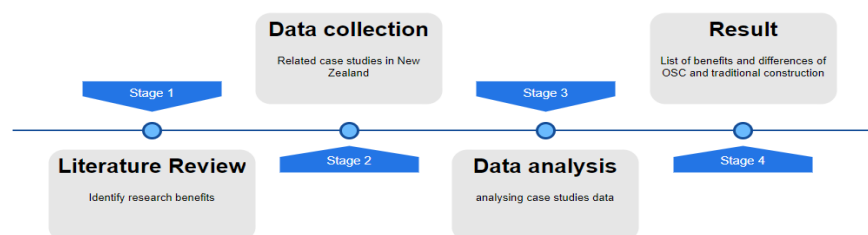


Figure 2-15: Research processes

Following the literature review, the research will conduct a further case study to investigate offsite construction practices' impact on global warming. These case studies will examine specific examples within the New Zealand housing industry to provide real-world insights into how OSC methodologies affect greenhouse gas emissions by life cycle analysis for A1–A3. By combining theoretical insights from the literature review with practical observations gleaned from the case studies, this research aims to provide a comprehensive understanding of OSC's role in the housing sector and environmental sustainability efforts in New Zealand.

2.4.4 Results

2.4.4.1 Findings

The case study focuses on the New Zealand building industry and involves a comparison of CO₂ emissions associated with three materials: timber, steel, and concrete. The primary objective of the paper is to analyse the environmental impact across stages A1–A3 of construction. Stages A1–A3 in construction, referred to as the product stage in life cycle

assessment, represent the initial phases of a building's life cycle, covering raw material supply, transportation, and manufacturing. Stage A3 encompasses the conversion of raw materials into construction products, involving energy use and emissions from the manufacturing processes. Together, these stages capture the environmental footprint of material production prior to their arrival at the construction site. To achieve this, it is essential to assess the carbon footprint of the transportation sector involved. This involves calculating the emissions generated by transporting materials over various distances. For instance, the transportation distance 290 kilometres, while the distance is 248 kilometres. Subsequently, materials are shipped, covering 811 and 23924 kilometres, respectively (Naylor Love). To determine the CO₂ emissions associated with each material, the emission CO₂ for each transportation mode is multiplied by the corresponding distances, as outlined in Table 2.11.

Table 2.11: The carbon footprint of transporting each element

Transport emissions for elements (kg CO ₂ eq per m ³)		
Material	Location 1	Location 2
Glulam	31.69 Kg	95.25 Kg
CLT	18.46 Kg	101.06 Kg
LVL (and glulam)		89.79 Kg

Stage A1 represents the initial phase of raw material extraction, and A3 encompasses the manufacturing stage. The table below presents specific details based on different building elements for analysis of the building components using various materials. Table 2.12 provides an overview of timber materials such as Glulam, CLT, and LVL, emphasising their application in construction projects. Additionally, it outlines the carbon emissions associated with each stage of the construction process, showcasing the environmental impact of incorporating these materials into the building.

Table 2.12: Building Detail with Timber Element

Material	Quantity	Units	Results
Framing timber H1.2	67	M ³	-48,394
Glue laminated timber	234	M ³	-154,393
Cross-laminated timber	2,101	M ³	-1,483,306
Laminated veneer lumber	419	M ³	-333,943
50 MPa concrete	1,991	M ³	911,878
Structural steel	315,040	Kg	897,864
Steel reinforcing bar	177,578	Kg	704,985
Particleboard or osb flooring	97	M ³	-36,909

On the other hand, Table 2.13 based on the steel usage in the building, shows that the upfront carbon result is greater than the timber building. Upfront carbon refers to the carbon emissions released during the entire lifecycle of a product, encompassing processes such as mining, processing, transportation, and manufacturing.

Table 2.13: Building Detail with Steel Element

Material	Quantity	Units	Upfront carbon results
30 MPa concrete	67	M ³	-48,394
40 MPa concrete	234	M ³	-154,393
Structural steel	2,101	M ³	-1,483,306
Steel reinforcing bar (rebar)	1530	M ³	463,590
50 MPa concrete	3551	M ³	1,374,237
Structural steel	721000	Kg	2,054,850
Steel reinforcing bar (rebar)	234561	Kg	931,207
Steel reinforcing wire mesh	1645	M ³	6,416

The table below demonstrates the concrete quantity and upfront carbon for this building, and it is obvious that the result of this type of material is much greater than the rest. These tables elucidate the environmental impact of different construction materials throughout their production stages. For instance, concrete with 40 and 50 MPa strengths for various usages, mesh and rebar for concrete that requires also demonstrated.

Table 2.14: Building Detail with Concrete Element

Material	Quantity	Units	Upfront carbon results
40 MPa concrete	4,256	M ³	1,647,072
50 MPa concrete	1,045	M ³	478,610
Structural steel	75,498	Kg	215,169
Steel reinforcing bar (rebar)	473,049	Kg	1,878,005
Steel reinforcing wire mesh	3,187	Kg	12,429
Steel structural deck (comflor)	6,786	M ²	217,152

Based on findings from the case study, the upfront carbon emissions associated with timber amount to 457,782 units (kg CO₂ eq). This figure represents a reduction of 10.55% compared to steel and 9.7% to concrete materials. This finding reveals the importance of the usage of timber in buildings. Furthermore, the study indicates a relatively similar level of upfront carbon emissions between steel and concrete. In other words, the disparity in upfront carbon emissions between steel and concrete is minimal, as demonstrated by their approximate equivalence in the study's results.

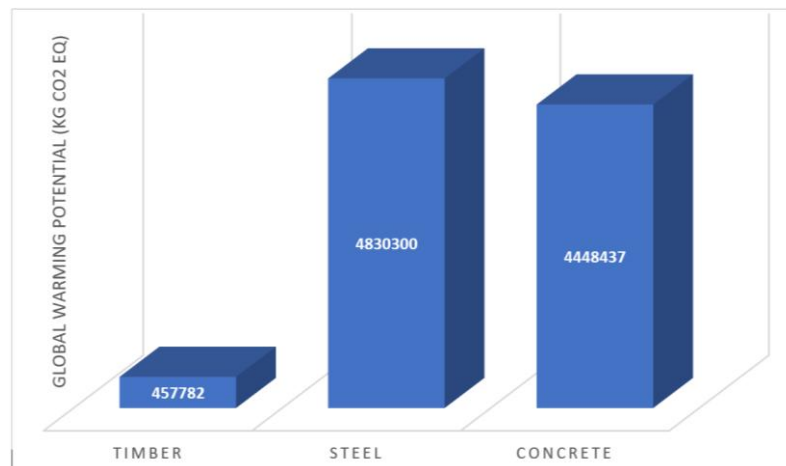


Figure 2-16: Global Warming Potential for Timber, Steel, Concrete

2.4.4.2 Discussion

In this section, first, explain the influential factors for carbon emission of elements and then discuss the best material for reduction purposes. Timber generally produces lower carbon emissions than steel and concrete due to the natural CO_2 absorption by trees during their growth. The methods used in timber processing are less energy-intensive, resulting in reduced emissions during production. Timber sourced sustainably can further decrease its carbon footprint. It typically requires shorter transportation distances, particularly when sourced locally, which helps minimise associated carbon emissions. Its lightweight nature also leads to lower emissions during transport. Timber construction can be more resource-efficient, generating less waste. Its potential for prefabrication in OSC allows for quicker assembly, thereby reducing emissions related to construction activities. At the end of its life cycle, timber can be reused, recycled, or biodegraded, allowing for the potential absorption of CO_2 over time. When untreated with harmful chemicals, timber can enrich the soil with nutrients.

The steel production process is highly energy-demanding, largely due to the extraction and processing of iron ore in blast furnaces. This process releases a significant amount of CO_2 , contributing to the high embodied carbon associated with steel. Although recycling can reduce some emissions, the initial production stage remains a substantial source. It is denser and tends to incur higher transportation emissions. The requirement to transport raw materials for steel production further adds to overall emissions, especially when these materials come from distant locations. Steel structures can also be prefabricated, but the assembly process is often labour-intensive and may require additional energy for welding and other joining methods. However, steel's strength can lead to lighter structures, potentially resulting in material savings. Steel is

highly recyclable, which can greatly lessen its carbon footprint if recycled correctly. However, if it is not recycled, the emissions from its production phase remain a concern.

Concrete production relies on cement, a major contributor to carbon emissions. The calcination of limestone during cement manufacturing releases considerable CO_2 . While concrete is known for its durability and longevity, the production phase significantly adds to its carbon footprint. Due to its bulkiness, concrete is usually produced close to construction sites, which can help reduce transportation emissions. However, the materials needed for concrete, such as sand and gravel, may still lead to emissions if transported over long distances. The curing process for concrete is lengthy, which can prolong the construction timeline and increase emissions due to extended machinery use and on-site activities. While concrete can also be recycled, this process is more complex, and a significant amount often ends up in landfills, leading to additional emissions if not managed effectively.

All three materials contribute to operational carbon emissions, which depend on the energy efficiency of the building and the energy sources employed. The thermal performance of each material can affect overall energy consumption. For instance, timber has inherent insulating qualities, resulting in lower operational emissions compared to steel and concrete structures that may need additional insulation.

The comparisons indicate that timber generally has the lowest carbon emissions across its lifecycle compared to steel and concrete. Also, the case study reveals that timber material should be the best choice for reducing global warming. The key factors contributing to these differences include the energy intensity of production processes, transportation emissions, construction efficiency, and end-of-life management. By pinpointing these factors, the case studies offer a clearer perspective on how the choice of materials affects carbon emissions in construction, thus guiding more sustainable building practices. However, there are barriers to implementing the timber, like supply chain management, supply chain issues, market acceptance, or regulatory hurdles. To overcome the barriers to implementing timber elements in the construction industry in New Zealand, future research on optimising supply chain management reveals the most important factors required (Nesarnobari et al., 2024d).

The results of this research carry important implications for policymakers and regulatory agencies focused on fostering sustainable construction practices and addressing the challenges posed by climate change. By pinpointing the most effective materials for lowering greenhouse

gas emissions in construction, governments can formulate specific policies that promote the adoption of environmentally responsible building methods.

Governments may implement financial incentives, such as tax breaks or grants, for builders and developers who opt for timber in their projects. By alleviating the initial costs associated with these materials, such incentives can encourage wider adoption and boost demand within the construction sector. Developing rigorous building codes and standards that emphasise using low-carbon materials can steer the construction industry toward more sustainable practices. Policymakers can back educational, and training initiatives designed for architects, builders, and construction professionals to deepen their knowledge of sustainable materials and construction practices. Offering resources and insights into the advantages of timber, OSC can help change industry norms and encourage innovative building techniques. By utilising the insights derived from this research, governments and regulatory bodies can formulate policies that promote the use of timber and other sustainable materials in construction and align with broader global environmental objectives, ultimately paving the way for a more sustainable future.

2.4.5 Conclusion and Further Research

Recent literature reviews have emphasised the growing concern surrounding global warming, with the construction sector being a major contributor responsible for as much as 40% of total emissions. As a result, urgent actions to mitigate these impacts are crucial. This paper aims to tackle this pressing issue by investigating offsite construction methods utilising various materials to shed light on their environmental footprints. Initially, an in-depth review of the literature focused on the New Zealand market revealed timber as the predominant choice for construction materials in the region. Subsequent case studies were conducted to compare the environmental footprints of timber, concrete, and steel components. The results of these studies notably highlight the relatively lower environmental footprint associated with timber components compared to concrete and steel alternatives.

While these findings provide valuable insights for optimising material selection, decision-making is influenced by various factors. Material availability is a key consideration, followed by geographical location and soil conditions. However, the intended use of the building may be the most influential factor. It is important to note that the validity of these findings depends on the absence of any disruptions or obstacles within the supply chain of the building components.

In the event of issues such as crane, train, or ship failures, damage to components during manufacturing, or fluctuations in moisture levels affecting timber, the outcomes may be altered, potentially exacerbating global warming. Therefore, addressing and resolving these barriers and challenges that hinder the supply chain process is essential for mitigating environmental impact. Proactive measures to overcome such obstacles are crucial for ensuring the sustainability of construction practices and minimising their adverse effects on the environment.

Incorporating timber in OSC is essential for lowering greenhouse gas emissions and promoting sustainable building practices within the construction sector. It is imperative for industry leaders and policymakers to take proactive measures by enacting supportive policies and initiatives that emphasise the use of timber and other environmentally friendly materials. By advocating for timber OSC, these key stakeholders can pave the way for a more sustainable future, making a meaningful impact on global efforts to address climate change.

3 Research Methodology

3.1 Introduction

This research investigates how adaptive offsite construction supply chain management (OSC-SCM) strategies can improve project cost, construction time, and material waste performance in New Zealand's panelised residential construction sector. Given the complexity, uncertainty, and interdependencies inherent within panelised OSC supply chains, an integrated mixed-methods methodology was adopted. The research combines systematic literature review, qualitative investigation, system dynamics modelling, probabilistic simulation, surrogate modelling, and multi-objective optimisation to develop and evaluate adaptive OSC-SCM strategies.

The methodological framework was designed sequentially, with each stage informing the subsequent stages of analysis and model development. Qualitative findings from industry stakeholders informed the development of a system dynamics model, which was subsequently integrated with Monte Carlo simulation, Random Forest surrogate modelling, and metaheuristic optimisation techniques to analyse system behaviour and identify optimal supply chain strategies under uncertainty. This chapter presents the research philosophy, research design, data collection and analysis procedures, modelling and optimisation processes, validation methods, ethical considerations, and the overall methodological framework adopted in the study.

3.2 Research Philosophy and Paradigm

A research philosophy refers to the underlying set of beliefs and assumptions that guide how knowledge is developed and interpreted within an academic study. It shapes how researchers view reality (ontology), how they acquire and validate knowledge (epistemology), and how these beliefs influence methodological choices (Sutrisna, 2009). The four main research philosophies identified by Bryman and Bell (2015) are pragmatism, positivism, interpretivism, and realism (Bryman, 2015). Each philosophy embodies distinct assumptions about the nature of reality and the process of gaining knowledge about it.

The study of reality's nature and what may be learned about it is known as ontology. Bryman and Bell (2015) state that ontology is concerned with the presumptions that researchers make regarding the nature of the social world, particularly whether social phenomena are created through social interactions or exist independently of social actors. Researchers' perceptions of

reality are shaped by these ontological presumptions, which determine whether they see it as subjective and multifaceted or objective and single. This leads to two major ontological stances: constructionism, which maintains that social realities are actively created through shared meanings and human interaction, and objectivism, which maintains that social phenomena exist independently of human perception and can be studied as objective facts (Bryman, 2015). Ontological stances influence the selection of research methodologies and the interpretation of results, especially in intricate domains like construction management, where social and material realities are significant.

The nature of knowledge and the connection between the researcher and what can be known are topics covered by epistemology. According to Saunders, epistemology deals with knowledge acquisition methods, the definition of valid knowledge, and the extent to which the researcher can be segregated from the research process (Saunders et al., 2016). By outlining the strategy for gathering and analysing data, it impacts the technique and procedures (Sutrisna, 2009).

According to positivism, reality is external to the researcher, objective, and measurable through empirical research. This way of thinking places a strong emphasis on finding generalisable laws, testing hypotheses, and analysing quantitative facts. This epistemological stance traditionally influences the use of quantitative research methodologies that are frequently applied in construction management studies that concentrate on quantifiable results like time, cost, and safety performance.

From a methodological perspective, positivism emphasises the use of structured techniques such as surveys, experiments, and statistical analyses to establish cause-and-effect relationships. Researchers adopting this approach favour a deductive logic, starting with existing theories or models and testing them through empirical observation and experimentation (Mark Easterby-Smith, 2012). Positivists strongly focus on gathering measurable facts to test theories and improve hypotheses, and they rigorously follow the rules of logical thinking. Accordingly, this paradigm is thought to be most suited for quantitative research techniques like surveys and experiments (Saunders et al., 2016). Through rigorous data analysis, construction management frequently uses positivism to analyse quantifiable outcomes like project cost, time, and safety performance. This allows for the production of conclusions that are both generalizable and replicable.

In contrast to positivism, interpretivism holds that reality is subjective and socially produced. Interpretivism, according to Bryman and Bell (2015), is concerned with comprehending the experiences and meanings that people ascribe to social phenomena. According to this theory, in order to comprehend human behaviour, researchers need to interact with participants' viewpoints, frequently using qualitative techniques like case studies, observations, and interviews. In construction management, interpretivist research is especially useful for examining stakeholder relationships, organisational culture, and decision-making processes since it acknowledges different realities and aims to offer deep, contextualised insights.

Positivism and interpretivism represent two distinct research philosophies with differing assumptions about the nature of reality and how it should be studied. Positivism is primarily associated with the natural sciences and adopts an objective approach, viewing reality as external and independent of human perception. Its subject matter focuses on nature and seeks factual, measurable information. Positivist research relies heavily on deductive reasoning and typically uses large sample sizes to ensure generalisability. In contrast, interpretivism is concerned with human interactions and adopts a subjective approach, emphasising that reality is socially constructed through meanings and experiences. It focuses on interpreting the social reality, relying more on inductive reasoning and small but in-depth samples to gain a detailed understanding (Figure 3-1). While positivism aims at fact-finding through empirical measurement, interpretivism seeks to understand the interpretation of meaning within social contexts (Saunders et al., 2016).

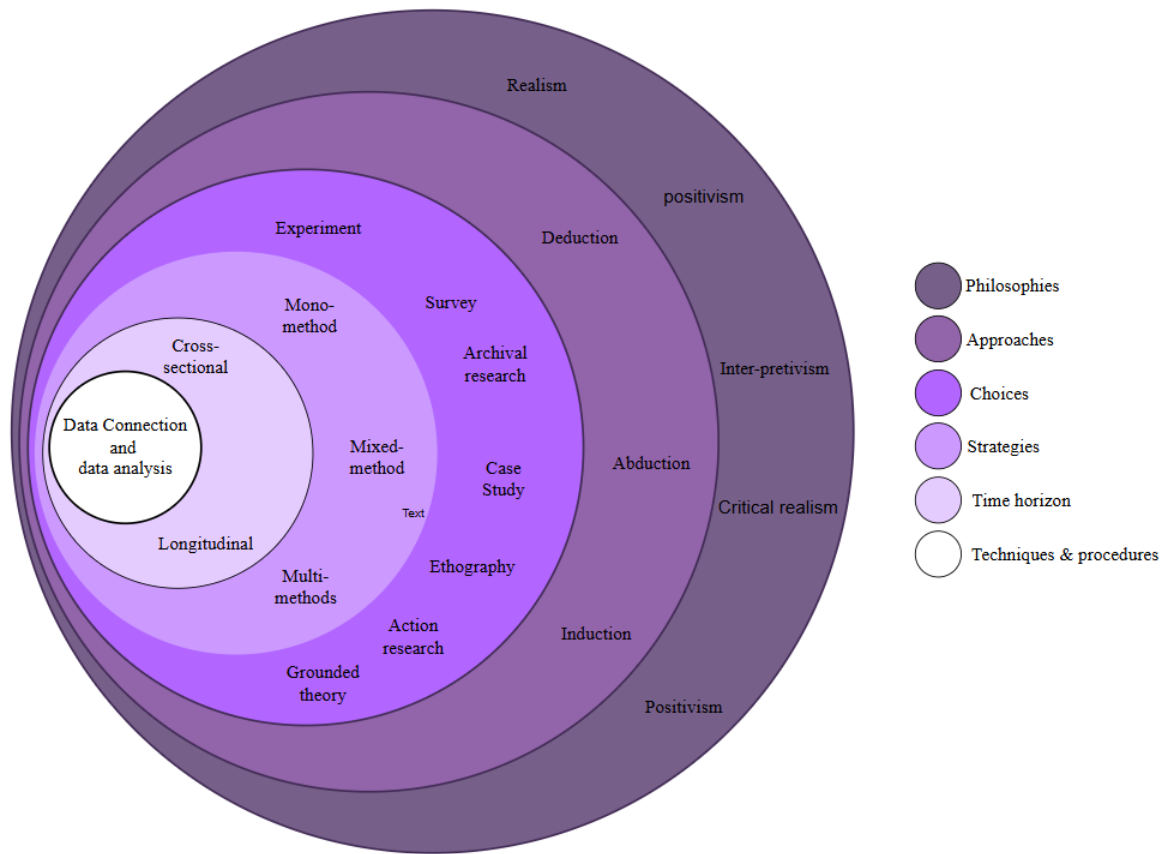


Figure 3-1: Research Onion (Saunders et al. (2007))

While the previous section discussed the broader philosophical foundations underpinning research methodologies, the following section specifically outlines the philosophical and methodological positioning adopted for this study and explains its relevance to the investigation of adaptive OSC-SCM systems within New Zealand's residential construction sector.

3.3 Research Philosophy Adopted for this Study

This study is grounded in a post-positivist epistemological stance, acknowledging that while an objective reality exists within offsite construction supply chains, it can only be understood imperfectly due to system complexity, challenges, and contextual influences. Within this framework, both empirical measurement and contextual interpretation are necessary to meaningfully examine and improve supply chain management (SCM) performance in offsite construction (OSC).

Therefore, the research is predominantly deductive in structure, as existing OSC-SCM theories and prior literature informed model conceptualisation and optimisation development. Nevertheless, inductive inquiry was integrated through qualitative interviews and empirical insights to refine system relationships, contextual variables, and practical industry dynamics

relevant to the New Zealand residential OSC sector. Accordingly, the study adopts a mixed-methods research design, integrating quantitative techniques, such as system dynamics modelling and multi-objective optimisation, with qualitative methods, including expert interviews. Quantitative methods provide the analytical rigour required to model, simulate, and optimise key performance variables such as time, cost, and material efficiency, while qualitative inquiry contributes contextual understanding by capturing organisational practices, decision-making processes, and practitioner insights that influence system behaviour.

This methodological integration reflects the socio-technical nature of OSC-SCM, in which measurable performance outcomes are shaped by interactions among technical, organisational, environmental, and human factors. Method selection is therefore driven by fitness for purpose, ensuring that the research remains empirically robust while adequately representing real-world complexity. Through this approach, the study generates knowledge that is both scientifically credible and practically relevant for improving offsite construction supply chain performance (Figure 3.2).

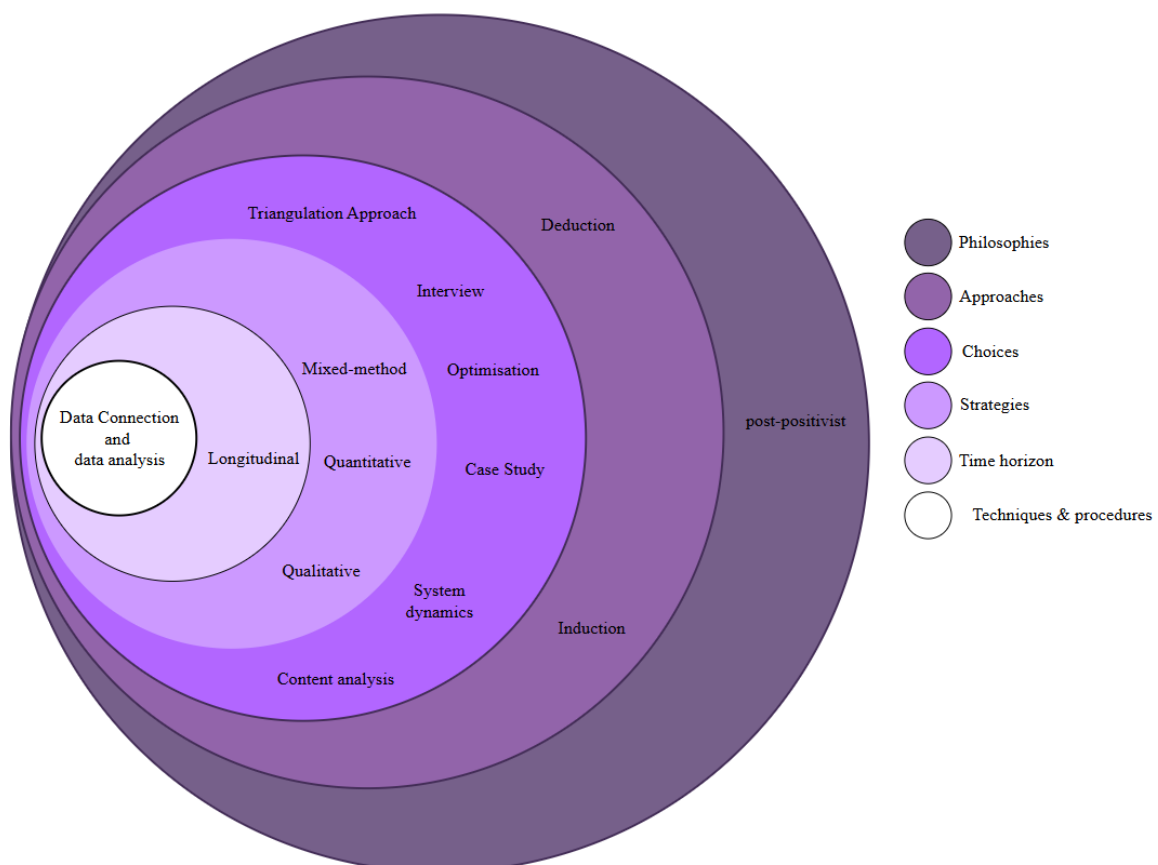


Figure 3-2: Research onion adopted for this research Saunders et al. (2007)

3.4 Research Conceptual Framework

A conceptual framework is a depiction of the main ideas, variables, and connections between them in a research project (Mbachu J, 2002). By showing how various components relate to and impact one another based on accepted theories or past knowledge, it acts as a guide for the investigation. Moreover, it facilitates the organisation of thoughts and clarifies the main emphasis of the study and the interactions between other aspects. The conceptual framework establishes the foundation for developing research questions, hypotheses, and techniques (Mbachu, 2006). It is the key concepts and variables specific to the study of OSC and SCM and their interrelationships.

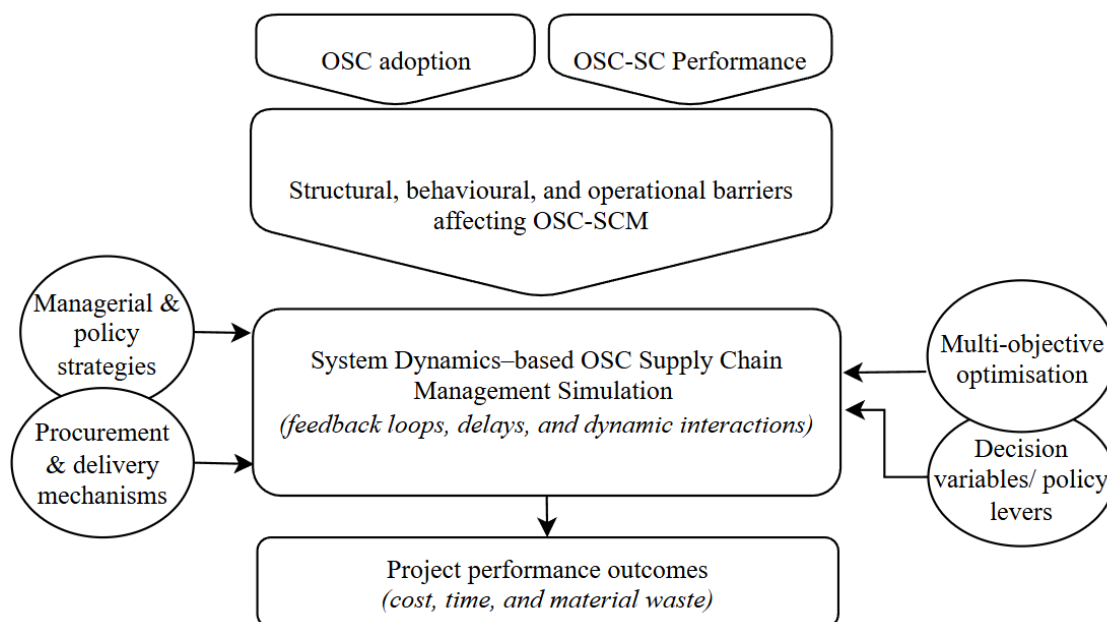


Figure 3-3: Conceptual Framework

The conceptual framework outlines the key factors influencing the adoption of OSC and SCM practices within housing construction projects. This framework provides a holistic view of the optimisation process by investigating the challenges faced and the related strategies from various perspectives. Since the research focuses on applying SCM throughout the delivery of OSC projects, the framework highlights critical factors affecting adoption, elucidating how challenges are managed and identifying the primary stakeholders responsible for execution. Consequently, the study will examine adoption barriers, corresponding mitigation strategies, the underlying factors shaping both barriers and approaches, accountable stakeholders, levels of optimisation, and organisational challenges across multiple scales, including project and

industry levels. The following illustrates the research framework in detail, followed by a description of the methods selected for this study.

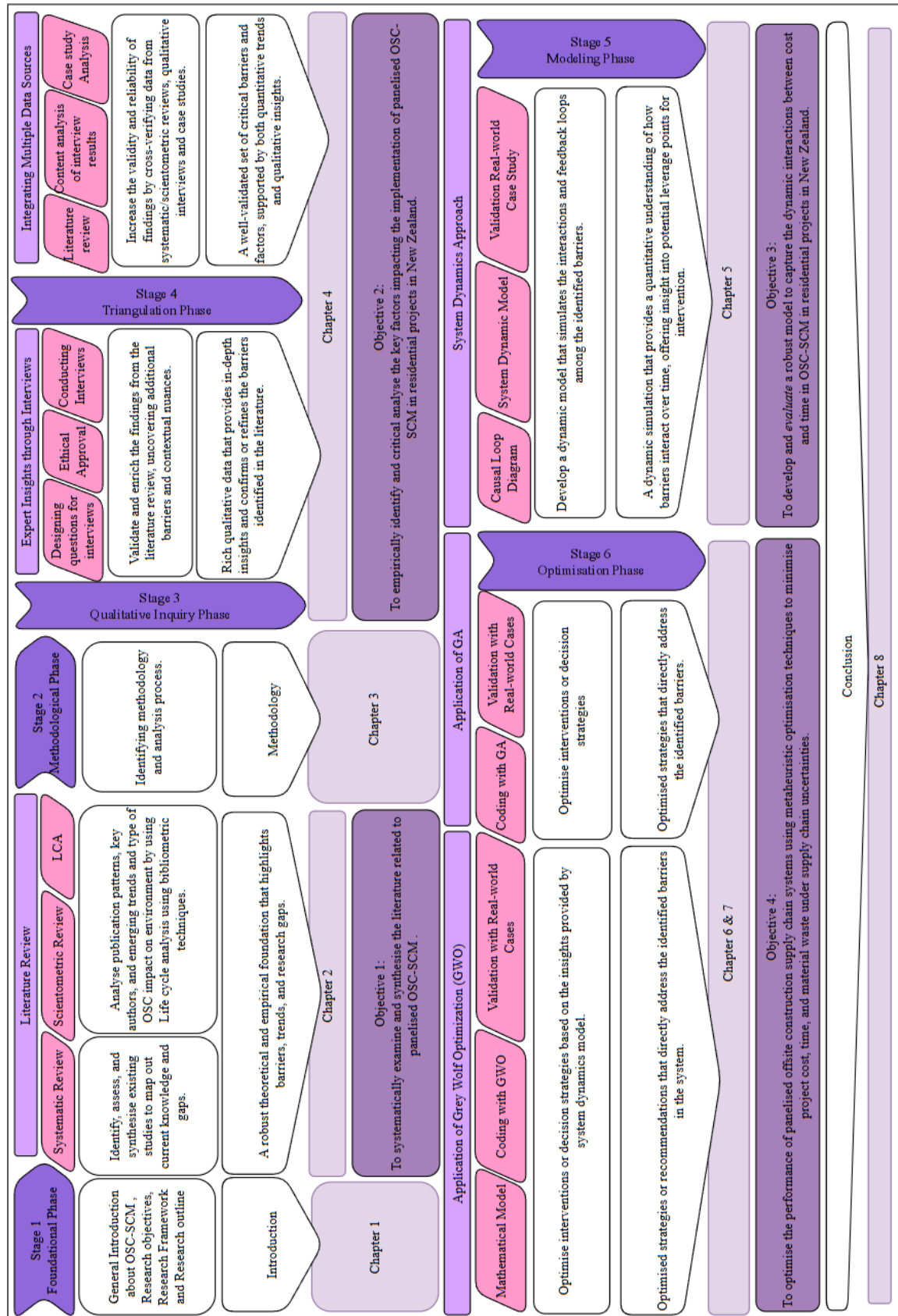


Figure 3-4: Research Framework

Based on the adopted philosophical and methodological positioning, the following section presents the conceptual framework developed to guide the investigation of OSC-SCM barriers, system interactions, uncertainty conditions, and optimisation processes throughout the research.

3.5 Research Approach

The research approach establishes the general plan and strategy for carrying out a research design, directing data collection, analysis, and interpretation (Saunders et al., 2016). Deductive and inductive are the two primary categories into which it is typically divided. A deductive technique, which is frequently connected to quantitative research, starts with preexisting beliefs or hypotheses and tests them through empirical observation (Sutrisna, 2009). The quantitative research approach prevents participants from discussing their personal experiences. In contrast, an inductive technique, which is usually associated with qualitative research, entails gathering data and creating ideas or patterns based on the findings (Bryman, 2015). Interviews using open-ended questions that allow participants to freely express their thoughts are instances of qualitative research methodologies. Some studies use a mixed method, integrating both deductive and inductive aspects to capitalise on the advantages of both quantitative and qualitative methodologies, depending on the research objectives and issues (Amaratunga, 2002). The validity and reliability of the study are enhanced by choosing a suitable research approach, which ensures consistency among the research philosophy, methodology, and techniques.

Qualitative and quantitative research differ in several fundamental aspects. Qualitative research typically follows an inductive approach, aiming to test theories, while quantitative research is deductive and focuses on generating theories. Ontologically, qualitative research is traditionally influenced by constructionism, viewing reality as constructed, whereas quantitative research is traditionally influenced by objectivism, considering reality as external to and independent of the researchers. Epistemologically, qualitative studies are rooted in interpretivism, emphasising subjective understanding, while quantitative studies follow positivism, seeking objective knowledge. Regarding social reality, qualitative research sees it as constantly shifting, whereas quantitative research treats it as external and objective. In terms of data analysis, qualitative research is descriptive, while quantitative research typically presents data in numerical values. Finally, qualitative research usually involves small sample sizes, contrasted with the large samples typical of quantitative research.

This study uses a mixed-methods approach to capture both the measurable components of project performance and the in-depth organisational and contextual factors impacting implementation, given the complexity of SCM optimisation in OSC. While qualitative data from case studies and interviews offers deeper insights into barriers, stakeholder roles, and strategic actions within the OSC supply chain, quantitative data makes it easier to quantify efficiency, costs, and time. This combination makes tasks easier. A more thorough and reliable combination, which also guarantees practical relevance and validates results from various approaches. Furthermore, the practicality of the research questions demands adaptable methodological decisions that best capture the complex phenomena being studied.

Following the identification of the research approach and methodological orientation, the overall research design was structured to systematically integrate qualitative investigation, dynamic modelling, probabilistic simulation, and optimisation processes within a sequential mixed-methods framework.

3.6 Research Design

A research design is essential to any research aim since it provides a methodical framework that guides the entire inquiry and ensures that the research questions are satisfactorily addressed (Yin, 2018). A carefully thought-out research design establishes the procedures for gathering, analysing, and interpreting data, thereby aiding the preservation of the study's coherence and rigour. Bringing the research concept, technique, and practical procedures into alignment significantly improves the findings' validity and reliability (Creswell, 2017; Saunders et al., 2016). A robustly developed research design is crucial in conducting academic research, but even more so in more complex domains like construction management to address complex problems, balance qualitative and quantitative methods, and generate significant, valuable discoveries that advance theory and practice (Gray, 2021). In the initial stage, a preliminary literature review, supported by informal discussions with an academic expert conducted to clarify the research direction and refine the research objectives. This was followed by an extensive literature review to identify key offsite construction supply chain management (OSC-SCM) challenges, global barriers, and relevant project stages within the housing sector. The second stage focused on empirical data collection through semi-structured interviews and case study analysis. Case studies are used to support model validation in a real-world OSC-SCM context. A triangulation approach was employed to synthesise qualitative and quantitative evidence, enabling the development of an OSC-SCM framework grounded in both industry

practice and prior research. In the third stage, the identified barriers and interactions were structurally conceptualised using causal-loop diagrams, which served as a qualitative structuring tool exclusively. These conceptual relationships were then translated into a quantitative stock–flow system dynamics model to simulate dynamic behaviours, feedback mechanisms, and time-dependent interactions within the OSC-SCM system. The system dynamics model undertakes structural and behavioural validation to ensure its credibility prior to further analysis. The fourth stage employed the validated system dynamics model as a simulation engine for multi-objective optimisation. A formal optimisation problem was formulated to simultaneously minimise project time, cost, and material waste, subject to constraints. Surrogate modelling and parameter calibration were incorporated to enhance computational efficiency, followed by validation and robustness analysis of the optimisation outcomes. The final stage involved synthesising the results and finalising the thesis write-up. Beyond predictive improvement, the proposed framework provides a robust decision-support foundation for practitioners and policymakers, enabling barrier-informed configuration of OSC supply chains under stochastic conditions. Collectively, these stages form an integrated methodological framework that systematically addresses the research objectives and supports robust, data-driven conclusions. Accordingly, this research adopted a sequential mixed-methods design structured into four interrelated stages, as illustrated in **Error! Reference source not found..**

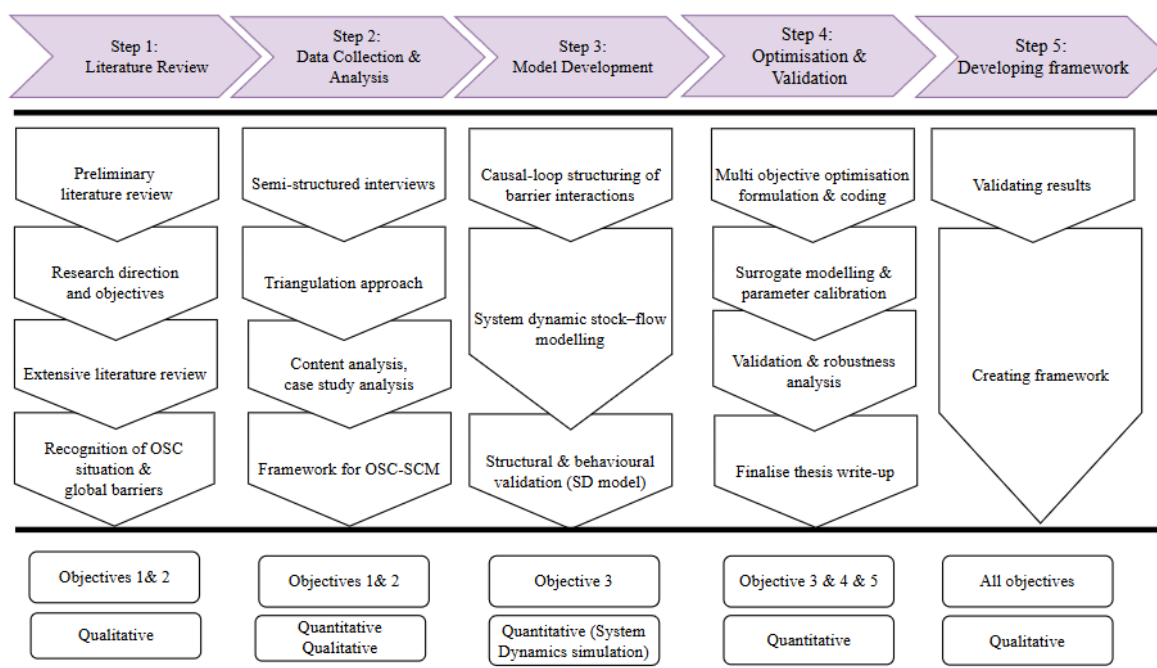


Figure 3-5: Research Design

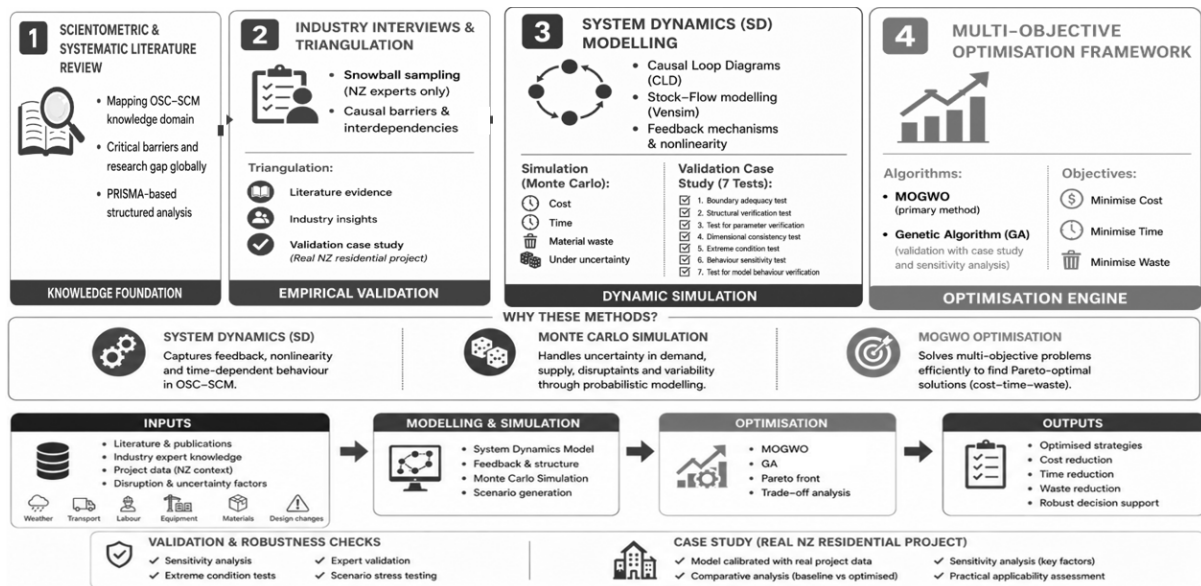


Figure 3-6 : Whole process of thesis

3.6.1 Data Collection & Analysis

The goal of this research is to enable wider adoption of offsite construction (OSC) supply chain management in New Zealand’s residential sector by systematically identifying critical factors and barriers, modelling their dynamic interactions, and applying metaheuristic optimisation techniques to minimise project time, cost, and material waste. Reflecting the study’s philosophical foundation and adoption of a mixed-methods design, the overall aim is further reflected into four research objectives. An outline of the research framework, linking the objectives with the chosen methodologies, is presented in Table 3.1. Additionally, the analytical techniques planned for use are detailed. The subsequent section offers a concise overview of the data collection and analysis approaches. This study uses literature review, semi-structured interviews, case studies, system dynamics modelling, and the Grey Wolf Optimiser (GWO) method to gather and validate data.

Table 3.1: Research objectives, methods and analysis

No	Research Objectives (RO)	Methods	Analysis
1	To systematically examine and synthesise the literature related to panelised OSC-SCM.	Literature review	Systematic thematic synthesis and scientometric analysis, Life cycle analysis and systematic literature review
2	To empirically identify and critical analyse the key factors impacting the implementation of panelised OSC-SCM in residential projects in New Zealand.	Triangulation approach	Systematic literature review, qualitative content analysis, case studies analysis
3	To develop and evaluate a robust model to capture the dynamic interactions between cost and time in OSC-SCM in residential projects in New Zealand.	Literature review, causal-loop diagram and stock-flow model in systems dynamics	Simulation-based analysis using a validated system dynamics model
4	To optimise the performance of panelised offsite construction supply chain systems using metaheuristic optimisation techniques to minimise project cost, time, and material waste under supply chain uncertainties.	Literature review, integration of system dynamics simulation with metaheuristic Optimisation (GWO, machine learning-assisted surrogate modelling, GA)	Robustness and validation testing, Multi-objective trade-off analysis, Pareto front interpretation.

3.6.2 Literature Review

A thorough literature review forms the essential theoretical groundwork for any research study (Bryman, 2015; Snyder, 2019). In addition to strengthening the study's theoretical framework, literature reviews guide researchers in identifying and defining the research problem (Snyder, 2019). For the purposes of this research, a systematic and scientometric review was undertaken, encompassing a comprehensive examination of academic and institutional literature, including peer-reviewed journal articles, doctoral theses, authoritative textbooks, industry guidelines, and technical reports pertinent to OSC-SCM.

The literature review guided this study to (1) examine the current state of OSC research both globally and within New Zealand; (2) establish a conceptual framework for this study; (3) identify key barriers associated with OSC; and (4) gain insight into the SCM methodologies utilised by various researchers in this field.

3.6.3 Scientometric Review Method

The initial phase of this research involves a thorough examination of global research trends. Science mapping serves as both a descriptive and diagnostic tool that efficiently processes large volumes of bibliometric data to uncover systematic patterns within the literature (Cobo et al.,

2011). This method enables researchers to gain insights and detect relationships between concepts that might be overlooked in manual reviews, while also minimising subjective bias (Su & Lee, 2010). A scientometric review, a specific science mapping approach, visually represents the connections and relationships among relevant studies, countries, and frequently co-occurring keywords (Jin et al., 2019; Saad et al., 2021). Consequently, this technique has been applied across various fields, including offsite construction (OSC) management (Li, Shen, & Xue, 2014) and supply chain dynamics (Darko et al., 2020).

VOS viewer and CiteSpace were selected to generate the visual maps for this research (Chen, 2020; Chen & Xiao, 2016). Their growing use in construction engineering and management literature is evident in topics such as OSC sustainability (Wuni & Shen, 2020b), OSC with Building Information Modelling (BIM) (He et al., 2017), and building control systems (J. Y. Park and Z. Nagy, 2018). VOS viewer provides essential functionalities for visualising scientometric and bibliometric networks (van Eck & Waltman, 2010; van Eck & Waltman, 2014), while CiteSpace excels in visualising various network structures, detecting clusters and emerging trends, and producing cluster and timeline views (Chen & Samarasinghe, 2020).

The analysis was conducted in two phases: first, co-citation analysis was used to pinpoint the most highly cited publications, and second, keyword analysis helped identify emerging themes in the fields of OSC and SCM. This phase not only mapped the existing body of research but also highlighted areas where further investigation is needed. Through a comprehensive and systematic review of diverse literature, this stage successfully fulfilled the study's first objective.

3.6.4 Systematic Review Method

A systematic review was carried out using the scientometric technique to identify, assess, and synthesise all pertinent literature (Mirzaei et al., 2020). This was selected due to the comprehensive review of all available evidence, research, and informed all aspects of OSC-SCM and research questions (Wang, Hu, H., et al., 2019).

PRISMA 2020 framework (Page et al., 2021) was employed, which provides a structured methodology to minimise bias and improve transparency (Cavalieri et al., 2019; Razkenari et al., 2018), as well as a standardised tool for categorising studies in areas such as OSC-SCM (Liu Y. et al., 2020; Wang, Hu, H., et al., 2019).

First, precise research aims were defined, and explicit inclusion and exclusion criteria were set. Next, multiple databases are systematically searched, applying uniform screening and selection procedures. Finally, the extracted data from eligible studies were critically appraised and integrated to produce an objective synthesis of current knowledge, identify gaps, and outline priority areas for further investigation.

3.6.5 Semi-structured Interview Method

Open-ended questions were developed for the interviews, concentrating on the current status of the OSC industry, its challenges, and issues related to material waste (Donthu et al., 2021; Snyder, 2019). These questions were designed to guide data collection. Subsequently, the interview questions were refined and validated through preliminary discussions with five project managers. Participants were invited to help clarify or improve items unclear or poorly phrased in the scale. Due to the specialised nature of the field and potential limited availability of suitable participants, a combination of purposive and snowball sampling techniques (Dawson, 2009) was employed to recruit qualified interviewees. Snowball sampling is particularly effective in accessing networks or communities within OSC (Atkinson, 2001) and reaching hidden populations that are difficult to contact through traditional sampling methods (Biernacki, 1981). Additionally, it fosters trust and rapport between researchers and participants, as referrals often come from trusted contacts within their network (Goodman, 1961). This study required participants with relevant managerial experience and responsibilities related to handling management challenges affecting project delivery. Consequently, all interviewees were professionals at the management level, including principals and CEOs, each with over ten years of experience in the OSC industry (A. Mohammadi, 2018; Dalton, 2013; K. Manley, 2019; Zolghadr et al., 2022). Additional interviews were conducted to ensure data saturation, confirming that the sample size was sufficient and the data collected were comprehensive. The collected data were then imported into NVivo 14 for detailed analysis. NVivo provides a powerful environment for qualitative analysis, enabling researchers to track specific segments of the interviews and the ideas they contain (Bazeley, 2014; Lewins, 2014). Through careful coding and categorisation, recurring themes and significant patterns were identified (Braun, 2006). The interviewees' responses were analysed using content analysis and compared against the innovation strategies of the participating companies and existing literature. These codes were subsequently organised into broader themes reflecting common trends in the data (Glaser & Strauss, 2017).

3.6.6 Triangulation Approach

Triangulation is a research approach that involves using multiple methods, data sources, theories, or investigators to study a phenomenon. The purpose of triangulation is to increase the credibility, validity, and comprehensiveness of research findings by cross-verifying information from different perspectives (Babaeian Jelodar M. & Shu, F., 2021a; Cooper, 2012; Jonsen & Jehn, 2009; Taylor et al., 2011).

The methodological triangulation approach aimed to (1) recognise the most influential and primary factors that lead to the internal efficiency of SCM, (2) identify the impact of recognised barriers on performance and efficiency, and (3) develop a framework for addressing the interdependency of barriers in SCM.

The reliability and validity of the findings were strengthened through methodological triangulation, which integrated various data sources, including scientometric and systematic reviews, content analysis, and case studies (Gray, 2021). NVivo was instrumental in handling extensive datasets and offered essential tools for conducting an in-depth and comprehensive analysis (Gibbs, 2017). Insights gained from this review informed the creation of the conceptual framework, which subsequently directed further research phases such as expert interviews and the formulation of a system dynamics model (see Chapter 4).

This research adopts a triangulated approach by integrating findings from literature review, qualitative interviews, and quantitative modelling. The literature review informs the identification of key OSC-SCM barriers, which are then validated and refined through interviews and case studies. These insights are subsequently incorporated into the system dynamics model and further evaluated using optimisation techniques.

3.6.7 Data Analysis

Software such as NVIVO and Vensim, as well as MATLAB and Python, were used to analyse data gathered from interviews and other data-collection techniques. The sections that follow provide brief explanations of the data analysis methods used.

3.6.7.1 Content Analysis

According to Hashemnezhad (2015), content analysis is a methodical and impartial approach to analysing qualitative material gathered verbally, visually, or in writing. Researchers use this method to analyse semi-structured interviews, case studies, and literature. It can assist in extracting themes from qualitative data, which can then be categorised for easier interpretation.

A Systematic Literature Review (SLR) was undertaken in Chapters 2 to comprehensively identify relevant studies on OSC-SCM. Within the SLR process, content analysis was employed as the primary analytical method to extract, code, and thematically categorise drivers, barriers, and influencing factors affecting OSC-SCM adoption and performance.

3.6.7.2 System Dynamics

System Dynamics (SD) is a method that uses simulation to analyse how complex systems behave over time in response to feedback. It illustrates causal connections between variables through stock–flow diagrams and feedback loops. The strength of system dynamics (SD) lies in its ability to analyse the behaviour of complex systems by focusing on the collaboration and interactions among their components (Yuan H., 2014). It is often characterised as a computer-based simulation approach, implemented through tools such as Vensim PLE, that facilitates the study of dynamic patterns in social and economic systems (Liu et al., 2020). The challenges associated with OSC-SCM are conceptualised as a complex, open system with numerous interconnected information, material, and economic flows among various parameters (Maqsoom et al., 2019). SD provides a framework to construct a comprehensive information feedback system that captures these pervasive barriers in OSC-SCM, thereby clarifying the logical relationships between system variables (Ajayi, 2016; Li, Shen, & Alshawhi, 2014). This approach enables the aggregation and visual representation of flows of energy and information between the system's internal and external environments, accurately reflecting the system's evolutionary behaviour. The capacity of SD to simulate intricate interdependencies and feedback mechanisms within OSC supply chains underscores its suitability for this research, as it allows for modelling how variations in one aspect influence others through feedback loops. To uncover the interface of factors, the causal loop was used and to uncover the effect of these factors on the stock and flow model was used, and both are presented in chapter 5 of this thesis.

3.6.7.3 Optimisation

Optimisation is the term for a collection of mathematical and computational methods intended to identify, from a range of potential solutions, the most efficient way to solve a problem while meeting predetermined restrictions. SCM optimisation plays a critical role in increasing operational efficiency by optimising resource allocation, scheduling, inventory levels, and logistics to reduce costs, shorten lead times, and enhance service quality. The integration of multiple steps in OSC increases supply chain complexity. Many interrelated factors and risks are present during these phases, including shifting material availability, labour shortages, and transit delays. By methodically analysing these variables, optimisation techniques can find

solutions that strike a compromise between conflicting goals, such as cutting waste and project length while keeping expenses under control.

A multi-objective optimisation framework in a construction project setting typically seeks to simultaneously minimise factors such as material waste, project duration, and costs. Improving one objective may impact the others, necessitating a balanced approach. The Grey Wolf Optimiser (GWO), a nature-inspired metaheuristic algorithm introduced by Mirjalili (2014), has demonstrated effectiveness in diverse engineering and optimisation applications. In this research, GWO was employed within a multi-objective framework to address the goals concurrently. Unlike traditional single-solution approaches, GWO enables project managers to identify multiple efficient alternatives, known as Pareto-optimal solutions, thereby supporting more informed decision-making. To complement this, the Genetic Algorithm (GA), an evolutionary optimisation technique based on natural selection principles, was also applied. GA contributes by exploring diverse solution spaces and providing comparative insights, ensuring that the optimisation framework is robust, versatile, and validated across different metaheuristic approaches.

To incorporate the critical factors inherent in construction projects, Monte Carlo simulations (MCS) are integrated to provide a probabilistic model of the project environment rather than deterministic estimates (Pant & Srinivas., 2019). This model captures real-world factors such as weather variability, traffic conditions, material, machine reliability, and fluctuating availability of labour and equipment. By generating a range of potential scenarios for cost, waste, and project duration, Monte Carlo simulations facilitate stochastic or resilient optimisation frameworks. The GWO then optimises solutions that perform well across these varied scenarios, for instance by minimising worst-case impacts or estimating expected costs and durations over all simulations. Essentially, GWO evaluates potential solutions under randomised conditions, enhancing robustness (Zhou, Gao, et al., 2013).

Offsite fabrication and other construction projects are often characterised by uncertainties, including variable activity durations, unpredictable material costs, and deviations in waste quantities from initial forecasts. Monte Carlo simulations, which model inputs as random variables instead of fixed values, are a well-established technique to capture such unpredictability (Pant & Srinivas., 2019). This approach helps identify risks like cost overruns or schedule delays by providing probability distributions of potential outcomes. By accounting for these uncertainties, Monte Carlo simulation offers more accurate estimations of project

timelines and budgets, aligning with theoretical foundations in project management. Furthermore, Monte Carlo simulations provide decision-makers with probability distributions, such as those representing total project cost or completion time, enabling a clearer understanding of the likelihood of achieving project objectives. This probabilistic perspective is especially valuable in the context of OSC (Hussein, Eltoukhy, Darko, & Eltawil, 2021) (Chapter 7).

The validity and robustness of the proposed modelling framework were ensured through a combination of case study validation, sensitivity analysis, and scenario analysis. The case study provided real-world grounding, while sensitivity and scenario analyses demonstrated the model's stability and reliability under varying supply chain conditions.

Chapter 4: Qualitative Analysis of Supply Chain Barriers Affecting Residential Offsite Construction Performance

Research Objective 2, which examines, to empirically identify and critically analyse the key factors impacting the implementation of panelised OSC-SCM in residential projects in New Zealand. is directly addressed in the paper titled “Toward Seamless Delivery - Qualitative Unravelling of Supply Chain Constraints in Offsite Construction”, which is under review in the ASCE journal. The impact of these barriers on material waste, time, and cost, as well as their interactions within the wider supply chain, is given special attention.

The chapter outlines the primary issues affecting New Zealand, including fragmented procurement processes, inadequate transportation infrastructure, a shortage of workers and cranes, and weather-related environmental constraints. It demonstrates how interrelated these barriers are, with delays in one area leading to inefficiency in another. Delays in design approvals, for instance, can lead to production shortages, exacerbating schedule conflicts in transportation and resulting in delays during onsite assembly.

The chapter provides a detailed understanding of OSC supply chain behaviour under actual project settings by qualitatively revealing these systemic interdependencies. The results set the foundation for the modelling work in Chapter 5 by highlighting the areas that most urgently require integration, teamwork, and process improvement. This is observed in practice, ensuring that the model's representation of dynamic interactions is firmly grounded in constraints.

By creating a system dynamics (SD) model to depict interdependencies and feedback loops within OSC–SCM, this chapter satisfies Research objective 4. The model replicates how various risk factors, including weather, traffic, crane availability, and labor constraints, impact cost and time performance using causal loop diagrams and stock-flow structures. The chapter illustrates the usefulness of SD in capturing uncertainty and dynamic change by addressing the research issue of how system dynamics modelling can depict complex interactions. In the following chapter, this model serves as the basis for incorporating optimisation.

4 Toward Seamless Delivery: Qualitative Unravelling of Supply Chain Constraints in Offsite Construction

The current chapter is based on the following article:

Nesarnobari, S., Shahzad, W. M., Jelodar, M. B., and Sutrisna, M. (2026). “Toward seamless delivery: Qualitative unraveling of supply chain constraints in off-site construction.” *Journal of Architectural Engineering*, 32(2), DOI: 10.1061/JAEIED.AEENG-2191.

Abstract

The urgent need for affordable housing requires addressing shortages efficiently, which can be achieved through Offsite Construction (OSC). Although widely used globally, OSC adoption remains limited in many countries, including New Zealand. Recent studies have identified barriers related to Supply Chain Management (SCM) as the main impediment to OSC’s broader implementation. Thus, successful OSC deployment is heavily dependent on effective SCM, which is often characterised by complexity and fragmentation. This research explores the critical barriers to OSC-SCM of design, raw material preparation, manufacturing, transportation and assembly. It adopts a triangulation approach, integrating an in-depth global literature review, which is then verified and mapped to show how mitigation strategies intervene at different SCM stages. These insights are contextualised through expert interviews and case studies in New Zealand. The study also proposes a comprehensive framework to analyse the interdependencies between various barriers within the OSC supply chain. It highlights the importance of understanding the impact of these barriers to develop strategies that optimise SCM performance. Ultimately, this research aims to advance the wider application of OSC techniques by addressing the major barriers that currently limit their full potential in architectural and engineering projects. The results show that critical factors are the most significant barriers, with regional factors like market size, dispersed populations, and unique geographical challenges intensifying these problems. The study recommends pilot projects in real-world environments to evaluate and refine SCM methods, and further research into automation and optimisation to improve OSC supply chain efficiency.

Keywords: Offsite Panelised System, Timber, Housing Sector, Barriers, Supply Chain Management, Engineering.

Practical Applications

This study offers practical insights for policymakers, contractors, and manufacturers involved in OSC (Offsite Construction) projects. Through interviews with key industry stakeholders, it identifies the major factors influencing OSC-SC (Offsite Construction-Supply Chain)

performance, including design coordination, manufacturing capacity, transportation logistics, and labour availability. Recognizing these challenges helps practitioners prioritise actions that can enhance efficiency and reduce project risks. The findings also highlight strategies to improve collaboration across the SC and support evidence-based decision-making for managing cost, time, and material waste in future OSC projects.

4.1 Introduction

According to government agencies on the housing crisis globally, it is critical to pinpoint the barriers preventing more people from having access to reasonably priced homes (Mitchell. et al., August 2023; Saiz, 2023; Stephens, 9 September 2022). In response to expediting construction processes and addressing the housing shortage, companies are exploring innovative approaches, such as OSC (Nesarnobari et al., 2024c). OSC methods, especially panelised systems, are becoming increasingly common in the construction industry due to their ability to increase quality, reduce prices, and improve efficiency. OSC which prefabricates building components in a controlled factory environment before assembly on-site, offers significant advantages over traditional construction methods. The controlled environment provides opportunities to improve construction speed, efficiency, safety, sustainability management, waste reduction (Tsz Wai et al., 2021). Despite its advantages, adoption remains minimal, currently less than 20% (Nesarnobari et al., 2022).

The necessity of efficient SCM is outlined as essential to successfully implementing OSC (Wang, Hu, H., et al., 2019). Moreover, integration into conventional Supply Chain (SC) remains challenging due to an insufficient understanding of the associated barriers (Wang, Shen, H. C., & Zuo, J., 2019). The necessity to collaborate with numerous parties, such as suppliers, manufacturers, transportation companies, and construction companies, each with its procedures, deadlines, and standards, exacerbates these difficulties. Previous literature highlights that these SCM challenges are compounded by material-specific considerations and contextual factors that influence OSC deployment in different countries. Consequently, identifying the gaps in existing OSC-SCM research is essential to understand where further investigation is needed (Alhawamdeha & Lee, 2024; Clyde Zhengdao Li et al., 2024; Nesarnobari et al., 2024c). Recent literature shows a growing shift toward engineered-timber solutions such as CLT and LVL, driven by their lower embodied carbon, rapid installation, and suitability for modern manufacturing approaches (Dani et al., 2022; Kremer et al., 2025; Nelson et al., 2022) however, evidence on their SC implications remains limited and fragmented. The

review identifies three major gaps: 1) Existing studies highlight systemic challenges contributing to the low adoption of OSC, yet their implications for the New Zealand context remain underexplored. 2) There is a lack of research on panelised systems within OSC, particularly on timber-based elements like CLT and LVL, despite their growing relevance to sustainable construction. 3) There is insufficient in-depth evaluation of cost, time, and material-waste dynamics within OSC-SCM, leaving a gap in understanding how these factors interact to influence panelised system performance (Nesarnobari et al., 2024c).

According to the identified gap, evaluating the interdependency of critical barriers to the system is crucial to enhancing OSC adoption in the residential sector (Nesarnobari et al., 2024c). The barriers of the panelised system identified the same issues in line with the available results in the literature (Nesarnobari et al., 2024c). It was also proposed that a thorough investigation into the root cause analysis and impact of barriers on OSC is required. Consequently, this study aims to address these gaps using a triangulation methodology. This approach makes it possible to thoroughly examine the intricate and situation-specific barriers in OSC-SCM, making it easier to record in-depth observations and various perspectives. The research gaps are emphasised by its particular attention to the up-to-date barriers, which provide a thorough and relevant understanding of SCM difficulties in OSC. For this purpose, the objectives are: 1) To recognise the most influential and primary factors that lead to the internal efficiency of SCM. 2) To identify the impact of recognised barriers on performance and efficiency. 3) Develop a framework for addressing the interdependency of barriers in SCM (Nesarnobari et al., 2024b).

This study provides a novel contribution by analysing OSC-SCM barriers as interdependent system phenomena. Prior studies tend to examine barriers in isolation or focus on international contexts, whereas this research develops a context-specific framework that maps how technical, organisational, and logistical challenges interact across the panelised SC. This system-level perspective, grounded in the unique characteristics of New Zealand's dispersed and small-scale industry, offers new insights not previously captured in OSC literature.

Another distinctive contribution of this research lies in its triangulated methodological approach, which integrates evidence from the literature, expert interviews, and industry case insights to analyse OSC-SCM barriers specific to the timber-based system within the New Zealand residential sector.

4.2 Literature Review

OSC involves manufacturing components in a controlled environment and then delivering them to the construction site for assembly (Goodier & Gibb, 2007). This process relies on an efficient and productive SC to ensure smooth operations and timely materials delivery (Li et al., 2016). SCM encompasses the strategic planning, implementation, and management of the movement of products and services from their origin to final destination (Nkolika J. Peter et al., 2020) requiring the incorporation of operational ideas like Lean Construction, Just-in-Time and optimisation manufacturing in addition to efficient planning and supplier collaboration. Theories, which emphasise waste reduction and synchronised material flows, are critical in addressing the delays and environmental impacts (Bello, 2023; Wasim, 2020) that can hinder OSC from achieving its potential to reduce energy, water, and raw material usage, as well as lowering CO₂ emissions (Moradibistoun, 2019).

In contrast to conventional methods, the OSC-SC involves unique challenges due to its fragmented nature, with producers, suppliers, developers, contractors, and distributors playing key roles (Ikonen et al., 2013; Mostafa, Dumrak, et al., 2014) and barriers that directly affect process efficiency. Drawing on SC integration and coordination models, closer collaboration among these parties could alleviate issues stemming from disjointed operations. Moreover, the diffusion of innovation theory helps explain why OSC adoption may lag; many industry stakeholders perceive these innovative practices as complex or incompatible with traditional construction. In support of this, Stakeholder theory emphasizes that, in order to expedite project delivery, early participation and the development of trust among all parties are essential. OSC is expected to be more than 50% efficient in utilising energy, water and raw materials. This technique reduces 30-70% of environmental impacts and decreases 35% of (Carbon Dioxide) CO₂ emissions and 65% of waste generation (Moradibistouni et al., 2019). However, these barriers to SCM hinder the OSC from reaching these achievements (Wuni & Shen, 2020b). A literature review revealed little research on the OSC-SCM. Comprehensive literature reviews revealed the critical factors in recent years. For instance, in the raw material process, the quality of the material is one of the challenging issues that factories face, even for imported ones. This issue impacts the manufacturing part significantly and delays project delivery. Also, the cost of the materials was affected due to the shortage of material supply in the market (Kamali & Hewage, 2016). For the design echelon, the standard for offsite elements causes issues for various kinds of design, such as seismic and fire-resistant performance complications, longer design phases and consent. These lead to poor flexibility for design, limited size of elements,

and reluctance to change the design. Skilled labour shortage for offsite elements is a critical factor based on the special requirements for manufacturing, transportation and assembly. This leads to an increase in element cost and time, as well as defects and damage during transportation and assembly (Employment, 2022). The Table 4.1 demonstrates the factors that affect the SC from the literature review.

Table 4.1: Barriers of OSC-SCM based on the literature review over a decade

Supply Chain Processes	Challenges	References
Raw material sourcing	Material Quality	(Hsu, 2019), (Yang et al., 2021),
	Material Supply	(Mao et al., 2016) (MBIE, 2023)
	Material importing issues	
Design and planning	Lack of design standards & codes	(Bello et al., 2023; Chen et al.,
	Poor design flexibility	2023; Choi et al., 2017; Hsu et al.,
	Complications on seismic performance	2018a; Hwang et al., 2018; Jalali
	Complications on fire-resistant performance	Yazdi et al., 2021; Li et al., 2022;
	Lack of experienced designer	Xu et al., 2022) (Sooriyamudalige et
	The limited size of elements	al., 2020)
	longer duration (design phase)	
	Lack of innovation	
	Resistance to change	
Manufacturing	Construction consent	
	Lack of manufacturing capacity	(Bello et al., 2023; Chen et al.,
	Lack of skilled labourers	2023; Hamzeh et al., 2017; Ma et
	Higher manufacturing cost	al., 2018; Rahman, 2014; Wang D.
	Incompetence of manufacturers	et al., 2018) (Nesarnobari et al.,
	Defects	2024b)
	Loss of productivity	
	Quality control	
	Increased risk due to uncertainties	
Transportation	Escalated in the deficiency of labour training	
	Poor road condition	(Akinradewo et al., 2021; Chen et
	Higher transportation cost	al., 2023; Choi et al., 2017; Hamzeh
	Lack of suitable vehicle	et al., 2017; Hussein et al., 2023;
	Potential damage	Lee et al., 2021; Mostafa et al.,
	Delay due to logistic issues	2018; Nesarnobari et al., 2024b; Son
	Incompetence of suppliers	& Hieu, 2021; Xiong et al., 2022)
	Traffic conditions	
	Products Size	
Assembling	Cost of labour	
	Lack of technician on-site	(Cao et al., 2022; Choi et al., 2017;
	Complexity of connection	Hamzeh et al., 2017; Nesarnobari et
	Assembly limitations	al., 2023; Rahman, 2014;

Floor area conditions	Sooriyamudalige et al., 2020;
Production size	Wasim et al., 2020; Xu et al., 2022)
Cost of labour	
Limited site space	

Results on stakeholder misalignment and the sluggish dissemination of OSC are echoed in the UK by the continued use of traditional procurement methods and cultural opposition, patterns that closely align with procurement-related barriers reported in New Zealand (Martin et al., 2024; Masood et al., 2021). U.S. builders often perceive traditional site-building as adequate and express concerns that offsite methods may limit design flexibility and increase the risk of late design changes (Hudson, 2024). This indicates a general reluctance toward change within the industry, reinforced by a conservative construction culture and complex contractual processes that contribute to negative perceptions of OSC among both the public and industry (Razkenari et al., 2020). Comparable perceptions have been documented among New Zealand builders, who often cite similar barriers and uncertainties regarding OSC uptake (Masood et al., 2023).

Exhibiting issues with integration and dissemination that are comparable to those observed locally. Low trust and dispersed stakeholder networks have been recognised as major problems in Australia, where the web of parties involved in volumetric modular building results in inadequate cooperation and communication breakdowns (Lin et al., 2021). These issues are similar in many nations, indicating that the OSC-SCM barriers discovered are not exclusive. International OSC research consistently highlights the need for lean efficiency, integrated SC, and proactive stakeholder engagement, even while specific manifestations differ by location (e.g., consumer attitudes in the US or Australia).

Drawing insights from literature reviews, various challenges for SCM have been identified. Among variants of OSC, panelised systems, particularly those utilising timber-based components, have gained significant attention due to their structural efficiency and sustainability potential. These two-dimensional panels, including, curtain walls, metal frame panels, Laminated Veneer Lumber (LVL), Cross-Laminated Timber (CLT), and Structural Insulated Panels (SIPS) which play a crucial role in accelerating the construction process while reducing onsite labour dependency. Studies (Bruno, 2019, Lazarevic, 2020) have highlighted that timber-based panels contribute to sustainable development, economic growth, and climate change mitigation. According to the Building Research report (Carradine, 2020), adoption rates

of these panels remain substantial. CLT (40%), LVL (70%), SIPs (50%), reflecting their growing role in modern housing delivery. Despite this progress, persistent SC and coordination challenges continue to constrain broader implementation, indicating research gaps (Figure 4-1).

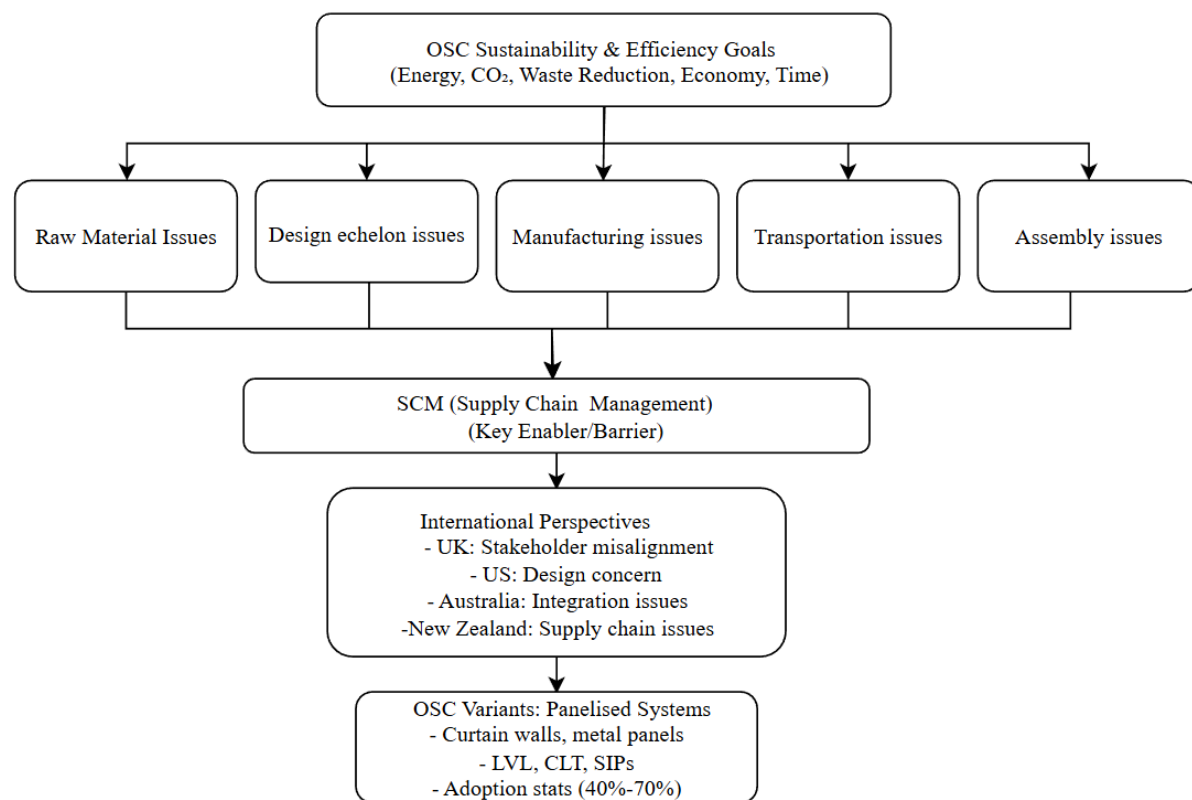


Figure 4-1: Concept visualisation

4.3 Research Method

This study examines the interrelationship between SC barriers affecting the implementation of panelised timber systems in construction practices by employing a triangulated methodological design that integrates a global literature review, expert interviews, and case studies. The literature review synthesised international OSC–SCM evidence and identified a set of critical barriers for design, raw material preparation, manufacturing, transportation and assembly, while New Zealand served as the contextual case for assessing the relevance and applicability of these globally recognised challenges. This combined approach provides not only a theoretical foundation but also a novel methodological contribution, as the triangulation of multiple data sources enables a major rigorous explanation of cause-effect relationships between barriers and their corresponding mitigation strategies (Babaeian Jelodar M. & Shu, F., 2021b; Cooper, 2012; Jonsen & Jehn, 2009; Taylor et al., 2023). The methodology employed in this study extends beyond validation; it facilitates the systematic mapping of how mitigation strategies intervene at different stages of the OSC-SC, thereby strengthening the explanatory

power of the findings. Methodologically, this research proceeded in two key phases: first, conducting a thorough literature review and expert interviews, and second, validating and refining the results through four case studies. Content analysis was chosen as the primary method to analyse the identified barriers due to its ability to process large volumes of textual data from semi-structured interviews and extract deeper insights that structured approaches might overlook (Ghansah, 2024). The semi-structured interview combines structured and open-ended questions, enabling a comprehensive exploration of complex issues (Vernikos, 2013). This approach is particularly advantageous because it offers flexibility and captures subtle participant insights (Miles, 1994). Additionally, it facilitates the investigation of diverse perspectives while ensuring consistency and depth in data collection, which is especially critical in OSC contexts where stakeholders may have varying viewpoints and experiences (Bryman, 2016). Four case studies were examined to validate the findings from the interviews. These case studies were further analysed to support the results, and a framework was subsequently developed by mapping the identified barriers and key stakeholders based on the insights gathered. Finally, five expert reviews were conducted to validate the proposed framework.

SCM in OSC must uncover the complex interactions among various stakeholders, including manufacturers, suppliers, logistics providers, and construction firms. To achieve this, it is essential to identify the precise nature of these interactions to determine the optimal solutions. Semi-structured interviews enable a thorough exploration of these complex and context-specific barriers within OSC-SCM (Masood et al., 2023). This method collects detailed insights and diverse perspectives from industry stakeholders, comprehensively understanding the challenges and potential solutions. In addition to providing rich qualitative data, these help participants establish a relationship that encourages frank and open conversation. It also helps to learn more about the precise details of the study, such as factors influencing decision-making, implementation strategies, and improvement areas for OSC-SCM. (Creswell, 2016; Patton, 2014). Then, a content analysis was performed to comprehensively examine the SCM barriers of the panelised system for OSC in the housing domain. It is helpful for this field due to the possibility of examining textual data systematically. Content analysis can identify critical issues and best practices in SCM by examining literature and interview transcripts (Qiang et al., 2015). This can lead to more effective project delivery and resource usage. Furthermore,

content analysis systematically evaluates how different elements, such as market conditions, technology developments, and regulatory changes, affect the SCM (Ghansah, 2024).

4.4 Expert Interviews

For interviews, a set of 29 open-ended questions was formulated, focusing on the present state of the OSC industry, its associated challenges, and material waste, and was devised for data collection. In the next stage, interview questions were refined: The content was validated through interviews with five project managers with over five years of experience, hailing from two distinct owner organisations and involving two senior academics. These individuals were invited to enhance items deemed unclear or inaccurately expressed in the scale. A combination of purposive and snowball sampling techniques (Dawson, 2009) was used to recruit qualified interviewees, reflecting the field's specialised nature and participants' limited availability. Snowball sampling allowed access to established OSC networks and professionals who are often difficult to reach through conventional sampling methods (Atkinson, 2001; Biernacki, 1981; Goodman, 1961). People with relevant management and experience are needed for this research, as participants must have responsibilities that directly deal with management challenges that impact delivery. Therefore, interviewees comprised professionals and senior executives holding managerial or principal roles across various OSC domains. All participants had more than ten years of experience in the OSC industry within the New Zealand context (A. Mohammadi, 2018; Dalton, 2013; K. Manley, 2019; Zolghadr et al., 2022). This research involving human participants was conducted in accordance with institutional ethical standards (Number: 4000026647). All participants provided informed consent prior to participation, and confidentiality and anonymity were maintained throughout the study. One more interview was done to verify that saturation had been reached. This procedure confirms that the sample size is enough and that the data collected is thorough. Interviews were conducted through a Microsoft Teams conversation, and the participants were assigned codes to safeguard their privacy. All information was transcribed into textual data. The voice recordings were meticulously reviewed to validate the accuracy of data transcription. Then, data were segmented into a subset within 'NVIVO 14' for thorough analysis. NVIVO, a robust workspace for qualitative analysis, facilitates the tracking of specific segments of interviews and the ideas encapsulated within them (Bazeley, 2014; Lewins, 2014). Identifying recurring themes or significant trends requires carefully coding and categorising data (Braun, 2006). The comments of interviewees were compared using content analysis and matched with the innovation strategies of the participating firms and the body of existing literature. These codes were then

grouped according to likely themes that indicate more widespread trends in the information (Glaser & Strauss, 2017).

Although the case studies and interviews were carried out in New Zealand, the research takes an analytical rather than a statistical generalisation method (Yin, 2018), where the objective is to expand theoretical understanding rather than make numerical generalisations. As a result, the results offer transferable insights pertinent to other nations that face comparable difficulties in implementing and adopting OSC-SC.

4.4.1 Case Studies

This research utilised an exploratory and comparative case study methodology to investigate critical barriers thoroughly. Case studies were employed to enhance the understanding of barriers, their interdependencies within the SC, and their effects on projects. Three distinct housing projects in New Zealand were selected to identify the key factors influencing New Zealand's OSC sector. The selection was based on several criteria: the availability of comprehensive project information and documentation, the diversity in project scale and complexity, and the representativeness of different geographic locations and SC configurations within New Zealand. Although the primary focus of the study was to understand SC barriers, the cases naturally include projects employing offsite panelised systems (such as CLT/SIPs). This variety provides additional context and reinforces the representativeness of the sample, ensuring that the findings reflect the complex and multifaceted nature of OSC in New Zealand's construction industry. For this study, a collective multiple case study methodology was used. Each case is treated as a separate "experiment" in which similar research questions are investigated. By comparing cases, researchers can replicate findings across different contexts, thereby enhancing the external validity and robustness of the conclusions. An in-depth analysis of these cases provides extensive data and specific details that might be challenging to obtain through other data collection methods (Cooper, 2012). Conducting comprehensive case studies allows for the exploration of complex projects from various perspectives and can either confirm or challenge the findings from the literature review (Woodside, 2010). A structured framework or guidelines is essential for extracting and organizing information from the four case studies and classifying project data. The selection process followed several criteria. The projects had to: 1) Feature a high degree of OSC. 2) Integrate sustainable or low-carbon products. 3) Offer sufficient access to data, reports, and stakeholders. 4) Represent a similar building type. 5) These initiatives have been initiated by different organisations within the past five years. As a result, four townhouses were selected (Figure 4-2). This methodological choice aligns with the

need to explore complex socio-technical systems, where understanding interactions and emergent behaviours is critical, and cannot be fully captured through reductionist or purely statistical approaches.

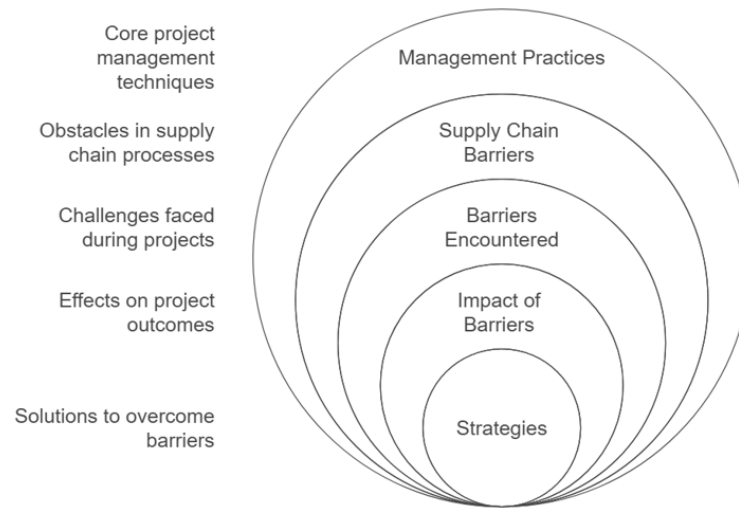


Figure 4-2: Case Study Framework

This framework, designed for comparative case study analysis, draws on Yinian's perspective, which emphasises using multiple data sources and the triangulation of findings (Andújar-Montoya et al., 2020). Such an approach ensures the replication of logic and satisfies the burden of proof (Taylor et al., 2011). It breaks down the project information for each case into management practices, offsite type, SC process, barriers, Barriers Encountered, the impact of barriers, and strategies, which form the units of analysis. It facilitates systematic documentation and enables meaningful comparisons among the three cases. The methodology relies on standardised replication of analysis across the cases, which is made feasible through the development of a uniform case study framework (Babaeian Jelodar & Shu, F., 2021). This approach represents a widely recognised method for designing and conducting case studies (Andújar-Montoya et al., 2020). Because project information is highly contextual, certain units of analysis are required to classify the information and analyse each case. In addition, a comparison of the cases will be very difficult without standard units of analysis.

Four distinct New Zealand housing projects were included in the study, each varying in size, complexity, and location to ensure a broad spectrum of the OSC industry. This selection provided comprehensive project data and documentation, enabling an in-depth analysis of SC barriers. Each project is handled as a separate "experiment" by using a collective multiple case study methodology (Yin, 2014). This made it possible to duplicate and compare results in various contexts. External validity is strengthened when barriers and themes appear

consistently across cases, increasing the likelihood that the results are transferable beyond the selected examples. Document reviews and publicly available data primarily informed case studies, and examining these materials, additional information was requested, and the data gathered from each case were compared to enhance the discussion and the application of the tools. The four cases differ in project size, ranging from 100 to 500, and volume, from 30,000 to 150,000 units. Project values vary significantly, with Case 3 being the highest at 165,000,000 and Case 2 the lowest at 32,000,000, while project durations span from 12 to 35 months. All projects include wall, floor components, with most also including stairs, except Case 2, which excludes stairs. The selected case studies were purposefully chosen based on their comparable characteristics, including project typology, adoption of panelised offsite construction methods, and similar supply chain structures. This alignment enables a consistent analytical basis for cross-case comparison, facilitating the identification of recurring patterns and shared supply chain challenges across the cases. While the findings are derived from a limited number of case studies within the New Zealand context, the study adopts an analytical generalisation approach rather than statistical generalisation. The insights generated are therefore transferable to similar OSC-SCM contexts, where comparable structural and operational conditions exist, supporting the broader applicability of the proposed framework. This approach is consistent with established case study research methodologies, where theoretical and analytical insights are generalised beyond the specific cases examined.

4.5 Findings

The insights gained from interviews and case studies offer a thorough understanding of the challenges, needs, and potential areas for improvement. The study's findings present a detailed analysis of the barriers encountered at SCM in OSC projects, as well as a qualitative content analysis. Critical factors and interrelationships were identified within the material resources, production, transportation, and installation, and their impacts on cost, time, and material waste were thoroughly examined. Based on detailed interviews with industry professionals and an extensive literature review, this section explains how these barriers affect the SC and suggests strategies for mitigation. The content analysis provides crucial insights into the challenges faced by OSC projects, emphasising the necessity for enhanced coordination, quality control, and logistical planning to improve overall project efficiency and minimise waste.

Beyond identifying well-documented challenges in the international OSC literature, the findings reveal several issues that appear to be specific to a particular context. These have a

prominent impact on a small and geographically dispersed market. These context-specific insights extend existing knowledge on OSC–SCM barriers.

4.5.1 Interview Analysis

Evaluation of the revealed factors from the literature review was done by preparing and analysing open-ended questions. Each stage factor is explained and analysed in the following sections.

4.5.2 Material Sourcing Stage

The material stage involves preparing, ordering, transporting and storing (Nesarnobari S. et al., 2022a). Raw material stages for OSC involve a well-coordinated process to ensure efficiency and timely project completion (Ginigaddara et al., 2021). Identifying the required raw materials based on project specifications, obtaining accurate quantity estimates, and establishing relationships with reliable suppliers are part of meticulous planning before starting construction (Lin et al., 2021). Otherwise, the barriers hinder the commencement of the project, increasing the project construction cost and raising carbon dioxide emissions (Salama, 2020). Practitioners in several cases addressed these upstream risks by securing local suppliers and establishing early procurement agreements, which mitigated delays caused by long import lead times and reduced exposure to external barriers. For ordering parts, it is crucial to account for lead times, potential delays, moisture, transportation and weather conditions. To manage these uncertainties, companies applied logistics buffering, such as ordering surplus stock or extending delivery windows, which acts as a downstream mitigation strategy to absorb transportation delays rather than eliminate their root causes. The barriers that the company faces during the ordering can affect transportation, storage, and manufacturing. For instance, if the material moisture is more than standard codes, a delay will occur, and it is undeniable (Hussein & Zayed, 2021). Therefore, this strategy can generate secondary challenges that propagate into other stages of SC and should be anticipated accordingly. The interviews underline an important concern relating to cost uncertainty and the impact of unforeseen expenses on project costs. For instance, ID-2 stated, *“The main issue is fluctuation in fuel prices and transport levies. You can end up with drastic differences from one month to the next”*. Most state transportation issues like weather conditions for delivery, delays in importing pieces for machines and glue for elements. Rainy weather can affect the material quality, so timber is more valuable. ID-11 *“Usually, the biggest issue we can face with the material will be the non-standard material.”*. Quality is the most important consideration; they mentioned

the material moisture and the need for regulation standards: *“When they don't have sufficient material to supply for the market, they do not pass us the graded material. Then we have to grade it by ourselves, which is one extra process we don't like to do”* on the performance of components as mentioned by ID-3. To counteract inconsistent quality, some factories adopted in-house grading and onsite training, which are downstream strategies intended to correct deficiencies after material arrival, though they add cost and processing time. In addition, material availability is a critical aspect and a potential bottleneck affecting the timelines. Many factories commonly use warehouses to mitigate standardisation issues. Still, this practice introduces new challenges, such as mould formation due to the high moisture levels in region. Across the cases, the absence of early procurement planning and supplier diversification contributed to 10–25% increases in material-related costs and project delays, whereas projects that implemented early sourcing strategies reduced these impacts to below 10%.

It can be concluded that although some strategies reduce impacts on project results, they are not consistently applied and often introduce secondary issues that affect other parts of SC.

4.5.3 Design Stage

The design phase in OSC holds paramount importance, as design inaccuracies often lead to manufacturing errors. To mitigate this issue, many factories adopt the practice of freezing the design before commencing manufacturing (Ekanayake, 2021; Rahimian et al., 2017). This mechanism was shown to reduce downstream delays by limiting the order of late-stage changes. However, due to client considerations, occasional design modifications are necessary, resulting in project delays ID-9. In these instances, mitigation shifts from upstream prevention to downstream correction, where additional coordination meetings or digital model updates help contain the propagation of delays but cannot fully eliminate their impact on time and cost. A major hindrance during the design stage is the experience level among designers. It appears in most of the interviewee's response ID-4: *“Secondly, consultants, architects, engineers, etc. that don't have the expertise or experience they sometimes sell themselves that they do, but they've never done anything, and they don't actually understand, particularly architects because they need to take a lead role in coordination.”*. This error propagated downstream, resulting in 10–25% increases in cost and time. However, designers who implemented BIM integration or weekly multidisciplinary design reviews were able to reduce these impacts to approximately 8–10%. Additionally, collaboration issues (Rotimi et al., 2022) between these professionals contribute delays, a phenomenon called "design cooperation." Some individuals erroneously associate design mistakes with manufacturing errors, which is not always

applicable and, in certain cases, can be attributed to the standardisation of design (Navaratnam, 2019). By linking these design-stage mitigation practices to measurable performance variations, this study demonstrates a key identification where, in SC, specific design interventions apply the strongest leverage on cost, time, and quality outcomes.

4.5.4 Manufacturing Stage

Producing components for offsite elements, particularly panelised systems, involves utilising machines, labour, and factory environments. The manufacturing process is initiated with the meticulous control of raw materials, followed by the actual manufacturing phase (Li et al., 2016; Nakano et al., 2020). Various factories adopt different approaches, with some employing full automation while others still require skilled labour in their operations (Almughrabi et al., 2021; Chen & Samarasinghe, 2020). Subsequently, preparations for transportation are undertaken as an integral part of the overall manufacturing process. Machine failures or the need for machine services may arise in the manufacturing process. Per the provided information ID-13, *“if there is a requirement to service machines, production halts for approximately half an hour”*. Interestingly, this interruption does not significantly impact the production rate. However, the scenario changes when it comes to replacing or experiencing unexpected failures in machine components, as these events are not preplanned and can adversely affect the production rate. However, unplanned breakdowns and component failures, particularly those requiring imported replacements, produce downstream barriers that increase production time and related costs by 10–25%. Due to the location of the region, importing pieces of the machines also raises challenges. *“Assume your derail is damaged; there is no technology for that one here. Then you have to bring that simple piece from Germany. Again, this is the other issue.”* To mitigate this, some factories adopted upstream strategies such as stocking critical spare parts or implementing predictive maintenance schedules, which reduced the frequency and severity of breakdowns, limiting their impacts to below 5–10%. Therefore, machine breakdowns and service barriers influence manufacturing. Moreover, skilled labour is scarce, prompting many to adopt an in-factory training (ID-1) strategy. This downstream mitigation mechanism reduces the error rate but does not fully address the upstream challenge of insufficient labour supply; nevertheless, factories using structured training reported reduced rework and waste. Manufacturing errors are often attributable to human mistakes that increase waste generation. Another issue pertains to market challenges, suggesting that the government should enhance client awareness about offsite elements to boost demand (ID-5). Additionally,

concerns persist regarding the element's moisture levels: ID-15, "*Bringing down the moisture content of the environment and the material is quite difficult*".

By connecting these manufacturing-stage mitigation strategies with measured performance impacts, this section demonstrates how mapping specific SCM interventions, whether upstream or downstream, directly influence cost, time, and waste outcomes within the OSC manufacturing process.

4.5.5 Transportation Stage

The transportation of elements is a critical factor in the case of oversized elements, which requires careful management. Therefore, various transportation challenges include equipment failure, traffic congestion, adverse weather conditions, road limitations, crane failures and shortages (Moradibistouni et al., 2017). These factors collectively contribute to errors and disruptions in the transportation process (Sooriyamudalige et al., 2020), leading to more carbon dioxide emissions and global warming (Wasim et al., 2020). According to ID-14's observations, the concerns *around "Wind and Rain issue"* are the most frequently occurring problems that impact various SC sectors. Wind and rain are two unfavourable weather conditions that cause complexity and disruptions at different SC stages (Nesarnobari et al., 2024a). In the cases analysed, weather-related barriers extended transportation times by 10–20%. This common challenge necessitates innovative solutions and attention from all concerned parties. Among these challenges, ID-3 brings attention to the shortage and failure of cranes, stating, "*the main issue is their equipment shortage.*" (Chen & Samarasinghe, 2020). Addressing this labour shortage emerges as a crucial aspect of enhancing the overall effectiveness of transportation in the context of the discussed scenarios. The lack of appropriate crane availability constitutes an upstream capacity constraint that, when unaddressed, can propagate delays of 15–25% into transportation and assembly operations. Conversely, companies that adopted proactive fleet planning, such as pre-booking cranes or securing backup units, were able to limit downstream disruption to below 10%. The shortage of cranes is primarily linked to selecting the appropriate crane size based on the dimensions of the panels, which may rise by traffic. The scarcity of qualified personnel to manage and oversee transportation operations poses significant hurdles, impacting the efficiency and reliability of the entire process. In response, some firms implemented downstream mitigations such as employing multiple smaller cranes or redistributing lifting tasks; while this reduced immediate delays, it increased carbon emissions and shifted the burden to later stages, showing that not all mitigation mechanisms address upstream causes. Occasionally, the absence of a crane necessitates additional expenditures or

sometimes, to decrease transportation delays, companies' strategy is to use smaller cranes and increase the number of cranes, leading to increased carbon dioxide emissions.

4.5.6 Onsite Assembly Stage

Assembly of the big panels is critical because of the size, weather, and topography of the region (Dunn, 2019). As declared in most countries with the same weather conditions, they faced the same problems for assembly (Anvari et al., 2016). For instance, ID-8 states, *"The biggest one would be the weather"*. Adverse weather conditions stand out as a primary factor influencing the assembly process. Rain can have an impact on the quality of timber elements, even though it is evident that wind can shift significant parts and result in element failure or safety problems for labourers. Across the cases, weather-related disruptions extended assembly time by 15–25%. The challenges that limited the assembly are associated with road limitations, as highlighted by ID-5, which states, *"road limitation issues need to be addressed."* Additionally, there is a concern about ensuring the appropriate crane size for the task, as mentioned in ID-12, which notes that *"sometimes the problem is the size of the crane."* This implies that if the correct crane size is unavailable, there is a necessity to transport either with a smaller or larger crane, inevitably leading to increased costs, time and more carbon dioxide (Nesarnobari et al., 2024d). Additionally, considerations such as machine availability and the associated expenses further contribute to the complexities faced. A significant problem that causes delays and expenses in this region is floor conditions; it is related to the topography of this country, which is accessibility to the site. Incorrect crane allocation is an upstream planning issue that can escalate assembly costs and delays by 15–25%; in contrast, projects that used early crane-capacity assessments or pre-booked backup cranes limited disruption to under 10%. This issue requires more management and proper equipment, as mentioned in ID-15 *"The only delays would be around site access "*. Each aspect plays a crucial role in shaping the operational landscape, highlighting the multifaceted challenges encountered during the assembly process. In response, some teams employed downstream strategies such as temporary ground stabilisation or alternate access routing; although these measures reduced immediate standstill time, they increased cost and carbon emissions, showing that downstream mitigations shift rather than resolve upstream terrain constraints.

4.5.7 Barriers Impact of Project Construction Cost of Delivery

Although OSC elements reduced the overall cost of construction, when the project faced barriers in SC, it could significantly impact the construction cost (Nesarnobari et al., 2024d).

The expenses incurred to complete a project and make it commercially viable are known as project construction costs (Mao et al., 2016). Clients prioritise project construction costs over all other factors when choosing construction methods, this impacts the uptake of OSC. Previous research and recent interviews demonstrated the effect of the barriers on the project construction cost of the project (Nesarnobari et al., 2024b).

Cost-effective factors that are revealed as straightforward cost influential are the cost, which includes difficulties in obtaining raw materials, cost uncertainty of materials, and any damages through the SC of elements. Moreover, factors that indirectly cause cost increases are delays due to weather, labour expenses, regulatory compliance, and site preparation (Agapiou, 2022; Li, 2020). The acquisition of materials may increase costs because of material price volatility, resource scarcity, or reliance on suppliers with constrained production capabilities (Salama, 2020). Another barrier is the logistics, where the weight or size of prefabricated components might result in higher shipping costs and more complicated arrangements or damage or delay during bad weather (Masood et al., 2021; Moradibistouni et al., 2017). Furthermore, depending on the region and personnel availability due to special skilled requirements, labour costs related to expert assembly and installation may change (Chen & Samarasinghe, 2020). Preventive management techniques are crucial to minimising their effects, maximising cost savings because these SC impediments raise the entire cost of prefab. According to seventeen interviews, most respondents suggest that various issues impact each stage of the process by approximately 10-25%. Additionally, seven interviewees noted that the manufacturing costs were affected by 5-10%. The predominant impact falls within 5-25%. This result is proven by previous research regarding critical factors impact's on the cost of project construction (Nesarnobari et al., 2024d).

4.5.8 Barriers Impact on Time of Delivery

Despite the benefits of reducing the total construction time, some barriers arise through the SC that lead to delays (Shahzad et al., 2023). Various barriers throughout the SC can significantly impact the system's delivery time due to the SC's complexity (Nesarnobari et al., 2024d). For instance, delays in obtaining materials, manufacturing flaws, transportation problems, a lack of competent workers, and assembly-related problems lead to delivery delays. Material shortages, supplier lead times, and quality concerns are some of the reasons that might cause delivery delays (Jiang & Wu, 2021; Luo et al., 2020; Xiong et al., 2022). A lack of skilled employees, design flaws, machine faults, and problems in the machine can all lead to production defects (Mao et al., 2016; Xue et al., 2018; Zhang et al., 2018). Problems with

transportation include traffic, roads, crane availability, weather, and delays at the construction site (Cho et al., 2021; Li et al., 2016; Zhang et al., 2018). Weather, site circumstances, crane availability are additional factors that can cause assembly challenges (Chen et al., 2023; Li et al., 2018; Pheng, 2001; Wuni & Shen, 2020b). The SC's barriers collectively affect how long it takes to deliver, underscoring the significance of proactive management and mitigation techniques to expedite procedures and minimise delays. This indicates that these barriers lead to 10-25% delays in each process stage. The previous research proof the impact of the factors on delivery time (Nesarnobari et al., 2024d).

4.5.9 Barriers Impact on Waste of Materials

In recent years, rapid urbanisation and developmental activities have led to a surge in waste generation, particularly in construction waste, sparking severe environmental concerns and exacerbating the issue of global warming. Research indicates that construction activities alone account for a significant portion, approximately 30-40%, of landfill waste (BRANZ, 2025), further straining environmental resources and exacerbating waste management challenges. With the diminishing availability of landfill space, the disposal of construction debris presents formidable hurdles, including potential health hazards and ecological repercussions. Consequently, there is a pressing need to address and minimise waste output within the construction industry. OSC emerges as a pivotal strategy, with studies suggesting that it could reduce construction waste by nearly 60% (Kim, 2008). Despite its promising potential, implementing OSC in construction remains relatively limited, posing a barrier to achieving significant waste reduction goals (BRANZ, 2025; Luo & Shahzad, 2020; Malik et al., 2019). Addressing this gap and promoting the widespread adoption of OSC practices could be crucial in mitigating construction waste and fostering sustainable development practices.

The primary contributors to heightened waste generation, as emphasised by the majority of participants, revolve around factors such as "Design errors," "Manufacturing errors," "element failure during transportation and assembly," and "Raw material quality". These factors lead to inefficiencies in the construction process and contribute to increased waste accumulation. A predominant strategy recognised by industry experts to curb the escalation of waste involves proactive intervention during the design stage. By addressing potential issues early on, such as material selection, component compatibility, and assembly processes, firms can significantly reduce the likelihood of waste generation throughout subsequent stages. However, despite the evident benefits of early intervention, adopting such measures remains relatively uncommon. For instance, only one company in New Zealand currently incorporates Design For

Manufacturing and Assembly (DFMA) principles into their design practices, highlighting a pervasive gap in industry-wide implementation. Additionally, reported levels of waste production vary among respondents, with less than 5%, 5-10%, and 10-30% being cited by 40%, 28%, and 32% of participants, respectively. These findings underscore the need for greater emphasis on optimising waste reduction strategies and the broader adoption of DFMA principles within the construction sector to foster a more sustainable and efficient approach to building practices.

4.6 Case Study Results

Case Study 1 examines a significant offsite timber housing in Auckland, undertaken by Constructions Ltd, involving the development of 450 sustainable homes. This project encountered notable challenges related to raw materials supply (quality and cost issues), Weather Conditions (delays for transportation/assembly), Design Changes (due to the need for sustainability of material design changes), and a lack of labour. Inconsistent timber supplies and varying material quality from suppliers, as other barriers, led to delays and increased costs. Case Study 2 explores panelised timber housing, focusing on constructing 100 residences. This project faced barriers to material preparation due to machine failure, material preparation delays. Therefore, the delay affected the onsite activities, faced challenges regarding weather conditions. Also, due to the project's location, the site preparation and the delivery of the elements faced issues. Heavy rainfall caused element damage, and heavy wind stopped and delayed assembly. Case Study 3 investigates a timber project, which involved the development of 500 homes. This project highlighted challenges related to design issues, good quality material, time delivery, coordinating diverse SC, including manufacturing delays and integrating prefabricated components into urban settings. All the challenges affect the project budget over time. Moreover, material waste due to damage to elements was demonstrated.

The case study was selected based on its relevance to panelised OSC projects in New Zealand, availability of data, and its representation of typical supply chain conditions. This ensures that the findings are contextually grounded and suitable for validating the proposed modelling approach. The purpose of the case study is to validate the applicability of the system dynamics and optimisation models in a real-world OSC-SCM context. The case study data were used to inform, calibrate, and evaluate the developed models.

Table 4.2: Summary of case studies

Case study	Barriers through the supply chain	Impact of these barriers	Strategies implemented	Key outcome
450 housing development- Auckland	The housing development in Auckland faced significant hurdles when the supply of timber was delayed due to global material shortages. Heavy rainfall disrupted transportation and onsite schedules, and mid-design changes were needed to meet new sustainability targets. A shortage of skilled labour created inefficiencies during installation.	Delays in project schedule and increased costs due to rework and inefficiencies.	Local sourcing of materials, modular design for flexibility, worker upskilling programs, and weather-aware scheduling.	Completed over 450 homes built to high sustainability standards, establishing a vibrant community despite experiencing delays and budget overruns.
Student housing in Auckland	The project encountered inconsistent production bottlenecks at the offsite factory and delayed output. Therefore, the delay affected the onsite activities and faced challenges regarding weather conditions. Onsite constraints due to limited space, complicated logistics, and heavy rainfall caused element damage; heavy wind stopped assembly and led to delay. They suffered from a lack of supply chain coordination.	Increased project costs and timelines have caused delays and logistics issues.	Stricter quality assurance protocols, optimised production schedules, just-in-time delivery, and protective transport measures.	All barriers and challenges cause delays and expenses that reduce profit or sometimes lead to a decrease in the project's budget.
500 medium-density affordable houses- Auckland	The project for the residential sector was the delivery of more than 500 houses. Due to the size of the project, design issues, good quality material, delivery on time, coordinating diverse supply chains, including manufacturing delays and integrating prefabricated components into urban settings were demonstrated.	These barriers led to potential delays and required rigorous quality assurance processes and supply chain management.	Collaborated with stakeholders to streamline processes, develop adaptable designs, and implement workforce training programs.	For large projects, SCM needs to reduce delays and achieve optimum project expenditure.
208 housing development	Housing development has faced integrating diverse housing typologies and rising material prices. Compliance with evolving building codes and sustainability criteria demanded adjustments mid-project. Also, weather conditions for transportation and preparation of the site were affected. Transportation faced issues due to the road conditions. lack of good quality equipment, equipment defects	Barriers cause delays and cost overruns due to complex design and supply chain issues.	Collaborated with multiple suppliers, used BIM for design coordination, secured fixed-price contracts, and engaged with regulators early.	Delivered 208 sustainable homes, providing diverse housing options for the community.

Case study 4 examines a large-scale housing development involving the construction of 208 offsite timber homes. This project encountered barriers such as lack of good quality equipment, equipment defects, logistical issues like poor road conditions, potential damage to elements during transit (road condition), which impeded the timely delivery and installation of materials and components. *Table 4.2* provides a summary and contextual background of these case studies. The detailed examination of each case reveals how these projects navigated the identified barriers, offering concrete evidence that supports the critical factors derived from the research.

Through the triangulation of literature, interviews, and case studies, this research confirms the prevalence and impact of barriers such as material availability and importing issue, quality issues, cost uncertainty, design errors, lack of designer coordination, and weather conditions on SCM in OSC in Auckland (Table 4.3).

Table 4.3: Comparison results for case studies

Case Study	Material Barriers	Design Barriers	Manufacturing Barriers	Transportation Barriers	Assembly Barriers
450 Housing Development - Auckland	Shortage of timber due to global material shortages caused delays in supply.	Mid-design changes were needed to meet new sustainability targets, increasing complexity.	Prefabrication delays impacted delivery and disrupted timelines.	Heavy rainfall affected site access and transportation schedules, leading to disruptions and inefficiencies.	Skilled labour shortages led to inefficiencies during installation and increased rework requirements.
Student Housing - Auckland	Delays in sourcing high-quality materials impacted prefabricated elements.	Limited design flexibility caused constraints in adapting to urban layouts and weather conditions.	Production bottlenecks at offsite factories caused delayed outputs, increasing lead times.	Complicated logistics and transportation delays due to adverse weather conditions and site restrictions.	Heavy wind caused damage to prefabricated elements during assembly and delayed installations.
500 Medium-Density Affordable Houses	Rising material prices and lack of standardisation increased costs and procurement time.	Design complexity due to modular integration required mid-project revisions, affecting timelines.	Manufacturing delays are due to coordination issues and the integration of prefabricated components.	Issues with supply chain coordination and delivery timelines slowed installation in urban settings.	Integration challenges of prefabricated components required frequent modifications during assembly.
208 Housing Development	Material price hikes and compliance with evolving codes led to delays and adjustments during supply.	Complexity in integrating diverse housing typologies required additional adjustments to meet requirements.	Quality assurance challenges caused defects in prefabricated components, leading to additional revisions.	Weather-related transportation disruptions and road restrictions delayed material delivery.	Poor quality equipment and errors during assembly caused inefficiencies and increased costs.

Table 4.3 summarises the case study comparisons using the framework outlined in Figure 3. The comparison is conducted based on the five units of analysis defined within the case study

framework, showcasing the theoretical replication logic necessary for the case studies (Babaeian Jelodar & Shu, F., 2021).

The case studies reveal a series of material, design, manufacturing, transportation, and assembly barriers affecting OSC projects, while also illustrating how specific mitigation strategies interrupted barriers propagation, reduced downstream impacts. Material shortages and price fluctuations were a common issue across all cases, leading to delays and increased costs; however, the mitigation strategies varied in effectiveness. For example, the 450 Housing Development in Auckland, early supplier engagement and diversified sourcing partially interrupted the propagation of timber shortages by securing alternative material streams, thereby reducing the severity of downstream delays. In contrast, the 208 Housing Development implemented reactive procurement measures that failed to prevent price escalation impacts, resulting in continued delays and cost overruns. Design barriers also emerged prominently, with mid-design changes required for sustainability targets in the 450 Housing Development were supported by collaborative design workshops, which reduced downstream coordination conflicts and facilitated smoother integration during manufacturing. Conversely, in the 208 Housing Development, the introduction of additional typologies without early-stage design coordination led to recurring revisions that propagated delays into procurement, manufacturing, and scheduling activities. Both scenarios reveal how evolving standards and adaptability issues significantly affect timelines and resource management.

In the manufacturing phase, quality assurance protocols and factory-site coordination mechanisms were implemented with varying levels of success. The 500 Medium-Density Affordable Houses projects introduced digital tracking to minimise error propagation between factory stages; however, it was not successful in reducing rework during assembly. Meanwhile, the Student Housing project's mitigation strategies were insufficient; production bottlenecks persisted, indicating that the measures taken did not interrupt the escalation of manufacturing delays. Transportation barriers were primarily linked to weather barriers and road restrictions. Some projects employed flexible delivery windows and contingency routing, which reduced downstream installation delays. Others, with rigid delivery schedules, experienced cumulative impacts where transportation delays propagated directly into assembly inefficiencies. Assembly-phase mitigation strategies also varied. The 450 Housing Development implemented targeted labour upskilling, which reduced assembly errors and prevented downstream rework, whereas the 208 Housing Development, affected by inadequate equipment and workforce

shortages, showed that the mitigation efforts failed to prevent cascading impacts on installation quality and schedule performance.

4.7 Discussion

According to the SC definition, effective management should extend from the raw material stage to the assembly part (Nesarnobari et al., 2024b). This holistic view underpins the study, where the interview questions and case study design were developed to capture the comprehensive nature of OSC-SC. The data indicate that barriers across SC, such as material shortage, design complexity, and logistic challenges, significantly affect project cost, time, material waste. The findings reveal that these barriers do not operate in isolation; rather, they are interdependent, where barriers at one stage of the SC propagate into subsequent stages, amplifying delays and cost impacts (Mostafa et al., 2018; Son & Hieu, 2021). Material quality issues are related to other regulations that deal with manufacturing, and they have to be controlled before manufacturing starts, which leads to an increase in cost due to the high standard of warehouses. Also, the location of the country is essential for importing materials to the country, which leads to over-budget projects and delays. Earlier studies demonstrated that the interplay between skilled labour shortage and logistical constraints exacerbates delays in OSC projects (Jalali Yazdi et al., 2021; Lee et al., 2021; Mai et al., 2025). The analysis concluded that inexperienced design teams and challenges in importing raw materials and equipment can disrupt SC (Hsu, 2019). Recent government reports indicate an increase in design codes and standards; however, the lack of these codes leads to errors in design. Furthermore, while several studies have pointed to technological solutions like high-standard test labs to overcome seismic and fire-resistance barriers, this analysis suggests that while improvements in testing standards have mitigated some barriers, they have not fully addressed the deeper issues related to skill shortages and inadequate SC planning. The persistent lack of skilled labour, a barrier observed in multiple international contexts (Mai et al., 2025), is also evident in our study and significantly impacts overall project performance. Most of the solutions for increasing quality control and reducing preparation time deal with automation, unless the training behind the new technology and maintenance of this machinery are raised as one of the biggest issues in the area.

For instance, adverse weather conditions and challenging road and site conditions contribute significantly to transportation and assembly delays and increased carbon dioxide emissions. This finding is consistent with literature from Lee 2021, Liu 2023, which documents the impact

of environmental factors on OSC performance (Lee et al., 2021; Liu & Luo, 2023). The case study results underscore the critical role of SC integration in mitigating barriers. The case study's findings emphasise that the client's understanding and inexperience with designers emerge as a substantial challenge. This observation aligns with the work of Nguyen (2022), who argues that effective knowledge transfer and capacity building are essential for enhancing OSC performance (Nguyen et al., 2021). Moreover, while improvements in testing standards have addressed some performance issues, such as seismic and fire-resistance barriers, these results indicate that persistent challenges remain. Specifically, the inefficiencies in logistics, compounded by weather and road conditions, create a cascade of delays affecting subsequent stages of production and assembly. The comparative case evidence shows that some interventions, such as strengthened design coordination, diversified material sourcing, and improved factory-site communication, successfully interrupted barrier propagation, whereas others, such as reactive scheduling or late-stage corrections, failed to reduce downstream impacts. The multi-case analysis reveals that despite some barriers being well-documented in the literature, others are context-specific. For instance, while material shortages and transportation delays are common themes in global OSC research, the pronounced impact of local weather conditions and regional road quality on project timelines is particularly evident in our New Zealand cases. These findings highlight that New Zealand specific contextual conditions, such as geographic isolation, import dependence, market size, and weather volatility, intensify SC barriers far more than in larger or better-connected markets. Also, it demonstrated that while theoretical models of SC integration are broadly applicable, localised factors must be considered to develop effective mitigation strategies.

The case study results reinforce the interview findings: material shortages, design complexity, production inefficiencies, transportation delays, and assembly faults collectively compromise project deadlines, budgets, and quality. The empirical data from our New Zealand cases are particularly valuable because they not only confirm these challenges but also reveal the interplay among them, for example, how poor-quality control, importing materials, and machinery maintenance in prefabricated components exacerbate delays during projects. Navigating up and down the roads in geographical areas and tackling weather conditions pose difficulties for the OSC processes of transportation and assembly. A significant problem that most countries had was a shortage of skilled labour. More focus should be placed on solving this part; having a well-managed SC is also essential (Table 4.4). Overall, the novelty of this study lies in demonstrating where along the SC interventions produce the greatest leverage.

Table 4.4: Perceived Barriers to OSC-SCM in Prevalence Order

Stages	Challenges
Raw material	Quality issues
	Availability of material
	Cost uncertainty
	Material supply
	Importing material issues
Design and planning	Lack of design standards & codes
	Lack of experienced design
	Lack of designer's coordination
	Lack of client comprehension
	Design errors
Manufacturing	Lack of skilled labours
	Lack of good Quality equipment
	Defects
	Increased risk due to uncertainties (machine failure)
	Importing Machine pieces issues
	Market issues
Transportation	Weather conditions
	Poor road condition/ Traffic congestion
	Potential damage
	Lack of suitable vehicle
Assembling	Lack of labour
	Weather Conditions
	Limited site space/ Error on site
	Crane availability
	Price variation of Cranes

This study contributes to the literature by providing a detailed, context-rich analysis of OSC-SCM barriers. The findings not only confirm much of the existing research but also highlight emerging challenges, particularly those related to environmental and regional factors. Comparing these results with recent studies (Wang et al., 2022), demonstrates that a comprehensive, integrated approach to SCM is essential, also to reduce barriers and maximise performance in OSC. Strong SC planning, optimising SC and better management, and improved logistical techniques are essential. These insights offer practical implications for improving OSC processes and set the stage for future research to refine SC strategies in the face of dynamic, real-world challenges.

4.7.1 Proposed Framework

Effective SCM is critical to the successful delivery of panelised OSC systems due to the interdependencies among design, procurement, manufacturing, transportation, and assembly processes. The proposed framework (Figure 4-3) integrates these phases to illustrate how technical, organisational, and environmental variables collectively influence project performance. By mapping the relationships among barriers, stakeholders, and performance indicators (time, cost, and material waste), the framework provides a comprehensive representation of OSC-SCM dynamics within the New Zealand context. Beyond conceptual illustration, this framework serves as a decision-support and mitigation-mapping tool, enabling practitioners to identify critical leverage points within the SC and understand where targeted interventions yield the greatest impact.

To ensure its validity, the framework was reviewed by a panel of five independent expert validators, three professors, senior academics specialising in construction management and industrial optimisation, and two design managers from leading OSC firms. These experts differed from the initial interviewees, who provided operational insights during the data collection stage. The validators were purposefully selected based on their extensive experience (over fifteen years) and their ability to provide strategic, methodological, and managerial perspectives rather than operational viewpoints. Their feedback informed refinements to the structure and clarity of relationships in the final framework, enhancing its theoretical soundness and practical applicability. By making the interdependencies between design, procurement, manufacturing, logistics, and assembly explicit, the framework guides practitioners toward prioritising upstream actions, particularly in design coordination, early procurement planning, and material sourcing, where mitigation has the strongest ability to prevent downstream escalation. The proposed framework is theoretically grounded in established supply chain management principles, particularly process integration, coordination, and performance optimisation, as widely discussed in the construction and operations management literature. It further draws upon systems thinking perspectives to capture the dynamic and interdependent nature of OSC supply chain processes, where multiple stages interact to influence overall project performance. This theoretical grounding ensures that the framework extends beyond a purely empirical representation and contributes to the conceptual understanding of OSC-SCM.

Cost and time are selected as the primary performance dimensions due to their fundamental role in defining project success within construction management theory and practice. These dimensions are consistently identified in the literature as critical indicators of supply chain

efficiency, directly reflecting the effectiveness of coordination, resource utilisation, and process integration across project stages. In the context of offsite construction, where scheduling dependencies and cost structures are tightly coupled, these metrics provide a robust basis for evaluating supply chain performance.

Moreover, in the New Zealand construction context, persistent challenges related to project delays and cost overruns further reinforce the relevance of these dimensions as key decision-making criteria.

By outlining the sequential phases, important challenges, cost drivers, and the roles of various stakeholders, an integrated SC framework provides a thorough roadmap for managing the entire OSC-SC with the costs, barriers, and key stakeholders at each stage from design to assembly. This structured visibility helps project teams anticipate how delays or inefficiencies propagate through later stages, enabling integrated SCM planning that minimises cost overruns, time delays, and material waste. In practice, project managers, SC planners, engineers, architects, and logistics companies can utilise this framework to pinpoint critical flaws, streamline processes, and implement plans that reduce delays, material waste, and cost overruns. The stakeholders include owners/developers, architects, engineers, contractors, suppliers, logistics companies, and on-site assembly teams responsible for specific OSC process aspects. The framework ensures that SC challenges are addressed holistically by involving all these groups. This integrated approach facilitates improved coordination among different functions. It allows for proactively identifying issues, like material shortages, transportation delays, skill shortages, and carbon footprint, that can cascade through the SC and affect overall project performance. The illustration emphasises how various phases are interdependent, highlighting how problems in one area (such as delays in imports or a lack of skilled workers) can affect the operation of the entire SC. This capacity to trace how early-stage decisions influence downstream outcomes is a central novelty of the framework, distinguishing it from descriptive OSC models by providing actionable pathways for intervention. Because the framework explicitly links barriers to their mitigation points, it supports systematic decision-making for selecting the most effective strategy at the correct stage of the SC.

The proposed framework leads to potential strategies for mitigating identified barriers and enhancing SCM efficiency:

- Early collaboration among stakeholders, namely designers, manufacturers, suppliers, is required lead to reduction in lead time.
- Working on codes and standardisation to facilitate more accessible procurement, minimising SC.
- Facilitate strategic decision-making by optimising the SC, which minimises delay, waste, costs, and global warming, leading to enhanced management. It employs

advanced planning and scheduling techniques and centralised distribution centres to improve material, process handling and delivery efficiency.

- Digital tools such as BIM should enhance coordination across SC early in design stage.

To deal with SCM challenges, researchers are required to develop and apply optimisation techniques to alleviate planning and delivery processes. Moreover, the government and stakeholders should implement regulations facilitating investment and code upgrades. In addition, the designers should cooperate more interactively and employ digital resources to avoid conflicts. This framework is also applicable to the architectural part of the construction.

4.8 Conclusion

The housing sector has been facing challenges and shortages over the years. OSC, particularly timber panelised systems, hold considerable promise; however, the uptake has been relatively low due largely to inefficiencies in SCM. This study aimed to evaluate the critical factors hindering the application of OSC and their impact on the SCM. It is envisaged that resolving the current issues with the low implementation of timber panelised systems will enhance the uptake, increase efficiency and consequently reduce the material waste and carbon footprint. A key contribution of this study is moves beyond simply identifying OSC–SCM barriers and instead explains how these barriers interact, where mitigation strategies can intervene most effectively, and how these interventions shape supply-chain performance.

Result Shows that key SCM challenges, from acquiring raw materials to manufacturing, transporting, and on-site assembly, have a negative impact on project cost, time, and material waste. By analysing how mitigation strategies interrupt or fail to interrupt barrier propagation across these stages, the study provides a clearer understanding of actionable mitigation pathways rather than generic problem lists. This conclusion is based on three steps: literature reviews, expert interviews, and several case studies. A comprehensive literature review revealed that the main issue lies within the SC of the OSC, requiring an in-depth analysis to recognise and identify the SCM barriers. A qualitative study was conducted by interviewing various experts and stakeholders within the OSC industry. A content analysis was performed on the raw data, revealing the major barriers affecting raw materials, design, manufacturing, transportation and onsite assembly. Then, four case studies were analysed to evaluate the interview results. This approach also offers timber-specific and regionally grounded insights, reflecting the distinctive constraints of New Zealand's market size, geography, environmental conditions, and reliance on imported materials. A triangulation technique was utilised to

validate and map the findings (Babaeian Jelodar & Shu, 2021b; Cooper, 2012; Taylor et al., 2011). Overall, the study presents an empirically validated framework that links barriers, mitigation strategies, and performance outcomes, offering practical guidance for enhancing the efficiency and resilience of timber-based OSC-SC. The main issues affecting delivery costs and material waste were SC delays caused by weather and traffic conditions, labour shortages, machine failure, and material quality. A comparison of these with the issues found in the literature clarified that some of these are more dominant in special regions due to their unique topography, location, climate and regulations, while some others exist but at a lower level. These results highlight the necessity of a thorough SCM framework that tackles new problems, including workforce shortages, environmental interruptions, and more conventional operational difficulties. Results highlight dominant barriers influenced by New remote locations, small market size, dispersed population, and unique geography, resulting in higher costs and longer lead times. This underscores the critical role of efficient SCM, focusing on the most pressing issues to address operational inefficiencies and mitigate challenges. Proper SCM leads to efficient delivery with minimised delay, reducing cost and waste. Hence, it is revealed that the optimisation of SCM is a potential solution to achieve sustainability and competitiveness in OSC operations.

The analysis provides policymakers with a number of specific recommendations, including the need for governments to create uniform SC and design norms, encourage sustainable practices with tax breaks or subsidies, and promote cross-sector cooperation. The proposed four-step structure encourages more SC integration, a greater use of digital tools (such as automation and real-time monitoring), strict risk management, and a significant emphasis on capacity building and workforce training for industry stakeholders. These steps are necessary to guarantee the timely delivery of raw materials, optimise production procedures, and set up effective distribution networks that save expenses and delays. By triangulating literature, stakeholder interviews, and real project cases, the study provides one of the few multi-source empirical examinations of OSC-SCM challenges within a regional panelised housing context.

A roadmap for further research, Pilot projects should be implemented to evaluate and improve new SCM methods in real-world OSC environments. While comprehensive cost-benefit evaluations of new SCM methods and technology can uncover the most economical solutions, comparative worldwide benchmarking studies can assist in identifying best practices. Although the empirical validation is based on New Zealand cases, applying the framework in other regions would be a valuable avenue for future research.

Additionally, investigating the application of automation in OSC can boost efficiency and minimise human error in the SC. Analysing successful and unsuccessful SCM implementations in OSC projects worldwide will help discover best practices and key insights. Thorough cost-benefit analyses of various SCM strategies (optimisation) and technologies are needed to determine the most cost-effective solutions for OSC. Additionally, identifying workforce skill gaps and developing training programs and educational curricula will equip professionals with the necessary competencies for effective OSC-SCM (MBIE, 2022).

Chapter 5 Development of a System Dynamics Model for Cost–Time Interdependencies in Offsite Panelised Construction Supply Chains

In order to address Research Objective 3, which is to model, the system dynamics (SD) technique was implemented resulting in an SD model that captures the interdependencies of barriers in OSC-SCM, this chapter expands on the modelling framework that was introduced in the Paper with the title “System Dynamics Model on Cost-Time Estimation for Supply Chain Management of Offsite Panelised Systems in the Housing Sector” which is under review in the construction innovation journal.

The methodological underpinnings of system dynamics are presented in this chapter, along with an explanation of the way it can describe complex, feedback-driven processes in supply chains for the construction industry. The reinforcing and balancing feedback structures that influence behaviour in design, manufacture, transportation, and on-site assembly are mapped using causal loop diagrams, or CLDs. The dynamics of cost and time performance are then simulated by converting these conceptual maps into stock-flow models, considering material waste.

The SD model offers a comprehensive perspective on the convergence of various factors influencing project outcomes by capturing these interdependencies. It transcends static cause-and-effect assumptions and demonstrates the chain reaction of barriers in a tightly coupled supply chain. The chapter ends by presenting the model as a decision-support tool that can conduct scenario testing and sensitivity analysis. It also sets the stage for its integration with multi-objective optimisation in Chapter 8, where trade-offs involving time, cost, and waste are formally assessed.

5 System Dynamic Model on Cost-Time Estimation for Supply Chain Management of Offsite Panelised Systems in the Housing Sector

The current chapter is based on the following article:

Nesarnobari. S., Shahzad. W., Jelodar. M. B., Sutrisna. M., “System Dynamic Model on Cost-Time Estimation for Supply Chain Management of Offsite Panelised Systems in the Housing Sector”, 2025, Journal Paper Submitted (Under review).

Abstract

Purpose: The offsite construction (OSC) supply chain must undergo revolutionary improvements in skills, capacities, and capabilities because of the shift to Industry 5.0. However, ongoing supply chain 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 research seeks to improve OSC-SCM processes while expanding the talent and capability base needed for construction ecosystems prepared for Industry 5.0.

Design/methodology/approach: A System Dynamics (SD) modelling approach is employed to quantitatively analyse cost and time dynamics under multiple disruption scenarios. The model incorporates key barriers, 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 results of the simulation demonstrate the complex relationships that exist between supply chain (SC) performance, operational capacity, and personnel capability in OSC. The findings point toward important leverage areas where focused interventions, like digital design integration, improved worker training, and rapid logistics planning, can increase productivity, cut waste, and hasten Industry 5.0 transformation preparedness all at once.

Originality/value: In the OSC context, this research presents a novel integration of SD modeling and Industry 5.0 capability development, 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.

5.1 Introduction

The housing sector faces significant challenges in meeting the growing demand for timely, high-quality, and affordable housing, exacerbated by rapid population growth (Nesarnobari et al., 2024b; Stephens, 2022). To address these issues, the industry is increasingly adopting OSC, a method renowned for its speed, quality, and cost-effectiveness (Nesarnobari S. et al., 2022a). However, OSC's complexity and the challenges within its SC have slowed its adoption rate. Recognising the vital role of SCM in addressing these hurdles, the housing sector has begun prioritising SCM strategies to realise the OSC potential (Nesarnobari S. et al., 2022c).

Despite the growing use of OSC techniques, efficient SCM remains a significant barrier. Several barriers hinder its seamless integration into traditional construction SC, including fragmentation, logistical challenges, lack of standardisation, and varying regulatory requirements (Nesarnobari et al., 2024d). These issues disrupt the smooth flow of resources, information, and supplies, resulting in delays, increased costs, and compromised quality. Strategic SCM practices can help mitigate these issues and unlock OSC's full potential. This would enable stakeholders to deliver faster, more affordable, and higher-quality housing solutions to meet the increasing demand (Wang, Hu, H., et al., 2019). SC gaps often necessitate the development of tailored models addressing all SCM aspects. Given the complexity, scale, and brief duration of projects, particularly in OSC, such models must effectively manage the myriad interactions. These include information flow, procurement processes, logistics, helping to minimise financial repercussions of reworks (Peter et al., 2020).

Challenges such as labour shortages, material quality issues, and transportation delays not only inflate costs but also disrupt project schedules, leading to unpredictable performance. Current approaches frequently fail to consider the dynamic and interdependent nature of these barriers, resulting in suboptimal mitigation strategies. This research focuses on offsite panelised systems, which are widely adopted globally and offer scalable solutions for addressing housing demands (Carradine, 2020). Using SD methodology, the study identifies and analyses the key barriers impacting SC efficiency in OSC and proposes strategies to overcome them. By examining how these factors interact, the research provides a more realistic understanding of the challenges and informs decision-making, reducing the risk of costly barriers. Additionally, it highlights strategies to enhance resource efficiency, contributing to both environmental and economic benefits.

5.2 Background

5.2.1 Barriers to SCM

All facets of the 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 J. Peter 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, Dumrak, et al., 2014). Early studies (2008-2016) primarily addressed foundational challenges in OSC-SC. However, from 2018 onwards, research shifted toward 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, blockchain, and simulations, to enhance decision-making and address complex SC barriers (Nesarnobari et al., 2024b). This progression highlights the strategies' evolution from addressing basic coordination issues to adopting sophisticated, technology-driven solutions to optimise OSC-SC performance. These theoretical foundations collectively shape the study's SDs modelling approach, ensuring it captures the complexity and dynamic interactions within OSC-SC, thereby bridging theoretical insights with practical applications (Nesarnobari et al., 2024b).

Furthermore, the unpredictability of import material costs might pressure financial planning and budgetary restrictions. Inadequate quality checks or machine mistakes might result in element 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 that can operate complicated equipment and meet stringent quality control requirements is also critical. Skill gaps or a lack of labour can cause production schedule disruptions and lower the final product quality (Chen H. a. S., D.A.S., 2020). There are unique difficulties when moving massive parts 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 throw off transportation plans and cause expensive delays. In addition, delays may result from logistical issues, including traffic, weather, and road limitations (Hsu et al., 2018a). The weather, site circumstances, and labour constraints all affect assembly procedures, adding to the complexity of 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 navigate the complexity of the OSC-SC successfully.

Zhao et al. (2022) utilised an SD-based neural network model to predict delays in OSC projects, highlighting the importance of dynamic modelling in mitigating project risks (Zhao, 2022). The following year, Dabirian et al. employed SDs to plan, forecast, and manage cash flow in construction projects, demonstrating its versatility in addressing financial complexities (Dabirian, 2023). Furthermore, Liu and Luo (2023) applied SD to improve the accuracy of total project cost estimation for general contractors, ultimately enhancing profitability (Liu & Luo, 2023). Similarly, Yuan et al. (2023) advanced construction accuracy in precast components by identifying causal relationships and pinpointing the most sensitive factors affecting outcomes (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 like global warming (Wasim et al., 2020), complicate SC integration, mainly due to an insufficient understanding of these challenges (Wang Z.-L. et al., 2019). SDs are designed to analyse and manage such intricate feedback systems by viewing a system as a network of interdependent elements (Marzouk & 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 & Azab, 2014). SD offers a framework for examining dynamic interactions, feedback mechanisms, and evolving behaviours within the OSC-SC, while 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 (Nesarnobari S. et al., 2022c).

Table 5.1: Supply Chain based on literature review

Supply Chain Processes	Challenges	References
Raw material sourcing	Material Quality	(Hsu, 2019), (Yang et al., 2021), (Mao et al., 2016)
	Material Supply	
	Material importing issues	
Design and planning	Lack of design standards & codes	(Bello et al., 2023; Chen et al., 2023; Choi et al., 2017; Hsu et al., 2018a; Hwang et al., 2018; Jalali Yazdi et al., 2021; Li et al., 2022; Xu et al., 2022) (Hsu et al., 2018b)
	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	
Manufacturing	Construction consent	(Bello et al., 2023; Chen et al., 2023; Hamzeh et al., 2017; Ma et al., 2018; Rahman, 2014; Wang D. et al., 2018)
	Lack of manufacturing capacity	
	Lack of skilled laboures	
	Higher manufacturing cost	
	Incompetence of manufacturers	
	Defects	
	Loss of productivity	
	Quality control	
	Increased risk due to uncertainties	
Transportation	Escalated in the deficiency of labour training	(Akinradewo et al., 2021; Chen et al., 2023; Choi et al., 2017; Hamzeh et al., 2017; Hussein et al., 2023; Lee et al., 2021; Mostafa et al., 2018; Son & Hieu, 2021; Xiong et al., 2022)
	Poor road condition	
	Higher transportation cost	
	Lack of suitable vehicle	
	Potential damage	
	Delay due to logistic issues	
	Incompetence of suppliers	
	Traffic conditions	
	Products Size	
Assembling	Cost of labour	(Cao et al., 2022; Choi et al., 2017; Hamzeh et al., 2017; Rahman, 2014; Wasim et al., 2020; Xu et al., 2022)
	Lack of technician on-site	
	Complexity of connection	
	Assembly limitations	
	Floor area conditions	
	Production size	
	Cost of labour	
	Limited site space	

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 due to 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 for mitigating delays, improving cost efficiency, and enhancing 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). These findings indicate that while panelised construction has the potential to improve schedule performance, its effectiveness is highly dependent on the reliability and coordination of the supply chain.

5.3 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 then triangulation methodology was employed to identify and evaluate barriers. This methodology involved a comprehensive literature review, semi-structured interviews, and case studies, which were used to refine the identified factors specific to the residential sector. In the third stage, a causal loop diagram was developed based on evaluated factors to recognise their effect on the SC process. Subsequently, the SD approach was applied to create a cost-time model tailored for offsite panelised systems in the housing sector. The rest stages involved validating the model using a real case study and discussing the results to inform future research directions.

5.3.1 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 & Jehn, 2009). This method can enhance the validity and reliability of the findings by employing multiple methods and data sources (Andújar-Montoya et al., 2020). Researchers can reduce biases, cross-verify data, and develop a more thorough grasp of the subject by combining various methodologies (Davis, 2018). For example, integrating case study validation with qualitative techniques like literature reviews and interviews enables a more thorough analysis

because the advantages of one approach can offset the disadvantages of the other. In this research, triangulation involves validating the key factors impacting the SC. Semi-structured interviews were conducted, offering a balanced approach between structured and open-ended questioning to enable an in-depth exploration of complex topics (Vernikos, 2013). 29 open-ended questions were developed to gather data, focusing on the current state and challenges of the OSC. 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. All interviewees were professionals and principals at the management level with over ten years of experience in OSC industry. The sample size of fifteen semi-structured interviews is considered sufficient for qualitative research, as data saturation was achieved, with no new themes emerging in the later stages of data collection. This aligns with established qualitative research practices, where depth of insight is prioritised over sample size. Then, content analysis was done to analyse qualitative data, and case studies were analysed to verify findings. The case studies were selected based on: They must exhibit an OSC high level, incorporate sustainable or low-carbon products, provide broad access to data, reports, and stakeholders, represent a similar building type, and have been initiated by various organisations within the past five years. Data collected from interviews, case studies, and literature review were triangulated to enhance the validity and reliability of the findings. Insights obtained from different sources were cross-checked and validated through subject matter consistency across the supply chain stages.

5.3.2 System Dynamics

SDs were 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 H., 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 potential of OSC, for the past years. The barriers of OSC-SCM are explained as a complex, open information feedback system involving many information flows, material flows, 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, Shen, & Alshaw, 2014). It gathers information and visually

represents the flow between the system's internal and external environments while precisely 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 comprehending how various elements, including standardisation, logistics, regulatory compliance, interact and impact 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. Through the integration of empirical data from several case studies, the SD model provides a significant understanding of the dynamic behaviour of SCs, 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, 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 following framework.

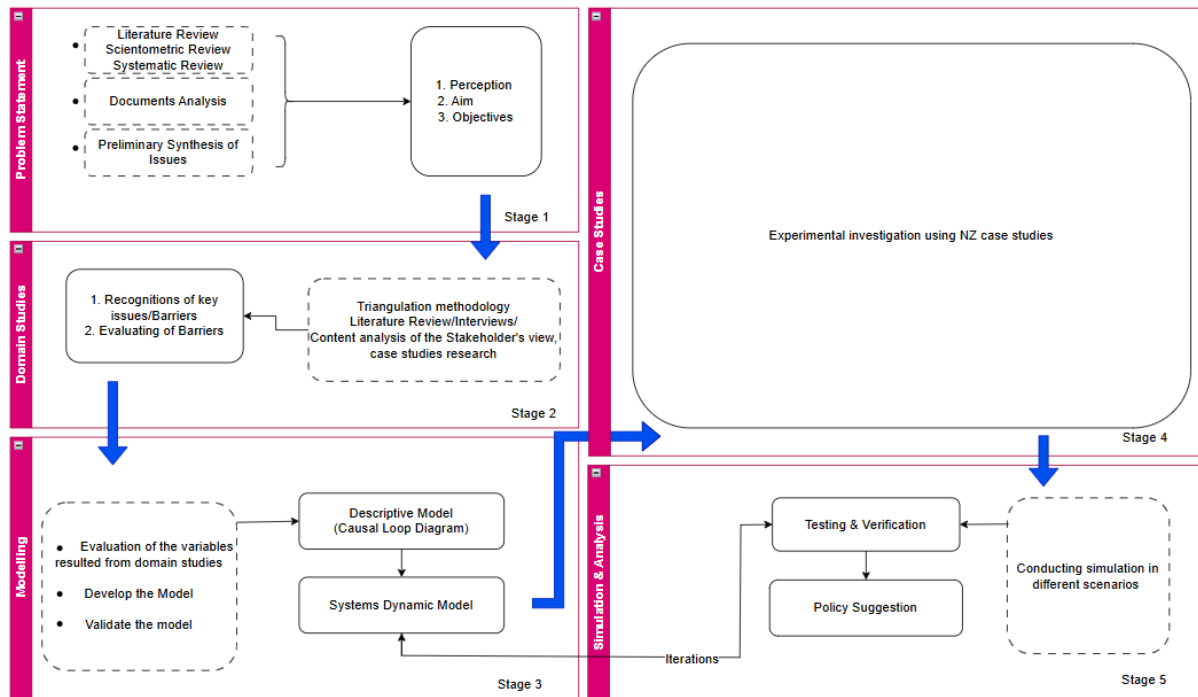


Figure 5-1: Methodology Framework for System Dynamics

5.3.3 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 process of OSC-SCM lies within the system boundary, which includes building design, manufacturing, transportation, and assembly. Project costs and additional expenses are accounted for within these processes.

The study employs the SD model to explicitly incorporate indicators across project costs, delivery times, and material waste. The supply chain flow of the panelised system in OSC encompasses five primary stages: design, raw material procurement, manufacturing, transportation, and assembly. Within the delivery time framework, the design phase involves

measurement, 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 site. Finally, 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 factory, storage. Manufacturing costs account for machinery and labour, while logistic costs encompass equipment, labour, crane or lifting operations. Assembly costs similarly include installation, labour, crane/lifting requirements. Manufacturing cost forms a substantial component of total construction cost; therefore, similar trends are expected. However, analysing them separately allows clearer identification of cost drivers within each supply chain stage.

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

5.4 Results

5.4.1 Challenges in SCM

To achieve the research objective (Vernikos, 2013), fifteen 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, insufficient quality control of materials, defects in elements, 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 the vulnerabilities in SC.

The interplay between logistical challenges and regulatory barriers is evident in the transportation phase. Factors such as road restrictions, vehicle suitability, and delays due to logistics inefficiencies compound the problem of transporting. 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 due to 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 & a lack of experienced design coordination hinders project initiation. Interviews revealed a recurring theme concerning clients' comprehension of design regulations and limitations in 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 in transporting equipment, such as CNC pieces, with servicing and repairs being expensive and time-consuming due to a lack of expertise locally. The figure illustrates how barriers feed into broader systemic inefficiencies.

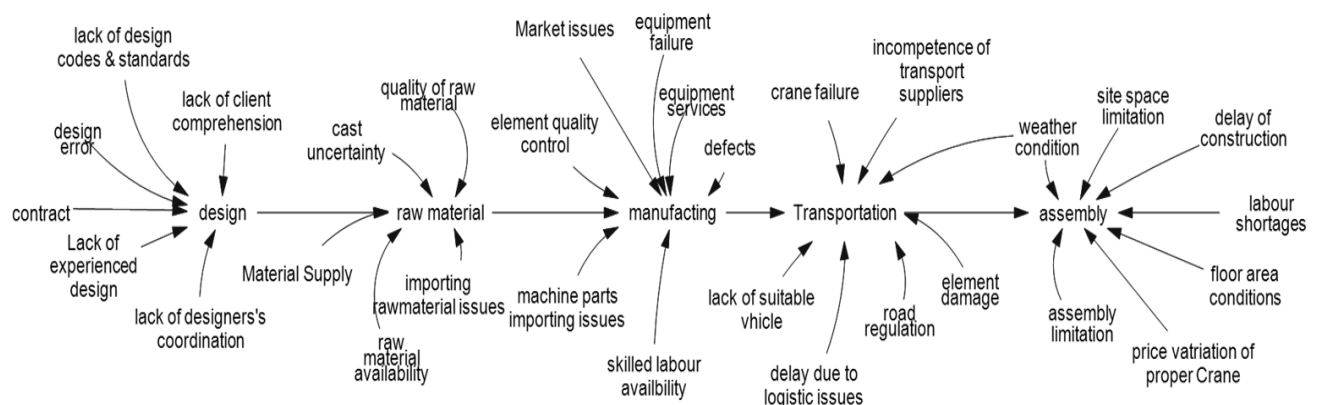


Figure 5-2: Mapping the challenges of the supply chain of OSC from triangulation methodology

5.4.2 Model Development

5.4.2.1 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 that by visualising a model's cause-and-effect interactions between the variables. The CLD may

demonstrate how each variable interacts to affect the system dynamically. The feedback loop indicates the dynamic behaviours of the model (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 can be either positive or negative. It's termed a negative feedback loop when it includes an odd number of negative causal links. Conversely, if it consists of an even number of negative causal chains, it's called a positive feedback loop. Feedback loops can be reinforcing and balancing loops, and they were either demonstrated by R or B. In the early stages of SD modelling, the causality diagram provides a theoretical framework for further modelling efforts (Ekanayake, 2021). All the loops are reinforcing; therefore, they are mentioned as R. The causal loop graphic highlights critical feedback processes that affect overall time and capital cost while illuminating the dynamic interdependencies. The diagram shows balancing loops that, when properly addressed, can stabilise processes and reinforce loops that worsen delays and inefficiencies.

Feedback Loop 1 (R1) involves the correlation among design change, expenses, duration, adherence to design codes and standards, and design error. When errors arise in the design process, they trigger adjustments in the design, resulting in prolonged design durations and increased costs. Consequently, this loop is anticipated to exhibit a negative feedback pattern.

Feedback Loop 2 (R2) involves the interplay between 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 decrease crane availability and extend transportation time, resulting in increased costs. This loop is also considered a positive feedback loop.

Feedback Loop 4 (R4) involves installation costs, time, installed components, labour costs, labour availability, and element damage. Installing components leads to increased labour availability and reduced element damage. Consequently, this loop is considered a negative feedback loop. The interdependence of these elements highlights the significance of tackling

these feedback loops holistically to improve SC efficiency and project performance by showing how inefficiencies in one stage of the OSC process can spread.

5.4.2.2 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 regulating the way system components interact are visualised. As a computational algebraic representation (Ajayi, 2016), stock-flow diagram enables quantitative analysis and mathematical simulation of a model, expanding beyond mere evaluation through causal and the use of trees (Wang T. et al., 2018).

A diagram is employed to assess the possible effects of the project by examining the interconnectedness depicted in Figure 5-3. 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 75 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 like 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 like 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.

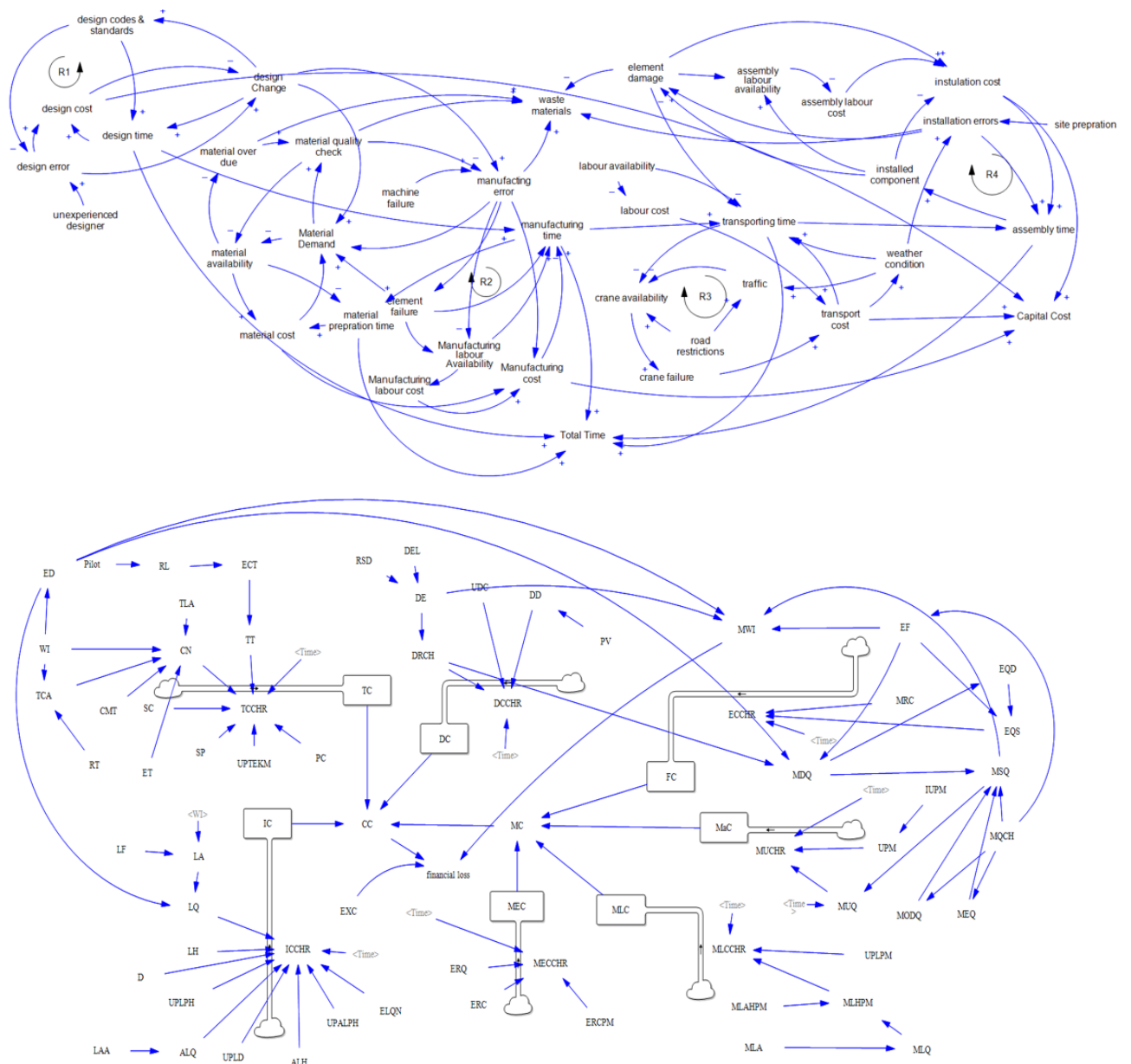


Figure 5-3: Causal-loop and stock-flow diagrams of supply chain management

5.4.3 Data Collection

Case studies for data-collection were chosen based on: (1) projects that employed panelised construction methods, specifically panelised systems, to reflect current OSC practices; (2) diversity in project size, scope, and complexity to ensure the model could handle various scenarios and challenges; (3) availability of detailed data on project duration, costs, and SC processes. Case Study A, involving 150 medium-density residential houses in Ohakune, and Case Study B, comprising 250 residential units in Auckland. These projects provided insights

into different OSC environments, with Case Study A focusing on logistical challenges in remote locations and B addressing complexities in high-density urban 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 project time and interviews with relevant managers. The chosen case studies include a range of initiatives in size, scope, and complexity. Because of its diversity, the model can handle various variables and scenarios frequently 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 SD model, with the simulation period set to 12 months, from 2024 to 2025. Detailed project and progress updates were analysed to calibrate and validate the SD model. Sensitivity analysis, inspired by Sterman (2000), was employed to identify critical factors influencing SC performance.

5.4.4 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 guaranteeing scenario correctness (Richardson, 1981; Sterman, 1992). The model was validated using seven tests (barlas, 1996). (1) Boundary adequacy test, Assures that important and significant factors and concepts are sufficiently taken into account (Qudrat-Ullah & Seong, 2010); In test 1, validation was done by conducting interviews with representatives from the literature review(Nesarnobari et al., 2024b), and the focus group contained one industry and two academic experts who had previously assisted in collecting data. (2) Structural verification 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) Test for parameter verification, Verifies parameter values using real-world descriptive and numerical data (Ajayi, 2016); In test 3, the constants utilised 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) The dimensional consistency 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: 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) to zero, leading to an approximate 54% decrease. 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 compared to when it is one. 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, subsequently, higher material demand costs. This observation underscores the consistent responsiveness of the model's variables and suggests the potential for verification with additional variables. (6) Behaviour sensitivity 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) Test for model behaviour verification, 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 (EXC1 & EXC2), demonstrating that the projected costs closely align with actual construction costs. For case studies, the projects experienced smooth progress without encountering significant barriers during months 5 to 7. As a result, the project costs either showed a slight increase 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, detailed analysis was presented in Figure 5-4.

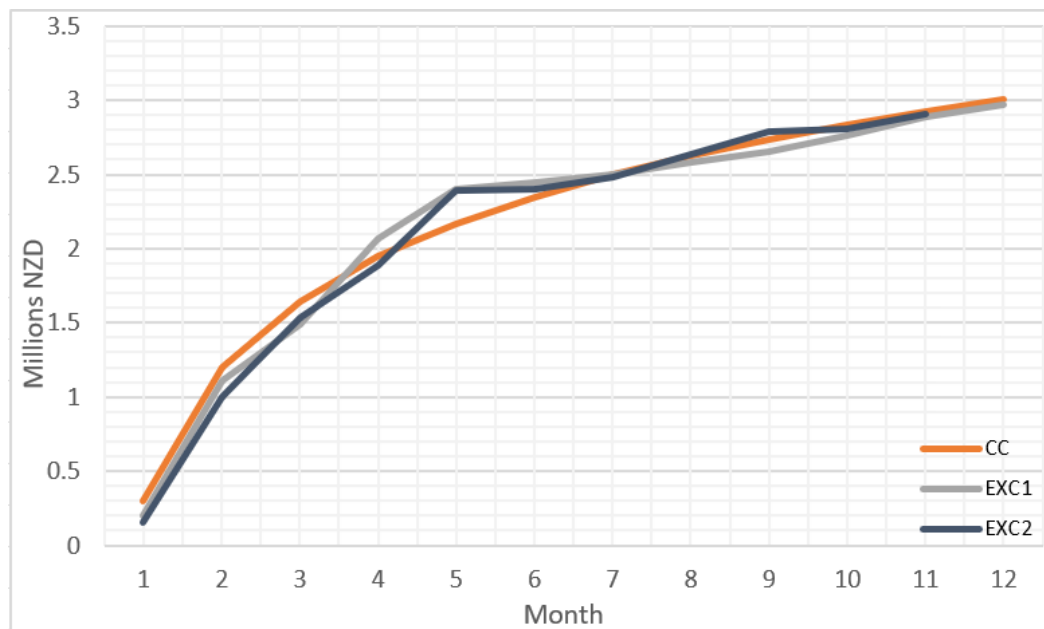


Figure 5-4: The model behaviour verification

5.5 Results of Simulation and Discussion

5.5.1 Basic Simulation

As outlined, the critical barriers influencing the cost and time required to deliver the offsite panelised system were identified, including factors such as material quality control, manufacturing labour availability, equipment failure, transportation limitations, weather impacts, and labour shortages (Appendix A). 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 meters, 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 231kilometres from the

manufacturing facility. The scenario analysis results are accurate and can represent the real-world circumstances surrounding the manufacture.

The simulation results in Figure 5a show the construction cost (CC) components: 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 5b, 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.

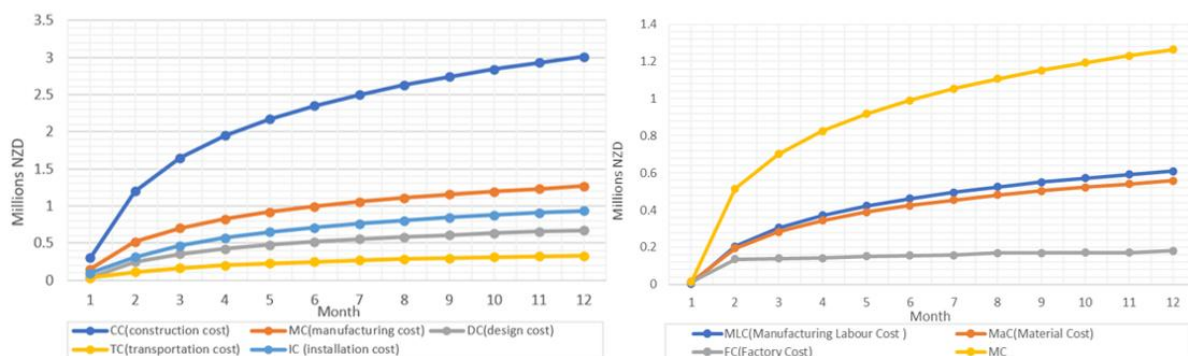


Figure 5-5: The Construction Cost simulation results, b: The Manufacturing Cost simulation results

5.5.2 Scenarios Discussions

5.5.2.1 Project Cost

The simulation findings, which shed light on the construction project cost (CC) under four different scenarios, show how important barriers are in affecting project overall. These scenarios provide a thorough knowledge of cost behaviour for the project by capturing the dynamic correlations between 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 & CC2 prices early in the project schedule and continuing to have the highest construction project cost. This highlights how vital equipment availability is 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 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 strong repair techniques are crucial for reducing manufacturing delays and the expenses that come with them.

5.5.2.2 Manufacturing Cost

The simulation results shown in the figure indicate how the entire manufacturing cost (MC) over 12 months is affected by four significant scenarios. Every scenario depicts significant barriers faced throughout the construction process and their effects on rising project costs.

Delays caused by a lack of skilled workers for CNC equipment maintenance 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 brought on by equipment failures. To avoid expensive 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 MC2 scenario. The cost increase shown in the figure is mild and stays over the baseline for the project's duration. The trade-off between time recovery and financial impact is demonstrated by the fact that, although extending shifts might aid in schedule maintenance, this strategy significantly raises labour expenditures for the entire cost of the project. Stricter quality checks are the driving force behind MC3, which exhibits the most significant cost escalation of all the scenarios. The dramatic rise in project expenses, evident early in the schedule and sustained throughout the year, underscores how crucially raw material price swings affect 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. Last, MC4 (Manufacturing Errors), which considers rework caused by manufacturing flaws and unsuccessful quality tests, raises prices above MC1 but 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 significance of managing material pricing volatility, guaranteeing equipment reliability, and putting effective labour and quality management measures into practice.

5.5.2.3 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). The four scenarios modelled were 50% increase in DEL, 50% drop in DEL, 50% increase in RSD, & 50% decrease in RSD. These situations shed light on how differences in designer skill and standard clarity 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 associated costs.

Compared to the baseline scenario, 50% improvement in adherence to standard degree requirements for 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 large rise in design costs when adherence to standards dropped by 50%. Due to a lack of clear criteria, mistakes were made at the first design stage, resulting in expensive redesigns and manufacturing delays.

The simulations highlight how important it is for designers to be proficient and to follow explicit design guidelines to save design expenses and guarantee 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 give professional training and the development of uniform design codes priority.

5.5.2.4 Transportation Cost

The findings show the total transportation costs (TC) under five scenarios that examine how weather and pilot vehicles affect OSC. As the baseline conditions for transportation, the scenarios include "Pilot Zero," in which there are no pilot vehicles, "Pilot 1," with one pilot vehicle, and "Pilot 2," with two pilot vehicles. Two weather-related scenarios also examine 50% increase and 50% decrease 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& 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 need the assistance of a pilot truck to navigate correctly.

The weather-related scenarios demonstrate how weather has a significant influence on transportation expenses. The cost trajectory is steepest when unfavourable weather conditions increase by 50% since they decrease operational efficiency, cause delays, and raise the risk of damage to carried materials. The need for remanufacturing and retransportation further increases costs due to these damages. On the other hand, the scenario highlighting the advantages of nice weather in preserving efficiency and lowering risks shows the lowest costs

among the weather-related scenarios, with 50% reduction in unfavourable weather circumstances. 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), emphasising the necessity of backup plans, constant monitoring, and strong logistics techniques to lessen its effects.

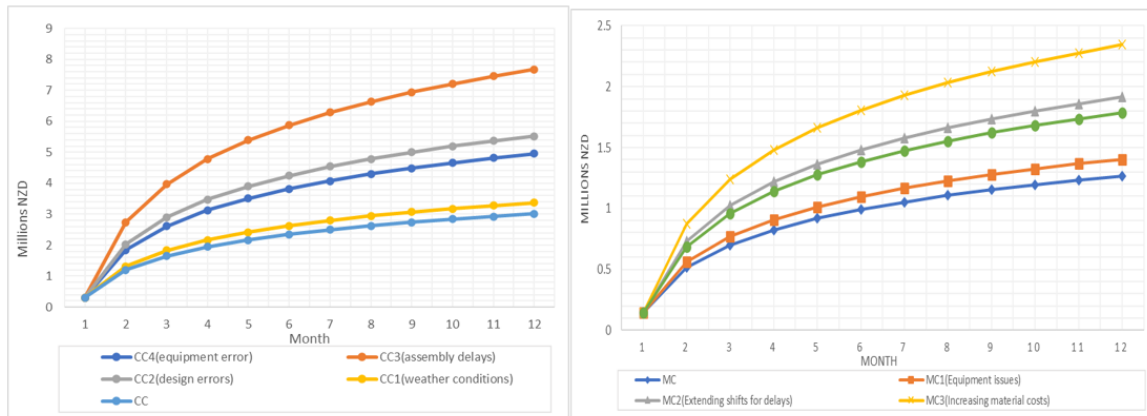
5.5.2.5 Assembly Cost

Four scenarios are examined in the installation costs (IC) analysis: two that deal with assembly delays (with increases of 50% & 25%, respectively) and two that deal with lifter availability and labour-related delays. A 50% increase in delays in the assembly delay scenarios leads to the most significant installation costs, followed by 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.

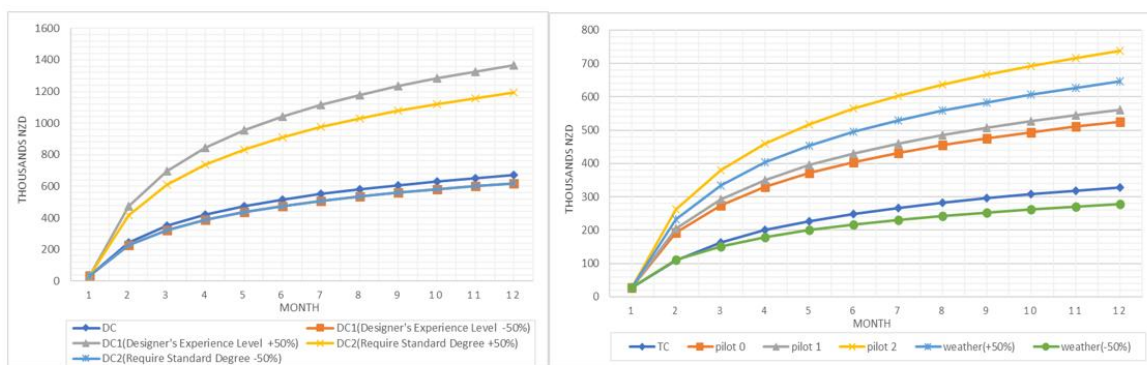
Delays caused by labour shortages have the same effect on installation costs as those caused by other factors, such as bad weather or difficulties at the job site. This result emphasises labour availability is important to preserving project budgets and schedules. To lessen these effects, it also underscores the need for effective staff planning, training, and retention initiatives.

In contrast, lifter availability has a comparatively smaller influence on installation costs 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 concentrate on more urgent problems, such as labour management, and to reduce delays caused by external influences.

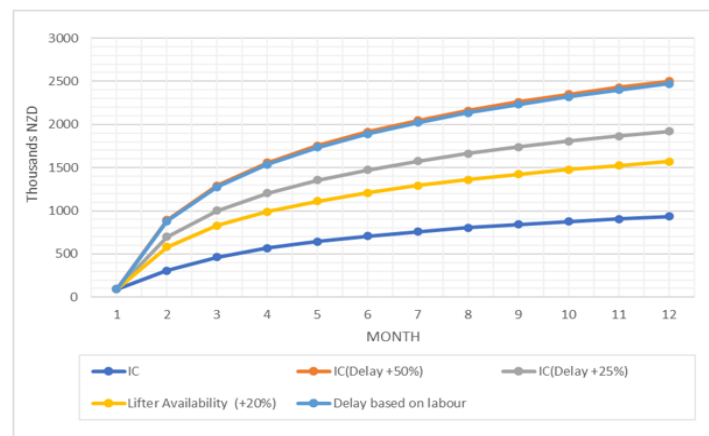
The analysis emphasises that the leading causes of increased installation costs are delays, particularly those due to personnel availability and assembly interruptions. Optimising installation costs and improving overall project performance will require addressing these delays through better scheduling, resource allocation, and labour management techniques. The results imply that to lower cost escalations successfully, the focus should be directed at addressing labour shortages and outside delay factors, even though lifter availability is still stable.



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 5-6: Result of different scenarios

5.6 Management Discussions

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. (2024) and Liu et al. (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, 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 the 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 SDs into SCM for OSC, providing a comprehensive framework to evaluate interdependencies between 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. 2021) by addressing real-world scenarios, such as equipment delays and material waste, offering nuanced insights into cost and time optimisation (Liu & 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 findings from Hussein et al. (2021) on the importance of capacity building and process standardisation in OSC for enhancing project efficiency and profitability (Hussein, Eltoukhy, Karam, et al., 2021a).

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 et al. (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 et al. (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.

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. (Zhang Y., Lei, Z., Han, S., Bouferguene, A., & Al-Hussein, M., 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 further enhance SC and efficiency.

5.7 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 allows stakeholders to model and test the effects of various technical and managerial interventions, enabling the identification of optimal solutions in advance.

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 results identify key cost-influencing barriers, including assembly tower rental expenses, weather and road constraints, and equipment repair delays. Critical scheduling factors include design changes, element failure, and adverse weather conditions. These insights enable stakeholders to prioritise solutions addressing design errors, labour availability, and maintenance planning. Furthermore, the study's cost-time evaluation model, rooted in SD and real-world scenarios, provides a quantitative analysis of panelised cost and delivery performance, enabling stakeholders to anticipate and mitigate challenges effectively.

In conclusion, this study advances theoretical and practical knowledge of SCM in OSC. The novelty lies in integrating SDs with real-world scenarios, enabling a nuanced understanding of cost-time dynamics across SC. To attain next-generation construction performance, the research emphasises the significance of developing human-centric skills, increasing operational capacity, and boosting digital-human collaboration by integrating the model inside the framework of Industry 5.0 transition. The research offers actionable insights for practitioners by providing strategies to address logistics, material sourcing, and regulatory compliance issues, while promoting workforce training, capability development, and stakeholder coordination as catalysts for Industry 5.0 readiness. Future research could extend the model by incorporating additional variables and testing it across diverse practical contexts to further enhance its robustness and applicability. This study lays the foundation for improving the efficiency and effectiveness of OSC-SCs, equipping stakeholders with advanced tools to optimise decision-making in an era of human-technology synergy.

Chapter 6 and 7 Integrated System Dynamics and Optimisation Framework for Time–Cost–Waste Trade-offs in Offsite Construction Supply Chain Management

This chapter is based on a Paper with the title “Unlocking the Full Potentials of Offsite Construction (OSC) by Optimising Its Procurement and Delivery” published In Routledge Handbook of Construction Project Procurement and Delivery (pp. 350-370). Routledge, and “Time–Cost–Waste Trade-offs in Panelised Offsite Construction Supply Chain Management”, which is under review in the Journal of Engineering Buildings and directly tackles Research Objective 5. This objective involves integrating system dynamics modelling with metaheuristic optimisation to assess trade-offs and suggest strategies for minimising project duration, costs, and material waste.

This chapter addresses the enhancement of off-site construction supply chain management (OSC–SCM) with the dual objective of reducing project duration, minimising expenses, and restricting material waste. This chapter utilises two optimisation methods: the Genetic Algorithm (GA) and the Grey Wolf Optimiser (GWO). GA, which was first applied in a precast OSC case study, acted as a benchmark method to show the feasibility of optimisation in assessing procurement and delivery trade-offs. Though GA proved effective for two-objective problems (time and cost), its limitations became apparent when dealing with higher complexity and the need for diverse Pareto-optimal solutions.

The study proposes a Multi-Objective Grey Wolf Optimiser (MOGWO) that incorporates system dynamics modelling and Monte Carlo simulation to overcome these limitations. This framework broadens optimisation to encompass three objectives, time, cost, and waste, while accounting for the probabilistic challenges associated with OSC projects. The comparative analysis of GA and GWO demonstrates that while the former establishes a robust baseline, the latter enhances convergence, exploration, and solution diversity. This chapter shows a methodological evolution from precedent to innovation by integrating these two approaches, establishing the foundation for empirical validation in Chapter 10.

6 Unlocking the Full Potentials of Offsite Construction (OSC) by Optimising Its Procurement and Delivery

The current chapter is based on the following article:

Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Unlocking the full potential of offsite construction by optimising its procurement and delivery. In *Routledge Handbook of Construction Project Procurement and Delivery* (pp. 350-370). Routledge.

ABSTRACT

The decision on procurement route to be taken by a construction project in the early stage of its lifecycle has been considered one of the most important decisions influencing the success of the project. Different procurement routes have been featured and researched, particularly over the last two decades ranging from the traditional to partnering styles, including various new and innovative ways of procuring construction projects. Different procurement routes maybe better suited or in some cases even specifically designed for different types of construction project. In parallel to the rise of these innovative procurements, the delivery methods of construction projects also experienced advancement, including adaptation of philosophies and techniques from other industries such as manufacturing. One of these advancements in delivery is the offsite construction (OSC) methods that aim to shift a significant proportion of the site activities to a controlled environment to reduce risks, reduce waste, increase productivity and achieve many other advantages while also addressing post-COVID needs to reduce on-site work. Previous research reported various special issues, and specific challenges facing the procurement and delivery of offsite construction projects with increased proportions of work carried out in factories like; fragmented supply chain, lack of skills and education, and compliance framework suited to conventional practices. Higher production costs, early design freeze, and standardised designs sometimes disadvantage the clients. Optimising the procurement and delivery challenges of OSC is critical to utilise the full potential of this novel and less conventional construction technique.

This book chapter describes the development of a framework to optimise procurement and delivery of OSC projects. The initial development of the framework is based on a thorough literature review followed by a case study based in New Zealand to finalise the framework. The findings reported here are expected to guide industry practitioners in procuring and delivering OSC in their own projects in a more optimised manner as well as contributing to the further development of the overall body of knowledge in OSC in particular and in construction management in general, particularly given that the trends towards more offsite construction are expected to accelerate.

6.1 Introduction

An entire structure can be broken down into several prefabricated components using the innovative construction technique known as offsite construction (OSC). These components are then transported to the construction site and installed directly (Jin, 2018). These building components can be full-volumetric modules, panelised elements, or prefabricated components, such as beams, columns, slabs, staircases, and so on (Innella, 2019). They can be manufactured from various materials, including concrete, steel, wood, and composites, for construction and infrastructure projects. Compared to the conventional construction process, OSC has some potential benefits. These include less dependency towards particular construction skills/trades, better construction safety, higher quality end product, reduced construction waste, faster construction, and so on (Darlow et al., 2021; Nesarnobari S. et al., 2022c; Sooriyamudalige et al., 2019). Offsite construction sometimes referred to as offsite manufacturing (OSM), can be a creative way to boost output and satisfy rising housing demand in many countries, including New Zealand. It holds the potential to increase the productivity of the building sector even further (Nesarnobari S. et al., 2022a). Also, it is a cutting-edge building technique whose percentage contribution to the completion of construction projects is rising quickly, including in New Zealand (JC Burgess, 2013). The shortage of affordable housing in New Zealand, for example, and the rising demand for new homes necessitated the use of more innovative and efficient project delivery methods rather than relying on conventional construction approaches. OSC has been identified as a potential leverage point to overcome the shortcomings of traditional construction methods. However, this particular technique of the construction encounters various challenges mainly stemming from a lack of implementation and coordination (Bakhtiarizadeh E et al., 2021; Zhai, 2016). The execution of OSC has been considered a complex procedure that demands rigorous planning and structure of the process from the beginning to the end of the project, mainly to synchronise the manufacturing,

construction, and assembly processes (Sutrisna et al., 2018). It also requires timely delivery as delay in the delivery of components typically increases the project's delivery time and costs (JC Burgess, 2013).

As it is evident, productivity, innovation, and the likelihood of conflict and disputes have all been connected to procurement strategy efficacy (Jelodar et al., 2016, BRANZ, 2013, Mosey, 2011, Wilkinson and Scofield, 2010). Due to this, OSC has been gaining momentum and is increasingly being used to address many of the problems related to construction around the world. Construction is a significant sector in many economies including in New Zealand, involving a large number of stakeholders (PrefabNZ., 2015). A framework for integrating project teams is defined in the construction procurement systems (CPSs), which are based on both formal contractual connections and informal communication channels in the project's procurement networks (Lopez R. et al., 2017). Diverse levels of team integration are experienced in practice due to the different authorities and responsibilities assigned to project participants in CPSs (Love PED et al., 1998). For instance, when the designing and building phases are overlapped in a Design-Build (DB) procurement system, thus it is expected to bring a higher level of integration (Cheng MY, 2008). Evidence suggests that certain CPSs used in the delivery of traditional in-situ construction projects, such as Design-Bid-Build (DBB), Design-Build (DB), and management-oriented approaches, predominate in the development of OSC projects (Pan W. et al., 2008). Given the amplified significance of team integration in OSC projects involving stakeholders from construction and manufacturing sectors, it is essential to understand the use of these CPSs in OSC projects. Therefore, this chapter aims to (a) examine the procurement and delivery of offsite projects in the New Zealand context and (b) develop a framework to optimise the procurement and delivery of offsite construction projects.

The structure of the subsequent part of this chapter is organised to provide the research background on OSC procurement and delivery, followed by identifying factors contributing to their optimisation from the literature. An optimisation tool known as the Genetic Algorithm (GA) is proposed and explained in the research method section. Then, the data analysis and results section provide the foundation for discussing how to optimise OSC projects in the discussion and implication section. This is followed by the development of optimising framework for OSC projects. In the end, conclusions are drawn, considering the research contributions and limitations.

6.2 Literature Review

6.2.1 Procuring Offsite Construction Projects

Creation and realisation of construction projects take place through an integrated development process involving methodology, technology, and procurement procedures (Crosthwaite, 2000; Flanagan, 1994; Nesarnobari S. et al., 2022a, 2022c; Ofori, 2003). Although using the correct methodology and technology is important for project execution, the process of securing and procuring the project is very critical (Dada, 2004). The procurement process determines the structure of stakeholder duties, risks, and authority, which is essential for ensuring the seamless delivery of projects.

By nature, offsite construction is a complex process; hence the efficiency of the procurement process becomes more critical in offsite construction. The complexity involved in offsite construction is due to supply-related aspects like the reliability of suppliers (M. Arashpour, 2016) and the inclination to exclude or include a specific supplier (C. Chandra, 2007). Unreliability in supply can lead to a production delay, poorer service standards, and cost escalations (K.S. Lm, 2009).

While the benefits of offsite construction approach are becoming more widely recognised (Hussein, Abdelrahman E. E. Eltouky., et al., 2021), they are currently coupled with significant difficulties, particularly in material acquisition (Hussein, Eltouky, Karam, et al., 2021b). In offsite construction projects, each component has a specific purpose (Salari et al., 2022). All project components must be available when needed in order for the project to be successful (Yazdani et al., 2021). As a result, supply chain techniques should be implemented and investigated in this construction system to limit the risks associated with the timely procurement of construction components (Hussein, Eltouky, Karam, et al., 2021b).

The existing body of knowledge demonstrates that traditional purchasing techniques are used to get overseas imports required for applications in offsite construction (Hussein, Abdelrahman E. E. Eltouky., et al., 2021). As a result, the way of working in existing procurement methods makes it difficult for contractors to include offsite construction in their projects (Chen & Samarasinghe, 2020). Fabricating and procuring prefabricated/manufactured building components is typically time-consuming (Goodier & Gibb, 2007). Also, manufacturers offer limited alternative offsite construction components (Arif, 2010). These issues have led to the delayed growth of offsite housing in New Zealand; for example, Shahzad (2011) noted that

factors related to supply chain and procurement are significantly limiting the uptake of OSC in New Zealand.

In the OSC approach, material procurement is a multi-tiered supply chain that begins with preparing comprehensive design and shop drawings for structural components made in a factory or workshop (Hussein, Eltoukhy, Karam, et al., 2021b). These components are then warehoused and sent to construction sites where they are to be installed. These components are customised to the needs of each project. As a result, offsite manufacturers cannot produce these components before receiving orders (Hussein, Eltoukhy, Karam, et al., 2021b). Furthermore, the weight and volume of these components mean that contractors are typically unable to keep considerable buffer stockpiles to mitigate supply delays (Hsu et al., 2018b; Hussein, Eltoukhy, Darko, & Eltawil, 2021). Any unforeseen action in the component supply chain at the procurement strategies has a knock-on effect on the future stages, leading to inefficient off-site construction. Therefore, new modelling techniques are necessary to apply supply chain models to off-site construction techniques.

Some potential benefits of OSC include bulk procurement, increased time efficiency, and lower material and labour costs. The capacity to reallocate waste streams potentially saves project expenses for both the client and the contractor. Furthermore, the certainty of pre-set costs and timetables allows both clients and labourers to plan their capital expenditure (Burgess. et al., 2013).

The Resource-Based View (RBV) is a series of theories that contends businesses can create a competitive advantage by utilising internal resources that are valuable, rare, not imitable, and organised for value capture. According to the RBV, procurement can provide a competitive advantage when obtaining resources that add value, are scarce, expensive to copy, or have no replacements (Barney, 2012). Identification and management of value-added creative suppliers can enhance procurement efficiencies. However, there is no single ideal procurement plan that can fully optimise the capabilities of offsite construction. Thus, a strategy should be developed based on rational policy and in line with the client's objectives and the nature of their project. Finnie (2017) outlined the decision-making criteria for such a strategy as under:

- Involvement of the client in the construction process
- Separation of design from management
- Reserving the client's right to alter the specification
- Clarity of client's contractual remedies

- Complexity of the project
- Speed from inception to completion
- Certainty of price

6.2.1.1 Classification of Procurement

For any building project, a variety of procurement options are typically available. Rowlinson and McDermott (1999) explain the argument over whether to use the terms "system" or "model" to describe the alternatives due to the lack of precise definitions. However, the following procurement models are universally acknowledged now. These usual procurement models are DBB (Design-Bid-Build), Regular Contract, and DB (Design and Build), where the contractor is responsible for both design and construction. In CM (Construction Management) model, the head contractor subcontracts all trade packages. In MC (Management Contracting), the client hires all trade contractors directly and a consultant to manage them (Finnie et al., 2018).

According to El Asmar et al. (2013), a project delivery system determines the link between the various project stakeholders and their time of participation in building a facility. This delivery system, based on Mesa et al. (2016) has three types: design-bid-build (DBB), construction management at risk (CMR), and design-build (DB). In DB, the contractor is responsible for both design and construction; in traditional contracting, the client hires a design team to create the design, which is then tendered to builders; in MC, the head contractor subcontracts all trade packages, permitting them to have participated during the design stage more like a consultant; and in CM, the client hires all trade contractors directly and a consultant to manage them.

6.2.1.2 Suitability of Procurement models for OSC

Elnaas et al. (2009) advise that procurement methods should encourage the sharing of cost and buildability knowledge among manufacturers, constructors, and designers for clients and consultants to make knowledgeable design decisions on projects utilising OSC (Elnaas H. et al., 2009). The buildability restrictions of OSC constrained OSC to be handled by single-stage procurement; for example, the contractor may not see the design until it is fully completed. Kirkham (2007) makes a convincing case for how, as a design is established, the opportunity for new value decreases, and the cost of change rises. Traditional lump sum contracts have a significant advantage in that the procedures are well understood, and standard forms of construction contracts provide familiarity and reliability due to being well tried in law cases

(Kirkham R., 2007). Traditional lump-sum contracts remain the dominant contract form. However, OSC contracts are typically specific to a project. Thus, the primary barrier to the uptake of OSC is the reluctance to adopt unknown processes. Two significant obstacles to innovation have been identified as owners' risk aversion and ignorance of contemporary construction techniques (Jergeas & Put, 2001). Thus, an appropriate procurement plan for improving OSC should allow contractors' input into the design, allocate design and buildability risks properly, allow for competitive lump sum pricing, and use a standard model that can be used repeatedly (Finnie et al., 2018).

The DB procurement would be more suitable for OSC projects with a simple design and without change during construction. The client retains control of the design in CM and MC, but the consultant or head contractor may suggest planning and buildability. By combining design and construction, the project may move along more quickly, and OSC components can be bought in advance to prevent delays. If prices are comparable, MC may be preferable to CM for inexperienced clients due to its lower risk exposure. Under CM, the client hires the specialised contractors directly and assigns a consultant to supervise them, assuming more risk than the head contractor's single point of responsibility.

6.2.2 Delivering Offsite Construction Projects

Policymakers and the construction industry are continuously seeking innovation to enable better delivery of construction projects. OSC projects are one way to construct quicker and easier with many other advantages (Bakhtiarizadeh et al., 2019). OSC has multiple potential benefits, for example, reductions in greenhouse gas (GHG) emissions, a reduction in the duration of construction time, a reduction in defects, and a decrease in delays due to bad weather conditions (Burgess et al., 2013). Exposed sites with adverse weather conditions can negatively impact onsite construction, which may raise the delivery cost. Due to the fact that many projects are being completed concurrently, offsite construction frequently requires a larger volume of deliveries to the facility on fewer trucks. With a well-organised just-in-time (JIT) ordering system and sufficient hardware supplies on site to keep the work flowing, trips to fetch different products can be reduced. Reduced transportation has positive effects on the economy and environment. However, the JIT strategy might result in more shipments delivered than would have otherwise been in a bulk load (Voordijk, 1999). Increased emissions per load and higher transportation costs incorporated into the materials due to longer operator shifts are two possible adverse environmental effects of this way of delivery (Burgess. et al., 2013). The benefits of bulk purchase, superior economics in loading delivery vehicles, and the possibility

to store items for future projects are the key reasons for reducing GHG emissions from transportation with offsite production solutions. One of the most important stages in the construction of the offsite project is the delivery of manufactured pieces. Because the majority of the components are created in a factory, the transportation of these components to the site should be given special care. The topography of the locations may result in more complex transportation with additional costs involved. Therefore, this part of the study aims to determine hindering factors in the choice of this method. The study's outcome will indicate advantages and disadvantages existing in delivery methods and processes in the offsite and traditional approaches.

Transportation constraints include flaws and design considerations for manufactured components' weight and size (Moradibistouni et al., 2018). Cranes are used to lift these components, and this process poses considerable safety risks for the onsite workers. Unsuitable or inadequate lifting equipment can also cause health and safety problems. Furthermore, there is an absence of bespoke procurement process, as OSC products are typically sold on credit, heightening the danger of late or non-payments. There is a need for supply chain and procurement innovation to assist offsite construction projects enterprises in connecting more closely with customers in equal contractual commitments (Chen & Samarasinghe, 2020).

Transportation is one of the most significant aspects affecting uptake of offsite construction, as transporting large manufactured components necessitate legal considerations and logistical constraints (Moradibistouni & Gjerde, 2017). An initial stage in developing the design of OSC components should be to investigate the maximum amount of load that can be delivered without requiring oversized load permission, that ends up increasing the delivery time and cost. In New Zealand for example, based on the investigation and assuming a trailer height of 1.5m, the maximum permissible length, width, and height of a cargo, what can be transported on New Zealand's highways without requiring further permission is 20m x 2.55m x 2.8m (Moradibistouni et al., 2017). Other concerns, such as craning constraints for a modular (volumetric unit) or factory completed structure, could compress these limits even further (Moradibistouni et al., 2017). Also, the New Zealand economy is relatively small, labour and machinery expenses are relatively high, and substantial transport equipment must be used from production to delivery to the site, increasing freight prices. Prefabricated houses building enterprises must invest significantly in improving their logistic abilities and skills, particularly for two-dimensional (2D) (panelised) and three-dimensional (3D) items. Durability and quality are essential factors in the shipping of offsite construction items. Furthermore, there is the risk

of obtaining expensive transportation services, while the lack of onsite storage typically impedes using just-in-time (JIT) techniques (Masood R. et al., 2021).

Risks have traditionally been viewed as integral to project delivery and as such, must be managed. Typically, project risk management "includes the activities related with recognising, analysing, and responding to project risks, including maximising the results of favourable events and reducing the repercussions of unfavourable ones" (PMI, 2013). The design phase has been regarded an important activity in the design of an offsite construction project but also carries particular risks that can affect whole projects (Sutrisna & Goulding, 2019).

Coordination and communication must be effective and efficient throughout the whole process of delivering an offsite construction project, including project planning, procurement, supply chain scheduling, assembly and construction, and delivery (Kamali & Hewage, 2016). To complete the project on time, the communication between the process players must be harmonised (Stroebele & Kiessling, 2017). Industrial firms do not typically use any standardised information-sharing methods to communicate information openly. To communicate and share information, e-mails, phone calls, face-to-face conversations, and meetings are employed. However, transparent and trustworthy information sharing between these players may be lacking (Sooriyamudalige et al., 2020).

Conventional construction methods usually suffer from different issues: air pollution, delay in delivery, contamination of the environment, and cost escalation. OSC approach has been recognised as an effective solution to these problems by reducing defects, lowering lifecycle time and costs, improving the quality of final deliverables, and growing sustainability (Darlow et al., 2021; Luo & Shahzad, 2020; Shahzad, 2011).

In countries like New Zealand, it is necessary to increase the automation of its production facilities through OSC to meet high housing demands. For example, the country is now dealing with a shortage of approximately 130,000 houses, existing leaky housing stock, and a skills gap in the building industry (MBIE, 2019). To get more benefits from OSC, the factories, for example, should ideally be located close to the suppliers to minimise the distances needed for material transportation. In addition, offsite home should also require fewer vehicles on the road. For example, as deliveries become more regular, the trucking company dispatcher can schedule return loads so the trucks do not come back empty (Buckett et al., 2014). On the other hand, the supply is typically more erratic with a stick-built or traditional construction job site. Hence

it would be challenging to achieve this high degree of coordination and fuel savings (Kaufmann & Remick, 2009).

6.3 Proposed Optimisation Framework

Different offsite components delivered by various suppliers may come from different regions for construction projects in large areas. The schedules of transportation of offsite components to the job site are developed based on the assembly schedule. As previously discussed, the contract for each OSC project is specific, which bears risks to the projects. Thus, the procurement level may face many obstacles and risks, leading to a decreased uptake of offsite construction. To study such a complex problem, first, the effective factors for the delivery of OSC projects are identified. Figure 6-1 summarises the factors affecting OSC delivery at different stages based on literature review conducted in this study.

Delivery of OSC								
		Design	Manufacturing	Transportation	Site Assembly	Finalisation and completion		
INTERNAL	CLIENT REQUIREMENTS		Material Types					
			Material Related Conditions					
	PROJECT REQUIREMENTS	Construction Types	Setup Times	Traffic Conditions	Inaccurate Interface			
		Construction Features	Material Types	Pilot Vehicle	Safety concerns (on-site workers)			
			Material Related Conditions	Road Restrictions on the route				
			Number of Products	Weather Conditions				
			Loss of Productivity	Size of Products				
			Degree of Standardisation	Crane Numbers				
				Potential Damages During Transportation				
				Labour Shortage				
				Cost of Labour				
				Defects				
				Equipment Failure				
					Floor Area			
				Product's Width				
				Changes in On-site Requirements				
				Procurement and Delivery Strategies				
EXTERNAL	REGULATIONS	Project Location		Location				
		Planning Regulations		Highway Agency Requirements		Certificate of Construction Completion		
		Construction Consent						
			Quality Control					
		Health and Safety						

Figure 6-1: Factors affecting OSC delivery

Delivery of offsite construction can be separated into preparation delivery and after manufacturing delivery of the product to the site. Purchasing raw materials, acquiring materials, and making modular products all fall within the preparation phase, as shown in Figure 6.1. The construction company prefers to buy lower-priced materials from nearby supplier locations to save on shipping expenses and ensure there are no product shortages or delays due to market fluctuations and various material pricing. The ultimate supplier choice and quantity order decisions may be influenced by the cost of materials and transportation delays. Accordingly, a low-cost raw materials supplier may be located relatively far from the

manufacturing site and carry goods with substantially higher transportation expenses, as shown in Figure 6.1. These phases are divided into internal and external factors. For example, from manufacturing to assembly, the product's width, labour shortage, unexpected work, defects, and equipment failure, affect the delivery. Onsite requirements, and procurement methods, affect the whole phase. Transportation is affected by traffic and restricted movement. Also, the Assembly and Transportation are affected by the weather, size of the products, number of cranes, and damage.

Off-site work begins as soon as the raw materials are delivered to the prefabrication factory. The offsite manufacturing costs are made up of the labour and equipment costs from the power needs and air conditioning/ventilation, standardization, quality control, and procurement method (Zhu et al., 2021). Additionally, all completed components are transiently stored in a manufacturing warehouse before the assembly phase, incurring expenditures for inventory management. In order to account for its maximum factory production rate and storage capacity, the prefabrication factory must create an effective output plan. The on-site construction scheduling for the assembly phase typically starts when the factory inventory capacity is almost at capacity. The preparation process, supply activities, product delivery, and on-site assembly are part of the offsite construction phase (Nesarnobari S. et al., 2022a). The inventory state needs to be dynamically balanced between the manufacturing amount (the products to be stored) and the products to be carried to the project locations as the offsite products start to be delivered to the building site (Zhu et al., 2021). As a result, the factory continuously modifies its prior output scheme, and the first-period raw material acquisition and transportation are adjusted in accordance with the inventory constraints and stored offsite goods (Arashpour, 2017). Additionally, the project location is crucial for striking a balance between prices and timeliness (Roos, 2021; Wang, Hu, H., et al., 2019). The distance between the factory and the construction site, which affects transportation costs as well as fixed investment costs for foundation preparation and temporary facilities at various sites, should be considered by the construction enterprise when evaluating potential site conditions (Mostafa, 2018) The usual goals of the construction industry are to reduce overall costs and delays through decision on site selection, product manufacturing and storage, material procurement and delivery, and construction scheduling within the constraints of operating capacity, inventory balance, and product demand (Salari et al., 2022).

6.4 Research Method

Several factors contributed to the complexity of the OSC delivery. Multi-objective methods are highly robust in solving the trade-offs between different objectives. Since the proposed method of optimising the delivery and procurement of OSM relies on multiple criteria, a multi-objective solution must be deployed to solve the problem. In the face of the delivery cost optimisation problem of offsite construction with a wide range of specifications, a genetic algorithm can better and quickly search for the optimal solution with minimum time. The approach adopted in this study is Genetic Algorithm (GA) optimisation, which has been implemented in various multi-objective applications. The genetic algorithm solves problems that are not well suited for standard optimisation algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear (Matlab, 2022). Since the delivery of OSC is a kind of objective function that is nondifferentiable and stochastic from affective factors. Hence, it is fitted for optimising the delivery process. This research examines the optimal delivery planning of offsite construction with the multi-objective of minimising the total cost and time in MATLAB software.

Over time, GA imitates the natural process of evolution. It employs variable string coding (chromosome encoding), randomly generates a set of potential solutions (the initial population), ranks those solutions after determining their fitness (chromosome evaluation), preserves the best ones, and then uses them to create new potential solutions (genetic operators). A GA transforms the present population into a new one by repeatedly applying genetic operators (such as crossovers and mutations). A workable solution will be discovered by repeating chromosome evaluation and using genetic operators, or the GA will iterate a predetermined number of cycles (Anvari et al., 2016).

The definition of chromosomes, the creation of genetic operators, and the mechanism for population management that selects which chromosomes in each population to use the genetic operators on are the essential components of GAs. In GAs, a fitness function is also defined to assess each chromosome's quality. A crossover operator (or marriage) mixes the genes of the parent set after randomly selecting two chromosomes (parent set) to produce offspring. The offspring produced by the crossover of more fit chromosomes replace the chromosomes with lower fitness values. A mutation operator modifies offspring DNA to avoid local optima during the search process. The mutation is a genetic operator used to maintain genetic diversity from

one generation of a population of genetic algorithm chromosomes to the next. It is analogous to biological mutation (Anvari et al., 2016).

6.4.1 Mathematical Modelling

This section provides the state transition equation, initial conditions, constraint conditions, and fitness functions to model the cost and delay reduction based on the genetic algorithm in this chapter.

Index

The relevant parameters are introduced in the following to help with the problem description.

Indices

- r : Set of raw material suppliers, $R = \{1, 2, \dots, R\}$
- s : Set of construction sites, $S = \{1, 2, \dots, S\}$
- k : Set of modular product types, $K = \{1, 2, \dots, K\}$
- m : Set of transportation mode $M = \{1, 2, \dots, M\}$
- w : Set of weeks during the preparation period, $W = \{1, 2, \dots, W\}$
- t : Set of weeks during the construction period, $T = \{1, 2, \dots, T\}$

Decision Variables

- τ_k^m : Binary variable which equals 1 if transport mode m is chosen to transport building element k
- N_{rkw} : Raw materials quantity for product k procured from supplier r in period w
- N_{rkt} : Raw materials quantity for product k procured from supplier r in period t
- N_{kw} : Production quantity of product k in the factory in period w
- N_{kt} : Production quantity of product k in the factory in period t
- N_{skt} : Quantity of product k transported and assembled at site s in period t

Parameters

- $\tilde{P}_{rk}$: Unit procurement raw materials cost from supplier r for offsite product k
- VO_k : Unit volume production for product k in the factory
- VR_k : The volume of raw materials required for unit modular product k
- D_k : Demand for product k at project site over the whole project
- $PC_{\max k}$: Maximum production capacity for product k in the factory
- $AC_{\max sk}$: Maximum assembly capacity for product k at site s
- AU_k : Unit assembly and construction cost for product k at site s over whole construction
- LC_{kw} : Unit procurement labour cost for offsite product k during period w
- LS_{kw} : Unit procurement labour shortage cost for offsite product k during period w
- F_{kt} : Unit procurement inaccurate interfaces cost for offsite product k during period t
- C_{in} : Unit inventory cost for product k in the factory
- d_r : Distance from supplier r to the factory
- d_s : Distance from the factory to construction site s
- L_r : Quantity of raw material r that can be loaded on the truck
- L_k : Quantity of modular product k that can be loaded on the truck

$\overline{TR}$: Unit cost of the truck transportation by unit distance
 C_z : The cost of transportation mode z
 h_m : The height restriction on transport mode M
 h_k : The height of the building element
 w_m : The width restriction on transport mode M
 w_k : The width the building element
 C_{kt} : The cost of k product during the t period
 T_{da} : Delay of transportation if damage occurs
 T_{md} : Delay of material delay if it occurs through transportation
 T_{cn} : Delay if crane number is not enough through transportation
 T_{ef} : Delay if equipment failed through transportation
 T_{ls} : Delay if there are labour shortage during transportation
 T_{sr} : Delay if there are requirements form site
 T_c : Time of delay because of transportation limited
 IC_{max} : Maximum inventory capacity in factory
 U_k : Unit production cost for product k
 I_{kw} : Production inventory for product k during preparation

Restrictions

All production process have their restriction; the following is a list of restrictions in its mathematical form for OSC production and delivery. These restrictions set the boundary conditions for the mathematical model.

$0 \leq N_{kw} \leq PC_{maxk} ; \forall k \in K; \forall w \in W$ $0 \leq N_{kt} \leq PC_{maxk}; \forall k \in K; \forall t \in T$	The manufacturing rate of various product types produced in the factory is in a pre-defined range with minimal manufacturing assumed to be none and the maximum being the preparation and construction periods capacity limits.
$0 \leq N_{skt} \leq AC_{maxsk} ; \forall k \in K; \forall s \in S; \forall t \in T$ $if\ s = 0\ N_{skt} = 0$	The assembly rate for modular product k at construction s is less than the maximum limit.
$I_{k,w-1} + N_{kt} = I_{kw}; \forall k \in K; \forall w \in W$	Describe the constraint relationship between the state variable I_{kw} and the decision variable N_{kt} in the factory during the preparation period.
$0 \leq \sum_{k=1}^K VO_k C_{in} \leq IC_{max}, \forall k \in K; \forall w \in W$	Ensures that the quantities of the stored product during the preparation period are always less than the factory's inventory capacity.
$\sum_{r=1}^R \sum_{k=1}^K (\sum_{w=1}^W N_{rkw} + \sum_{t=1}^T N_{rkt}) \geq \sum_{k=1}^K VR_k D_k, \forall r \in R; \forall k \in K; \forall w \in W; \forall t \in T$	Constraint is given to ensure that the raw material demand for all product k can be satisfied by the sum of the number procured during preparation (N_{rkw}) and construction periods (N_{rkt}).
$\sum_{k=1}^K \sum_{t=1}^T N_{rkw} \geq \sum_{k=1}^K D_k, \forall s \in S; \forall k \in K; \forall t \in T$	Constraint is given to ensure that the sum of the manufactured products transported to the construction site meets the project demand (Geraci 1982).
$N_{rkw}; N_{rkt} \geq 0; \forall k \in K; \forall w \in W; \forall t \in T$	Raw materials quantities delivered are not negative.
$I_{kw} = 0, \forall k \in K$	Available modular product quantity at the factory at the beginning of the construction period is zero.

6.4.1.1 Manufacturing Cost

In the offsite construction, first, the factory procures the raw materials from multiple suppliers. The price of the raw materials set $\tilde{P}_{rk}$, with the whole procurement cost being:

$$\sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W \tilde{P}_{rk} N_{rkW}$$

Raw materials price is considered a triangular fuzzy number to account for price fluctuation (Lam et al., 2010). The expected value for the raw materials price can be written as follows:

$$\tilde{P}_{rk} \rightarrow E[\tilde{P}_{rk}] = 1/2[(1 - \pi)r_1 + r_2 + \pi r_3]$$

After collecting raw materials, the factory starts to produce offsite component, the U_k is unit production cost so the cost of manufacturing is $\sum_{k=1}^K \sum_{w=1}^W U_k N_{kW}$

Therefore, based on the Zhu et al. (2021) and Jablles (2019), the sum of the procurement and manufacturing, and labour costs are inventory cost in factory for the period w:

$$\begin{aligned} \text{PMC} = & \sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W (E(\tilde{P}_{rk})N_{rkW} + U_k N_{kW} + LC_{kW}N_{kW} + F_k N_{kW} + 1/ \\ & 2(I_{k,w-1} + I_{kW})VO_k C_{in}) \end{aligned} \quad (6.1)$$

6.4.1.2 Assembly Cost

After the foundation preparation, the prepared products transfer to the site and are assembled. The assembly cost includes the cost of unit assembly multiplied by the number of products needed during the period:

$$\text{APC} = \sum_{k=1}^K \sum_{t=1}^T E(\tilde{T}\tilde{R})C_{kt} + (AU_k + LC_{kt} + LS_{kt} + F_k) N_{skt} \quad (6.2)$$

6.4.1.3 Transportation Cost

The transportation cost includes transferring raw materials and products from the factory to the site. This cost is determined based on the number of raw materials and construction products, and the critical element is the distance of the factory from the site. Due to the weather, traffic, and the location's topography, transportation may have some delays. Thus, the uncertain parameter $\tilde{T}\tilde{R}$ based on (Xu, 2013) multiplied the cost to sum up the related delays. The transfer cost of raw material during period t, is: $N_{rkt}/L_r E(\tilde{T}\tilde{R})d_r$. Where L_r and L_k are the load

capacity per truck when delivering raw materials and products and d_r and d_s are the transportation distances for the trucks travelling from suppliers and the factory. The transfer cost of product to the site also equal to $N_{skt}/L_k E(\widetilde{TR})d_s$. Based on the capacity of the transportation mode, $h_k w_k$ the total area of components constructed using OSC, $h_m w_m$. This is then rounded up as demonstrated by the ceiling in and is multiplied by the cost and the variable, τ_{kt} that determines the model of transportation adopted: $\tau_{kt} C_z(\frac{h_k w_k}{h_m w_m})$ (Hammad et al., 2019).

Therefore, the total cost is:

$$TRC = \sum_{s=1}^S \sum_{k=1}^K \sum_{w=1}^W \sum_{t=1}^T (N_{rkt}/L_r E(\widetilde{TR})d_r + N_{skt}/L_k E(\widetilde{TR})d_k + LC_{kwt}d_r N_{skt} + LS_{kwt}d_r N_{skt} + \tau_{kt} C_z(\frac{h_k w_k}{h_m w_m})N_{skt}) \quad (6.3)$$

6.4.1.4 Objective 1: Minimising Total Cost

To optimise the delivery cost, the first model objective is to minimize the total cost (TC) in delivery period. TC, as defined in Eq. (8.4), is the sum of the cost terms (Eqs. (6.1)e(6.3)) previously discussed, which includes the raw material delivery, manufacturing costs (PMC and TPC), assembly costs in construction period (APC), and transportation costs from the raw materials suppliers to the factory and from the factory to the project sites (TRC).

$$Min TC = PMC + APC + TRC \quad (6.4)$$

6.4.1.5 Manufacturing Delay

The factors related to the time that may cause delay during the manufacturing multiplied by the number of products show the manufacturing delay.

$$PD = \sum_{k=1}^K \sum_{t=1}^T (E(\widetilde{TR}) + T_c + T_{ls} + T_{da} + T_{cn} + T_{md} + T_{ef}) N_{kw} \quad (6.5)$$

6.4.1.6 Transportation Delay

Some factors like equipment failure, weather, traffic or restricted travel time, and shortage of labour causes transportation delay. Therefore, for considering these factors, the following equation was used:

$$TD = \sum_{k=1}^K \sum_{t=1}^T (E(\widetilde{TR}) + T_c + T_{ls} + T_{da} + T_{cn} + T_{md} + T_{ef}) N_{kt} \quad (6.6)$$

6.4.1.7 Assembly Delay

After manufacturing and transportation, the environmental factors that affect the assembly time is calculated as below:

$$AD = \sum_{k=1}^K \sum_{t=1}^T (E(\widetilde{TR}) + T_c + T_{ls} + T_{da} + T_{cn} + T_{md} + T_{ef} + T_{sr}) N_{kt} \quad (6.7)$$

6.4.1.8 Objective 2: Minimising Delay

The second model objective entails minimising delivery delay. By combining the production, transportation, and construction delay (Eqs. (6.5)e(6.7)), the total delay caused during the offsite construction and transportation and assembly process can be calculated and optimised, as shown in Eq. (8).

$$\text{Min } T = PD + TD + AD \quad (6.8)$$

6.4.2 Implementing the Framework: A Case Study Project

A case study design was chosen to investigate the optimisation process through minimising cost along with the time of the project. In this context, a collaboration-based questionnaire is needed. The main environmental factors that impact the delivery and procurement of the project are adopted to assess the potential of the offsite construction project. The study is focused on a manufactured precast components in an Auckland manufacturing unit. The purpose of using a case study is to demonstrate the implementation of the proposed method in a real OSC project. Interviews were conducted with precast concrete suppliers involved in manufacturing and assembly of components. Although the case study is conducted within a specific organisation,

the analysis is undertaken from a holistic supply chain perspective, capturing interactions across multiple stages and stakeholders.

The host organisation is involved in manufacturing and transportation of components, not design nor the assembly. As the purpose of the case study is to simply demonstrate a proof of concept on how the proposed optimisation can be implemented, the data collection only collected datasets during manufacturing and transportation. Hence the optimisation calculation excluded the assembly to simplify. Because of their widespread use in the market and the size of the element for transport implications, precast components were chosen in this instance for offsite manufacturing. Offsite building activities are more effective and produce a lot less waste, but the manufacturing and shipping costs still need to be taken into consideration. As a result, by balancing the demands for profitability and time reduction, optimisation tends to regulate these devaluations within an acceptable range rather than lowering the cost.

The multi-objective optimisation framework aims to obtain a set of trade-off solutions between contradictory objectives (time and cost), where each objective function needs the transformation solution under a certain transformation time. Accordingly, the computation time required to find the balance for the contradictory objectives can be quite lengthy. For instance, dynamic programming based on state and transition equation could take substantial time to calculate. However, the conversion of model (9) into its equivalent single-objective model after the insertion of the attitude T (maximum time that project must end) has simplified the optimisation with only integer variables and piecewise functions. The model is then implemented and solved using MATLAB 2019a, which has been widely adopted for optimisation problems. The equation number 9 is used as fitness function for the GA optimisation performed in this study. The apparent contradiction between time and cost arises from the need for accelerated production and delivery, which often requires additional resources, higher-quality materials, and increased coordination efforts. As a result, reducing project duration typically leads to increased upfront costs, reflecting a fundamental trade-off in OSC supply chain management.

$$\text{Min } TC = PMC + TRC \quad (6.9)$$

$$PD + TD \leq T$$

Based on the company duties the factors that affect the assembly and design phase are not included. The data affect that the manufacturing and transportation was gathered from a case-study of a precast concrete supplier. The information gathered is summarised and presented in Table 1. From theory and method, the parameters $\tilde{P}_{rk}$, $\tilde{TR}$ and I_{kw} are fuzzy numbers because uncertain decision-making environment are converted into their expected values in a ratio to the maximum/minimum values (Xu, 2015 and Grzegorzewski, 2008). For example, uncertain factors affecting determination of these fuzzy numbers are weather conditions and potentially internal and global supply chain pressures which have a moderating effect on the precast component manufacturing and delivery. Input data for definition of these fuzzy numbers were defined from case study interviews. However, these numbers are not affecting the precast component in the current case study, because the data collection was conducted in spring season and weather was not an issue; in addition, after reopening of borders, import of material has been without issues or delays. A full inventory is assumed due to maximum number of cranes in use assumption. As design are fixed without any changes during manufacturing procurement method assumption on DB. Table 6.1 presents data derived from a single case study project. Due to data limitations, detailed statistical measures such as standard deviation were not available; however, sensitivity analysis was conducted to address variability.

Table 6.1: Dataset from the case study

Labour shortage	50%
Labour cost increase	\$8 per hour
Weather factors to be included	Only during winter months
Transportation limit	Only height (under 4 meter)
Material cost	5% every 3 months
Material limit	Imported
Crane numbers	18 units/day
Time of transportation	Not any specific time
Production capacity	7 tables
Lost productivity	1 week
Cost of transportation	\$100k
Cost of manufacturing	\$500k
Time of transportation	2 weeks
Time of manufacturing	1 week

For lifting and hoisting components, and any damage during lifting or equipment failure extra cost and time should be assumed. To overcome these problems, a maximum number of days to cure the concrete is required, but components should be lifted before the lead time required for

deliver to avoid delay. In the meantime, manufacturing of the next batch of component can reduce any delay or labour costs. This stage is more labour intensive as more parallel tasks are performed. Figure 6-2 flow chart illustrates the phase of the manufacturing and delivery model based on the case study information gathered. As demonstrated, some delivery factors affect the equation.

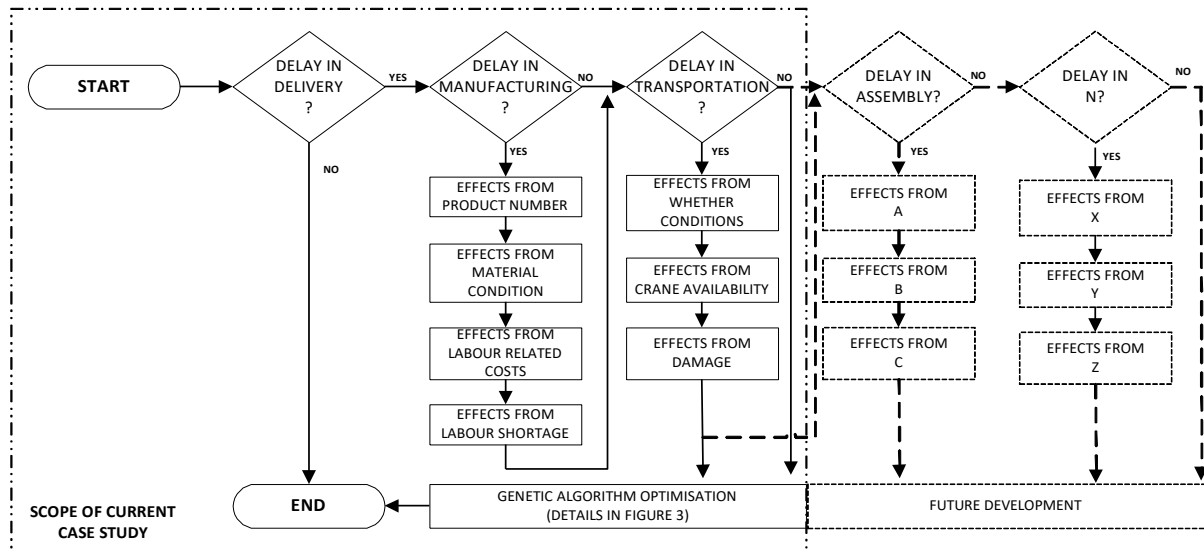


Figure 6-2: Flow Chart of Model Based on Case Study

6.4.2.1 GA Optimisation Process

As mentioned above the evaluation criteria for optimisation of OSC delivery in this chapter are cost and time. The dominate objective function is minimising the completion time of project T (objective 2). The second objective function is minimising the total project cost TC (objective 1). The number of workers on the construction site has a significant impact on time in precast construction projects, as mentioned earlier. Hence, the number of on-site workers per day is constrained. The two objective functions T and TC are computed for all chromosomes in each generation. The chromosomes are then ranked according to T. Figure 6.2 provides schematic Illustration of the solution approach based on GA optimisation. Solutions with identical completion times are ordered according to their total project cost TC.

Table 6.2: Crossover Operator

Sample parents in generation population	Manufacturing Cost (NZ\$)	Manufacturing Time (days)	Equipment Failure Cost (NZ\$)	Equipment Failure Time (days)	Transportation Cost (NZ\$)	Transportation Time (days)	Labour cost (NZ\$)	Labour time (days)
Parent 1	100k	4	100k	4	100k	7	400k	5
Parent 2	200k	4	70k	3	100k	7	300k	5
Parent3	100k	5	100k	4	120k	6	200k	3
.								
.								
.								
parent n	500k	4	0	0	200k	4	500k	6

Offspring 1 input	500k	4	0	0	120k	6	400k	3
Offspring 2 input	100k	5	100k	4	100k	7	400k	5

An example of crossover operator provided in Table 6.2: Suppose parent 1, and parent 2 are selected to create two offspring. The crossover operator randomly divides the sub-strings of the parents into two resource-based sets and swaps the genes into the sub-strings of each set. Hence, the offspring inherit the sequence of operations processed on resources from their parents. After applying the crossover operator to parent 1 and parent 2, it can be seen in Table 2 that child 1 (or offspring1) inherits the operation sets (with the same order). The symmetric process is applied to create child 2 (or offspring 2). The new children that are created using the crossover operator will then be decoded to get a feasible schedule.

6.4.2.2 Fitness Function

Fitness function is defined so as to determine the quality of individuals, and it is usually relevant to the objective function to be optimised. The greater the fitness of a chromosome is, the greater its survival probability. In this study, the fitness function is defined based of formula 9 of section 4.2; as $F(T) = 35.71 \cdot T(1) + 14.28 \cdot T(2) + 35.71 \cdot T(3) + 1600 \cdot T(4)$, where T is any individual in the population. Fitness function is illustrated in Figure 3.

6.4.2.3 Mutation and Crossover

Crossover, mutation and migration operators have been applied in this optimisation. The resource-based crossover operator proposed by (Qing-dao-er-ji & Wang, 2012) was used. The

mutation operator was adopted to get a feasible schedule. First, a single chromosome is chosen to create a new offspring. Then, the mutation operator randomly selected a sub-string from the selected chromosome and changes the position of two operations within the sub-string of the parent chromosome, taking into account the precedence relationships. This operator preserves the assignment property of the parent chromosome and changes the sequence of operations. The new child will then be decoded to get a feasible schedule. The migration operator generates a number of new chromosomes. The genetic operators can be stopped (by the user), if an acceptable solution which satisfies the total project's time and the project's cost is found. In this case, the corresponding schedule, including the utilised number of labour over time, is reported as the output. Otherwise, the algorithm will continue searching for a "better" solution. The crossover used is shown in Table 2 of this chapter. This represents that off-spring input is a combination of each part of each input, for example, the first part of offspring 1 and the rest part of offspring 3. This combination will be done for all inputs to the input n to generate all ones. The flow chart below illustrates a schematic illustration of the solution approach.

There are two scenarios for this purpose. First if the manufacturing time decreases instead of seven days by increasing the number of labours. Second scenario is decreasing time of the transportation instead of one week by employing more labour to have maximum transportation number in a day. For these scenarios based on the data from the case study; the factory's minimum time for manufacturing was found to be 4 days and the minimum time for transportation to be 7 days. These outputs of the optimised equation in MATLAB.

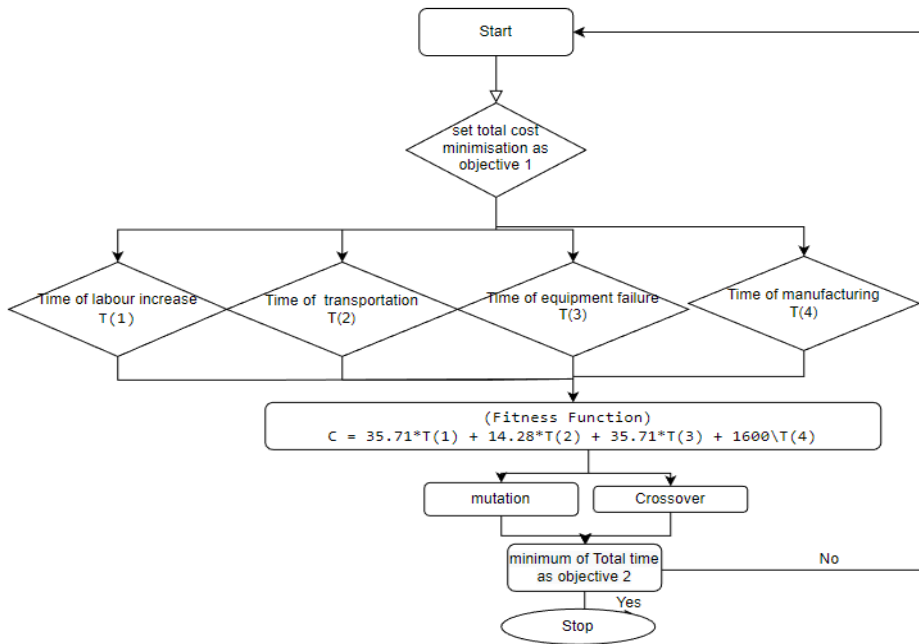


Figure 6-3: Schematic Illustration of the Solution Approach based on GA Optimisation

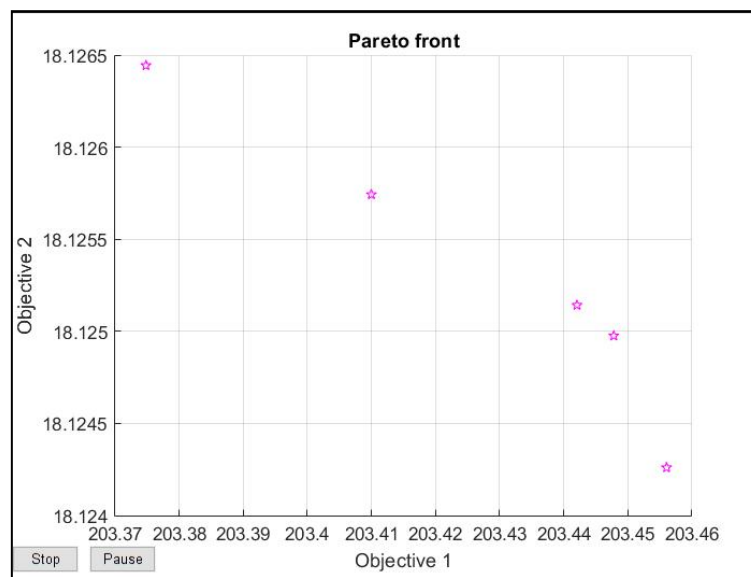


Figure 6-4: Diagram of the pareto front of the GA optimisation

Based on the optimised solution and pareto front in generated in Figure 6-4 the labour increase with cost implications can reduce the time of transportation and manufacturing. According to different delivery requirements an optimised solution can be generated. This is illustrated via the points indicated in Figure 4. In addition, the affective factors for the total cost are labour cost and equipment failure.

6.5 Discussion

To support the optimisation of delivery procedures for OSC, this research has presented an optimisation based on genetic algorithm model. The component products utilised were typically created to order and specifically intended for usage in one project. Precast component items are often larger when compared to the materials utilised for ordinary construction projects. Because of this, their storage facilities are usually limited at manufacturing and construction sites. This study assumes that the business constantly tries to fill the warehouse to address this problem. Ideally, products are dispatched daily to the construction sites in response to the demand after being cured and shipped from the factory to the warehouse.

The model was specifically developed to deal with issues of uncertainty at building sites based on different delay factors. The leading delays that frequently happen on construction sites are used to create scenarios, including bad weather, wind, late deliveries, a labour shortage, and several types of product failure. The scheme includes an optimal manufacturing schedule spanning from the period of the project for manufacturing to delivery after the commencement of the onsite construction. Here the most favorable scheme is the one that yields the lowest production cost and expected values of total operational cost for all possible demand profiles.

In this study, the model can assist an OSC factory in creating the ideal production schedule based on the curation time for precast concrete. Thus, the model can significantly assist managers tasked with making decisions for production planning in a limited amount of time. The second circumstance is handling demand that is far in the future. To prepare the component in a precise amount of time, the inventory should be filled to the factory's maximum capacity with the maximum number of workers. Thus, this model helps to find the time for preparing the component with a maximum capacity of labour to minimise the time and total cost. The cost performance of precast panelised systems is influenced by higher initial manufacturing and transportation costs, as well as specialised handling requirements. However, these costs may be partially offset by reduced on-site labour and improved construction efficiency. While both panelised and precast systems fall under offsite construction, their supply chain structures differ significantly in terms of material characteristics, transportation requirements, and assembly processes. Therefore, the comparison in this study aims to highlight how these differences influence cost, time, and material waste performance, rather than to directly equate the two systems.

6.5.1 Limitations and Recommendations for Future Studies

Although demonstrated the proof of concept for further optimising the procurement and delivery of an OSM project, the current case study is of a simple OSC (precast) project and its scope is limited to the manufacturing and transportation phases. A complete fabrication schedule and operating procedures in different OSC systems were not included in the case study. The optimisation modelling that are suggested in this study also contain a few assumptions. These assumptions will need to be further validated in a more complex OSC projects. In addition, this study focuses only on a single planning period. It does not include the influence of the precedent planning period on the current planning period.

6.6 Conclusion

This chapter discussed many aspects of OSC delivery while arguing that appropriate procurement should be deployed throughout. It specified the criteria and methods required to choose the level of OSC delivery that best meets the bottom line of time. A multi-objective optimisation model was proposed and presented utilising an OSC case study project as part of this optimisation methodology. This model is built on an optimisation framework composed of several constraints and objective functions. The multi-objective problem was resolved using a genetic algorithm (GA) optimisation technique. An analysis of the trade-off between multiple objectives was carried out. According to study findings, implementing this methodology holds the potentials to lower the overall cost of components through delivery. This study adds to our understanding of OSC optimisation techniques and necessary trade-off judgments, particularly considering other procurement goals. It offers a more comprehensive and analytical method for making intelligent choices for procuring and executing OSC projects.

The case study demonstrated how to deal with the variable component delivery schedules by employing the optimisation model from both the project planning and project control perspectives. In the same case study, a separate simulation model was created. The optimisation model was the analytical tool used for calculating the effect of various component delivery times on the project budget. Based on the same instance, a quantitative and visual method is used to illustrate the relationship between the component delivery date and the project's overall cost. In order to keep the overall project budget within predetermined bounds, practitioners might use the derived budget-constrained delivery time window as critical decision assistance.

Future work aims to examine the full effects of a broader range of interruptions, further expand and test the model against full scale OSC projects to further optimise and continue pushing the boundaries of various facets of OSC.

7 Time–Cost–Waste Trade-offs in Panelised Offsite Construction Supply Chain Management

The current chapter is based on the following article:

Nesarnobari, S., Shahzad, W. M., Jelodar, M. B., and Sutrisna, M. (2026). “Time–cost–waste trade-offs in panelised offsite construction supply chain management.” *Results in Engineering*, 30, 110365. <https://doi.org/10.1016/j.rineng.2026.110365>

Abstract

The construction industry continues to face challenges, including poor quality, lower productivity, and pressing issues that limit the efficient delivery of housing. Modern methods of construction, particularly offsite construction (OSC), are increasingly promoted for their potential to improve quality, reduce time, cost, and enhance productivity. However, existing studies show that OSC adoption is hindered by fragmented supply chains, limited quantitative modelling, and a lack of optimisation-focused research for panelised systems. Furthermore, few studies integrate probabilistic barriers into OSC supply chain analysis on timber panelised system. OSC adoption, therefore, remains limited in many countries due to delays, inefficiencies, and waste across the supply chain. This study develops a multi-objective optimisation model for the panelised OSC supply chain (design, raw material preparation, manufacture, transport and assembly) to address these barriers. Drawing on key factors such as supplier capacity, transportation time, and material availability, a Grey Wolf Optimiser is applied to minimise project duration, cost, and waste simultaneously. The model is tested using a residential panelised housing case in New Zealand. Results demonstrate significant improvements, with project duration reduced by ~10%, costs lowered by ~7–8%, and material waste reduced by ~4–5%. The findings provide a quantifiable basis for enhancing OSC performance and offer decision-makers a tool to evaluate trade-offs between competing objectives. By integrating optimisation into Offsite Construction-Supply Chain Management (OSC-SCM), this research supports more resilient and efficient housing delivery and provides insights for accelerating OSC adoption in New Zealand and beyond.

Keywords: Offsite Construction (OSC), Supply Chain Management (SCM), Panelised Housing, Grey Wolf Optimiser (GWO), Multi-objective Optimisation, Construction Productivity and Efficiency

7.1 Introduction

Offsite construction (OSC) has gained recognition within the construction industry for its sustainability (Hu et al., 2019), improved safety (Li et al., 2015), cost-effectiveness (Khalili & Chua, 2013), superior quality (Nesarnobari S. et al., 2022c), reduced carbon emissions (Nesarnobari S. et al., 2022a), and shorter production times (Taghaddos et al., 2014). Panelised systems denote a sophisticated OSC method in which both structural and non-structural components, are built in a controlled factory setting and then transported to the construction site for assembly. Panelised system offers particularly Cross-Laminated timber (CLT), which accounts for approximately 32% of panelised timber use, and Laminated Veneer Lumber (LVL) at around 50%, are increasingly favoured in New Zealand's housing sector (David Carradine, 2024). However, despite these benefits, long-term barriers persist, affecting collaboration across the supply chain (SC) process (Shahzad et al., 2023). Supply chain barriers contribute to extended project durations, increased capital requirements, and coordination challenges among diverse stakeholders, creating a highly complex environment where delays, inefficiencies, and waste frequently occur. Persistent problems such as rework, low productivity, cost overruns, and excessive material waste continue to undermine project performance, highlighting longstanding structural weaknesses within OSC-SCM. These challenges continue to impede the widespread adoption of this system, despite the increasing demand for more efficient workflows, inadequate planning, and insufficient modelling of interdependencies among design, procurement, manufacturing, logistics, and on-site assembly (Nesarnobari et al., 2024a). These inefficiencies are compounded by limited transparency, poor coordination, and inconsistent communication among supply chain actors, frequently resulting in payment delays, procurement disputes, and disruptions to delivery processes. External challenges, including natural disasters (weather and wind), labour shortages, and volatile material prices, have further intensified these challenges, highlighting the vulnerability of OSC-SCM and underscoring the need for more resilient, adaptive, and technology-enabled approaches (Castelblanco, 2026). The primary objective of supply chain management (SCM) is to minimise system costs while ensuring that goods and services are produced and delivered at the right time and place to meet demand (Nesarnobari et al., 2024b). Each link within SC is interconnected, meaning that the performance of one stage can influence the overall profitability and efficiency of the entire system (Nesarnobari et al., 2024d). Effective SCM across different phases is essential to maximising overall profitability. Consequently, close coordination within SCM is crucial, as it directly impacts construction budgets and timelines

(Nesarnobari et al., 2024b). Panelised construction, through its distinctive features, like standardised production, improved insulation, and minimised material waste, supports the nation's goals for sustainable, energy-efficient housing (Nesarnobari et al., 2024b), making it essential to thoroughly understand its impact on SCM to optimise project outcomes effectively. Most studies examine isolated aspects of OSC delivery rather than offering integrated, system-level insights into how technical, organisational, environmental, and external factors collectively shape project performance. Recent studies have highlighted the growing relevance of digital technologies, optimisation methods, and data-driven decision support tools for enhancing OSC-SC. Other studies explore coordination mechanisms, production scheduling, or digital enablers, but they typically analyse isolated stages of the supply chain and rarely integrate multi-objective optimisation across time, cost, and material waste. Moreover, existing research seldom incorporates factors such as weather disruptions, labour variability, or transportation issues, which are critical to the performance of panelised systems, especially in the New Zealand context. These limitations reveal a clear research gap. However, research remains limited in several areas: A lack of holistic frameworks that integrate OSC supply chain stages and quantify their interactions, Limited optimisation-based studies, particularly for panelised timber systems, despite their increasing use in New Zealand, Insufficient modelling of stochastic conditions (e.g., weather, labour availability, logistics reliability) that significantly affect OSC performance for design, material preparation, manufacturing, transportation and assembly. A gap in multi-objective optimisation research capable of simultaneously addressing time, cost, and material waste. Therefore, the main aim is to model OSC-SCM by considering realistic factors such as communication and interaction among SC practitioners, activity duration barriers, traffic and weather conditions, delays due to resource or labour unavailability, and cost uncertainties. Then: assess the impact and interaction effects of logistics and construction decisions on key performance measures of OSC-SCM, namely project duration, logistics and construction costs, and material waste. Last: determine the near-optimal choices for preparation, logistics, and construction to reduce duration, costs, and material waste, thus improving the sustainability of OSC-SCM. By providing an integrated design, logistics, assembly perspective that connects design choices with production, transportation, and on-site assembly, this study promotes OSC-SCM. By incorporating stochastic variables like traffic, weather, and labor availability into a multi-objective Grey Wolf-based optimisation framework, it offers decision-support tools in the face of uncertainty and permits balanced trade-offs between time, money, and material waste. Thus, the work poses the following questions: How can the dynamic interdependencies of panelised OSC-SC be captured by an integrated design–

logistics–assembly model. And how much can multi-objective optimisation techniques improve decision-making while cutting waste, time, and expense in practical situations.

7.2 Background

The theoretical framework explores both the global challenges faced in SCM and the unique difficulties inherent in its processes. It is based on an extensive literature review that examines various SCM definitions and dissects the obstacles encountered at each stage of SC.

7.2.1 Barriers to Supply Chain Management

The OSC-SC is often conceptualised as a dynamic system comprising multiple interacting entities, where effective coordination among these entities is vital to meeting customer demands and ensuring supply chain success (Nkolika J. Peter et al., 2020). For these stages, various stakeholders actively and passively contribute to OSC-SC, enabling the forward flow of materials and the backwards flow of information (Mostafa, Dumrak, et al., 2014). Therefore, to achieve efficient SCM, it is crucial to investigate these stages to enhance the adoption of OSC. For this purpose, all aspects were systematically analysed using the Scopus database over the past decade. A systematic literature review was conducted to identify barriers to global OSC implementation, aiming to provide a comprehensive view of the challenges.

The unpredictability of imported material costs can strain financial planning and budgets. Inadequate quality checks or machine errors during manufacturing may lead to defective components (Li et al., 2018). Factory equipment requires regular maintenance, but malfunctions can result in delays and increased costs (Chen et al., 2023). Maintaining a skilled workforce capable of operating complex machinery and adhering to strict quality control standards is critical, as skill gaps or labour shortages can disrupt production schedules and compromise product quality (Chen H. a. S., D.A.S., 2020). Transporting large components from factories to construction sites presents unique challenges, including compliance with transportation standards, securing permits, and managing logistics for smooth and timely deliveries (Arashpour et al., 2018). Unforeseen disruptions like road closures, adverse weather, or mechanical failures can derail transportation plans and lead to costly delays. Additional logistical constraints, like traffic, weather, and road regulations, further complicate the process (Hsu et al., 2018b). Assembly procedures are influenced by weather, site conditions, and labour availability, increasing the complexity of the OSC process. Efficient planning and coordination are essential to adapt assembly activities to these challenges while maintaining safety and productivity standards (Anvari et al., 2016). Successful navigation of SC requires effective

collaboration, proactive problem-solving, and attention to detail among all stakeholders (Figure 1). The barriers identified create a highly non-linear, multi-modal optimisation landscape with local optima, mixed discrete–continuous variables, and discontinuities, making exact algorithms unsuitable.

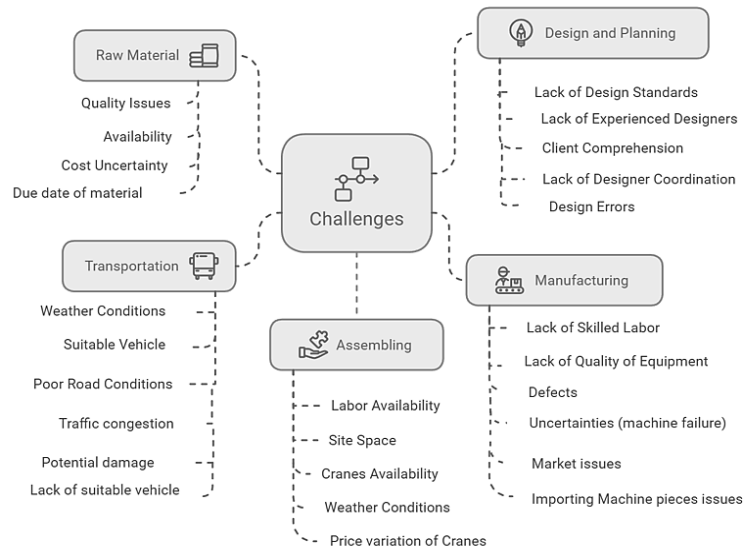


Figure 7-1: Mapping the supply chain for OSC adopted from literature review

7.3 Offsite Construction Supply Chains

Supply chain in offsite construction are increasingly conceptualising as dynamic, multi-tier systems requiring coordination across design, production, logistics, and assembly to achieve project performance objectives (Akkermans et al., 1999; Chandra & Fisher, 1994). Numerous studies have investigated optimisation approaches for OSC-SC addressing a range of problem settings including cost-time trade-offs (Khalili, 2013), inventory control (Hsu, 2019; Yang et al., 2018), transportation planning (Lee et al., 2021; Son & Hieu, 2021), resource allocation (Hyun et al., 2021), waste minimisation (Jalali Yazdi et al., 2021), and production scheduling (Wang Z., Hu, H., et al., 2018). A recent review by Hussein et al. (2021) revealed that despite the widespread application of optimisation methods (logical programming, simulation, metaheuristics, BIM scheduling) the review found a strong bias toward economic objectives, while environmental and social sustainability metrics remain under-explored. These findings confirm the need for novel unified, multi-objective optimisation models that can capture interdependencies across stages and sustainability concerns (Hussein, Eltoukhy, Karam, et al., 2021a).

Similarly, other research emphasise the fragmented nature of OSC-SC models, noting that most studies address isolated decision layers, such as assembly sequencing, factory capacity planning, or logistics routing, without fully integrating barriers for design, material preparation, manufacturing, transportation, and assembly (Hussein et al., 2022; Wuni & Shen, 2021). As a result, optimisation studies that simultaneously target time, cost, and material waste, particularly for timber panelised OSC systems, remain limited, despite their practical relevance for addressing long-standing performance challenges (Clyde Zhengdao Li et al., 2024; Hussein, Eltoukhy, Karam, et al., 2021b; Nesarnobari et al., 2024b).

Supply chains in OSC are increasingly conceptualised as dynamic, multi-tier systems requiring coordinated decision-making across design, production, logistics, and on-site assembly to achieve project performance objectives (Akkermans et al., 1999; Chandra & Fisher, 1994). Previous optimisation studies in panelised OSC-SC have contributed to improving performance at specific decision layers, including offsite manufacturing and production scheduling (Khalili, 2013; Wang, 2024; Wang D. et al., 2018), transportation and logistics planning (Son & Hieu, 2021; Zhang & Yu, 2020), inventory and buffer management, and, in more recent work, limited environmental considerations such as carbon emissions and energy efficiency (Ho et al., 2022; Xu, 2025; Zhou, 2025). Despite these advances, existing optimisation efforts predominantly address isolated sub-systems rather than the full OSC supply chain.

This limitation is consistently highlighted in recent review studies. For example, Hussein et al. (2021) demonstrate that although a wide range of optimisation approaches, including mathematical programming, simulation, metaheuristics, and BIM-based scheduling, have been applied in OSC research, the majority of studies remain biased toward economic objectives, with environmental and social sustainability indicators receiving limited attention. Subsequent reviews further confirm that most optimisation frameworks adopt single- or bi-objective formulations, typically focusing on time–cost trade-offs, while material waste is often treated implicitly or excluded as an explicit optimisation objective (Hussein et al., 2022; Nesarnobari et al., 2024c). Moreover, critical disruption and uncertainty factors such as adverse weather conditions, traffic congestion, labour and crane availability, material quality variability, and raw material importing risks are frequently simplified or neglected, limiting the realism and decision relevance of existing models (Clyde Zhengdao Li et al., 2024; Hussein et al., 2022). In contrast, the current study advances the state of knowledge by developing an integrated, uncertainty-aware, multi-objective optimisation framework for panelised offsite construction

that simultaneously minimises project time, total cost, and material waste across the entire supply chain. By explicitly modelling interdependencies between design, material preparation, manufacturing, transportation, and assembly, and embedding stochastic disruption factors within the optimisation process, this study provides a structurally unified and decision-relevant contribution that directly addresses the fragmentation and objective limitations identified in prior panelised construction optimisation research (Nesarnobari et al., 2024c).

These multi-objective problem settings illustrate that OSC-SC performance involves inherently conflicting criteria, such as cost, time, and material waste, requiring optimisation methods capable of evaluating trade-offs rather than optimising a single objective. Metaheuristic algorithms have gained significant attention due to their flexibility in addressing non-linear, multi-objective, and stochastic decision environments. A range of metaheuristic algorithms have been applied to SC optimisation, including Genetic Algorithms (GA), Particle Swarm Optimisation (PSO), Ant Colony Optimiser (ACO) (Son & Hieu, 2021). Each of these methods offers distinct strengths, ALO in combinatorial and dynamic routing, GA in handling both discrete and continuous variables (Nesarnobari et al., 2024d), PSO in simplicity and fast convergence (Zhang & Yu, 2020). However, these metaheuristic methods may exhibit premature convergence or loss of solution diversity when improperly tuned or applied, rather than as an inherent limitation of the algorithms themselves. Among the new algorithms, the Grey Wolf Optimiser (GWO) (Mirjalili et al., 2014) provides a balanced exploration–exploitation mechanism and has shown strong performance in uncertain inventory systems, logistics optimisation, and multi-objective supply chain decision-making (Sadeghi et al., 2023). Although GWO shares the simplicity and low parameter count of GA & PSO, it may still be susceptible to local optima and slow convergence, prompting researchers to develop enhanced variants. Recognising these trade-offs reinforces the potential of carefully adapted or hybridised GWO approaches for OSC-SC optimisation. Previous studies have proposed separate methods for assembly scheduling, logistics optimisation, production planning, but these models rarely integrate all stages of SC. Moreover, OSC projects often overlook critical uncertainties like traffic congestion/weather delays. This fragmentation limits their practical value, highlighting need for unified framework. As a state-of-art swarm intelligence algorithm, GWO has been widely adopted due to its robustness, computational efficiency, and ability to generate good-quality solutions across diverse domains, including engineering, medical decision-support systems (Faris, 2018) Given the complexity and interconnectedness of the OSC supply chain, including lead times, weather-related delays, material availability, and cost

drivers, GWO is well suited to support unified optimisation frameworks (Pham et al., 2023). Integrating GWO into OSC-SC can therefore enhance coordination, reduce delays, and optimise cost–time performance, improving the productivity and reliability of OSC processes (Zhou, 2018).

7.4 Methodology

The effectiveness of a well-coordinated SC in a panelised system is largely contingent upon a robust management and control strategy. To build a thorough management framework, it's necessary first to identify the complex drivers at design, raw material preparation, manufacturing, transportation and assembly. First, critical barriers are recognised and analysed using a triangulation approach, including a literature review, expert interviews, case studies. Comprehensive literature reviews have been done for the last ten years (discovery of barriers and gaps). For the interview, the selection process employed a combination of purposive sampling and the "snowball sampling" technique (Dawson, 2009) to ensure highly qualified participants. Findings were further validated using real-world case studies. The results identified 18 critical factors impacting the OSC-SC and highlighted the need to optimise SCM regarding project cost, duration, and material waste. Then, a causal loop (CLD) diagram was constructed (Vensim software) to illustrate the relationships between these critical factors. Reinforcing loops (R) were used to represent feedback mechanisms that reinforce effects over time, such as demand growth increasing production pressure and subsequently elevating the risk of delays. These loops provide a holistic understanding of how time, cost, waste, and logistical barriers interact across the OSC-SC, informing the design of the subsequent optimisation model (Forrester, 2008; Lin et al., 2024). At this stage, the system dynamics model was developed as a behavioural simulation tool. The SD model was subsequently used to generate time–cost–waste performance data across varying decision scenarios, which served as the foundation for the optimisation stage. As a systems-thinking tool that visually maps complex system dynamics models, a CLD is more than just a schematic; it offers a comprehensive problem perspective and enables the identification of reinforcing and balancing feedback loops. The final step established the optimisation model to recognise the optimum result for projects facing SC barriers. Due to the computational complexity of directly embedding the SD model within an optimisation loop, a surrogate-assisted optimisation strategy was adopted. Surrogate models were trained to approximate the SD-generated performance indicators and were used during the optimisation phase. Given the complexity of the OSC solution space, this study employs the GWO to search for high-quality, near-optimal

solutions to the defined decision variables (Mirjalili et al., 2014). As a metaheuristic, GWO exploitation mechanism makes it effective for approximating solutions in nonlinear, multi-objective supply chain problems involving factors such as lead times, costs, and material availability. Recent studies demonstrate that GWO can perform competitively in uncertain and dynamic supply chain environments (Qiu et al., 2024; Sadeghi et al., 2023), though performance depends on problem characteristics and parameter settings. In this study, GWO is applied as a practical tool to support improved decision-making within the OSC supply chain, and its suitability is evaluated through a case study. Consequently, an optimisation model was developed to improve the efficiency and productivity of SCM. This model was validated through case studies. The methodology of this research is shown in Figure 7-2. In this study, an integrated decision-support framework for OSC-SCM is developed by combining multi-objective metaheuristic optimisation under barriers with system dynamics modelling. A realistic depiction of time-cost-dependent behaviour in OSC supply chains is made possible by the framework's explicit capture of dynamic feedback mechanisms, nonlinear interactions, and barrier propagation across design, raw material preparation, manufacturing, transportation, and on-site assembly stages. To represent operational barriers in the real world, the model incorporates probabilistic barriers, including weather unpredictability, labour and crane availability, material problems, and logistics delays. Instead of relying on a single deterministic result, the optimisation component simultaneously minimises project duration, total cost, and material waste, yielding Pareto-optimal solutions that reveal trade-offs between conflicting performance objectives. A significant gap in the current OSC-SC optimisation research is addressed by applying the model to a residential panelised OSC case study, which demonstrates how coordinated planning and adaptive decision-making can enhance supply chain resilience, reduce waste, and increase productivity. This decoupled simulation–optimisation framework preserves the dynamic behavioural insights of system dynamics modelling while enabling efficient multi-objective optimisation.

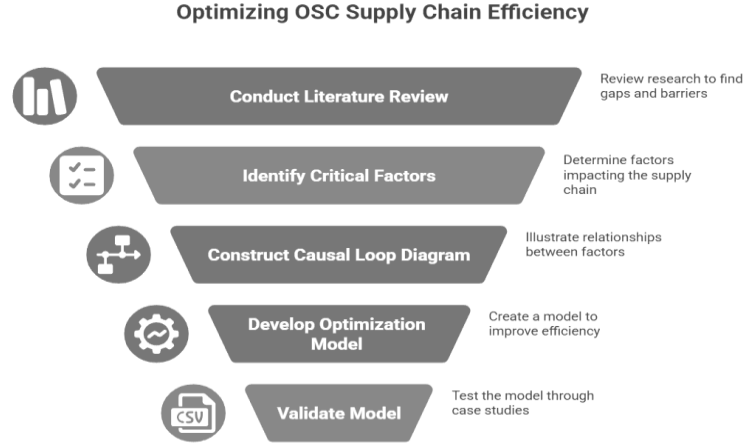


Figure 7-2: Methodology of the Research Paper

7.4.1 Notations

The notations used in this research and their definitions are demonstrated below.

Indices

c	Consultancy number, $c \in C$
r	Raw material suppliers, $r \in R$
y	Raw material in stock, $y \in Y$
w	Days for preparation period, $w \in W$
q	Ordered raw materials, $q \in Q$
K	Raw material types $k \in K$
p	Product types, $p \in P$
d	Days for production period, $d \in D$
m	Transportation days $m \in M$
f	Factory number, $f \in F$
s	Construction sites, $s \in S$
t	Days for the construction period, $t \in T$

Parameters: Factory

$PC_{\max k}$	Maximum production capacity for product k in factory
$MO_{\max sk}$	Maximum material ordered for product k at site s
$\tilde{M}_{rk}$	Unit procurement raw materials cost from supplier r for offsite product k
C_{kf}	Unit inventory cost for product k in factory f
VO_{kf}	Unit volume production for product k in factory f
VR_k	Volume (m3) of raw materials required for unit product k

Decision Variables

τ_k^m	Binary variable which equals 1 if transport mode m is chosen to transport building element k
N_{rkw}	Raw materials quantity for product k procured from supplier r procured in period w
N_{rkd}	Raw materials quantity for product k procured from supplier r procured in period d
N_{kw}	Production quantity of product k in the factory in period w
N_{kd}	Production quantity of product k in the factory in period d
N_{skd}	Quantity of product k transported at site s in period d
N_{skt}	Quantity of product k assembled at site s in period t

Parameters: Design

$DC_{\max kc}$	Maximum design capacity for product k in consultancy c
$\tilde{D}E_{kc}$	Unit Design cost of product k in consultancy c

Parameters: Transportation

$TC_{\max sk}$	Maximum transport capacity for product k to site s
L_k	Quantity of panel product k that can be loaded on truck
NL_{kt}	Quantity of panel product k that need to be transported on day t
d_s	Distance from the factory to the construction site s
$\tilde{C}$	Unit Cost of truck transportation by unit distance

Parameters: Assembly

$AC_{\max sk}$	Maximum assembly capacity for product k at site s
----------------	---

I_{kw} : Production inventory for product k during preparation

I_{kt} : Production inventory for product k during t period of construction

D_k : Demand for product k at site over whole project

C_{kd} : Unit Cost of k product during d period in factory

IC_{max} : Maximum inventory capacity in the factory

$\tilde{U}_k$: Unit production cost for product k

LC_{kw} : Unit labour cost for product k during period w

FC Fixed cost per day if factory is operating

d_r : Distance from supplier r to factory

AU_k : Unit assembly and construction cost for product k at site s over whole construction

C_{ak} : Cost of assembly delay based on the weather for product k

D_{skt} Demand of product k at site s on day t

Restrictions

All process has their restriction; the following is a list of restrictions in its mathematical form for OSC SC. These restrictions set the boundary conditions for the mathematical model.

$$0 \leq N_{kw} \leq PC_{maxk}; \forall k \in K; \forall w \in W \quad (7.1)$$

$$0 \leq N_{kd} \leq PC_{maxk}; \forall k \in K; \forall d \in D \quad (7.2)$$

$$0 \leq N_{kc} \leq DC_{maxkc} \forall k \in K, c \in C \quad (7.3)$$

$$0 \leq N_{skt} \leq AC_{maxsk}; \forall k \in K; \forall s \in S; \forall t \in T \quad (7.4)$$

$$if\ s = 0\ N_{skt} = 0$$

$$0 \leq N_{skd} \leq TC_{maxsk} \forall k \in K, s \in S, d \in D \quad (7.5)$$

$$I_{k,w-1} + N_{kt} = I_{kw}; \forall k \in K; \forall w \in W \quad (7.6)$$

$$I_{t-1,k} + N_{kd} - N_{skt} = I_{tk} \forall s \in S, k \in K, t \in T \quad (7.7)$$

$$0 \leq \sum_{k=1}^K VO_{kf} I_{kw} \leq IC_{max}, \forall k \in K; \forall w \in W \quad (7.8)$$

$$0 \leq \sum_{k=1}^K VO_{kf} I_{kw} + VO_{kf} N_{kd} - \sum_{k=1}^K VO_{kf} N_{skt} - \sum_{k=1}^K VO_{kf} N_{skd} \leq IC_{max} \quad (7.9)$$

$$\sum_{r=1}^R \sum_{k=1}^K \left(\sum_{w=1}^W N_{rkw} + \sum_{t=1}^T N_{rkt} \right) \geq \sum_{k=1}^K VR_k D_k, \forall r \in R; \forall k \in K; \forall w \in W; \forall t \in T \quad (7.10)$$

$$\sum_{k=1}^K \sum_{t=1}^T N_{rkw} \geq \sum_{k=1}^K D_k, \forall s \in S; \forall k \in K; \forall t \in T \quad (7.11)$$

$$\sum_{t=1}^T \sum_{k=1}^K N_{kt} \geq \sum_{k=1}^K D_k \quad (7.12)$$

$$\sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W N_{rkw} + \sum_{r=1}^R \sum_{k=1}^K \sum_{d=1}^D N_{rkd} \geq \sum_{k=1}^K VR_k D_k \quad (7.13)$$

$$N_{rkw}, N_{rkd} \geq 0; \forall k \in K; \forall w \in W; \forall d \in D \quad (7.14)$$

$$I_{kw} = 0, \forall k \in K \quad (7.15)$$

Constraints (7.1) to (7.3) define the allowable manufacturing and design rates for each product type within the factory. These constraints ensure that production quantities remain within a predefined range, where the minimum is zero and the maximum corresponds to the factory's capacity limits during both preparation and construction periods. Constraints (7.4), (7.5) restrict the transportation and assembly rates for product k at construction site s . They ensure that daily assembly and transportation activities do not exceed the operational limits imposed by crane capacity, labour availability, equipment, or site logistics. Constraints (7.6), (7.7) establish the relationship between the inventory state variable I_{kw} and the production decision variables N_{kw} and N_{kt} during the preparation period. These constraints maintain consistent inventory flow over time and guarantee correct inventory balance within the factory. Constraints (7.8), (7.9) ensure that the total quantity of stored products in the factory does not exceed inventory capacity. They prevent the model from allocating more items to storage than the facility can physically accommodate. Constraint (7.10) guarantees that the raw material demand for each product type k is satisfied by the total quantity procured across both preparation (N_{rkw}) and construction (N_{rkt}) periods. Constraints (7.11) – (7.13) ensure that the manufactured products transported to the construction site meet the project demand for each product type, consistent with classical material-requirement logic (Geraci, 1982). Constraint (7.14) enforces the non-negativity of raw-material quantities, ensuring that no procurement or delivery variable takes an infeasible negative value. Constraint (7.15) specifies that the available product inventory at the factory at the beginning of the construction period is zero, reflecting the assumption that all initial inventory is produced within the optimisation horizon.

7.4.2 Problem Description

OSC relies on project-driven, customised production with strict delivery deadlines. The panelised system follows a routine SC (Fig.7.1), illustrating the workflow from design to on-

site assembly. Management focuses on optimising production, transport, and assembly under time–cost constraints. Procurement is project-based, after which designers $c \in C$ prepare the required components $k \in K$. Orders are then sent to factories $f \in F$, where material preparation for component k takes ($w \in W$) time, each with a distinct preparation period $d \in D$. Components undergo P processing steps before being transported by crane $j \in J$ from factory to site $s \in S$, subject to batch-transport limits. Finally, components are assembled on site, during the production period, and t ($t \in T$) in the construction phase.

7.4.3 Problem Assumptions

Incorporating every real-world factor into a model can make it overly complex or prevent it from addressing observed issues. Effective models, therefore, rely on simplifying assumptions that reduce complexity while retaining core system features. In our approach, we assume fixed supplier numbers and facility capacities, a common simplification in SC models. While this aids tractability, it reduces flexibility when suppliers enter or exit the market or when capacity fluctuates. Fixed-capacity assumptions can lead to underutilisation and limit exploration of strategies, namely temporary capacity adjustments, which are often used in practice. Industry experts caution that even these “confident” assumptions can become risks under disruptions. Thus, while simplifications are necessary, recognising their limitations is essential, and incorporating flexibility, like allowing supplier numbers or facility capacities to vary within ranges, can improve realism and applicability.¹⁾ The location and number of suppliers, manufacturers, distribution centres and retailers are specific. 2) The capacity of each facility (supplier, manufacturer, distributor and retailer) is specific. 3) The amount of demand and the rest of the existing parameters are definitive. 4) Each retailer can receive a product from only one wholesaler for each product. 5) The same prefabricated component provided by different factories has the same structural performance. The only differences are unit price, mold quantity, transportation, and assembly cost. 6) The total quantity of prefabricated components of different types must wait until the total amount of prefabricated components on site meets the number of prefabricated components required by the onsite construction process before the relevant construction work can be carried out. 7) There are no production priority constraints among different components.

7.4.4 Problem Formulation

An efficient SC requires continuous improvement to minimise costs, optimise schedules, and reduce material waste. This study develops a multi-objective optimisation model for planning,

budgeting, and managing waste in the SC of a panelised OSC system. The model captures all major stages, design, material preparation, manufacturing, transportation, and assembly, each with associated risks and penalties. Design decisions (e.g., type, dimensions, interfaces) strongly influence downstream processes; errors or late changes create delays and added costs, which are treated as penalties. Once designs are finalised, raw materials are sourced from suppliers ($r \in R$) or warehouses ($y \in Y$), where proper storage reduces but does not eliminate preparation delays ($w \in W$). Manufacturing occurs in factories ($f \in F$) producing multiple product types ($p \in P$), with barriers such as machine failure or labour shortages causing penalties for production delays ($d \in D$). Transport of elements to sites ($s \in S$) by cranes ($j \in J$) is affected by weather, traffic, and site conditions; disruptions ($m \in M$) incur storage costs and delays. Finally, on-site assembly must follow a defined sequence, where delays ($t \in T$) extend project duration and increase costs. By embedding penalties for errors, shortages, and delays across all phases, the framework provides a comprehensive optimisation model that reflects the realities of OSC supply chains. These penalties are accounted for in the model, ensuring a comprehensive optimisation framework that addresses the critical stages of OSC. An inexperienced designer and high project complexity significantly influence the duration of the design process:

$$T_D = \alpha_{design} \cdot T_{complexity} \cdot (1 + \sigma_{revision}) \quad (7.16)$$

.In this formula α_{design} where is a coefficient representing design team productivity, $T_{complexity}$ where is the project design complexity factor (e.g., based on the number of design elements), $\sigma_{revision}$ where a fraction of time is added due to potential design revisions. Following the cost for design, the equation is demonstrated below, where is the cost of a design error and change, $\overline{UCD}_{kc}$ is the cost of designers for product k in consultancy c, T_D where is the number of hours for design. FDC is a fixed design cost. The model incorporates multiple consultants, focusing on the iterative, multidisciplinary design process rather than the final design product. Each consultant presents varying probabilities of rework, coordination delays, and domain-specific barriers that substantially affect the overall project cost, duration, and waste, despite all parties ultimately agreeing on a single final design

$$DEC = FDC + \sum_{k=1}^K \sum_{c=1}^C \overline{UCD}_{kc} T_D \quad (7.17)$$

Material preparation time is affected by the supplier and their load to the factory, In this formula Q_M , Where is the total quantity of materials to be prepared, R_S is the supply rate of materials (e.g., materials/hour), γ_l the efficiency of material preparation, and the time overhead due to

handling σ_s also added to the duration of material preparation. T_{lt} material preparation time. So, the formula is:

$$T_{Mp} = \frac{Q_M}{R_S} + \gamma_l \cdot T_{lt} + \sigma_s \quad (7.18)$$

The manufacturing time formula is represented below, Q_u is the number of units to be manufactured, R_p is manufacturing rate (e.g., units/hour), α_p is the efficiency of the production process, λ_s is setup time required for production, T_{dt} is additional time due to downtime (e.g. machine failure, labour shortage, material issues, etc.)

$$T_M = \frac{Q_u}{R_p \alpha_p} + \lambda_s + T_{dt} \quad (7.19)$$

The cost of preparation includes material preparation (MAC) and manufacturing costs (MC). In this equation, VCM represents fixed costs, while FCM denotes costs that remain flexible under disruptive conditions. A similar distinction applies to VCP (fixed costs) and FCP (flexible costs). Below is the cost equation for this process, N'_{rkw} is the raw material quantity for the reproduction of product k procured from supplier r in period w, LC_{kd} where is unit procurement labour cost for offsite product k during period d, N_f is the number of hours that labour works in the factory f, $\tilde{M}_{rk}$ is the unit procurement raw materials cost from supplier r for product k, Raw materials price is considered a triangular fuzzy number to account for price fluctuation (Lam et al., 2010). The expected value for the raw materials price can be written $\tilde{M}_{rk} \rightarrow E[\tilde{M}_{rk}] = 1/2[(1 - \pi)r_1 + r_2 + \pi r_3]$. N_{rkw} is the raw materials quantity for product k procured from supplier r in period w, I_{kw} is the production inventory for product k during preparation w, VO_{kf} is Unit volume production for product k in the factory f, C_{kf} is the unit inventory cost for product k in the factory f, I_{kd} is the production inventory for product k during production d, T_{Mp} is time of material preparation, T_M is manufacturing time.

$$\begin{aligned} MAC &= VCM + FCM \\ &= \left(\sum_{f=1}^F \sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W E(\tilde{M}_{rk}) N_{rkw} + 1/2(I_{k,w-1} + I_{kw}) VO_{kf} C_{kf} \right) T_{Mp} \end{aligned} \quad (7.20)$$

$$MC = VCP + FCP \quad (7.21)$$

$$= \left(\sum_{r=1}^R \sum_{f=1}^F \sum_{k=1}^K \sum_{d=1}^D E(\tilde{M}_{rk}) N_{kd} + 1/2(I_{k,d-1} + I_{kd}) VO_{kf} C_{kf} \right. \\ \left. + \sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W E(\tilde{M}_{rk}) N'_{rkw} + LC_{kd} N_f \right) T_M$$

After element preparation, the elements are ready to be transported to the site. Based on the factors that affect the transportation time equation, D_d , where is the distance between the factory and the construction site, V_s , where is vehicle speed, $\lambda_{l/unl}$, where is the time for loading and unloading T_T . T_d time of dealy during transportation based on any issues.

$$T_T = \frac{D_d}{V_s} + \lambda_{l/unl} + T_d \quad (7.22)$$

The cost-related transportation equation is:

$$VCT = FCT + \left(\sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W \frac{N_{skt}}{L_s} \cdot d_s E(\tilde{C}) + \sum_{r=1}^R \sum_{k=1}^K \sum_{t=1}^T \frac{N_{rkt}}{L_r} \cdot d_r E(\tilde{C}) \right) \cdot T_T \\ + \Delta IF(x) C_{tr} \quad (7.23)$$

C_{tr} is the rate of transported elements, N_{rkt} , is raw materials quantity for product k procured from supplier r procured in period t, L_r is the amount of raw material r that can be loaded on the truck, $E(\tilde{C})$ is the unit cost of truck transportation by unit distance, d_r , is the distance from supplier r to the factory, N_{skt} is the quantity of product k assembled at site s in period t, L_s is the quantity of panel product k that can be loaded on the truck d_s is the distance from the factory to the construction site s. And $\Delta IF(x)$ is the weather affected the transportation. For scheduling, the next step is assembly duration, shown in the equation below, Q_u the number of components or units to assemble, P_a is the assembly rate (units per day), α_a , is the utilisation factor (accounting for assembly efficiency), T_{cs} is the time for crane setup or operation, D_d , is the proportion of units requiring rework needed during assembly.

$$T_A = \frac{Q_u}{P_a \alpha_a} + T_{cs} + T_{dt} + \frac{Q_u}{P_a} \cdot D_d \quad (7.24)$$

Cost-related assembly equation is:

$$ASC = VCA + FCA$$

$$= FCA + \left(\sum_{k=1}^K \sum_{t=1}^T (\widetilde{AU}_k N_{skt} + LC_{kt} N_{skt}) \right) T_A + \Delta IF(x) C_a \quad (7.25)$$

$\widetilde{AU}_k$ is unit assembly and construction cost for product k at site s , LC_{kt} is unit procurement labour cost for offsite product k during period t , C_a is the rate of assembled elements. The extra operational cost on site is incurred when the daily demands on site are not met; then, the site is forced to operate beyond the planned initial working period to assemble the late-delivered panels, provoking an extra site cost. And $\Delta IF(x)$ is the weather affected the assembly.

The optimisation model evaluates material waste at five key stages of the OSC supply chain: raw-material procurement, design, manufacturing, transportation, and on-site assembly. Each stage reflects a distinct source of waste driven by defects, handling losses, rework, or project-specific inefficiencies. The corresponding formulations are described below. Raw material waste (W_R) represents the difference between the total quantity of material supplied Q_S and the portion that is usable in production Q_U . The unit of measurement is cubic metres, consistent with material-volume accounting used in timber and panelised systems. Design waste (W_D) reflects errors or inefficiencies introduced during the design phase. The term E_r represents the design error rate, which accounts for miscalculations, specification changes, detailing inconsistencies, or clash-related redesigns that force partial or complete reworking of already usable material Q_U . This captures situations where material is technically sound but cannot be used due to design revisions or inaccuracies. Manufacturing waste (W_M) consists of two components: M_L : material lost during manufacturing, such as cutting losses, trimming, breakage, or machining defects. R_p : production rework, referring to errors during fabrication that require replacement or correction of defective elements. Together, these components quantify the material inefficiencies inherent in factory-based production processes. Transportation waste, W_T , captures the quantity of material damaged during transport, represented by Q_D . Damage may occur due to improper loading, vibration/shock during travel, etc. This ensures that logistics-related losses are explicitly included in total waste estimation. Assembly waste represents the quantity of units damaged or rejected during installation at the construction site, denoted by W_A . This includes tolerance mismatches, handling errors, crane-related impacts, etc. Assembly waste therefore accounts for losses generated in the final stage of the OSC process, completing the full life-cycle waste tracking across the supply chain.

$$W_R = (Q_S - Q_U) \quad (7.26)$$

$$W_D = (E_r * Q_U) \quad (7.27)$$

$$W_M = (M_L + R_p) \quad (7.28)$$

$$W_T = (Q_D) \quad (7.29)$$

$$W_A = (Q_{DA}) \quad (7.30)$$

7.4.5 Model output

The output of this model minimises three objectives simultaneously (cost, time, and waste). The equation shows the total cost of SC.

$$C_{Total} = C_{material} + C_{design} + C_{manufact} + C_{transport} + C_{assembly} \quad (7.31)$$

$$T_{Total} = T_{material} + T_{design} + T_{manufact} + T_{transport} + T_{assembly} \quad (7.32)$$

$$W_{Total} = W_{material} + W_{design} + W_{manufact} + W_{transport} + W_{assembly} \quad (7.33)$$

And the ε -constraint is utilised to optimise these objectives. By treating time and waste as restricted objectives and minimising cost, the ε -constraint method redefines the multi-objective problem as a single-objective program. Therefore:

$$\text{Minimize } C_{Total}, T_{Total} < T \text{ \& } W_{Total} < W$$

7.4.6 Method GWO & Surrogate Machine Learning

The design to assemble the panelised system is an optimisation problem based on a multi-objective closed-loop SC network. In recent years, intelligent optimisation algorithms have emerged as the primary remedy for this issue (Nesarnobari et al., 2024b; Wuni & Shen, 2020a). Due to its structured exploration–exploitation mechanism, the Grey Wolf Optimiser (GWO) was selected for this study as a suitable metaheuristic to explore the complex solution space. As with other metaheuristic methods, its effectiveness depends on problem characteristics and parameter configuration, and it does not guarantee avoidance of premature convergence (Liu et al., 2022; Mirjalili et al., 2014; Tu et al., 2023). The GWO employs a leadership-based hierarchy that offers a structured search process, while genetic algorithms utilise stochastic genetic operators; as with all metaheuristics, the performance of both approaches is problem-dependent and influenced by parameter configuration. (Pace, 2022; Yu et al., 2023; Zhang, Dai,

& Shi, 2024). Mirjalili et al. (2014) presented the GWO, a metaheuristic algorithm inspired by nature (Mirjalili et al., 2014). The algorithm's search premise is straightforward, easy to apply, and offers a high accuracy of convergence and a quick solution time. Numerous optimisation difficulties have been effectively resolved using it (Arora & Kohli, 2018; Mirjalili et al., 2014; W. Long et al., 2016; Xingyu Jiang et al., 2020; Yao & H. L. Wang, 2016; Z. L. Wei et al., 2016). The algorithm simulates the three main hunting behaviours to search for, encircle, and attack prey. In a grey wolf pack, the alpha wolf serves as leader, making key decisions about activities like hunting, resting, and moving forward. The beta wolf, acting as a secondary leader, supports the alpha by helping with these decisions. The delta wolf follows the directives given by both alpha & beta, executing their orders and holding authority over omega wolf, who is at lowest rank. Overall, GW population is structured into a hierarchy with these distinct roles.

Encircling Prey: In the first stage, wolves begin to encircle the prey. This behaviour is mathematically modelled by updating each wolf's position relative to the best-known solution. Coefficient vectors are applied to balance exploration and exploitation, while the distance between the wolf's current position $X(t)$ and the prey's position $\vec{X}_p(t)$ is calculated and progressively reduced as wolves adjust their positions. This process simulates the wolves' natural tendency to close in on their target, bringing candidate solutions closer together and narrowing the search space toward promising optima. The distance is computed as follows:

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)|$$

Here, C is a coefficient vector defined as:

$$\vec{C} = 2\vec{r}_2$$

with v being a random vector in $[0,1]$. The wolf's position is then updated using:

where the coefficient A is given by:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a}$$

with a decreasing linear function from 2 to 0 over the iterations, and $r1_r1$ as another random vector in $[0,1]$. This mechanism causes the wolves to progressively tighten their circle around the prey.

Hunting: The hunting phase begins once the prey is encircled. At this stage, the leadership hierarchy, comprising the alpha, beta, and delta wolves, plays a central role. These wolves

represent the three best candidate solutions, and the rest of the pack adjusts their positions according to their influence. This cooperative movement refines the search, improves accuracy, and increases the likelihood of reaching the global optimum by effectively balancing exploration and exploitation. In this stage, the top three candidate solutions, represented by the alpha(α), beta(β), and delta(δ) wolves, guide the pack. The distances of a given wolf X from these leaders are computed as:

$$\vec{D}_\alpha = |\vec{c}_1 \cdot \vec{X}_\alpha(t) - \vec{X}(t)|, \quad \vec{D}_\beta = |\vec{c}_2 \cdot \vec{X}_\beta(t) - \vec{X}(t)|, \quad \vec{D}_\delta = |\vec{c}_3 \cdot \vec{X}_\delta(t) - \vec{X}(t)|$$

with corresponding coefficient vectors $\vec{c}_1$, $\vec{c}_2$, and $\vec{c}_3$ defined similarly to C . The candidate position updates based on each leader are:

$$\vec{X}_1 = |\vec{X}_\alpha(t) - \vec{A}_1 \cdot \vec{D}_\alpha|, \quad \vec{X}_2 = |\vec{X}_\beta(t) - \vec{A}_2 \cdot \vec{D}_\beta|, \quad \vec{X}_3 = |\vec{X}_\delta(t) - \vec{A}_3 \cdot \vec{D}_\delta|$$

where each A_i is calculated as: $\vec{A}_i = 2\vec{\alpha} \cdot \vec{r}_{1,i} - \vec{\alpha}$

Finally, the wolf's new position is determined by averaging these three positions:

$$\vec{X}(t+1) = \left(\frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \right)$$

This cooperative strategy enables the pack to exploit the best solutions found so far by converging their search around the prey.

Attacking Prey: During the attack phase, the algorithm shifts from exploration to exploitation as wolves close in on the prey. Step sizes are reduced to fine-tune positions, while the decreasing exploration parameter directs the wolves to converge around the prey. This focused search strengthens convergence and enables the algorithm to effectively “capture” the optimal solution.

In the attacking phase, the wolves close in on the prey by making finer adjustments. This is achieved by gradually reducing the value of $|A|$ (i.e., ensuring $|A| < 1$) so that the wolves take smaller, more precise steps toward the prey. The same position update formula is applied:

$$\vec{X}(t+1) = \vec{X}_p(t+1) - A \cdot |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)|$$

As the coefficient A decreases, wolves converge tightly around the prey, marking the “attack” phase where the search shifts from exploration to exploitation. This process refines solutions until an optimal or near-optimal candidate is reached. GWO has proven effective in addressing complex optimisation problems across fields such as SCM and engineering design. In this

study, GWO was applied to optimise the outputs of SD model, focusing on minimising material waste, time, and cost in OSC. The integration of GWO with SD modelling provided a robust framework for data-driven decision-making and improved SC efficiency (Mirjalili et al., 2014). Specifically, the system dynamics model was used to generate behavioural simulation data, surrogate models were trained on the SD outputs, and the optimisation was performed on the surrogate-based objective functions. GWO is particularly well-suited to construction SCM, where supplier selection, order allocation, production, transport, assembly must be coordinated under uncertainty. Its ability to manage nonlinear, discontinuous, multimodal cost functions allows it to balance exploration and exploitation effectively, producing reliable solutions in complex environments (Alejo-Reyes et al., 2020). With its conceptual simplicity and minimal parameter requirements, GWO integrates easily into existing SCM models, enhancing scheduling, dispatching, and resource use. Prior studies confirm its capacity to reduce costs, improve time management, strengthen competitiveness in construction SC (Pham et al., 2023). The framework of this research is presented in Figure 7.3.

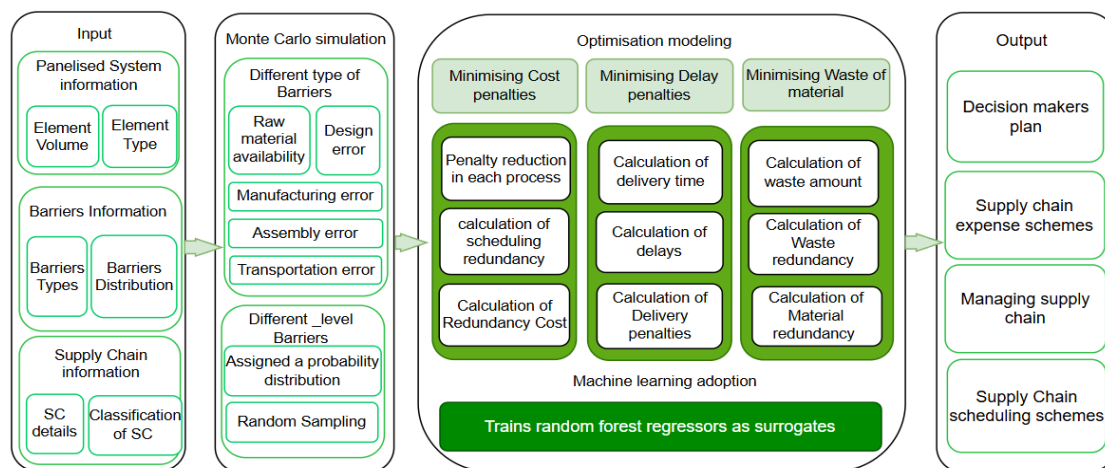


Figure 7-3: Framework of GWO

In this study, the Multi-Objective Grey Wolf Optimiser (MOGWO) was adopted (Makhadmeh, 2022) to minimise three conflicting objectives, total cost, total time, and total waste, across the probabilistic OSC supply chain (Sadeghi et al., 2023). The decision variables are modelled as continuous probability parameters (e.g., weather, traffic, labour and crane availability, material quality, machine failure) (Hsu et al., 2018a) and each evaluation of the objective function involves Monte Carlo simulation, making the optimisation problem highly non-linear, multi-objective, and computationally expensive (Frazier, 2018: Forrester, 2008 #1590). To address these characteristics, the classical GWO leadership hierarchy and position update mechanism (Mirjalili et al., 2014) was extended to a multi-objective setting using a Pareto-based archive

of non-dominated solutions (Mirjalili et al., 2016), from which three leaders are sampled to guide the swarm. This formulation enables the algorithm to approximate a diverse Pareto front of cost–time–waste trade-offs rather than collapsing the problem into a single scalar objective. Furthermore, to reduce the computational burden of repeatedly calling the simulation model, a surrogate-assisted strategy was employed, whereby three Random Forest regressors approximate cost, time, and waste, and MOGWO searches this surrogate space. During the optimisation phase, surrogate models replace computationally expensive simulation-based objective functions, while SD-based Monte Carlo simulations are used to generate and periodically update the surrogate training data. This combined MOGWO–surrogate framework is therefore well aligned with the stochastic, continuous, and computationally intensive nature of the proposed OSC-SC optimisation problem.

In optimisation problems, surrogate-based machine learning is employed when evaluating the actual objective function, which is computationally expensive, time-consuming, or involves complex models (Frazier, 2018). Rather than directly optimising the costly function, a surrogate model is trained on a limited set of evaluations to approximate the objective function. The computationally demanding objective functions cost, time, and waste were approximated using a surrogate modelling technique that used Random Forest regression. Across the specified decision variable space, 100 simulation-based samples and adaptive expansion 0.1 produced by Monte Carlo sampling using a 70/30 train–validation split, reporting predictive accuracy with R^2 /MAE/RMSE under 10 repeated hold-out runs (Yan et al., 2019). Like adaptive/self-learning GWO variants that modify step-size or convergence dynamics to prevent premature stagnation, the adaptive expansion coefficient=0.1 strikes a balance between exploration and exploitation. The model was re-fit every 5 iterations, ensuring robustness was quantified with independent validation rather than assumed (Zhang & Cai, 2024). These were used to train three distinct Random Forest regressors, each of which was made up of 50 decision trees. The dataset was divided into input variables that represented probability elements and outputs that corresponded to the objectives derived from the simulation; random-state control and consistent hyperparameter selection ensured model robustness even if cross-validation was not explicitly used. This model then predicts the function’s behaviour in unexplored regions of the design space, guiding the optimiser toward promising solutions (Shahriari, 2016). After each optimisation step, new candidate points are evaluated using the actual objective function, and the surrogate model is retrained with the new data to improve its accuracy. This iterative process continues until convergence to a satisfactory solution is achieved. Such an approach

not only reduces the computational burden but also enhances the efficiency of the search, as demonstrated in studies by (Forrester, 2008; Jones et al., 1998). Figure 7.4 presents the surrogate-assisted Grey Wolf Optimisation framework adopted in this study, clearly distinguishing between computationally expensive simulation-based evaluations and surrogate-based objective predictions used during the optimisation process.

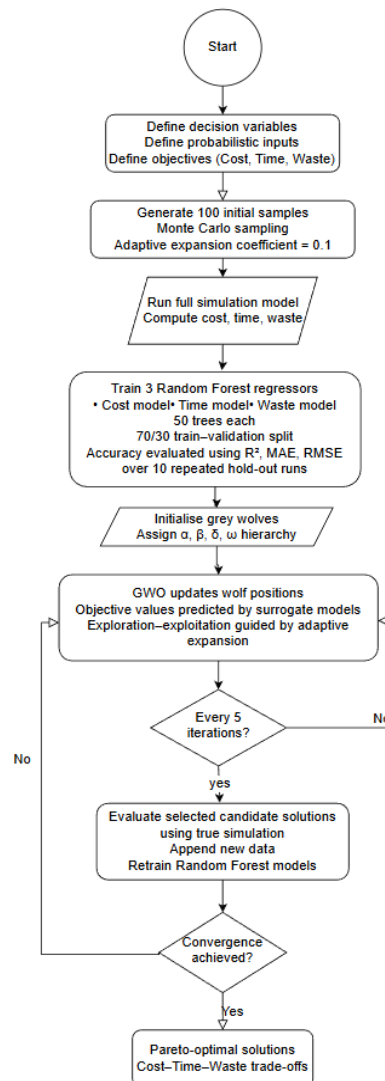


Figure 7-4: Flowchart of Optimisation

7.5 Supply Chain Barriers

The literature review and expert interviews were used to identify the dominant barriers affecting OSC supply chain performance. Event probabilities were obtained from published studies, project records, and expert judgement. Where available, rates of design errors, material delays, and equipment failures were extracted from empirical data; for barriers lacking direct evidence, probabilities were estimated based on industry trends. The CLD provides a

qualitative representation of the system's feedback structure (Ding et al., 2016). It depicts the causal relationships among key OSC–SCM variables and highlights the reinforcing and balancing feedback mechanisms that may amplify delays or stabilise processes (Hongping, 2011). Reinforcing loops (R1–R4) represent how labour constraints, material shortages, weather conditions, crane breakdowns, and design faults can compound delays and intensify cost and time pressures, while also capturing interdependencies among material demand, transport flows, and installation activities. As a qualitative tool, the CLD (Figure 7.5) identifies structural points where delays, cost escalation, or resource bottlenecks are likely to arise. To enable quantitative analysis, the CLD was translated into a stock–flow model using Vensim. In the quantitative model, system conditions, such as material inventory, production backlog, and assembly queue, were represented as stock variables, while manufacturing rate, transport rate, and assembly completion rate were modelled as flows. Probabilistic disruption factors, including rainfall, wind speed, material failures, design errors, labour shortages, and crane unavailability, were incorporated into flow equations as multiplicative modifiers (e.g., delay factors and capacity-reduction terms). These parameterised relationships allow barrier probabilities to dynamically alter flow magnitudes and propagate through the supply chain during simulation. Sensitivity analysis was performed to test the robustness of the quantitative model, given the uncertainty associated with the disruption probabilities. Key probability inputs were systematically varied, such as weather delays, crane failures, and material-related disruptions, while all other parameters were held constant. Adjusting selected probabilities by 10–15% enabled a quantifiable assessment of how each barrier influenced the resulting time, cost, and waste trajectories, thereby identifying the most influential barriers and supporting prioritisation of mitigation strategies in OSC–SCM.

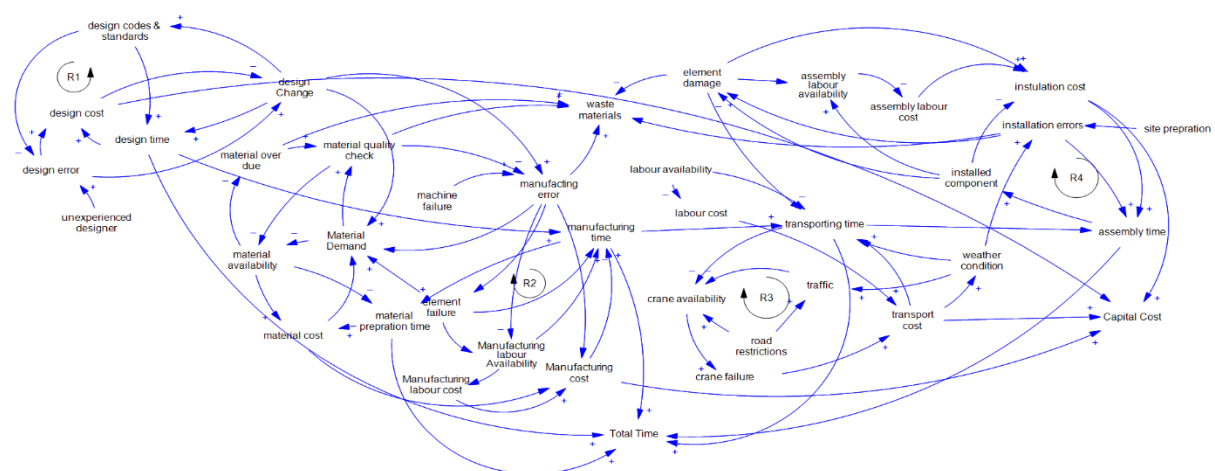


Figure 7-5: Causal-Loop diagram for OSC-SCM

7.6 Case study: Offsite Panelised System for the Residential Sector

To validate the effectiveness of the proposed model, this study conducted case studies on a representative offsite residential project in New Zealand. In this section, scenarios were designed, consisting of standard floor configurations. These scenarios were then subjected to data experiments. By evaluating the results of these case examples, model's performance and effectiveness in coordinated scheduling, budget and waste management problems of panelised resources, production, transportation and assembly considering SC barriers were rigorously tested and validated. Python is a versatile high-level language valued for its readability, portability, extensive library support, making it widely adopted across management applications. It has been used to build systems like library management platforms that improve efficiency through automation, and in portfolio management for implementing advanced financial models and optimisation techniques. Its simplicity and strong ecosystem of scientific and analytical libraries continue to drive its popularity (Srinath, 2017).

7.6.1 Case Background and Parameters

This study examines a medium-density residential project in Auckland, New Zealand, where a panelised OSC system is used to construct 250 two-storey buildings with prefabricated walls, floors, and staircases. The analysis used construction and transport data from the selected 24-month project segment (Figure 7-6). While valuable, results from a single area are not directly generalisable, as SC conditions vary widely across regions. Rural areas often face poor infrastructure, low efficiency, and high circulation costs, while urban contexts involve multiple nodes, short distances, and smaller batch deliveries. A logistics system designed for a dense city like Auckland may not function effectively in rural settings with limited road networks or warehouse capacity. International comparisons reveal that while exporting the same goods over the same distance costs 57% more from low-income countries, domestic trading costs in some developing countries are three to fourteen times higher than those in the United States. Low-income countries also have transportation costs that are about twice as high as those in high-income countries. Because of these discrepancies, which are caused by differences in market maturity, legal frameworks, and infrastructure quality, optimisation criteria like resource availability, supplier dependability, pricing, transit times can vary significantly between areas. The results of the Auckland instance should be realised as context-specific. Applying this optimisation method elsewhere would require recalibrating parameters for local conditions such as delivery distances, transport costs, supplier structures, and capacity limits. A multiple-

case research design across diverse places would test model's robustness, clarify which findings are unique to Auckland and which are generalisable.



Figure 7-6: Production, Transportation and Assembly Schematics of the Panelised System.

Data on component requirements, delivery schedules, vehicle loading, and transport times were gathered from operation plans, construction logs, and professional discussions. The prefabrication factory's trucks have a 30-ton capacity, with the site located 150 km away. Loaded transport operates at 40 km/h (25 km/h for oversized elements), with loading/unloading times of 20–40 minutes (40–60 min for oversized). Each two-storey house has 104 m² of floor area. Raw material preparation for panels takes 1 day, followed by simultaneous production of three elements in 1 hour using three machines. Delays incur a penalty of 10 per hour. Transport typically takes 3–4 hours, and onsite assembly of each unit requires 2 days. Table 7.1 summarises the project parameters.



Figure 7-7: The construction site of the project.

Table 7.1: Input parameters of the model

Data names	Parameter
Number of the construction site	1 site
Type of the panelised offsite system	3(wall, floor, stair)
Maximum numbers of panels can be manufactured	3 per hour
Maximum number of panels can be designed	15 days
Maximum of panels can be transported	20 panels
Maximum numbers of panels can be assembled	18 panels per day
Raw material cost of panel products	590\$
Design cost of panel products	350\$/h
Manufacturing cost of panel products	800 \$/m3
Transportation cost of panel products	310 \$/h
Assembly cost of panel products	150 \$/m2
Construction site fix cost (overhead)	2160\$/day
Maximum storage capacity on site	21 m ³
Maximum storage capacity at the warehouse	30 m ³
Inventory cost on site	2\$ m ³ /day
Inventory cost on warehouse	3\$ m ³ /day
Inventory cost at the factory	1\$ m ³ /day
Volume of the panel products	5280m ³ ,12000m ³
Distance between factory and warehouse	50km
Distance between warehouse and site	55km
Panels can be loaded on a truck from the warehouse to the site	20panels/truck
Maximum manufacturing fixed cost in a factory	2010\$/day
Maximum manufacturing rate	8 panels a day
Variable manufacturing cost	1000\$/panel
Adjustment factor for variable manufacturing cost	0.2

7.6.2 Quantifying the Barriers in the Panelised Supply Chain Process

For quantifying the barriers, the information on the primary causes of delays was gathered from relevant recourses of the case study, then the severity of schedule deviations of the various barriers to delay and expenses was quantified, and lastly, the mathematical formulation patterns

were used to establish the different patterns. Based on them, the possible scenarios were applied to find the best solution. Some barriers identified in the qualitative analysis are represented in the CLD using operational or measurement-oriented terminology. For example, material quality is captured through the variable Material Quality Check, while material importing and supply issues are represented through Material Availability and related procurement delay mechanisms.

7.6.2.1 Raw Materials-related barrier

The literature review and expert interviews were used to identify the dominant barriers affecting OSC supply chain performance. Event probabilities were obtained from published studies, project records, and expert judgement. Where available, rates of design errors, material delays, and equipment failures were extracted from empirical data; for barriers lacking direct evidence, probabilities were estimated based on industry trends. The CLD provides a qualitative representation of the system's feedback structure (Ding et al., 2016). It depicts the causal relationships among key OSC–SCM variables and highlights the reinforcing and balancing feedback mechanisms that may amplify delays or stabilise processes (Hongping, 2011). Reinforcing loops (R1–R4) represent how labour constraints, material shortages, weather conditions, crane breakdowns, and design faults can compound delays and intensify cost and time pressures, while also capturing interdependencies among material demand, transport flows, and installation activities. As a qualitative tool, the CLD (Figure 7.5) identifies structural points where delays, cost escalation, or resource bottlenecks are likely to arise. To enable quantitative analysis, the CLD was translated into a stock–flow model using Vensim. In the quantitative model, system conditions, such as material inventory, production backlog, and assembly queue, were represented as stock variables, while manufacturing rate, transport rate, and assembly completion rate were modelled as flows. Probabilistic disruption factors, including rainfall, wind speed, material failures, design errors, labour shortages, and crane unavailability, were incorporated into flow equations as multiplicative modifiers (e.g., delay factors and capacity-reduction terms). These parameterised relationships allow barrier probabilities to dynamically alter flow magnitudes and propagate through the supply chain during simulation. Sensitivity analysis was performed to test the robustness of the quantitative model, given the uncertainty associated with the disruption probabilities. Key probability inputs were systematically varied, such as weather delays, crane failures, and material-related disruptions, while all other parameters were held constant. Adjusting selected probabilities by 10–15% enabled a quantifiable assessment of how each barrier influenced the resulting time,

cost, and waste trajectories, thereby identifying the most influential barriers and supporting prioritisation of mitigation strategies in OSC–SCM.

Table 7.2: Raw material-related barriers

Barriers	probability
Raw material importing issues	3%
Material quality	4%
Raw material availability	12%

7.6.2.2 Design-related barriers

Based on triangulation approach and supporting documentation, design changes in panelised construction are primarily triggered by limited designer experience, incomplete coordination with engineers, and insufficient stakeholder communication. These factors were translated into probability values representing the likelihood of design revisions and errors, which directly influence design duration and rework costs in the quantitative model. Design-change probability increases the expected number of revisions, thereby extending engineering time and raising associated labour and overhead expenses. Because panelised systems typically finalise designs prior to manufacturing, the baseline probability of design errors is assumed to remain below 5%, consistent with industry practice. Furthermore, simpler and more standardised panel configurations decrease the likelihood of design rework by reducing modelling effort and interface complexity, which subsequently lowers error-related time and cost impacts.

7.6.2.3 Manufacturing-related barrier

Manufacturing-stage barriers in panelised production include CNC machine failures, raw material defects, labour shortages, and delays associated with importing specialised equipment. The probability values applied in this study were derived from a combination of factory operational logs, interviews with production managers, and cross-checks against typical performance patterns in the New Zealand offsite manufacturing sector. Factory managers reported that material-quality issues are effectively negligible because most timber components are manufactured in-house, with only adhesive products sourced externally. In contrast, CNC machine failures and equipment importation delays represent meaningful disruptions, with an estimated combined probability of 20%, reflecting the frequency of intermittent mechanical faults and the long international lead times reported in previous project cycles. Labour shortages were quantified based on daily workforce records and supervisor assessments, indicating approximately 10% probability of insufficient skilled operators and 5% probability

of general workforce unavailability, even with a mandatory five-hour equipment training programme in place. These percentages correspond to the proportion of production days in which performance falls below standard operating capacity. These values directly influence the quantitative model by reducing effective production rates and increasing downtime or rework-related costs during simulation runs. Machine failures decrease available processing capacity and extend activity durations, while labour shortages slow production flow and contribute to schedule variability. Case study evidence further demonstrates that worker availability is influenced by fatigue, task switching, and fluctuating daily productivity-factors that exacerbate uncertainty in manufacturing performance and justify incorporating these probabilistic disruptions into the supply chain model.

7.6.2.4 Transport-related barriers

Transportation performance in panelised OSC is primarily influenced by crane availability, traffic conditions, and weather-related disruptions. Although road load limits apply in central urban areas, they do not significantly affect medium-density housing projects in this case study. Weather conditions, particularly high winds and heavy rainfall, pose a more substantial risk, as they reduce transport speed, increase travel-time variability, and raise the likelihood of panel damage during handling and movement. Based on the case study and route characteristics, urban roads were assigned a low probability of barriers, while rural windy roads and mountain-pass routes were assigned medium probabilities of delay (Table 7.3). These probability values directly modify the transport-time and damage-rate parameters in the quantitative model: higher disruption probabilities increase expected travel time and fuel/labour costs, while also elevating the likelihood of transport-related waste from damaged elements.

Based on the triangulation methodology, design changes are influenced by factors such as the lack of experienced designers, poor communication with engineers, and limited stakeholder awareness. Inexperienced designers, the absence of proper codes, and inadequate communication with the design team contribute to design changes. Consequently, the probability of design changes and errors arising from these challenges and their impact on design costs is outlined in the table below. The probability of design errors in the panelised system is kept below 5% due to the finalisation of the design before the manufacturing process begins. Additionally, if the design is simple, the assembly and manufacturing processes will be easier, resulting in fewer errors.

Table 7.3: Probability of route segmentations and weather impact on transportation

Route segmentations	Probability	Weather impact	Probability
Urban road	0.02(low)	Clear weather	1
Windy rural road	0.04(medium)	Rainy day	1.3
Mountain pass	0.06(high)	Heavy rain or wind	1.5

In cases where transportation errors cause element failure, delivery loads are reduced to one-third of capacity. Traffic presents another challenge for transporting heavy elements, as early departures may avoid some constraints but cannot fully mitigate unpredictable events such as accidents, crane failures, or labour shortages. Based on site event logs, this study assumes that when such incidents occur, daily transport rates fall to roughly half of the planned deliveries (Table 7.4).

Table 7.4: Probability of traffic impact on transportation

Delivery status	Probability	Affected transportation
Normal	98%	18
late	2%	9

Although offsite elements are produced in controlled environments, transportation and assembly remain highly vulnerable to weather. Strong winds and heavy rain create major challenges, with prior studies identifying weather as one of the most critical barriers in OSC-SC (Hsu et al., 2018a). P.-Y. Hsu et al. further modelled these effects using a semi-trapezoidal relationship.

$$\Delta IF(x) = \begin{cases} 1 & , \quad 0 \leq x < a \\ 1 - \frac{(x - a)}{(b - a)} & , \quad a \leq x < b \\ 0 & , \quad x \geq b \end{cases}$$

Here, ΔIF denotes the influencing factor adjusted by weather condition. X Parameter a represents the threshold, the maximum wind speed or rainfall that does not impact transport; while b is the cancellation point at which construction halts. For wind, a=36 km/h and b=50 km/h (Li et al., 2013). For rain, a=5 mm/h, b=10 mm/h (Jung et al., 2016). The disrupted transport rate is calculated as the original rate multiplied by ΔIF . Potential daily assembly rates and their probabilities are then derived from historical weather data shown below.

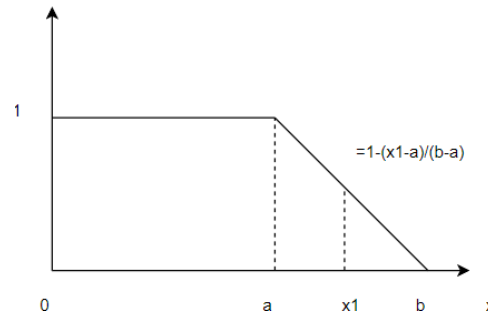


Figure 7-8: Relationship between weather conditions and the impacting factors

A semi-trapezoidal function Historical data is essential for predicting weather-related risks. This study draws on Auckland meteorological records from the New Zealand Met Service, including 63 years of daily rainfall data (1960–2023) and 28 years of wind speed data (1995–2023). A semi-trapezoidal function (Hsu, 2018; Gündüz, 2013) was applied to link module assembly rates with weather conditions, with interval values summarised in Table 7.5. The transportation impact reported in Table 7.5 is a dimensionless, normalised operational performance indicator. It represents the relative effectiveness of transportation activities under different weather conditions, scaled between 0 (complete disruption) and 20 (nominal operating conditions). These impact values are subsequently used within the stochastic simulation to adjust the effective transportation rate or travel time conditional on the realised weather scenario.

Table 7.5a: Probability of rainfall amounts across different intervals and factors affecting transportation rates

RAINFALL INTERVALS (MM/H)	PROBABILITY (%)	TRANSPORTATION IMPACT
$0 \leq \text{RAINFALL} < 5$	82.16	20
$5 \leq \text{RAINFALL} < 6$	2.31	16
$6 \leq \text{RAINFALL} < 7$	1.99	12
$7 \leq \text{RAINFALL} < 8$	1.55	10
$8 \leq \text{RAINFALL} < 9$	1.39	6
$9 \leq \text{RAINFALL} < 10$	1.10	4
$\text{RAINFALL} \geq 10$	9.52	0

Table 7.5b: Probability of wind amounts across different intervals and factors affecting transportation rates

WIND SPEED INTERVALS (KM/HR)	PROBABILITY (%)	TRANSPORTATION IMPACT
0 ≤ WIND SPEED < 36	35.18	20
36 ≤ WIND SPEED < 38	2.97	18
38 ≤ WIND SPEED < 40	7.33	16
40 ≤ WIND SPEED < 42	5.35	12
42 ≤ WIND SPEED < 44	4.76	10
44 ≤ WIND SPEED < 46	4.06	8
46 ≤ WIND SPEED < 48	3.17	5
48 ≤ WIND SPEED < 50	2.38	3
Wind speed ≥ 50	35.18	0

7.6.2.5 Assembly-related barriers

Assembly-stage barriers in panelised construction arise from land conditions, weather exposure, labour shortages, and crane availability. In New Zealand, topographical constraints introduce a 5% probability of land-related disruptions, which in the quantitative model reduce the effective assembly rate and extend the onsite duration. Crane availability, although generally reliable, is occasionally impacted by mechanical faults; interviews confirmed that even a single breakdown can halt lifting operations, so a 2% crane-failure probability was applied. All site workers completed two hours of equipment and safety training; however, daily assembly logs showed substantial variability in labour productivity. Productivity discount factors were therefore derived from recorded availability rates and historical assembly outputs, and then validated by the site manager. These probability-based factors directly modify the assembly-rate equations in the model, increasing expected time and labour costs and, in some cases, elevating the risk of installation-related waste (Table 7.6). Labour and crane availability were modelled using probabilistic status levels, where normal availability (with no productivity discount) occurred 80% and 98% of the time, respectively. Meanwhile, medium or low availability, associated with productivity discounts of 0.7 or 0.5, occurred with lower probabilities, reflecting reduced operational capacity.

Table 7.6: Crane and labour availability impact on assembly

Barriers	Status	Discount rate	Probabilities
Labour availability	Normal	1	80%
	Medium	0.7	15%
	Low	0.5	5%
Crane availability	Normal	1	98%
	Low	0.5	2%

The table below illustrates the impact of weather on the assembly rate. The adjusted assembly rate is calculated by multiplying the original assembly rate by ΔIF . Historical weather forecast data is used to determine the possible daily assembly rates of panels and their associated probabilities. The “assembly impact” reported in Table 7.7 is a dimensionless, normalised operational performance indicator. It represents the relative effectiveness of assembly activities under different weather conditions, scaled between 0 (complete disruption) and 18 (nominal operating conditions). These impact values are subsequently used within the stochastic simulation to adjust the effective assembly rate or assembly time conditional on the realised weather scenario.

Table 7.7a: Probability of rainfall amounts across different intervals and factors affecting assembly rates

Rainfall intervals (mm/h)	Probability (%)	Assembly impact
$0 \leq \text{rainfall} < 5$	82.16	18
$5 \leq \text{RAINFALL} < 6$	2.31	14
$6 \leq \text{RAINFALL} < 7$	1.99	11
$7 \leq \text{RAINFALL} < 8$	1.55	9
$8 \leq \text{RAINFALL} < 9$	1.39	5
$9 \leq \text{RAINFALL} < 10$	1.10	3
$\text{RAINFALL} \geq 10$	9.52	0

Table 7.7b: Wind speed probabilities fall within various intervals, each related to barriers in the assembly rate.

WIND SPEED INTERVALS (KM/HR)	PROBABILITY (%)	ASSEMBLY IMPACT
$0 \leq \text{WIND SPEED} < 36$	35.18	18
$36 \leq \text{WIND SPEED} < 38$	2.97	16
$38 \leq \text{WIND SPEED} < 40$	7.33	13
$40 \leq \text{WIND SPEED} < 42$	5.35	10
$42 \leq \text{WIND SPEED} < 44$	4.76	9
$44 \leq \text{WIND SPEED} < 46$	4.06	7
$46 \leq \text{WIND SPEED} < 48$	3.17	5
$48 \leq \text{WIND SPEED} < 50$	2.38	2
Wind speed ≥ 50	35.18	0

7.7 Result Analysis

The multi-objective optimisation framework evaluates project duration, cost, and material waste simultaneously, allowing for improvements in one objective to be examined alongside their effects on the others. Using the GWO in a multi-objective setting (Mirjalili et al., 2014), the model generates a set of Pareto-optimal solutions rather than a single plan, allowing project managers to visualise trade-offs between competing goals. Interview participants consistently indicated that major disruptions can elevate resource utilisation and associated costs by

approximately 20–25% under accelerated or constrained project conditions. These interview-based estimates were used as indicative ranges to calibrate the relative severity of barriers before quantitative modelling. At the same time, the computed Pareto front captures the resulting trade-offs more rigorously, showing, for example, that shortening project duration frequently requires higher expenditure or leads to increased waste.

barriers are represented through MCS, which treats barrier-related inputs (e.g., weather variation, traffic, material failure, machine downtime, and labour or crane availability) as random variables rather than fixed values. MCS generates a distribution of possible project outcomes, cost, waste, and duration, providing a probabilistic characterisation of barrier effects and revealing the likelihood of cost overruns or schedule delays (Pant & Srinivas., 2019). This is particularly valuable in OSC, where activity durations and material flows are inherently variable (Hussein, Eltoukhy, Darko, & Eltawil, 2021). In this study, thirteen influential barriers define the decision space and contribute to a comprehensive objective function that estimates the expected time, cost, and waste across the simulated scenarios. The GWO algorithm then searches this space, repeatedly assessing candidate solutions under randomly sampled conditions (Zhou, Zhang, et al., 2013), and rapidly drives the population toward high-performing regions. Convergence plots for cost and time confirm this behaviour: both exhibit substantial variability in early iterations, followed by a steady decline and stabilisation at lower values, consistent with the fast-convergence patterns reported for metaheuristic algorithms in the literature (Mirjalili et al., 2014; Pant & Srinivas., 2019).

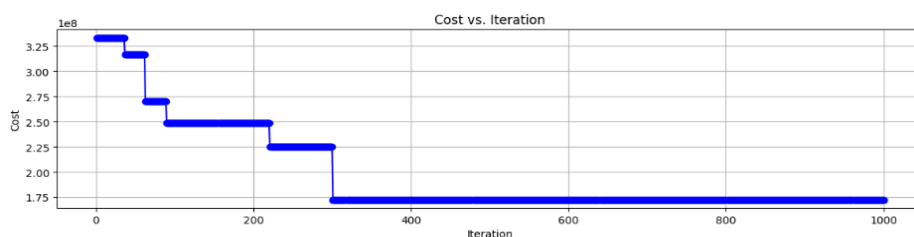


Figure 7-9: Cost-iteration Diagram

A set of key indicators was defined to evaluate the effectiveness of the GWO-based optimisation by comparing the optimised OSC plan with the original (pre-optimisation) project plan. Percentage improvements in material waste, total cost, and project duration were selected as the primary indicators, as they directly reflect the objectives of the multi-objective optimisation model. Specifically, the analysis measured: (1) Waste Reduction: the decrease in material waste generated during production, transport, and assembly; (2) Cost Savings: the reduction in the overall project expenditure; and (3) Time Efficiency Improvement: the

reduction in total project duration and the associated improvement in schedule performance. These indicators quantify the performance gains achieved by the optimised solution relative to the baseline, and the results are summarised in Table 7.1. The main findings are described below:

Table 7.8: Summary of Results

Objective	Minimum achievement	Maximum achievement	Optimal achievement
Cost (NZD)	1.722668e+08	2.028495e+08	1.766668e+08
Time (Days)	6.345644e+02	1.346775e+03	7505644e+02
Waste (m3)	2.325000e+01	2.558929e+01	2.325000e+01

7.7.1 Cost Result Analysis

Cost optimisation demonstrated potential savings of up to 7.8%. A major contributor to this improvement was the selection of cost-efficient yet durable panel materials that strike a balance between affordability and performance requirements. Logistics-related savings were also significant, arising from improved scheduling, optimised routing, and the reduction of transport delays. These gains were further supported by closer supplier coordination and more effective inventory management. However, the analysis also revealed necessary trade-offs. Pursuing the lowest-cost alternatives sometimes extended the overall project duration, particularly when cheaper suppliers or materials had longer lead times. Likewise, a strong emphasis on cost occasionally resulted in slight increases in material waste, as standardised component sizes did not always align with project-specific geometries, leading to additional trimming and offcuts. These outcomes reflect the inherent tension between competing objectives in offsite panelised construction and highlight the need to balance cost savings with schedule efficiency and material performance.

7.7.2 Time Result Analysis

Optimisation of the construction duration produced a notable 10% reduction, driven primarily by the effective standardisation of panel designs. Applying consistent panel specifications across multiple project elements reduced design complexity, accelerated approvals, and streamlined factory production workflows. Enhanced logistics performance contributed further to these improvements by ensuring timely component deliveries, reducing idle labour time, and minimising barriers on site. Shorter assembly phases and smoother handovers between construction activities were enabled through proactive route planning, coordinated scheduling, and strong collaboration with suppliers.

However, these time gains were accompanied by trade-offs. Achieving shorter durations occasionally increased project costs, particularly when accelerated manufacturing was required. Overtime shifts and compressed production windows elevated labour expenses and carried potential implications for worker fatigue and productivity. Additionally, meeting tight deadlines sometimes required priority procurement or premium freight services, further raising costs. These findings illustrate that although substantial schedule improvements are achievable, realising optimal outcomes in panelised OSC requires careful management of the cost–time trade-offs inherent in accelerated project delivery.

7.7.3 Material Waste Analysis

Waste optimisation yielded a 4–5% reduction, driven largely by improved design precision, more accurate material forecasting, and the implementation of just-in-time material management practices. The use of advanced CNC and automated cutting technologies further reduced dimensional errors and offcuts, lowering both material consumption and the labour required for rework. These efficiencies generated downstream cost benefits through reduced procurement volumes and shorter overall task durations. The GWO framework contributed to these improvements by optimising resource allocation and identifying opportunities for task overlap, thereby reducing project duration without introducing additional cost burdens. Early project turnover, lower indirect expenses, and reduced exposure to schedule disruptions highlight the advantages of simultaneously optimising waste, time, and cost.

However, the analysis also revealed notable trade-offs. Aggressive waste-reduction strategies often required higher-quality raw materials and more extensive early-stage planning, both of which increased upfront expenditure and, in some cases, extended pre-construction timelines. These outcomes emphasise that stakeholders must balance environmental gains with financial and scheduling considerations. Importantly, the optimisation also identified “free improvements”, instances where enhanced waste management directly reduced cost and time, shifting the project closer to the efficient frontier. While these findings align with the commonly reported benefits of OSC, such as faster delivery, lower costs, and improved sustainability performance, they also demonstrate that advanced optimisation techniques, like GWO, can amplify these outcomes beyond what traditional heuristic planning methods typically achieve.

7.7.4 Pareto Front Analysis

The Pareto front visualisation highlights the inherent trade-offs between cost, time, and waste. Results show that shorter project durations often raise costs due to quality control and material conservation, while waste reduction strategies are less sensitive to cost fluctuations. Clustering along the Pareto front indicates that the optimiser consistently identifies robust solutions across probability scenarios. For decision-makers, this means selecting options based on priorities and risk tolerance rather than relying on one-size-fits-all strategies. For example, moving from Option A (NZD 0.5M, ~600 days, ~50 m³ waste) to Option B shortens the project by ~400 days but increases costs by NZD 0.5M and waste by ~150 m³. Conversely, Option C nearly eliminates waste but adds NZD 1.5M and doubles the project time relative to Option B. Such explicit trade-offs help managers align decisions with stakeholder expectations and organisational goals. Based on the current New Zealand residential construction context, where project delays and labour shortages are critical constraints, Option B is considered the most suitable. Although it involves higher cost and increased material waste compared to Option A, it significantly reduces project duration, which is often the primary concern for developers and contractors. Option A may be preferable under strict budget constraints, while Option C, despite its environmental benefits, is less practical due to its excessive cost and extended project duration. This highlights that decision-making in OSC-SCM should be context-dependent rather than universally optimal.

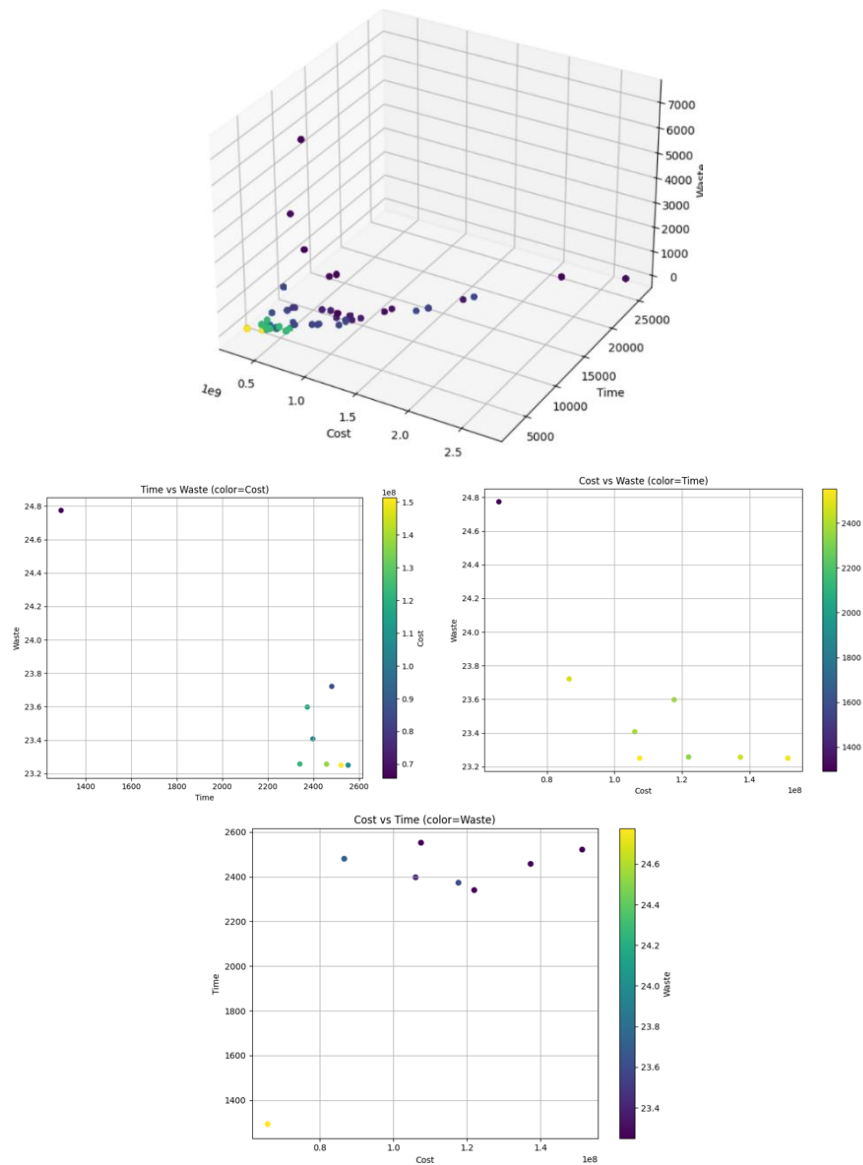


Figure 7-10: Pareto Front for Objectives

7.7.5 Sensitivity Analysis

A sensitivity analysis was conducted by systematically varying key system dynamics parameters to examine their influence on SD-generated time, cost, and waste trajectories. Results show GWO consistently converges across parameter changes, demonstrating robustness and stable performance under diverse input scenarios (Figure 7-11). The sensitivity analysis was subsequently expanded to include several extreme scenarios, including maximum equipment failure frequencies and worst-case weather circumstances (like protracted, intense rain and strong winds). A thorough investigation of these possibilities showed significant impacts on project time and expense. Long-term bad weather, for example, drastically lengthens project durations by interfering with assembly schedules and delaying transportation

logistics, reflecting difficulties frequently encountered in projects around New Zealand. Furthermore, scenarios that simulated frequent equipment failures, especially crane breakdowns, showed significant financial and scheduling ramifications, highlighting the need for strict maintenance procedures, routine equipment monitoring, and backup plans to lessen these barriers. Conversely, several other factors showed relatively little effect, suggesting that ordinary procedures rather than rigorous mitigation techniques may be used to manage their influence broadly. These results support the knowledge found in the body of literature on construction management, which often names equipment reliability and weather uncertainty as the main determinants of project performance (e.g., Pishdad-Bozorgi, 2018). In the real world, the comprehensive sensitivity maps produced by this deeper investigation are useful instruments for making decisions. High-risk variables can now be specifically identified and prioritized by project managers, allowing for more focused resource allocation and barrier management techniques. For instance, project teams can proactively schedule tasks under favourable conditions, obtain dependable backup equipment, create strategic buffer times within project timeframes by acknowledging the significant impact of harsh weather and equipment failures. Managers can therefore improve resilience, better predict possible disruptions, and respond strategically to barriers that are most likely to compromise project goals by methodically investigating these extreme scenarios.

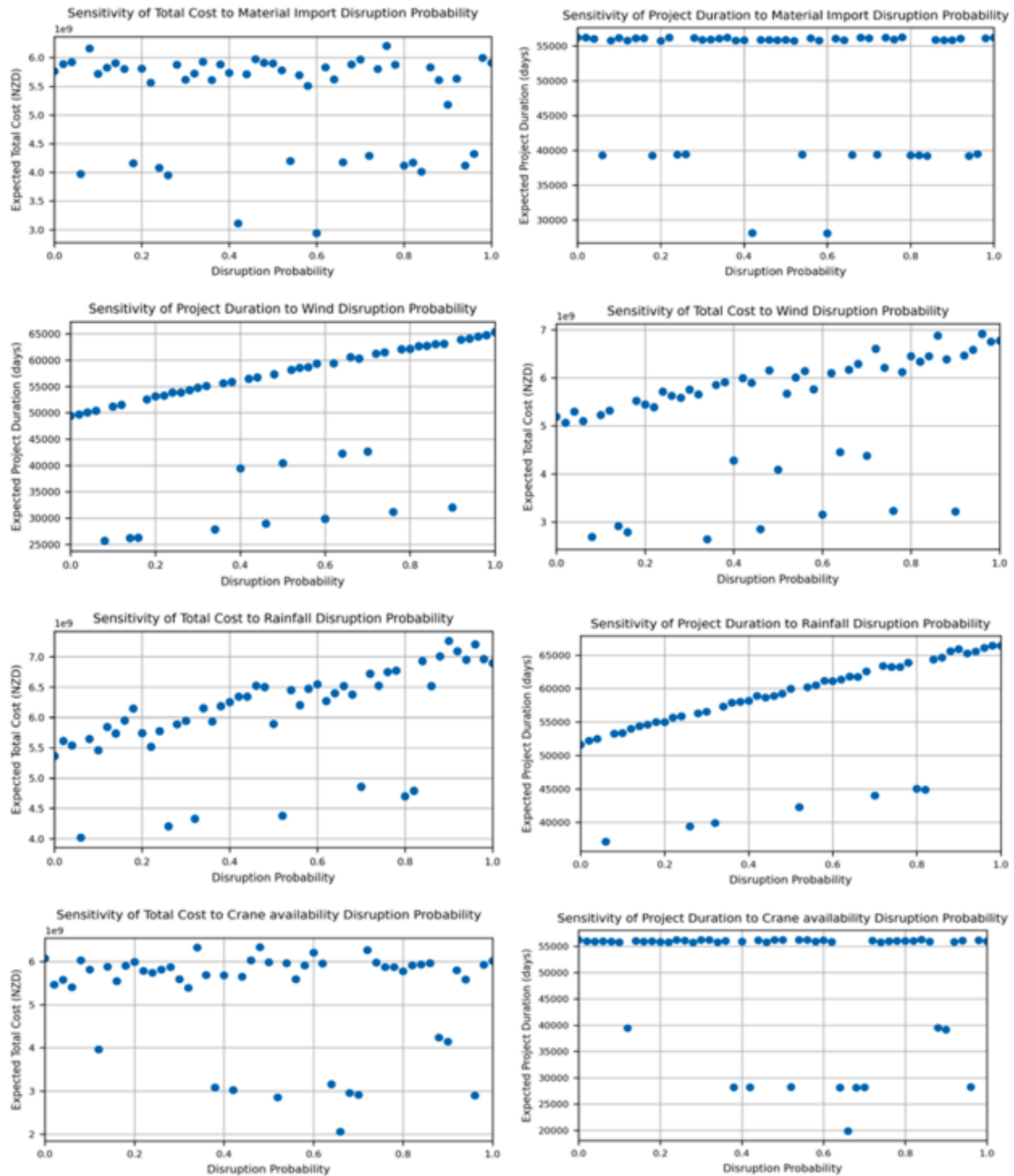


Figure 7-11: Sensitive Analysis

7.8 Conclusion and Recommendations

The present study addresses a substantive gap in OSC-SC research by developing a unified framework that simultaneously integrates design, production, transportation, inventory, and on-site assembly decisions stages that are frequently examined only in isolation. By modelling the panelised supply chain as a multi-echelon network operating under stochastic demand and variable component availability, the study advances theoretical understanding of how OSC systems behave as adaptive, interdependent structures rather than linear production pipelines.

The mixed-integer multi-objective formulation, which is NP-hard, underscores the importance of metaheuristics, such as GWO, in efficiently generating near-optimal solutions for high-dimensional, multi-criteria construction problems. Numerical results indicate meaningful improvements in project duration (~10%), total cost (~7–8%), and material waste (~4–5%), confirming the value of integrated decision-making in environments characterised by barriers and fluctuating resource conditions. From a practical perspective, the findings highlight several actions that industry practitioners can adopt to improve OSC-SC performance under uncertainty. Integrated planning and coordination across design, manufacturing, logistics, and on-site assembly are essential, particularly when supported by shared data environments and early supplier involvement to minimise interface errors and misalignment. Dynamic inventory policies also play a critical role, requiring frequent reviews, calibrated safety-stock levels, and a balanced consideration of holding costs versus component availability. The study further demonstrates that metaheuristic decision-support tools, such as the GWO model developed in this work, can be integrated into scheduling, routing, and planning systems to evaluate various disruption scenarios and quantify the effects of lead-time variability and changing demand. Digital technologies, including BIM-based coordination, RFID and IoT tracking, and blockchain-enabled smart contracts, offer additional opportunities to enhance transparency, real-time monitoring, and information flow across SC actors. Finally, strengthening cooperation and resilience through collaborative planning, risk-sharing agreements, and well-defined contingency strategies is vital for mitigating delays arising from labour shortages, weather disruptions, and equipment or crane failures, and aligns with lean and Just-in-Time delivery principles.

Overall, the study provides an integrated modelling and optimisation approach that enhances both theoretical understanding and practical decision-making capabilities within offsite construction supply chains operating under uncertainty. The theoretical implications of this work lie in its demonstration that OSC-SC optimisation requires a systemic rather than sequential perspective, reinforcing supply chain theory by showing how feedback mechanisms, stochastic inputs, and multi-criteria objectives interact to shape performance outcomes. Nevertheless, the research has limitations. The model is validated using a single panelised housing case study from New Zealand, which may limit generalizability to OSC typologies. Several assumptions should be refined as more empirical data become available. Future studies could extend the framework by testing different OSC product families (e.g., volumetric or hybrid systems), incorporating carbon and social sustainability metrics, or embedding AI-based

predictive analytics for real-time decision-making. Cross-country studies and multi-project datasets would also strengthen generalisability and advance methodological rigour.

Chapter 8: Conclusion and Recommendations

8 Conclusion

8.1 Research Overview

This thesis presents an integrated investigation into the optimisation of offsite construction supply chains in the New Zealand residential sector, with a specific focus on panelised construction systems. The study was motivated by New Zealand's ongoing housing delivery and affordability challenges, in which delays, cost escalation, and material inefficiencies continue to constrain the timely provision of residential housing, despite growing interest in offsite construction as a potential solution. While offsite methods are frequently promoted in the New Zealand context for their potential to improve productivity, reduce construction time, and mitigate waste, industry experience indicates that these benefits were often undermined by systemic inefficiencies across the supply chain. In particular, time overruns, cost escalation, and material waste were commonly examined in isolation, obscuring the dynamic interactions and feedback mechanisms through which these performance outcomes emerge. Accordingly, the overarching aim of this research was to examine how systemic barriers and dynamic interdependencies across New Zealand's offsite construction supply chains influence cost, time, and waste performance, and to develop an integrated analytical and optimisation-oriented framework of addressing this complexity in a manner relevant to both industry and policy decision-making. Within New Zealand's housing system, these unresolved supply chain challenges worsen housing supply shortfalls and productivity constraints, reducing the effectiveness of offsite construction as a scalable, policy-endorsed solution to improve residential housing delivery. Addressing this disconnect between policy expectations and operational performance formed a central motivation for this research. Guided by the main research question, the thesis examined how integrated dynamic modelling and optimisation approaches could improve panelised OSC-SCM performance under supply chain barriers and uncertainty in the New Zealand residential construction sector.

Adopting a thesis-by-publication approach, this research was deliberately structured as a sequence of interrelated studies, each addressing a distinct yet complementary dimension of offsite construction supply chain management. The initial studies focused on establishing a robust empirical and conceptual foundation through systematic reviews and qualitative investigations. These studies identified recurring barriers, including stakeholder misalignment, procurement constraints, limited early design integration, and disruption-driven barriers, which

informed the modelling assumptions and system boundaries adopted in subsequent stages of the research. This research demonstrates that performance outcomes in OSC-SCM are not driven by isolated barriers but emerge from the dynamic interaction, feedback, and propagation of constraints across the supply chain.

To address this complexity, the research adopted an integrated mixed-methods approach combining literature synthesis, qualitative investigation, system dynamics modelling, probabilistic simulation, surrogate modelling, and multi-objective optimisation techniques.

Building on these insights, a system dynamics (SD) modelling framework was developed to represent the non-linear behaviour, feedback mechanisms, and time-dependent interactions inherent in offsite construction supply chains. The SD model enabled the explicit representation of learning effects, rework cycles, resource constraints, and barrier propagation across design, raw material preparation, manufacturing, transportation, and on-site assembly processes. This approach enabled the research to examine how localised decisions and barriers accumulate and evolve into system-level performance outcomes over time, outcomes that are not readily captured by static or scenario-based methods.

The SD framework was subsequently integrated with multi-objective metaheuristic optimisation and surrogate-based machine learning techniques. Project cost, time, and material waste were optimised simultaneously under probabilistic disruptions using a hybrid framework combining simulation, Random Forest Surrogate modelling, and Grey Wolf Optimisation. This integration enabled efficient exploration of trade-offs across competing objectives while maintaining computational feasibility. The integration and triangulation of qualitative, modelling, and optimisation approaches enabled the development of a comprehensive understanding of OSC-SCM behaviour across multiple analytical levels.

Overall, the findings of this thesis indicate that offsite construction supply chain performance cannot be meaningfully improved through isolated interventions or single-objective optimisation strategies. Instead, the research demonstrates the need for a systems-oriented, data-informed, and multi-objective decision-making approach that explicitly accounts for barriers, feedback behaviour, and cross-stage interdependencies. By synthesising qualitative insights, dynamic modelling, and advanced optimisation within a New Zealand context, this thesis provides an integrated contribution to both academic understanding and practical decision-making in offsite construction supply chain management.

The discussion begins by linking the findings to the research objectives and assessing how effectively these objectives have been met. This is followed by two dedicated sections that examine the research's theoretical and practical contributions to construction management, emphasising the main conclusions. The chapter concludes with a reflection on the study's limitations. The following sections synthesise the key findings in relation to the research objectives and research questions, before discussing the broader contributions, implications, limitations, and future research directions emerging from the study.

8.2 Research Objectives and Key Outcomes

Objective 1: To systematically examine and synthesise the literature related to panelised OSC-SCM.

Objective 1 was achieved through a comprehensive synthesis of literature on panelised OSC-SCM, including supply chain barriers, procurement challenges, logistics constraints, and environmental performance in the New Zealand residential construction context. The review established the conceptual and empirical foundation of the study by identifying critical interdependencies across design, manufacturing, transportation, and assembly stages.

The findings demonstrate that OSC-SCM challenges are not confined to individual supply chain stages but emerge from interconnected operational, organisational, and disruption-related factors. The review further highlighted the limited integration of dynamic modelling and optimisation approaches within existing OSC-SCM research, particularly regarding uncertainty and system-level interactions. These findings informed the qualitative investigation and subsequent modelling stages of the research by identifying the key variables, barriers, and system relationships underpinning OSC-SCM performance.

Objective 2: To empirically identify and critically analyse the key factors impacting the implementation of panelised OSC-SCM in residential projects in New Zealand.

Objective 2 was achieved through qualitative investigation of the barriers, enabling factors, and operational interrelationships affecting panelised OSC-SCM within New Zealand's residential construction sector. Semi-structured interviews with industry stakeholders provided empirical insight into the structural and operational challenges influencing supply chain performance across design, manufacturing, transportation, and assembly stages.

The findings revealed that OSC-SCM barriers are highly interconnected and cumulative in nature. Design changes, fragmented communication, procurement constraints, labour

shortages, logistics disruptions, and coordination inefficiencies were found to propagate across multiple supply chain stages, contributing to cost escalation, schedule delays, and material waste. The findings further indicate that upstream decisions and early-stage coordination play a critical role in shaping downstream project performance. Overall, Objective 2 provided an empirical understanding of the systemic relationships influencing OSC-SCM performance and established the foundational causal structure used in the subsequent system dynamics modelling stage of the research.

Objective 3: To develop and evaluate a robust model to capture the dynamic interactions between cost and time in OSC-SCM in residential projects in New Zealand.

Objective 3 was achieved through the development and evaluation of a system dynamics (SD) model representing the dynamic interactions, feedback mechanisms, and interdependencies influencing panelised OSC-SCM performance. The model incorporated key supply chain stages, including design, raw material preparation, manufacturing, transportation, and on-site assembly, enabling examination of the dynamic behaviour of project cost, construction time, and material waste under varying operational conditions.

The findings demonstrate that OSC-SCM performance is strongly influenced by feedback-driven system behaviour, particularly through rework cycles, delay propagation, resource constraints, and disruption accumulation across supply chain stages. The SD model further revealed that barriers introduced during early-stage activities can generate cascading downstream impacts that intensify over time if not effectively managed. Overall, Objective 3 established a dynamic analytical understanding of OSC-SCM behaviour and provided the modelling foundation required for the subsequent optimisation stages of the research.

Objective 4: To optimise the performance of panelised offsite construction supply chain systems using metaheuristic optimisation techniques to minimise project cost, time, and material waste under supply chain uncertainties.

Objective 4 was achieved through the integration of system dynamics modelling with metaheuristic optimisation approaches, including Genetic Algorithm (GA), Multi-Objective Grey Wolf Optimiser (MOGWO), Monte Carlo simulation, and surrogate-based modelling techniques. The optimisation framework was applied to evaluate trade-offs between project cost, construction time, and material waste under probabilistic disruption conditions and dynamic supply chain interactions.

The findings demonstrate that optimisation outcomes are highly sensitive to uncertainty, barrier propagation, and system-level interdependencies. Strategies that performed effectively under deterministic conditions showed variable performance when disruption scenarios and dynamic interactions were introduced. In contrast, adaptive and coordinated strategies involving early supplier engagement, procurement alignment, and integrated planning demonstrated greater robustness across multiple performance objectives.

Overall, Objective 4 demonstrated the value of integrated, uncertainty-aware optimisation approaches for improving OSC-SCM performance and for identifying balanced trade-offs between competing project objectives.

All objectives were achieved by integrating the qualitative investigation, system dynamics modelling outputs, and optimisation analyses into a unified conceptual framework for panelised OSC-SCM. The framework synthesises the relationships between supply chain barriers, dynamic system behaviour, uncertainty conditions, and optimisation-based decision responses across multiple supply chain stages.

The integrated findings demonstrate that OSC-SCM performance cannot be effectively improved through isolated interventions or single-objective decision-making approaches. Instead, the research shows that effective performance improvement requires coordinated, system-oriented, and adaptive strategies capable of addressing cross-stage interactions and competing project objectives simultaneously.

Overall, this thesis provides an integrated analytical foundation for understanding and improving panelised OSC-SCM performance in New Zealand's residential construction sector, while supporting more informed and adaptive supply chain decision-making under uncertainty.

8.3 Integrated Decision-Oriented OSC-SCM Framework

Building on the synthesis of findings across the research objectives, this section presents the integrated decision-oriented framework developed in this thesis. The framework consolidates empirical evidence, system dynamics modelling, and optimisation outcomes into a coherent structure that explains how OSC-SCM performance emerges under dynamic and different conditions. It serves as the interpretive bridge between the research findings and the theoretical and practical conclusions presented in the following sections. An integrated OSC-SCM framework is proposed based on the findings of this study.

The framework illustrates that OSC-SCM performance is not determined by isolated decisions or individual supply chain stages. Instead, performance outcomes arise from the dynamic interaction and propagation of barriers, feedback mechanisms, and regime-dependent decision responses across the supply chain. By structuring these interactions, the framework provides the basis for interpreting the theoretical contributions and practical recommendations discussed in Sections 8.3 and 8.4. The earlier framework developed in Chapter 4 section 4.7.1 predominantly adopts static, descriptive, or stage-based representations of the supply chain, focusing on identifying barriers, drivers, and best practices without explicitly modelling feedback effects, stochastic disruptions, or the propagation of impacts across supply chain stages. As a result, those frameworks provided limited explanatory power regarding how performance outcomes emerge over time or why interventions at specific stages fail to deliver expected improvements. In contrast, the final framework proposed in conclusion uniquely combines empirical evidence, system dynamics logic, and multi-objective optimisation insights to explicitly capture dynamic feedback structures, cross-stage barrier propagation, and regime-dependent decision responses under barriers. This integrated approach represents a substantive conceptual and methodological advancement over existing OSC-SCM frameworks, enabling dynamic, decision-oriented analysis of cost, time, and material waste performance.

The model outputs provide quantitative insights that support evidence-based decision-making. The robustness and applicability of the framework enable practitioners to make informed decisions under uncertainty, thereby improving performance in terms of cost, time, and material waste.

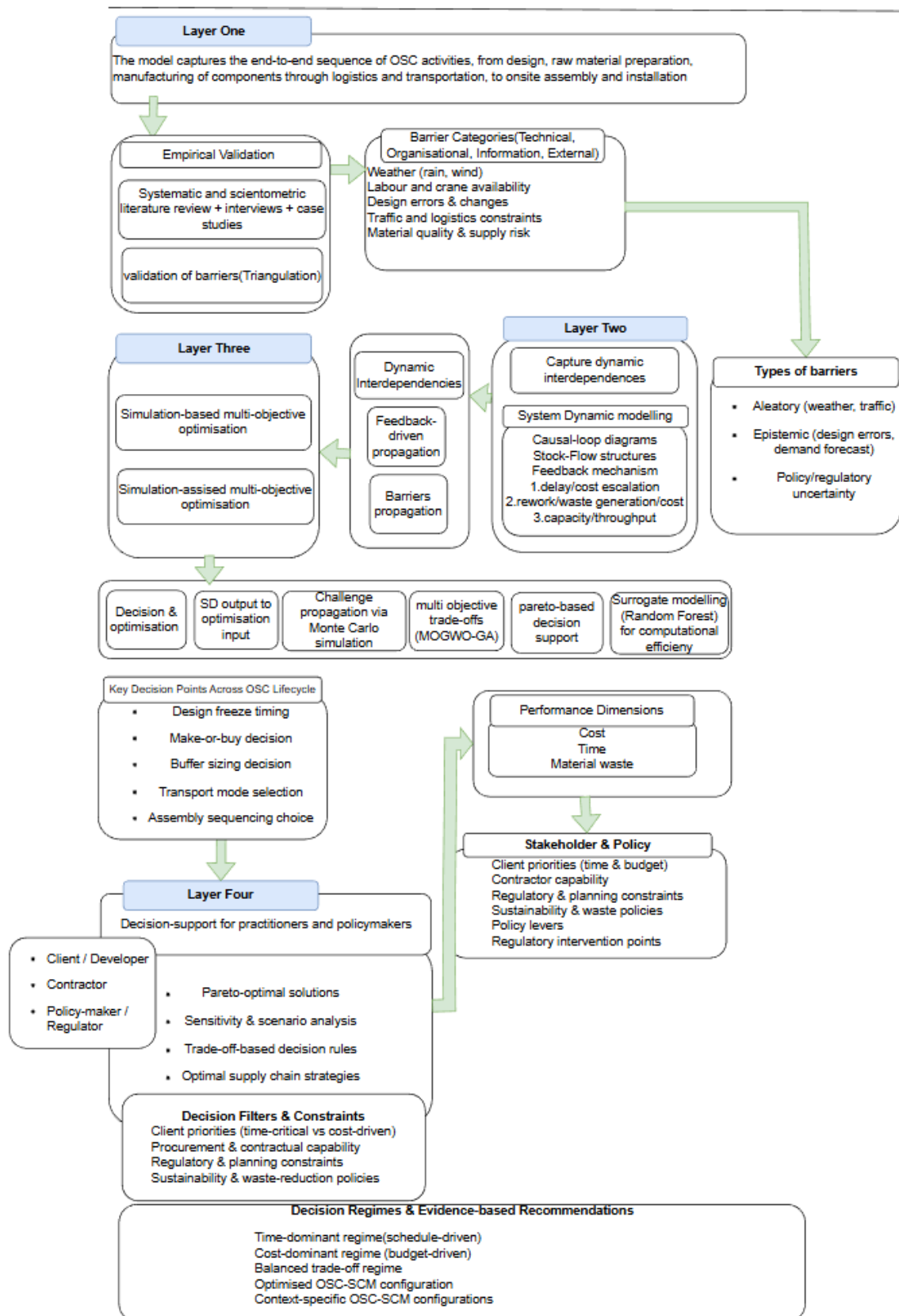


Figure 8-1: Integrated decision-oriented framework linking dynamic barrier propagation, system behaviour, and optimisation-based decision regimes in OSC-SCM

8.4 Integrated Synthesis of Empirical Findings

This section provides an integrated synthesis of the empirical findings presented across Chapters 4 to 7, explicitly aligning the findings with the research objectives and research questions developed throughout the thesis. The section demonstrates how the qualitative investigation, system dynamics modelling, and optimisation analyses collectively address the main research question and contribute to the development of the proposed OSC-SCM framework.

The findings collectively demonstrate that panelised OSC-SCM performance is governed by the interaction of dynamic barriers, operational interdependencies, uncertainty conditions, and feedback-driven system behaviour. Rather than functioning as isolated analytical stages, the empirical investigation, modelling, and optimisation components progressively build a multi-layered understanding of OSC-SCM performance within New Zealand's residential construction sector. The integrated findings reveal that project cost, construction time, and material waste arise from interconnected supply chain processes and cannot be effectively addressed by fragmented or single-stage interventions. Collectively, the empirical stages of the research establish a coherent analytical pathway linking barrier identification, behavioural explanation, uncertainty analysis, and optimisation-based decision evaluation within a unified OSC-SCM framework.

8.4.1 Alignment with Research Objectives and Research Questions

The findings presented throughout the thesis directly address the defined research objectives and collectively contribute to answering the main research question regarding the improvement of panelised OSC-SCM performance under supply chain barriers and uncertainty.

The literature review established the conceptual and contextual foundation of the research by systematically examining OSC-SCM barriers, operational constraints, environmental considerations, and supply chain characteristics within the New Zealand residential construction sector. The review identified the fragmented nature of existing OSC-SCM studies and highlighted the limited integration of dynamic modelling and optimisation approaches within current research.

The qualitative investigation subsequently identified the critical barriers, enabling factors, and operational interrelationships influencing OSC-SCM performance across design, manufacturing, transportation, and assembly stages. The findings demonstrate that supply

chain barriers are highly interconnected and cumulative in nature, with disruptions originating at upstream stages frequently propagating throughout the supply chain and affecting downstream project performance.

Building on these findings, the system dynamics modelling stage demonstrated how feedback loops, delay propagation, resource constraints, and disruption interactions dynamically influence project cost, construction time, and material waste over time. The modelling results confirmed that OSC-SCM performance outcomes emerge through nonlinear system behaviour rather than isolated operational events.

Finally, the optimisation stages evaluated how integrated optimisation approaches can improve OSC-SCM performance under conditions of uncertainty. The findings demonstrated that adaptive, coordinated strategies involving procurement alignment, supplier coordination, and integrated planning yield more robust performance outcomes than isolated or deterministic decision-making approaches. Collectively, the findings across all empirical stages directly address the research objectives and contribute to an integrated understanding of OSC-SCM performance in New Zealand's residential construction sector.

8.4.1.1 Convergence, Complementarity, and Trade-Offs Across the Findings

The empirical findings across the qualitative, modelling, and optimisation stages demonstrate strong convergence while also revealing important complementarities and operational trade-offs within OSC-SCM systems. Across all analytical stages, the findings consistently indicate that OSC-SCM performance is influenced by the interaction of multiple barriers rather than isolated operational issues. Design instability, labour shortages, procurement misalignment, logistics disruptions, and coordination inefficiencies repeatedly emerged as critical performance drivers across both qualitative and quantitative analyses.

Importantly, the convergence of findings across multiple methodological stages strengthens confidence in the consistency and validity of the overall research argument. Barriers identified qualitatively during the interview stage subsequently emerged as major drivers of delay propagation, rework accumulation, and performance deterioration in the system dynamics simulations. These same variables further influenced optimisation outcomes during the GA and MOGWO stages, demonstrating consistency between empirical observations, behavioural modelling, and optimisation-based evaluation.

At the same time, each methodological stage contributed a distinct layer of analytical insight. The qualitative investigation provided contextual understanding of supply chain barriers and stakeholder experiences within the New Zealand OSC environment. The system dynamics modelling stage extended these findings by explaining how barriers interact dynamically through feedback mechanisms and operational interdependencies over time. The subsequent optimisation stages translated these behavioural insights into decision-oriented trade-off analysis under uncertainty. Together, these stages created a progressive analytical pathway from empirical problem identification towards optimisation-based performance improvement.

The integrated findings further reveal that OSC-SCM decision-making involves inherent trade-offs between competing project objectives. Strategies prioritising cost minimisation were not consistently aligned with improvements in construction time or material efficiency under conditions of uncertainty. Similarly, strategies aimed at increasing operational flexibility and disruption resilience frequently required greater coordination effort, procurement adaptation, or early-stage investment. These findings reinforce the importance of adopting multi-objective, system-oriented decision-making approaches that balance competing operational priorities, rather than relying on deterministic or single-objective optimisation logic.

8.4.2 Triangulation and Methodological Integration

The integration of qualitative investigation, system dynamics modelling, probabilistic simulation, and optimisation analyses provided strong triangulation of evidence throughout the research process. Each methodological stage contributed complementary analytical capabilities while simultaneously addressing limitations associated with individual methods when applied independently.

The qualitative investigation established the structural and behavioural foundations of the OSC-SCM system by identifying key barriers, causal relationships, and operational interdependencies affecting project performance. The system dynamics modelling stage subsequently transformed these empirical insights into a dynamic representation of OSC-SCM behaviour, enabling examination of feedback structures, delay accumulation, and time-dependent system interactions. The optimisation stages then translated these behavioural insights into decision-oriented analyses capable of evaluating trade-offs among project cost, construction time, and material waste under uncertainty.

Importantly, each methodological stage strengthened the interpretive depth and analytical robustness of the overall framework. Qualitative analysis provided a contextual and industry-

grounded understanding but could not independently quantify system-level behaviour or evaluate optimisation trade-offs. System dynamics modelling captured behavioural complexity and dynamic interactions but did not independently identify optimal decision combinations under competing objectives. The optimisation stages enabled evaluation of alternative decision scenarios but relied upon the behavioural and structural insights generated through the earlier qualitative and modelling stages. Collectively, the integration of these methods produced a robust and comprehensive analytical framework capable of examining OSC-SCM performance across multiple levels of analysis.

8.4.3 Development of the Integrated OSC-SCM Framework

The proposed OSC-SCM framework emerged progressively through the integration of empirical findings, dynamic modelling outputs, and optimisation analyses developed throughout the thesis. Rather than representing a purely conceptual or abstract model, the framework constitutes a direct synthesis of the empirical evidence generated across the different stages of the research.

The qualitative investigation established the underlying structure of the OSC-SCM system and identified the primary barriers influencing project performance across design, manufacturing, transportation, and assembly stages. The system dynamics modelling stage subsequently explained how these barriers interact dynamically through feedback loops, delay propagation, resource constraints, and disruption accumulation over time. Finally, the optimisation stages translated these behavioural insights into decision-oriented evaluation of trade-offs and operational strategies under uncertainty conditions.

The integrated framework therefore demonstrates that OSC-SCM performance cannot be effectively improved through isolated interventions or stage-specific optimisation approaches. Instead, the findings indicate that effective performance improvement requires coordinated, adaptive, and system-oriented strategies capable of addressing cross-stage interactions, uncertainty conditions, and competing operational objectives simultaneously. The framework consequently provides an integrated analytical foundation for understanding and improving panelised OSC-SCM performance within New Zealand's residential construction sector.

8.5 Theoretical Contribution and Recommendation

This thesis advances the theoretical understanding of offsite construction supply chain management (OSC-SCM) by conceptualising supply chain performance as a dynamic, feedback-driven, and interaction-dependent phenomenon rather than a sequence of isolated operational activities. Existing OSC-SCM research has predominantly focused on fragmented supply chain stages, static barrier identification, or deterministic performance analysis. In contrast, this research demonstrates that project cost, time, and material waste emerge through the interaction, accumulation, and propagation of interconnected barriers across design, manufacturing, transportation, and assembly stages.

The research further contributes to theory by positioning panelised OSC-SCM as a complex adaptive system characterised by nonlinear feedback behaviour, delay propagation, resource constraints, and disruption interdependencies. By integrating qualitative findings with system dynamics modelling, the thesis provides a system-level explanation of how localised disruptions evolve into broader performance deterioration across the supply chain. This contributes a dynamic interpretation of OSC-SCM behaviour that extends beyond conventional linear and stage-based conceptualisations commonly adopted within construction management research.

In addition, the thesis provides context-specific theoretical insight into the New Zealand residential construction sector by identifying how import dependency, labour constraints, logistics variability, and coordination inefficiencies collectively shape OSC-SCM performance in a geographically isolated, disruption-sensitive construction environment. The proposed framework functions as a decision-support tool, enabling practitioners to assess the impact of supply chain disruptions and evaluate alternative strategies

8.6 Methodological Contribution

This thesis contributes methodologically by developing an integrated analytical framework that combines qualitative investigation, system dynamics modelling, probabilistic simulation, surrogate modelling, and multi-objective optimisation within a unified research structure. While previous OSC-SCM studies have typically applied these methods independently or in isolated analytical contexts, this research integrates them to capture the behavioural complexity and optimisation requirements of panelised offsite construction supply chains under uncertainty.

A significant methodological contribution lies in the integration of system dynamics modelling with Monte Carlo simulation and metaheuristic optimisation approaches. The research demonstrates how dynamic behavioural modelling can be combined with probabilistic disruption analysis and optimisation techniques to evaluate trade-offs between project cost, time, and material waste under varying operational conditions. This integration enables a more comprehensive analysis of OSC-SCM performance than conventional deterministic or single-method approaches commonly used in construction management studies.

The thesis further contributes methodologically through the incorporation of surrogate-based Random Forest modelling to improve computational efficiency during optimisation processes involving large-scale simulation outputs. The combined use of Genetic Algorithm (GA) and Multi-Objective Grey Wolf Optimiser (MOGWO) additionally provides comparative insight into multi-objective optimisation performance within OSC-SCM environments. Collectively, the methodological framework developed in this study establishes a scalable and adaptable approach for analysing complex construction supply chain systems characterised by uncertainty, interdependency, and competing performance objectives.

8.7 Practical Contribution and Recommendation

This thesis provides practical contributions through the development of an integrated and decision-oriented framework for improving panelised OSC-SCM performance within New Zealand's residential construction sector. The findings provide industry stakeholders with a structured basis for evaluating the impacts of supply chain barriers, operational disruptions, and coordination inefficiencies on project cost, construction time, and material waste.

The research demonstrates that many OSC-SCM performance problems originate from upstream decision-making processes, particularly those associated with procurement alignment, supplier coordination, design integration, and resource planning. By identifying the dynamic relationships between these factors, the framework supports more proactive and system-oriented decision-making across design, manufacturing, transportation, and on-site assembly stages.

In addition, the optimisation framework enables practitioners to evaluate trade-offs between competing project objectives under uncertainty conditions, supporting more adaptive planning and resource allocation strategies. The findings are particularly relevant to the New Zealand residential construction sector, where labour shortages, import dependency, logistics constraints, and environmental disruptions significantly influence OSC-SCM performance.

The framework, therefore, provides practical support for improving supply chain resilience, operational coordination, and sustainability-oriented decision-making within panelised offsite construction systems. While the findings are context-specific to New Zealand, the modelling framework is adaptable to other OSC-SCM contexts with appropriate parameter adjustments.

The findings provide practical insights for contractors, manufacturers, and policymakers to improve planning and resource allocation in OSC projects.

8.8 Research Limitations

This research focuses exclusively on panelized off-site construction (OSC) within the New Zealand residential construction sector. While panelised systems represent a significant segment of OSC adoption, the model does not explicitly capture the distinct supply chain structures, risk profiles, and operational characteristics associated with other OSC typologies, such as volumetric modular or hybrid construction systems. Consequently, direct application of the model to alternative OSC approaches would require modification of system boundaries, parameter values, and decision structures. Nevertheless, the system dynamics architecture and optimization framework developed in this study provide a transferable conceptual foundation for future adaptation to other OSC contexts.

The model primarily evaluates quantifiable supply chain performance indicators, including project cost, delivery time, inventory levels, production capacity utilization, and material waste. As a result, several influential factors were treated as exogenous variables and are not explicitly represented within the model structure. These include workforce capability, organizational culture, procurement strategies, stakeholder collaboration, regulatory interventions, and policy developments. Although such factors can significantly influence OSC implementation outcomes, their exclusion was necessary to maintain model tractability and analytical clarity.

A further limitation relates to the geographical and sectoral scope of the study. Model calibration, validation, and parameter estimation were undertaken using data from the New Zealand residential construction industry. Therefore, the numerical results and policy recommendations may not be directly transferable to commercial, industrial, or infrastructure construction sectors, or to jurisdictions characterized by different regulatory frameworks, market conditions, labor availability, or climatic environments.

The study also adopts a predominantly supply-side perspective and does not explicitly model market demand dynamics for off-site construction solutions. Factors such as client awareness, market acceptance, perceptions of quality, technology adoption resistance, financing constraints, and industry standardisation challenges were not incorporated into the system dynamics framework. These demand-side influences may affect the long-term scalability and market penetration of OSC regardless of improvements in supply chain performance. Future research should integrate demand generation and market adoption mechanisms to provide a more comprehensive assessment of OSC system behaviour.

Finally, the study is subject to limitations associated with data availability, parameter uncertainty, and modelling assumptions. Although empirical data were collected from multiple sources and sensitivity analyses were conducted to assess model robustness, some parameters had to be estimated due to limited availability of industry data. Consequently, model outputs should be interpreted as decision-support insights rather than precise forecasts of future industry performance.

8.9 Future Research

While this study provides an integrated, dynamic, and optimisation-based understanding of panelised offsite construction supply chain management (OSC-SCM) within New Zealand's residential construction sector, several important opportunities remain for further investigation and model development.

First, this research focused specifically on timber-based panelised OSC systems within the New Zealand residential sector to ensure analytical clarity and manageable system boundaries. Future research could extend the proposed framework to other offsite construction typologies, including volumetric modular systems, hybrid construction systems, and infrastructure-related OSC applications. Such extensions would enable investigation of how differing production logics, supply chain configurations, regulatory environments, and project characteristics influence system behaviour, disruption propagation, and optimisation outcomes. Future studies may adapt the current system dynamics and optimisation framework by re-specifying system boundaries, supply chain variables, and performance parameters relevant to alternative OSC contexts.

Second, future research could further extend the proposed optimisation framework by incorporating advanced resilience-oriented and adaptive optimisation approaches capable of responding to rapidly changing supply chain conditions and disruption scenarios. Expanding

the framework towards more adaptive optimisation environments may provide deeper insight into how OSC-SCM systems respond to dynamic operational variability, evolving market conditions, and complex decision environments over time. Future studies may also explore the integration of alternative optimisation techniques and intelligent decision-making approaches to further enhance supply chain responsiveness, flexibility, and strategic planning capabilities within offsite construction systems.

Third, while material waste was explicitly incorporated within the optimisation process, broader sustainability-related indicators were not comprehensively integrated into the current modelling framework. Future research could expand the proposed optimisation model by incorporating additional environmental and circular economy performance indicators, including embodied carbon emissions, life-cycle environmental impacts, material circularity, and design-for-disassembly considerations. Integrating life-cycle assessment approaches with dynamic optimisation models may provide a more comprehensive basis for sustainability-oriented decision-making within offsite construction supply chains.

Fourth, the findings of this research identified communication gaps, coordination inefficiencies, information fragmentation, and disruption-related rework as critical OSC-SCM barriers. Future studies could therefore investigate the integration of digital technologies, including Building Information Modelling (BIM), Augmented Reality (AR), Internet of Things (IoT) technologies, and digital twin systems, to improve real-time coordination, supply chain visibility, adaptive scheduling, and data-driven decision-making. Future methodological developments may further explore the integration of these digital technologies with system dynamics and optimisation approaches to support intelligent and responsive OSC-SCM environments.

Finally, the empirical calibration and validation of this study were conducted within the New Zealand residential construction context. Although the proposed framework captures broader system-level relationships and dynamic mechanisms applicable to OSC-SCM environments more generally, future international comparative studies would provide valuable insight into how labour markets, supply chain maturity, regulatory conditions, climatic variability, and procurement practices influence OSC-SCM performance across different countries and construction sectors. Comparative cross-country applications of the proposed framework may also contribute to broader validation, refinement, and generalisability of the modelling and optimisation approach developed in this thesis.

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10 Appendix A: Stock and Flow abbreviations

MATERIAL COST	MAC	STOCK
MATERIAL USAGE CHANGE RATE	MUCHR	Flow
UNIT PRICE OF MATERIAL	UPM	Auxiliary Variable
INCREASED PERCENTAGE UNIT PRICE OF MATERIAL	IUPM	Auxiliary Variable
MATERIAL QUALITY CHECK	MQCH	Auxiliary Variable
MATERIAL ERROR QUANTITY	MEQ	Auxiliary Variable
MATERIAL OVERDUE QUANTITY	MODQ	Auxiliary Variable
MATERIAL USAGE QUANTITY	MUQ	Auxiliary Variable
MATERIAL SUPPLY QUANTITY	MSQ	Auxiliary Variable
MATERIAL DEMAND QUANTITY	MDQ	Auxiliary Variable
MANUFACTURING LABOUR COST	MLC	Stock
MANUFACTURING LABOUR COST CHANGE RATE	MLCCHR	Flow
UNIT PRICE OF LABOUR PER MONTH	UPLPM	Auxiliary Variable
MANUFACTURING LABOUR HOURS PER MONTH	MLHPM	Auxiliary Variable
MANUFACTURING LABOUR QUANTITY	MLQ	Auxiliary Variable
MANUFACTURING LABOUR AVAILABILITY	MLA	Auxiliary Variable
MANUFACTURING LABOUR ACTUAL HOURS PER MONTH	MLAHPM	Auxiliary Variable
MANUFACTURING EQUIPMENT COST	MEC	Stock
MANUFACTURING EQUIPMENT COST CHANGE RATE	MECCHR	Flow
EQUIPMENT REPAIR COST PER MONTH	ERCPM	Auxiliary Variable
EQUIPMENT REPAIR TIME	ERC	Auxiliary Variable
EQUIPMENT REPAIR QUANTITY	ERQ	Auxiliary Variable
FACTORY COST	FC	Stock
ELEMENT COST CHANGE RATE	ECCHR	Flow
UNIT PRICE OF ELEMENT	UPE	Auxiliary Variable
ELEMENT QUANTITY DEMAND	EQD	Auxiliary Variable
ELEMENT QUANTITY SUPPLY	EQS	Auxiliary Variable
ELEMENT FAILURE	EF	Auxiliary Variable
MATERIAL WASTE INCREASE	MWI	Auxiliary Variable
MANUFACTURING REGULAR COST	MRC	Auxiliary Variable
ELEMENT DAMAGE	ED	Auxiliary Variable
DESIGN COST	DC	Stock
DESIGN COST CHANGE RATE	DCCHR	Flow
UNIT DESIGN COST	UDC	Auxiliary Variable
PROJECT VOLUME	PV	Auxiliary Variable
DESIGN REQUIRED CHANGE	DRCH	Auxiliary Variable
DESIGN ERROR	DE	Auxiliary Variable
DESIGN DURATION	DD	Auxiliary Variable
PROJECT VOLUME	PV	Auxiliary Variable
DESIGNER'S EXPERIENCE LEVEL	DEL	Auxiliary Variable
REQUIRE STANDARD DEGREE	RSD	Auxiliary Variable
TRANSPORTATION COST	TC	Stock
TRANSPORTATION COST CHANGE RATE	TCCHR	Flow
UNIT PRICE OF TRANSPORT FOR EACH KM	UPTEKM	Auxiliary Variable
TRANSPORT TIME	TT	Auxiliary Variable
EACH CRANE TIME	ECT	Auxiliary Variable
ROAD LIMITATION	RL	Auxiliary Variable
PILOT	Pilot	Auxiliary Variable
PILOT COST	PC	Auxiliary Variable

SPEED OF PILOT	SP	Auxiliary Variable
CRANE NUMBER	CN	Auxiliary Variable
TRANSPORTING LABOUR AVAILABILITY IMPACT	TLA	Auxiliary Variable
SPEED OF CRANE	SC	Auxiliary Variable
CRANE MAXIMUM TONE	CMT	Auxiliary Variable
ELEMENT TONE	ET	Auxiliary Variable
ROAD TRAFFIC	RT	Auxiliary Variable
TRANSPORTING CRANE AVAILABILITY IMPACT	TCA	Auxiliary Variable
WEATHER IMPACT	WI	Auxiliary Variable
INSTALLATION COST	IC	Stock
INSTALLATION COST CHANGE RATE	ICCHR	Flow
LIFTER HOURS	LH	Auxiliary Variable
LIFTER QUANTITY	LQ	Auxiliary Variable
LIFTER AVAILABILITY	LA	Auxiliary Variable
LIFTER FAILURE	LF	Auxiliary Variable
UNIT PRICE OF LIFTER PER HOUR	UPLPH	Auxiliary Variable
EXTRA LABOUR QUANTITY NEEDED DUE TO DELAY	ELQN	Auxiliary Variable
LABOUR AVAILABILITY	LAA	Auxiliary Variable
ASSEMBLY LABOUR QUANTITY	ALQ	Auxiliary Variable
ASSEMBLY LABOUR HOUR	ALH	Auxiliary Variable
UNIT PRICE OF ASSEMBLY LABOUR PER HOUR	UPALPH	Auxiliary Variable
DELAY	D	Auxiliary Variable
UNIT PRICE OF LIFTER DUE TO DELAY	UPLD	Auxiliary Variable
CONSTRUCTION COST	CC	Auxiliary Variable
MANUFACTURING COST	MC	Auxiliary Variable
EXPECTED COST	ExC	Auxiliary Variable

11 Appendix B: Ethics Approval



6/09/2022

Dear: Sanaz Nesarnobari

Re: Low Risk Notification - 4000026647 - Building capability and capacity of residential offsite construction supply chain management and Unlocking the Full Potentials of Offsite Construction by Optimising Its Procurement and Delivery

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our database for inclusion in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

If situations subsequently occur which cause you to reconsider your ethical analysis, please contact a Research Ethics Administrator.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research."

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director - Ethics, telephone 06 3569099 ext 85271, email humanethics@massey.ac.nz."

Please note, if a sponsoring organisation, funding authority or a journal in which you wish to publish requires evidence of committee approval (with an approval number), you will have to complete the application form again, answering "yes" to the publication question to provide more information for one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and Director (Research Ethics)

Research Ethics Office, Research and Enterprise
Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand T 06 951 6841; 06 95106840
E humanethics@massey.ac.nz; animalethics@massey.ac.nz; gtc@massey.ac.nz

12 Appendix C: List of Questions

Material Sourcing:

1. What kind of issues occur when you are preparing, ordering, and transporting materials for off-site construction (OSC) and if such issues arise, what are their frequency?
2. How do these issues/challenges affect your project timelines? (0-25%,25-50%,50-75%,75-100%)
3. How do these issues/challenges affect your project costs? (0-25%,25-50%,50-75%,75-100%).

Design:

4. What kinds of issues do you face during the design stage?
5. Are your designs flexible? If yes, what kind of changes can be made, and how do these affect the manufacturing stage? (0-25%,25-50%,50-75%,75-100%).
6. How do you handle design errors (If they occur)?
7. How do design-related issues/challenges affect your project timelines? (0-25%,25-50%,50-75%,75-100%).
8. How do design-related issues/challenges affect your project costs? (0-25%,25-50%,50-75%,75-100%).

Manufacturing:

9. What kind of challenges happen throughout the manufacturing stages? (For example, machine failure, error in manufacturing, or machine services).
10. Do issues impact production rates and the final pricing of elements (Number/time)? If yes, what do you think are the main reasons (The causes, such as labour and skilled worker availability, machinery (manufacturing equipment) availability and performance)?
11. What is your strategy to tackle any issues arising during the manufacturing stage? And what kind of issues are more likely to happen?
12. How do manufacturing-related issues/challenges affect your project timelines? (0-25%,25-50%,50-75%,75-100%).
13. How do manufacturing-related issues/challenges affect your project costs? (0-25%,25-50%,50-75%,75-100%).

Material Waste Part:

14. How does the factory measure the construction material waste?
15. Are there any issues that increase the material waste? (Material error, material quality, expired use by date for material, manufacturing errors, design errors, transportation errors).
16. If yes to the above, what is your strategy to decrease it?

17. When preparing the construction materials, what type of processes do you use? (For example, circular saw, plasma, water jets etc.).
18. For each type of cutting process, how much waste is typically produced? (A range as a %).
19. How do you optimise the use of materials used in the designs?
20. Do you have a waste optimisation process to help save costs?

Transporting Part:

21. For transporting and lifting construction elements, what are the key issues you experience? (Like weather, labour shortages or skills, crane failures, crane shortages, or equipment shortages).
22. Which of the issues from the question above are more likely to occur?
23. How do transporting-related issues/challenges affect your project timelines? (0-25%,25-50%,50-75%,75-100%).
24. How do transporting-related issues/challenges affect your project costs? (0-25%,25-50%,50-75%,75-100%).

Assembly Part:

25. How do you source construction equipment required for on-site installation?
26. Do you face any challenges in sourcing on-site installation equipment? (Details on availability from the suppliers, price changes, delivering the technology).
27. What are the common issues faced during the onsite assembly of elements? (Labour shortage, weather, equipment, road restriction, traffic, crash).
28. How do assembly-related issues/challenges affect your project timelines? (0-25%,25-50%,50-75%,75-100%).
29. How do assembly-related issues/challenges affect your project costs? (0-25%,25-50%,50-75%,75-100%).

Many thanks,

13 Appendix D : Author Contribution Forms

 MASSEY UNIVERSITY TE KUNINGA KI PŪREHUROA UNIVERSITY OF NEW ZEALAND		GRADUATE RESEARCH SCHOOL	
STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS			
We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Sanaz Nesarnobari		
Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
In which chapter is the manuscript/published work?	Chapter 2		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:¹ The student conceptualised and designed the study, identified the research gap, developed the methodological framework, conducted all the investigation and analysis, and led the interpretation of results and manuscript preparation. The supervisory team provided academic supervision, critical review and editing, as well as methodological and theoretical guidance. All authors reviewed and approved the final published version.			
Please select one of the following three options:			
☒ The manuscript/published work is published or in press Please provide the full reference of the research output: Nesarnobari, S., Shahzad, W. M., Babaeian Jelodar, M., & Sutrisna, M. (2025). Offsite construction supply chain management: a scientometric analysis and systematic literature review. Architectural Engineering and Design Management, 21(3), 467-490.			
☐ The manuscript is currently under review for publication Please provide the name of the journal:			
☐ It is intended that the manuscript will be published, but it has not yet been submitted to a journal			
Student's signature:		Main supervisor's signature:	
<i>This form should be placed at the beginning of each relevant thesis chapter.</i>			

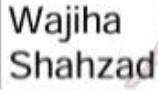
¹ Refer to the Massey University Publishing and Authorship guidelines ([OneMassey for staff](#), [Stream for students](#)) and/ or [Contributor Roles Taxonomy \(CRediT\) guidelines](#) for guidance.

Doctoral Research Committee
May 2023

STATEMENT OF CONTRIBUTION

DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sanaz Nesarnobari		
Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
In which chapter is the manuscript/published work?	Chapter 2		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ The student conceptualised and designed the study, identified the research gap, developed the methodological framework, conducted all the investigation and analysis, and led the interpretation of results and manuscript preparation. The supervisory team provided academic supervision, critical review and editing, as well as methodological and theoretical guidance. All authors reviewed and approved the final published version.			
Please select one of the following three options:			
☒	The manuscript/published work is published or in press Please provide the full reference of the research output: Nesarnobari, S., Shahzad, W., Jelodar, M. B., & Sutrisna, M. (2024). Investigation of the effects of supply chain disruptions on offsite construction projects. In International Conference on Engineering, Project, and Production Management (pp. 161-172). Springer, Cham		
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☐	It is intended that the manuscript will be published, but it has not yet been submitted to a journal		
Student's signature:	 Sanaz Nesarnobari	Main supervisor's signature:	 Wajiha Shahzad

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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.	
Student name:	Sanaz Nesarnobari
Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad
In which chapter is the manuscript/published work?	Chapter 2
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ The student conceptualised and designed the study, identified the research gap, developed the methodological framework, conducted all the investigation and analysis, and led the interpretation of results and manuscript preparation. The supervisory team provided academic supervision, critical review and editing, as well as methodological and theoretical guidance. All authors reviewed and approved the final published version.	
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Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
In which chapter is the manuscript/published work?	Chapter 2		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ The student conceptualised and designed the study, identified the research gap, developed the methodological framework, conducted all the investigation and analysis, and led the interpretation of results and manuscript preparation. The supervisory team provided academic supervision, critical review and editing, as well as methodological and theoretical guidance. All authors reviewed and approved the final published version.			
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Student's signature:	 Sanaz Nesarnobari Digitally signed by Sanaz Nesarnobari DN: cn=Sanaz Nesarnobari, email=Sanaz.Nesarnobari@massey.ac.nz, c=NZ, o=Massey University, ou=Massey University	Main supervisor's signature:	 Wajiha Shahzad Digitally signed by Wajiha Shahzad Date: 2026.06.19 10:34:04 +12'00'
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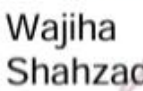
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Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
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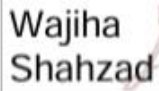
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Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
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Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
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Student name:	Sanaz Nesarnobari		
Name and title of main supervisor:	Dr Wajiha Mohsin Shahzad		
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