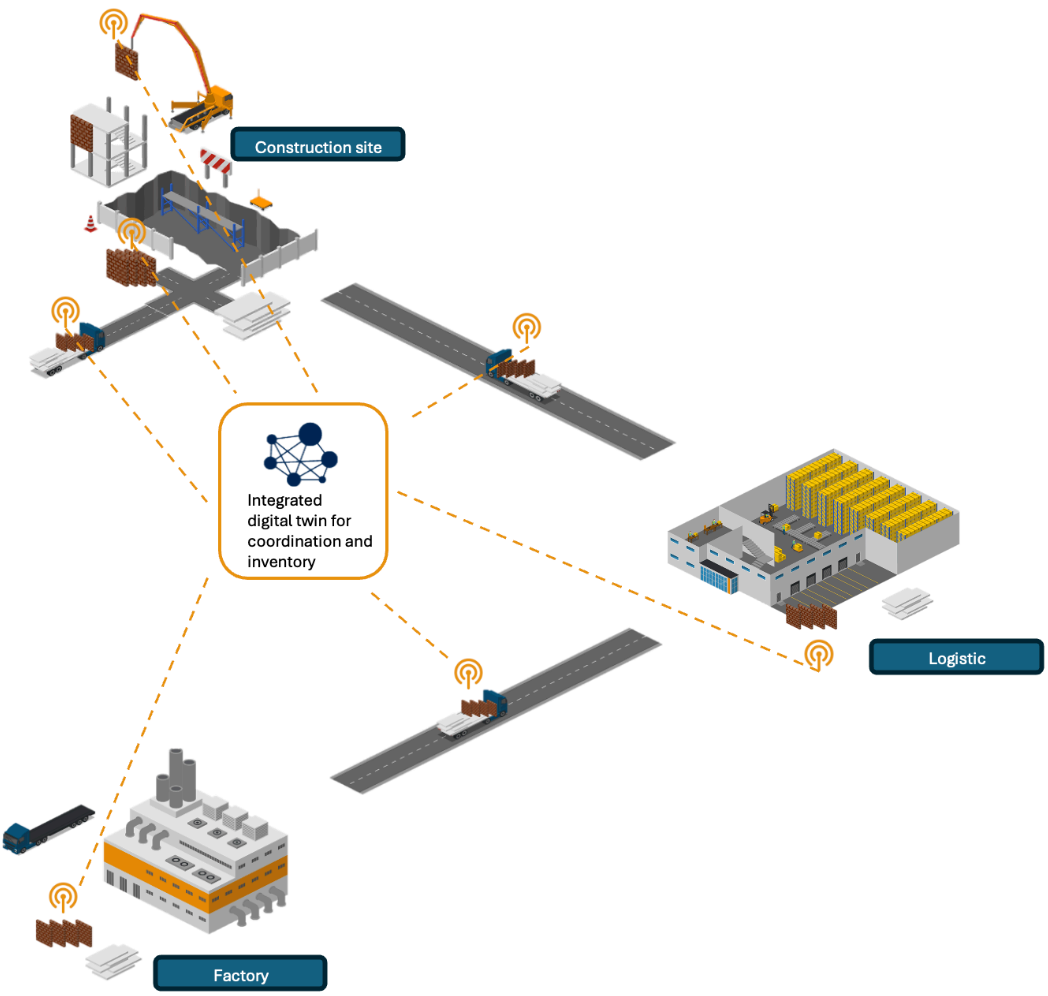
Integrated Digital Twins in Prefabricated Construction Supply Chain Coordination

- A hybrid simulation method

Stella Yongxue Tian

MSc Thesis
Construction Management and Engineering



TU Delft

Integrated Digital Twins in Prefabricated Construction Supply Chain Coordination

- A hybrid simulation method

by

Stella Yongxue Tian

to obtain the degree of Master of Science
at the Delft University of Technology,
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Graduation committee:

Chair:	Dr. Daniel M. Hall Faculty of Architecture and the Built Environment Department of Management in the Built Environment (MBE) Section of Design and Construction Management
First Supervisor:	Dr. Ir. Ranjith Kuttantharappel Soman Faculty of Civil Engineering and Geosciences Department of Materials, Mechanics, Management and Design (3Md) Section of Integral Design and Management
Second Supervisor:	Dr. Tong Wang Faculty of Architecture and the Built Environment Department of Management in the Built Environment (MBE) Section of Design and Construction Management

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TU Delft

Preface

This thesis marks the final chapter of my Master's journey, and I couldn't be more excited to finally be graduating. More than just a final project, this thesis has been my first real research experience, and it's meant so much more than just ticking off the last requirement. It's been a learning journey that has shaped not only my academic skills but also my personal growth.

I owe a huge thanks to my supervisors. Ranjith, thank you for always being responsive and providing such detailed guidance. Tong, your support, both academically and emotionally, has been invaluable. And Daniel, you kept me on track and made sure I didn't lose sight of the big picture—thank you for that!

I also want to express my gratitude to all the industry professionals who supported my research. Due to data anonymization, I can't name each of you, but to all eight of you, thank you for your invaluable insights and contributions.

To my family and friends, I honestly couldn't have done this without you. You've been there for me through every challenge, offering both practical help and emotional support. To my family, thank you for believing in my academic path, and to my friends, thank you for standing by me every step of the way.

There are so many more people I'd love to thank, but I'll keep those in my heart because sometimes words just don't do justice to true appreciation.

When I first chose this thesis topic, I'll admit it was a bit of an impulsive decision. A year ago, I had only basic knowledge of BIM and construction, with limited coding skills, and I barely knew anything about supply chain management or Digital Twins. But the moment Ranjith introduced me to this fascinating topic, I decided to dive in headfirst and spend over half a year on it. Thank you, Ranjith, for introducing me to this field, and thanks to myself for having the courage to take on this challenge.

I'm lucky that this thesis isn't the end of my academic journey but rather the start of future research with the same amazing supervisors. I'm excited about what's to come, and I hope to keep contributing to this area as I continue to learn and grow.

I hope you enjoy reading this thesis as much as I've enjoyed writing it!

- Stella Yongxue Tian
Delft, Netherlands
September 2024

Abstract

The construction industry is transitioning from traditional methods to an industrialized approach, aligning more closely with manufacturing systems where operational efficiency is key to project success. This shift is notably challenging within the prefabricated construction supply chain due to the complexity inherent in combining construction and manufacturing systems, each with its unique characteristics that differ from simpler systems. To effectively manage these complexities, digital twin-enabled simulations offer valuable insights into system behavior, enabling more effective management strategies. However, implementing these advanced simulations requires sophisticated techniques, as current methods often focus on single aspects, neglecting other crucial elements of supply chain management. This paper addresses these challenges by proposing a novel digital simulation approach that enhances supply chain coordination through a mixed-method framework. This framework integrates both micro-level constraints and macro-level tactical decisions, creating feedback loops between different layers of the system. A case study is conducted using supply chain tactics involving inventory and capacity buffers based on the developed model. The study contributes to both theoretical knowledge and practical applications by providing a comprehensive framework for understanding the operational functions of digital twins and offering insights for future academic model development in the prefabricated construction supply chain. It enhances the understanding of operational efficiency and supply chain coordination in this evolving field for both researchers and practitioners.

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Abbreviations

ABM Agent Based Modelling

ATO Assemble to Order

DES Discrete Event Simulation

DT Digital Twin

ETO Engineering to Order

HS Hybrid Simulation

MAS Multi Agent System

MTS Make to Stock

MTO Make to Order

PC Prefabricated Construction

PCSC Prefabricated Construction Supply Chain

SC Supply Chain

SCM Supply Chain Management

SD System Dynamics

1

Introduction

1.1. Background

Industry Context: growing trend towards prefabrication

The construction industry is a pivotal sector of the global economy. In recent years, it has undergone significant transformations from a traditional mode to an industrialization trend. Enhancing efficiency, reducing costs, and mitigating environmental impacts are some of the main concerns in the industry. A notable trend in this evolution is the shift towards prefabricated construction (PC)—a method that involves manufacturing parts of the building components off-site (in a factory) and then transporting them to the construction site for assembly. This method is recognized for its ability to improve sustainability, productivity, and quality and consequently realize reductions in deadlines, costs, and dependence on labor (Rocha, Ferreira, Pimenta, & Pereira, 2022). As a result, the global Prefabricated Building and Modular Construction Market size is expected to reach USD 120.4 billion and is projected to achieve a Compound Annual Growth Rate of 6.5% from 2023–2030 (Delvens, 2023).

Significance of Operational Efficiency in Prefabricated Construction

Operational efficiency is a key performance measure in the manufacturing industry. Prefabricated construction projects, with properties similar to manufacturing, also emphasize operational efficiency as a cornerstone for timely delivery, cost-effectiveness, and overall project success. In the prefabricated construction industry, the efficiency of operations directly influences the synchronization of the entire supply chain steps, from engineering and manufacturing components in a factory setting to their assembly on the construction site (Pan, Gibb, & Dainty, 2012). It also encompasses the management of information flow, ensuring that all stakeholders have access to timely and accurate data to make informed decisions (Arashpour & Isik, 2017). This holistic approach to operational efficiency, which combines both material and informational flows, is crucial to maximizing the benefits of prefabrication.

Complexity in Construction and Manufacturing

Despite the importance of operational efficiency in the PC industry, achieving it is not an easy task due to the complex nature of such projects. The construction and manufacturing sectors are characterized by inherent complexities that stem from their nature, such as the number of processes, technologies, stakeholders, and environmental factors. These complexities are further amplified in the context of prefabrication, where the integration of off-site manufacturing with on-site assembly introduces additional layers of coordination and logistical challenges (Stornelli, Ozcan, & Simms, 2021). Synchronization across the prefabricated construction supply chain (PCSC), from the initial design phase through manufacturing in controlled environments to the final assembly at the construction site, requires advanced management approaches.

Technological Innovations

To address this challenge, innovative management approaches are essential. As the development of Industry 4.0 continues, data-intensive aided decision-making methods such as machine learning or AI have been extensively used for predictive maintenance, optimizing the supply chain, and predictive production planning, among others (F. Hu, Bi, & Zhu, 2024). Digital tools like the Digital Twin (DT) to improve communication and coordination, integrating project delivery methods that encourage collaboration among all project stakeholders from the start, have proven to be promising (Boschert, Heinrich,

& Rosen, 2018). Using advanced logistics and supply chain management methods is also important to ensure that prefabricated parts are delivered on time.

1.2. Research Gap

The processes involved in construction and manufacturing are inherently complex, especially in prefabrication, where traditional management methods may no longer be adequate (Li, Shen, & Xue, 2014). To overcome these challenges, there is a need to focus on integration and the adoption of digital technologies to ensure smooth operations and timely project completion. Despite the recognized importance of operational efficiency in prefabricated construction supply chains and the potential of digital twin technologies, a significant gap exists: there is no clear way of utilizing and integrating digital twins across the entire supply chain to streamline processes and enhance operational efficiency through more informed decision-making.

1.3. Research Aim, Question and Scope

This research aims to fill the knowledge gap in Prefabricated Construction Supply Chain (PCSC) management by exploring supply chain coordination modes and developing a digital twin-enabled hybrid simulation method. It focuses on analyzing current coordination practices, identifying challenges with single modeling methods, and proposing a novel simulation approach that integrates diverse methods to more representatively capture complex interactions within the supply chain. A prototype will be developed to demonstrate the feasibility and practical applications of this framework, particularly using tactics like inventory and capacity buffers. Additionally, by testing various supply chain tactics under different scenarios, this study aims to demonstrate the effectiveness of the hybrid simulation approach in improving supply chain performance and provide detailed guidelines for future model development. This research will showcase how hybrid simulation, combined with digital twins, can offer valuable insights to improve management practices.
Following the described research gap and aim, the research question proposed for this paper is:

Main question: *How can a digital twin-enabled simulation help with prefabricated construction supply chain coordination?*
To answer it, three sub-questions are listed as below:
Sub-question 1: *What are the general supply chain modes in the context of prefabricated construction, and how are they coordinated?*
Sub-question 2: *How can this type of coordination be modeled using the advanced simulation capabilities provided by digital twins through a hybrid simulation method?*
Sub-question 3: *How can the proposed simulation approach aid in determining practical tactics for using different buffers in the supply chain?*

While the research aims to provide a new approach to simulating and improving supply chain coordination, its scope does not include improving the absolute accuracy of the simulation model itself. The prototype is built to demonstrate the feasibility and potential of the proposed approach rather than achieving perfect precision in the model's predictions. Therefore, while the model under a case study setting will be rigorously developed and tested, its exact accuracy is considered beyond the scope of this study.
The following chapters are divided as follows: Chapter 2 provides a thorough literature review to offer a better background on the research question and the current state of related issues. Chapter 3 introduces the research methods used in this paper and outlines the overall structure. Chapter 4 addresses the first research question by summarizing various supply chain coordination models. Chapter 5 answers the second sub-question by providing a detailed description of how different simulation methods can be matched to different stages and aspects of the prefabricated construction supply chain. Chapter 6 addresses the third sub-question by applying the model proposed in Chapter 5 to a real-life case of panelized construction. Chapter 7 discusses all the findings and results from Chapters 4, 5, and 6, and examines the limitations of the study. Finally, Chapter 8 presents the overall conclusions of the research and provides a comprehensive answer to the primary research question.

2
Literature Review

Following the three sub-questions, three types of literature are first searched and complemented by interviews. Section 2.1 introduces the general coordination problems in PPCSC, and how to understand this kind of problem using a complex system perspective and digital twin technology. Section 2.2 provides the state of the art of different simulation methods in previous studies and the advantages and disadvantages of them, and the identified potential direction to use the proper simulation method for it. Section 2.3 introduces some practical coordination and management methods applied mostly in this supply chain context, which provides basics as a practical case in the following case study part.

2.1. Complex Systems and Digital Twins: Understanding and Managing PCSC

2.1.1. Complex System for PCSC

Building upon insights from the preceding analysis, it becomes evident that the dynamic strategy formulation within supply chains encompasses intricate processes and variabilities. This necessitates a deep comprehension of both macro-level strategies, tactics, and micro-level constraints, thereby justifying the integration of complex systems theory into supply chain management. Complex systems theory provides a robust framework for the simulation and analysis of dynamic interactions observed at construction sites and manufacturing settings. The notion of complex systems within these fields allows for the dynamics of construction sites and manufacturing factories to be modeled and analyzed. However, what constitutes a system and what is considered a complex system have quite a lot of definitions. A taxonomy of systems lists a hierarchy of different systems: simple systems, complicated systems, a system of systems (SoS), complex systems, collaborative SoS, adaptive systems, and complex adaptive systems (Baldwin, Felder, & Sauser, 2011). And the systems beyond complicated systems can all be considered complex systems, which is a totally different concept rather than simply more elements. A complex system is two or more components that combine to produce from one or more inputs one or more results that could not be obtained from the components individually (Grieves & Vickers, 2016). Manufacturing organizations can be treated as complex adaptive systems consisting of an integrated assembly of interacting elements, designed to carry out cooperatively a predetermined objective, which is the transformation of raw material into marketable products (McCarthy, Rakotobe-Joel, & Frizelle, 2000). Bertelsen (2003) also acknowledge that construction projects and their related production processes should be treated from a complexity science perspective as three main characteristics of complex systems, autonomous agents, undefined value, and non-linearity, can be found in the construction industry.

Emergent properties and behaviors are distinguishing traits of complex systems. Emergent properties arise from interactions and interdependencies between constituents in complex systems and greatly affect system-level behaviors and performance (Johansen & Nejad, 2019). Notable emergent properties in literature include resilience, vulnerability, agility, flexibility, and adaptive capacity. Furthermore, supply chain dynamics are susceptible to emergent behaviors, which often surface unexpectedly due to alterations in the relational and dependency matrices among supply chain participants. These emergent behaviors often arise on account of the degree and extent of interactions among the subsystems,

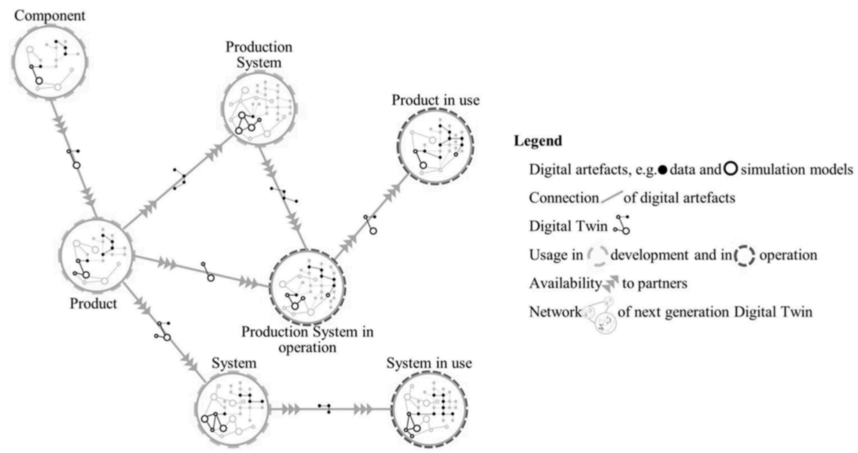

Figure 2.1: Linked digital twins in the whole value network. Source: (Boschert et al., 2018)

i.e., the degree and extent of the effects on other subsystems while changing structural or dynamic properties of a subsystem. These interactions – which are sensitive to the history of the subsystems and to their current context (Hogue & Lord, 2007) – can lead to both linear and nonlinear behaviors in complex systems. These transformations, irrespective of their magnitude, critically affect the decision-making processes, actions, and strategic choices within the supply chain framework. Incremental changes can accumulate, leading to significant and often undesirable emergent behaviors that pose challenges to supply chain synchronization, strategic planning, and relational dynamics among partners. Noteworthy among such phenomena is the 'bullwhip effect', where decision-making delays in downstream processes amplify undesirable outcomes upstream (Surana, Kumara, Greaves, & Raghavan, 2005). It could be caused by the amplification of demand distortion, rationing and shortage gaming, order batching, and price fluctuations among others (Abbasi & Varga, 2022). Understanding of emergence, emergent properties, and emergent behavior in projects can help better assess and manage the project. For example, emergent properties can be used to examine whether a project's complexity is aligning with its capacity to handle it (Zhu & Mostafavi, 2017). Despite the use of systems thinking in existing project management literature, emergent properties in project systems and their significant impacts on project performance have not been fully understood (Zhu & Mostafavi, 2017).

2.1.2. Digital Twins and Integrated Digital Twins

Digital twins are predominantly applied within the manufacturing sector. Achieving operational efficiency in real-time manufacturing settings presents a multifaceted challenge due to the unpredictability inherent in these systems. Numerous studies focus on this area; for instance, enhancing production control through detailed analysis of expected versus actual progress using virtual models allows for the real-time adaptation of manufacturing strategies (Tao & Zhang, 2017). Additionally, digital twins facilitate the simulation of various scenarios in part production processes, thereby proactively identifying and addressing potential issues to minimize downtime (Johansen & Nejad, 2019). The history of DT in construction is relatively brief compared to its emergence in the manufacturing and aerospace industries. Yet, this emerging technology is rapidly advancing and becoming a central focus within the construction sector. Digital twins in construction are used for several purposes, including monitoring progress, maintaining equipment, managing energy efficiency, and preventing accidents (Zhang, Cheng, Chen, & Chen, 2022). Besides the individual use of DTs, Boschert et al. (2018) prospected the paradigm of next-generation digital twin (nexDT) as shown in Figure 2.1. They claim that the current isolated DT models cannot fulfill all purposes and tasks across the entire lifecycle and the integration of multiple DT models for different business objectives is needed.

Existing research on DTs during the construction phase often overlooks the vital interactions between products and processes, focusing mainly on on-site activities without considering the manufacturing work that precedes. The absence of real-time information exchange between the DTs of construction and manufacturing processes can lead to the development of incompatible optimization strategies, adversely affecting the decision-making capabilities of construction managers. Without this crucial in-

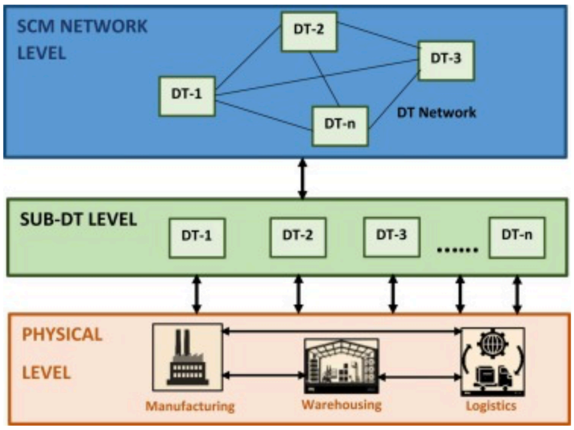

Figure 2.2: Levels in Sub-DTs for DT SCM network. Source: (Syed et al., 2024)

tegration, DTs risk falling short of their potential for enhancing control and optimization in construction projects (Custovic, Cao, & Hall, 2023).

2.1.3. Managing Complexity with Digital Twins in PCSC

In the realm of supply chain management, digital twins provide comprehensive oversight of both internal and external components of end-to-end supply chains. They facilitate the development of non-linear supply chain models through interactions with humans, devices, and other connected digital twins. These models enhance visibility across the supply chain, aiding organizations in identifying patterns, pinpointing opportunities for improvement, eliminating inefficiencies, and optimizing existing processes. For instance, a digital twin in the supply chain might encompass manufacturing machines, module components, transportation, warehouses, delivery trucks, assembly workers, and cranes to visually monitor and track the project's current status and progress (Ivanov & Dolgui, 2021). Moreover, digital twins enable the simulation of various "what-if" scenarios to accurately forecast potential supply chain risks, such as deviations in schedules (Park, Son, & Noh, 2021). Despite the promising potential of digital twins in supply chain management, particularly in logistics—which involves the production, storage, and delivery of modules—a significant opportunity remains underexplored in their integration, especially in the context of modular construction (Lee & Lee, 2021).
To be more specific, the conceptual framework of how DTs could be used for SCM is described in figure2.2 (Syed, Sharfuddin, & Amin, 2024), it shows the implementation of digital twins (sub-DTs in the figure) at various SCM levels, ranging from discrete components to comprehensive strategic planning within an SCM network. This approach underlines the criticality of embedding DTs at every phase of the supply chain to boost operational efficiency and enhance decision-making processes. Each component within the SCM is equipped with a sub-DT that actively captures and analyzes real-time data from its physical counterpart. This setup enables meticulous monitoring, thorough analysis, and precise optimization of operations at a detailed level.

2.2. Hybrid Modelling and Simulation in Construction Supply Chain

2.2.1. Modelling and Simulation Techniques Comparison

Simulation modelling is an important instrument in research for several reasons. It provides a valuable tool for approximating real-life behavior and hence can be used for testing scenarios. Additionally, the art of constructing the model itself may lead the modeller to a greater understanding of the real system. There are three main methods in use: Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Modelling (ABM) (Maidstone, 2012).
The comparison among all three methods is shown in Table2.1 with their essential focusing points, advantages, and applicability. As can be seen, they complement each other in many aspects such as level of detail, continuous and discrete, etc. This necessitates the combination of these methods. However, single modeling techniques often fail to capture the necessary properties of complex sys-

Table 2.1: Comparison of System Dynamics (SD), Agent-Based Modeling (ABM), and Discrete Event Simulation (DES)

Aspect	System Dynamics (SD)	Agent-Based Modeling (ABM)	Discrete Event Simulation (DES)
Approach	Top-down	Bottom-up	Event-oriented
Perspective	Macro and holistic	Spatial or social interactions between individuals and their environment	Focuses on the sequence and timing of events
Purpose	Understands structure behind complex phenomena	Combines time and space dimensions, revealing micro mechanisms of complex macro phenomena	Models the operation of a system as a discrete sequence of events in time
Philosophical Basis	Reductionism: breaking down complex entities into simpler components	Syncretism: integrating holistic analysis with detailed component interactions	Positivism: focuses on observable phenomena and events
Usage	Studies dynamic evolution processes under various scenarios	Effective cross-scale modeling method	Used primarily in operations research, manufacturing, logistics, and computer science
Strengths	Helps understand macro-level structure	Reveals micro mechanisms through simulations	Can accurately model complex logistical and operational systems
Criticisms	Does not fully capture interplay between macro and micro behaviors; insufficient for detailed micro-level analysis	Sensitive to small variations; requires extensive sensitivity analysis; often overlooks interactions with macro factors	Limited in representing continuous processes; tends to focus more on the operational details rather than the interactions at different scales
Suitability	Good for large-scale systemic analysis	Suitable for analyzing individual behaviors and interactions within a system	Ideal for systems where events occur at discrete points in time

tems due to their different abstraction levels and focuses. Hybrid simulation (HS), which integrates at least two modeling techniques, can help decision-makers evaluate the impact of micro-level actions on macro-level outcomes.

Researchers have also proposed HS frameworks for various fields over the last decade. To harness the strengths of both modeling techniques, integration strategies have been proposed. As outlined by (Ding, Gong, Li, & Wu, 2018), one approach is an ABM framework underpinned by SD principles, where macro-level objects (SD component) encompass micro-level agents (ABM component). Conversely, an SD framework based on ABM involves modeling agent interactions at the macro level and detailing their internal structures at the micro level. There are also proposed ways of how in an overall view these two simulation methods should interact based on their function and hierarchy as shown in Figure 2.3 by Nguyen, Howick, and Megiddo(2021). In the prefabricated construction supply chain setting, it is better for managers to continuously get feedback from the bottom performance and improve strategy; an integration/enrichment way seems promising (which we will discuss in the next section).

2.2.2. Modelling and Simulation with DTs in SCM

An agent-based method is a computational approach that models the interactions of autonomous agents with a view to assessing their effects on the system as a whole. Agents are defined as entities with their own set of behaviors, preferences, and abilities to make decisions. These agents can represent individuals, groups, organizations, or various components within a system. The agent-based modeling (ABM) technique allows the simulation of complex, dynamic phenomena resulting from the interactions of these agents within their environment. The construction industry involves numerous

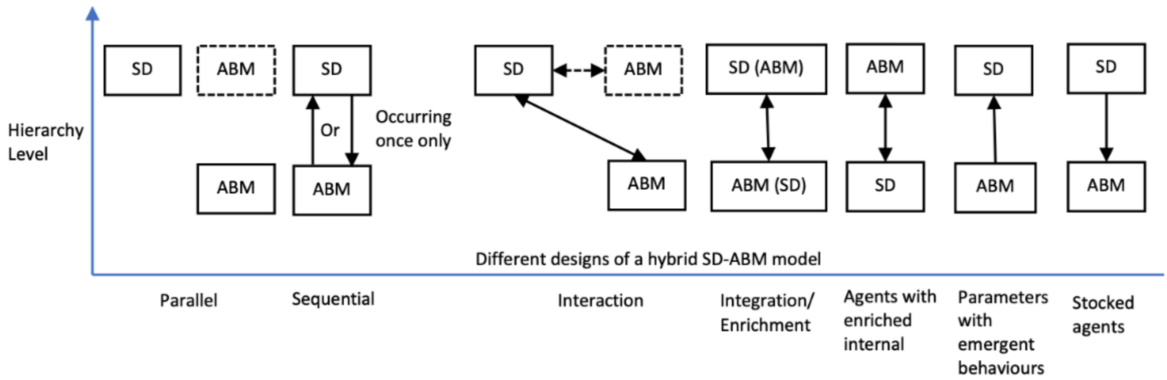

Figure 2.3: SD and ABM interacting mode. Source: (Nguyen et al., 2021)

stakeholders—including employers, designers, contractors, and subcontractors—who often operate from diverse geographic locations and have varying perspectives and objectives regarding the project. This diversity necessitates the adoption of distributed problem-solving approaches using multi-agent systems (MAS) to accurately replicate the characteristics and dynamics of construction projects (Aladag & Isik, 2019). In both manufacturing and construction domains, ABM and MAS are employed to simulate the behaviors of various actors such as workers, machines, materials, and management entities. This simulation aids in the analysis and optimization of processes. MAS are particularly valuable in construction engineering and management for addressing issues that require negotiation among parties, such as risk allocation, claim management, and supply chain management (Aladag & Isik, 2019). Regarding supply chains, these are networks composed of multiple independent or semi-independent entities, each with its own structure and responsibilities related to material and information flows. One of the significant challenges in supply chain management is enabling these entities to operate autonomously while ensuring effective cooperation. Agent-Based Models serve as a critical tool in depicting these interrelationships, providing a formal and simplified system representation—which can be as intricate as the interactions among all supply chain agents, from suppliers to manufacturers and distributors—and optimizing risk mitigation strategies (Orozco-Romero, Arias-Portela, & Marmolejo-Saucedo, 2020).

In the context of a prefabricated construction supply chain, the interaction and coordination among all parties are usually complex, ranging from macro-level stakeholder communication to micro-level operational connections. As construction projects grow larger and involve more participants, modeling and simulation (M&S) tools become essential for decision-making. The potential benefits of HS in the construction industry are significant due to its complex nature, where engineering, physical, and economic factors are closely interlinked with project constraints. In the specific context of prefabricated construction supply chain settings, both SD and ABM can explore complexity problems in a complex adaptive system.

2.2.3. Hybrid Simulation Method in PCSC

Based on these literatures, the way we use hybrid simulation could be firstly understanding the whole system: Perceiving the complexity of the whole picture of the context by the decision maker is criticized in the decision-making process. System Dynamics starts with the philosophy of building a structure representing the system. Using Causal Loop Diagrams (CLD) and Stock-Flow Diagrams (SFD), the modeler captures most of the factors of the system (Prusty & Mohapatra, 2016).

Agent-Based Modeling (ABM) adds a further layer of granularity by simulating the interactions of autonomous agents, each governed by distinct behavioral rules, which allows the examination of emergent phenomena from the bottom-up perspective. This approach is particularly effective in scenarios where individual behaviors and interactions significantly influence the overall system dynamics, such as when participating parties have their own decision-making ways.

Discrete Event Simulation (DES) complements both SD and ABM by focusing on the simulation of operations and processes as a sequence of discrete events in time. This method is highly effective in

environments where state changes are discrete and events are significant, such as manufacturing lines or hospital management systems. DES can help in pinpointing bottlenecks, optimizing process flows, and evaluating the impact of operational decisions on system performance.
Integrating SD, ABM, and DES within a hybrid simulation framework provides a comprehensive toolset for modeling complex systems across various scales and dimensions, enhancing the decision-making process by providing detailed insights into the dynamics at multiple levels of interaction.

2.3. Practical Prefabricated Construction Supply Chain Operational Coordination Tactics

2.3.1. Use of Supply Chain Tactics

Prefabricated construction is an innovative method where construction components cast on-site traditionally can be manufactured in an off-site factory and delivered to the construction site. This method has advantages such as being efficient and not being constrained by weather, etc. In this process, the prefabricated construction supply chain (PCSC) plays a key role in connecting construction sites and off-site factories (Wang, Hu, Gong, Ma, & Xiong, 2019).
Efficient execution and synchronization of upstream production steps with on-site construction activities are essential for completing projects on time and within budget. This involves a coordination process of aligning the production of construction elements, such as precast concrete components or structural steel elements, with the on-site construction schedule to minimize delays, optimize resource utilization, and enhance project productivity, etc. However, this is a challenging task as these activities are carried out in complex environments with different business objectives and strategies (Custovic et al., 2023).
Among this coordination, operational hedging is a typical strategy to mitigate heavy impacts caused by potential risks in the supply chain. Operational hedging involves extra investment to enhance logistics reliability and mitigate supply chain uncertainties. It encompasses strategies like lead-time hedging, which aims to buffer against unforeseen delays by adjusting due dates and reducing lead times, and space hedging, which uses buffer spaces near construction sites to manage early or late deliveries; a typical buffer reserving mechanism is shown in Figure 2.4. While these strategies can improve supply chain reliability, they also introduce trade-offs and potential conflicts between departments, such as increased pressure on production facilities and inefficiencies for logistics providers (Zhai, Zhong, & Huang, 2015). Zhai and Huang (2017) introduced an interaction mechanism between the building company and the prefab factory with regard to this problem. Zhai et al. (2017) also uses game theory to describe this scheme under different power structure settings.
Moreover, the hedging coordination between upstream element production facilities and on-site construction teams depends on robust communication limited by the lack of in-depth information tracking throughout the supply chain phases. This gap points to a promising research direction, as noted by Han, Yan, and Piroozfar(2023), which could lead to significant advancements in the field. Also, advancing information-level use of modern technologies like digital twins is an emerging and interesting direction to explore.

2.3.2. Different Buffers in PC Supply Chain

There are various buffers in the supply chain. Table 2.2 gives three commonly used buffers, and among them, buffer space (capacity) hedging and lead-time reduction (including setup time reduction, shipping time reduction, and production time reduction) are two commonly used operational hedging methods (Chung, Talluri, & Kovács, 2018). Previous works focus more on single optimization of these two different buffers or in a centralized way, but there are few examples of how these two strategies should be coordinated (Zhai, Xu, & Huang, 2019). What's more, the previous analytical thinking and methods still remain too static and although both time and inventory buffers function as a safeguard against uncertainties, there are significant distinctions between the two. While the time buffer is highly responsive, it is also significantly expensive despite its utilization. Conversely, the inventory buffer is comparatively less responsive and less costly, as it can be easily repurposed if not needed. Additionally, inventory buffer can maintain continuous operational flow, even if it encounters challenges at previous stages. On the other hand, the time buffer ensures the start time of the following stages is independent of ground conditions. Both the inventory and time buffers have their respective advantages and disadvantages, and in certain cases, they can complement each other (Lu, Liu, & Li, 2024).

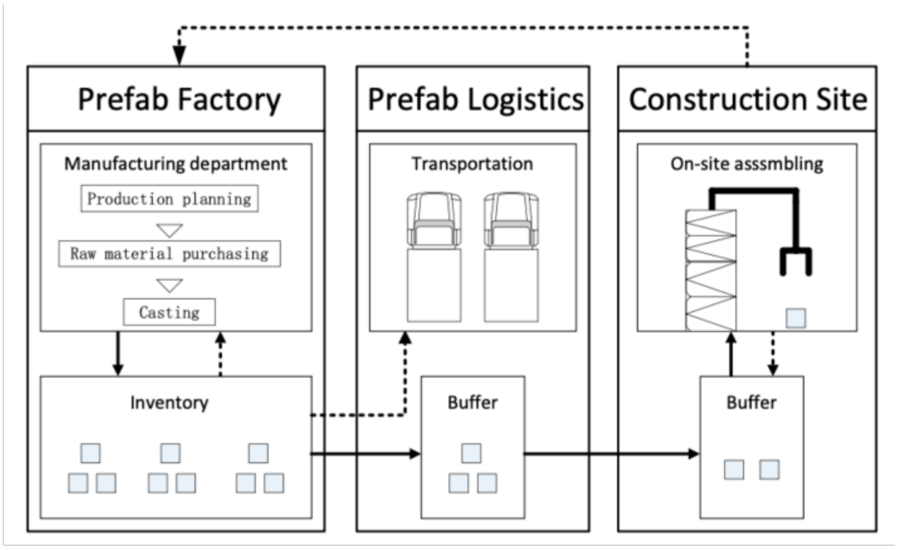

Figure 2.4: Buffers in Supply Chain. Source: (Zhai et al., 2015)

Table 2.2: Buffer Types, Descriptions, Benefits, and Challenges

Buffer Type	Description	Benefits	Challenges
Inventory Buffers	Act as decoupling points protecting both the demand and supply side from variability. Sized and used correctly, they protect supply chains from impacts of variability. Technology like AIMMS Inventory Planning can help calculate the right amount of inventory required for each SKU in various scenarios. This shifts the conversation from inventory reduction to using it as a strategic resource.	- Provide adaptability, allowing variability to be absorbed at decoupling points. - Use inventory as a strategic and tactical resource.	- Common sense approach but challenges arise from the 'unit cost optimization' mindset that doesn't accommodate variability. - Assumes lead times are stable and precise, limiting the approval for adopting strategic buffers.
Lead Time Buffers	Address lead time variability, where delays impact production but early arrivals do not. By inserting lead time buffers for critical or bottleneck resources, companies can ensure readiness for planned production. This prevents the supply chain from halting due to variability and delays.	- Allow for variability in planning, keeping flexibility amidst uncertainty. - Prevent supply chain halts due to variability and delays.	- Common sense approach, but often hindered by deterministic planning and stable lead time assumptions. - KPIs and targets based on precise forecasts prevent the adoption of strategic buffers.
Capacity Buffers	Involve leaving some spare capacity to respond to unexpected changes in demand that may overwhelm inventory buffers and impact service. It's about planning some burst capacity. Solutions like AIMMS S&OP can identify capacity pinch points or bottlenecks, and create capacity in those areas. If increasing capacity isn't feasible, inventory buffers can be increased instead.	- Create agility in the supply chain, allowing response to sudden changes in demand. Address unexpected issues effectively.	- Planning for spare capacity can be challenging due to cost implications. Requires balancing capacity creation and inventory buffer adjustments.

2.3.3. Dynamic Ordering Policy and Constraints in Prefabricated Construction Context

Dynamic Approaches for Decision Release and Control Construction sites typically order materials from manufacturing factories well in advance through a strategy known as ”lead-time hedging” to ensure the timely availability of products. This strategy, while beneficial for sales departments in meeting customer demands accurately and on time, imposes additional costs and operational pressures on manufacturing processes. Y. Hu, Guan, and Liu (2011) has shown how to coordinate lead times using game theory models. Traditional inventory management often relies on static policies such as fixed reorder points and order quantities, which fail to adapt to fluctuations in demand or lead-time variability and do not consider the correlations between these elements.

Furthermore, the capacity buffer—a critical tactic mentioned previously—is seldom managed in conjunction with other buffers, leading to reduced agility and responsiveness in manufacturing operations. An effective order release decision encompasses multiple factors, including the type of order, timing, and quantity. While basic formulas like the Economic Order Quantity (EOQ) may guide general order release plans, actual implementation often deviates, necessitating a robust manufacturing planning and control (MPC) system. MPC systems are engineered to optimize the flow of materials and goods and the utilization of resources such as personnel, equipment, and capacity. To manage the complexity inherent in the manufacturing department, it is beneficial to structure the management task hierarchically into top and base levels. These planning levels interact through directives issued by the top level (e.g., order release instructions) and feedback from the base level, ensuring that the top-level targets are achievable given the resource constraints at the base level (Haeussler, Schneckenreither, & Gerhold, 2019). This interaction involves using a predictive model of the base level within the top-level framework, allowing the top level to anticipate future states such as inventory levels, total available capacity, and flow times.

The critical interface between the top and base levels is the order release decision, which significantly influences the workload on the manufacturing station. This decision is typically based on the planned lead time, a key parameter in top-level hierarchical MPC models. Lead times represent the planned duration from order release to the entry of goods into finished inventory, whereas actual durations, known as flow times or cycle times, are observed through the production system and serve as a measure of performance.

2.3.4. Supply Chain Feedback Loops

In this way, feedback loops between the top and bottom levels are created. Even though they are often overlooked in logistics planning and execution, they ensure alignment and efficient execution of plans at strategic, tactical, and operational levels, as shown in Figure 2.5 created by Miller and Liberatore(2020). These loops are essential because higher-level planning decisions can sometimes be impractical when implemented at lower levels. To address this, feedback from lower-level planning (short-term operational) to higher levels (strategic and tactical) is vital; a description and example of such different levels of planning are shown in Table 2.3.

In a hierarchical logistics planning framework, higher-level decisions set constraints for lower-level decisions, promoting aligned decision-making across the organization. Feedback loops provide the mechanism for lower-level planners to inform higher-level planners, creating a closed-loop system. This system integrates top-down planning with bottom-up feedback, ensuring plans are feasible and aligned. Without robust feedback loops, logistics functions risk proceeding with impractical plans, often revealed during operational execution.

To effectively manage the complexity inherent in manufacturing firms, it is beneficial to structure the management tasks hierarchically, dividing them into a top level and a base level. These levels interact through directives issued by the top level (such as the specifications of which orders to release) and feedback provided by the base level. It is crucial that the objectives set by the top level are achievable, given the resource limitations at the base level. This necessitates the incorporation of a predictive model of the base level within the top-level framework to foresee future conditions such as inventory levels, total available capacity, and flow times.

An illustrative example of this interface between the top and base levels is the order release decision, which significantly influences the system’s workload. This decision primarily relies on planned lead times or stock levels, positioning it as a critical parameter in top-level hierarchical manufacturing plan-

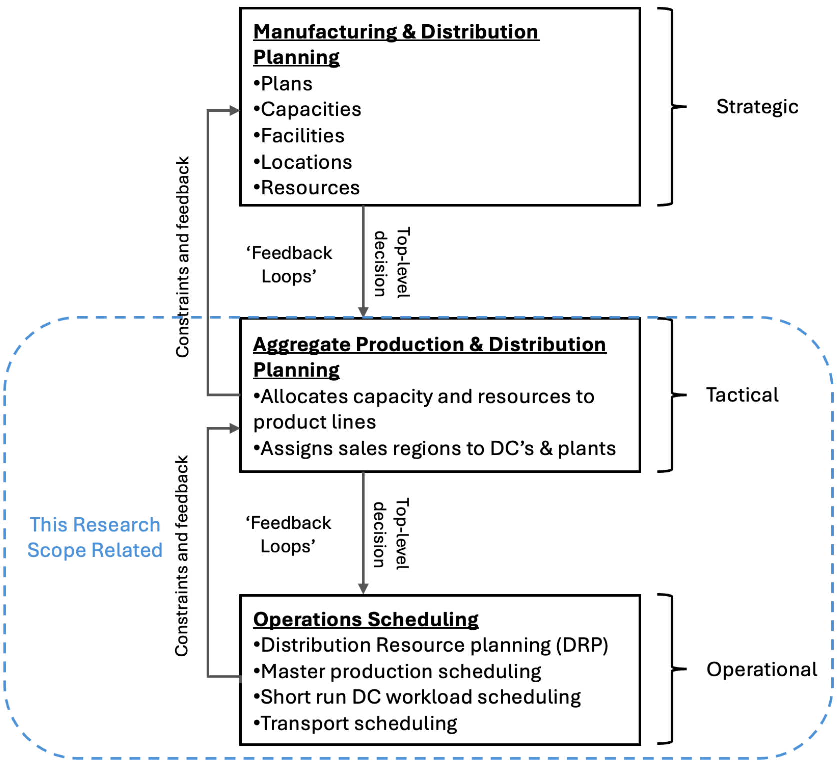

Figure 2.5: Hierarchy feedback from strategic to operational. Source: Adapted from (Miller & Liberatore, 2020)

ning and control models. Lead times are defined as the scheduled period between the release of an order and its receipt in the finished goods inventory. This planned duration can be contrasted with the actual time it takes for an order to move through the production process (Haeussler et al., 2019).

Table 2.3: Hierarchical Planning Levels and Examples

Planning Level	Description	Examples
Strategic Planning	Focuses on long-term decisions critical to organizational success, often involving significant resource allocation and management oversight.	Choosing factory locations and sizes, selecting suppliers, developing a global supply chain.
Tactical Planning	Concerns medium-term decisions that impact organizational effectiveness, requiring moderate resources and time compared to strategic and operational planning.	Managing inventory, setting transportation schedules, planning production cycles.
Operational Planning	Deals with short-term, day-to-day decisions to maintain organizational operations, demanding minimal resources and managerial involvement.	Designing warehouse layouts, scheduling production lines, managing order fulfillment.

2.4. Summary of Literature Review

As a summary shown in Figure 2.6, the framework presents an integrated view of digital twins across different layers and their relevance to the posed research questions. The literature review underscores that both construction and manufacturing systems, characterized as complex due to their numerous interconnected parties and dynamic processes, are yet to be fully understood. This complexity, especially when these systems are integrated and require increased interaction, aligns with the physical layer of the digital twin and is addressed by sub-question 1. Upon gaining a deep understanding of the processes within PCSC, digital twins emerge as crucial for advancing this knowledge. Their capacity for conducting advanced simulations provides an invaluable tool for building virtual models of these

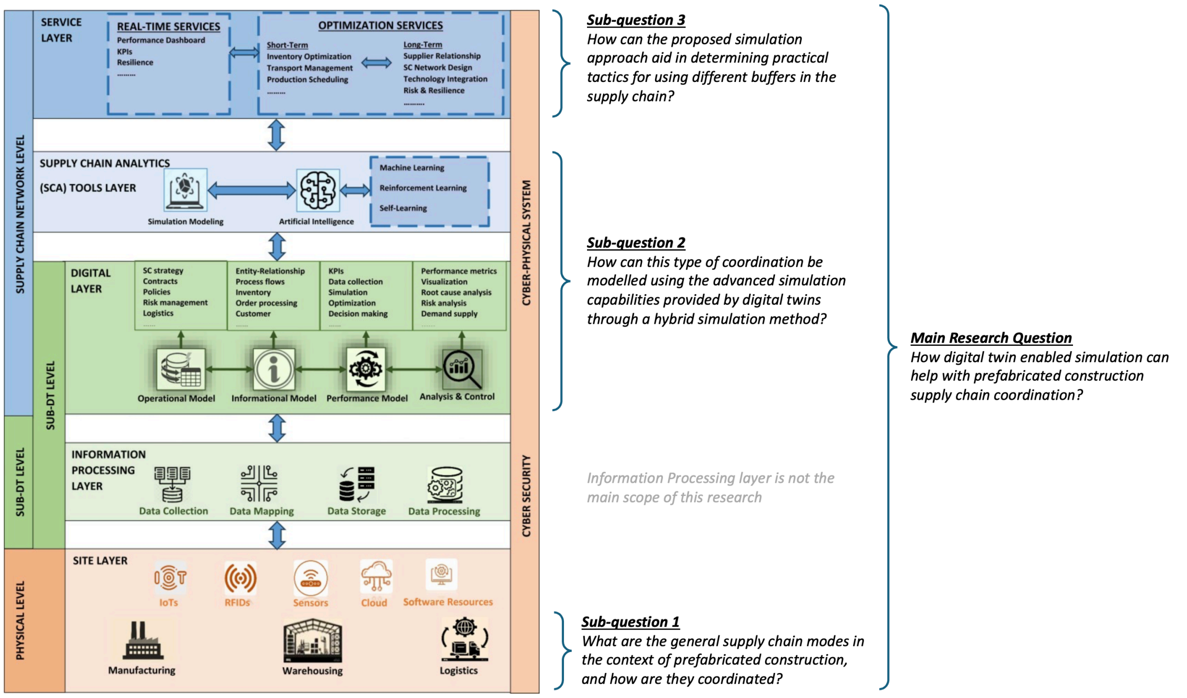

Figure 2.6: DTs for SCM and relations to research scope. Source: The author's own elaboration adapted from (Syed et al., 2024)

systems, thus facilitating their integration. This aspect falls under the digital layer of the digital twin and is further investigated in sub-question 2. Three primary simulation methods have been identified, each capable of representing various aspects of the supply chain. These methods, promising for modeling diverse processes and tactics, form the foundation for the service layer of the digital twin and are examined in sub-question 3. In particular, the strategic use of buffers in supply chains presents a notable area for deeper exploration. Ultimately, by addressing these sub-questions, a comprehensive understanding of how digital twins can aid in optimizing supply chain management is articulated through the main research question.

The subsequent chapters will apply the research methods outlined in Chapter 3 to methodically address these gaps.

3

Research Method

This research adopts a combined approach of experimental research and design science research. The methodology consists of several interconnected stages to ensure a comprehensive solution, as shown in Figure 3.1. The research roughly follows the sequence of each sub-question. Each sub-question includes three stages: data collection, model building, model adjustment, and validation, with some overlapping parts in the timeline. Data collection for the three sub-questions is conducted simultaneously at first. Then, regarding model building, they follow a sequential order due to their functionality, and a final validation is conducted for all three sub-questions.

3.1. Stage 1- Data Collection

In Stage 1, a literature review and semi-structured interviews were conducted to gather information about current prefabricated construction methods, the involved supply chain parties, coordination modes, and decision-making methods. Six interviews were conducted with participants from five different companies, covering three key areas within the prefabricated construction industry: construction, factory operations, and logistics. These participants, referred to as Interviewees 1 to 6, are detailed in Table 3.1. The company types are described in general terms to represent different perspectives in this context, though they vary slightly; for example, some are solely construction companies, others integrate design and construction, and some operate as factories but are part of companies that also engage in construction. The interviews aimed to understand the current supply chain and coordination processes in prefabricated construction, their inventory management along the supply chain, and the general recognition of digital twins. They focused on the following aspects to mainly address sub-questions 1 and 3, and to gather ideas for sub-question 2:

- Business overview and partnerships
- Main processes involved in prefabricated construction projects
- Business objectives and decision-making processes
- Internal uncertainties and challenges
- Supply chain coordination challenges
- Inventory management decisions
- Suggestions for the use of digital twins in supply chain coordination

A more detailed list of interview questions is provided in Appendix B.
Simultaneously, for sub-question 2, literatures were thoroughly analyzed to compare different modeling and simulation methods used, particularly in the context of construction supply chains. The comparison focused on their advantages, disadvantages, and how they could be integrated to simulate different aspects of the prefabricated construction supply chain (PCSC).

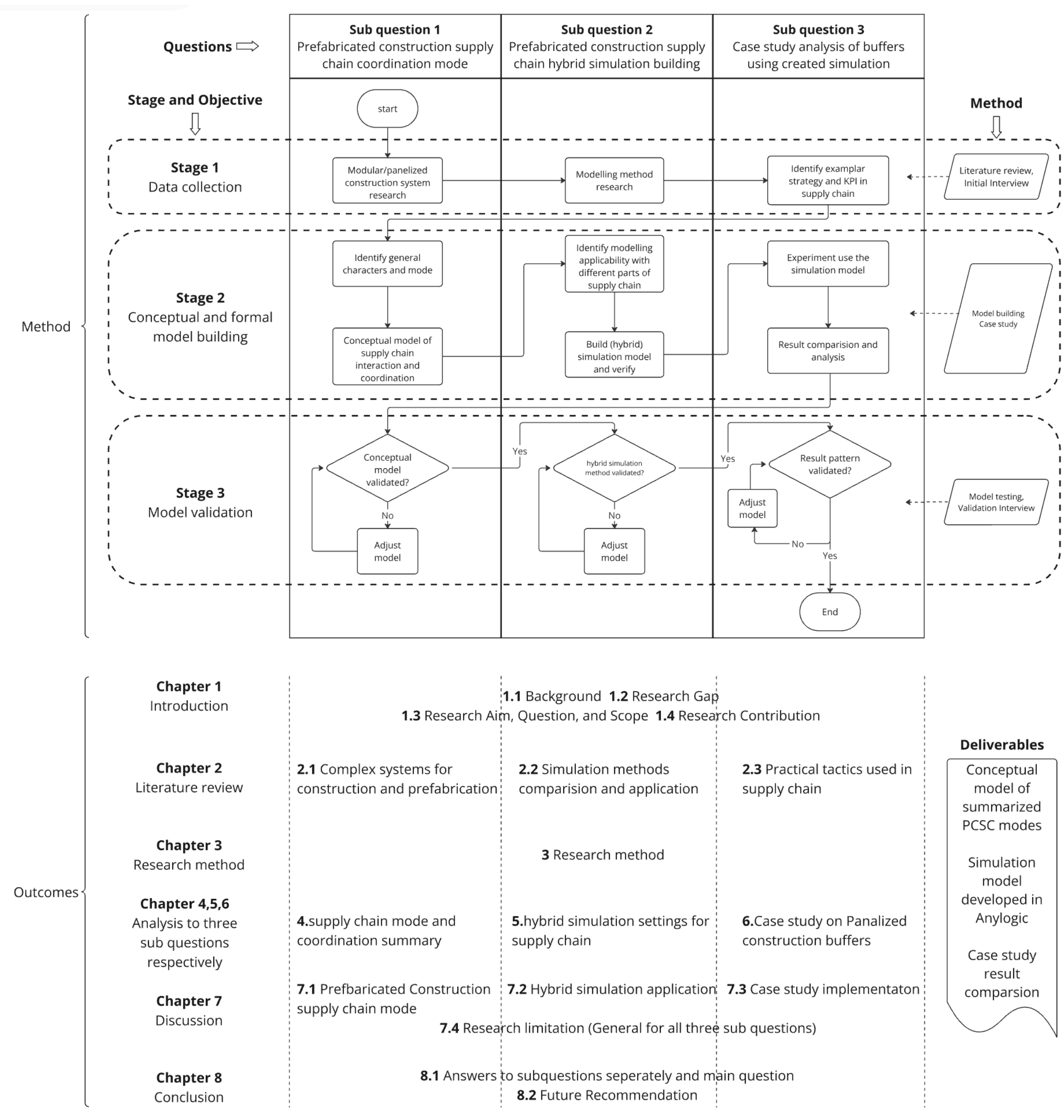

Figure 3.1: Research Method. Source: author's own elaboration

Table 3.1: Interviewee Information: Initial Data Collection

Interviewee ID	Company	Company Type	Field/ Department	Job Title	Interview phase joined
1	1	Construction	Innovation/ Executive	Head of Value Creation Department	Initial, Validation
2	2	Construction	Innovation/ Executive	Co-founder	Initial
3	3	Construction	Site project	Contract Manager	Initial, Validation
4	3	Construction	Site project	Project Manager	Initial, Validation
5	4	Factory	Module production factory	Head of BIM Process Management	Initial
6	5	Logistic	Logistic	Head of Concept Development	Initial

3.2. Stage 2- Conceptual and Formal Model Building

Based on the information obtained from the literature review and interviews, the current state of modular construction and coordination modes was summarized. The current level of development and integration of prefabricated construction were categorized with corresponding supply chain participants. A conceptual flowchart was generated to address Sub-question 1 generally.
Based on the conceptual model, a hybrid simulation model was developed for a general PCSC procedure. The model was initially verified for its integrity using printouts, interface functions, and relative value tests to ensure its functionality for sub-question 2.
Following the developed PCSC model, a hypothetical case study of a panelized construction supply chain was developed, where primary decisions were identified based on literature about inventory buffers and the different stages identified by the results of sub-question 3 in Stage 1, aligning them to apply tactics, strategies and key performance indicators (KPIs) to the case study model. Different scenarios of batch sizes were created to reflect tendencies in various modes of prefabricated construction supply chains. KPIs were collected and compared based on the case study model.

3.3. Stage 3- Model Validation

After the models for all the sub-questions were built, the conceptual and simulation models were further validated through additional interviews with industry professionals aimed at checking their accuracy and applicability, and gathering feedback for further improvement and application. Interviews were conducted with Interviewees 3, 4, 7, and 8, with information detailed in Table 3.2. The validation consisted of four main parts:

- The conceptual models' accuracy and applicability to industry cases

The first part of the validation focused on the conceptual models developed for each sub-question. Interviewees were asked to provide feedback on whether the described models accurately reflect industry practices and could be generalized across various real-world cases. This step was crucial for ensuring that the models are not only theoretically sound but also practical and applicable in diverse industry settings.

- The alignment of the modeling parts with real-life operations

The second part examined the individual components of the models, such as feedback loops and agent interactions. Interviewees evaluated whether these components accurately structure the supply chain mode and whether the interactions modeled among agents reflect realistic case scenarios. This feedback was essential for refining the models to better capture the dynamics of actual operations.

- The alignment of the hybrid simulation method with practitioners' decision-making

The third part assessed the hybrid simulation methods employed. Interviewees were asked if the method presented a comprehensive view that aligns with their intuitive and operational logic. This assessment helped ensure that the simulation models could effectively support decision-making processes within the industry.

- The reflection of hypothetical case study results on real-world situations

The fourth part involved validating the results of the case study that compared dynamic and static buffers. Interviewees provided insights into whether the results from different scenarios and buffers align with industry common sense and are realistically achievable. This feedback was pivotal in assessing the practical relevance and applicability of the simulation results. A detailed interview question list is provided in Appendix C.
After each part, the interviewees were asked to grade the model on a scale from 1 (strongly disagree) to 5 (strongly agree). After all three stages were completed, discussions were conducted for each sub-question and conclusions were drawn for each sub-question and the main question.

Table 3.2: Interviewee Information: Validation

Interviewee ID	**Company**	**Company Type**	**Field/ Department**	**Job Title**	**Interview phase joined**
1	1	Construction	Innovation/ Executive	Head of Value Creation Department	Initial, Validation
3	3	Construction	Site project	Contract Manager	Initial, Validation
4	3	Construction	Site project	Project Manager	Initial, Validation
7	6	Construction	Design	Civil Structure and Architecture Design Lead	Validation
8	6	Construction	Design	Modularization Manager	Validation

4

Prefabricated Construction Supply Chain Mode and Coordination

To answer Sub-Question 1 and provide context for Sub-Questions 2 and 3, the mode, contributing parties, and an overview of the processes involved must first be understood. A literature review and interviews are conducted to identify the key processes, decisions, and digitalization potentials of the prefabricated construction supply chain (PCSC). Although the general procedure is almost the same for all types of prefabricated construction, some significant differences can still be identified depending on the extent of prefabrication of the components and the level of technological integration between supply chain parties.

4.1. Prefabricated Construction Sorting

As a benchmark, traditional construction supply chains involve the supply of raw materials (e.g., lumber, concrete) directly to the construction site. In contrast, prefabricated construction offers different levels of material manufacturing before sending them to the site. Depending on the level of prefabrication and technology integration, prefabricated construction projects are generally divided into two types based on their prefabrication level and two types based on their technology integration, as indicated by the interviews.

Sort by Prefabrication Level

Table 4.1: Descriptions of Different Construction Concepts and Their References

Concept	Description
Prefabricated Components	Involves off-site manufacturing of basic structural elements like beams, columns, and slabs using reinforced concrete, steel, and wood. Reduces some on-site activities but still requires significant on-site construction efforts.
Panelized Construction	Major structural components such as walls, floors, and roofs are produced in factories as prefabricated panels. These panels are then transported to construction sites for assembly, reducing construction timelines and on-site labor.
Modular Construction	Entire sections of a building are fully constructed off-site in a factory setting. These modules are transported to the site and assembled into the final structure. Allows for stacking, joining, or layering based on architectural design.
Modular Integrated Construction	Integrates mechanical, electrical, and plumbing components along with interior finishes during the factory phase. Expedites the overall construction process and minimizes on-site installation. Offers the highest level of prefabrication.

Depending on the extent to which the components are prefabricated, the prefabricated construction type can be described as in Table 4.1, summarized by Attajer and Mecheri (2024) from Hussein, Eltoukhy, Karam, Shaban, and Zayed (2021), Lopez and Froese (2016), and Lawson, Ogden, and Goodier (2014). Among these, Panelized Construction and Modular Construction are the most representative types distinguished in this research and will be discussed further as a comparison, as they have multiple procedures in production, cross-docking, and add more complexity to the supply chain process. For the other two types, pure Prefabricated Components, with relatively simple components and procedures, do not involve many transfers and assemblies along the supply chain, while Modular Integrated Construction has similar procedures to, but with more components in the assembly process. All four types of prefabrication can be roughly categorized as either partially integrated or fully integrated.

Sort by Technology Integration

Depending on the degree of technology integration between the contractor and suppliers, the methods can generally be categorized into two types: the IFC-based uniform drawing and designing method and the independent drawing and designing method. The differences between these procedures vary with both prefabrication level and production modes.

4.2. Manufacturing/Production Mode of Procedures for PC

As described in the previous chapter, the construction industry is undergoing a transition from traditional, highly customized, and single-project-based construction methods to an industrialized approach. Consequently, the mode of the entire supply chain procedure and management decisions are sometimes combined in various manufacturing methods. The main manufacturing modes applicable in the context of the prefabricated construction supply chain (PCSC) are summarized in Table 4.2 .

The main differences of these production modes related to types of prefabrication is shown in Table

Table 4.2: Manufacturing/ Production Modes Applied in PCSC

Type	Description	Applicability	According Activity in PCSC
Engineer-to-Order (ETO)	Products are custom-designed and built to meet unique customer specifications.	When products are one of a kind and require highly customized engineering solutions.	The supplier receives and processes unique customer drawings, initiating the production process including: 1) Factory engineers refine and finalize the design based on the initial customer drawings. 2) The factory places specific orders with sub suppliers based on the confirmed design.
Make-to-Order (MTO)	Products are manufactured only after an order is received, allowing for some customization.	When customer demands are specific and vary significantly, necessitating customization after an order is placed.	Once the order is received, the factory casts and assembles the components, delivering them promptly to the construction site.
Make-to-Stock (MTS)	Products are manufactured based on anticipated demand and stored in inventory for immediate availability.	When demands are predictable, allowing for efficient mass production and storage in anticipation of customer orders.	The factory holds completed components in inventory, awaiting a final order from the construction site.
Assemble-to-Order (ATO)	Products are assembled from pre-manufactured components upon receiving customer orders, allowing for rapid fulfillment and customization.	When a product can be customized using a combination of standard components that are assembled after the order is received.	The main supplier (assembly station) receives components from various suppliers, ready to be assembled into final products and sent to the construction site.

4.3, in addition to the two main types of construction based on their prefabrication mode.

Table 4.3: Supply Chain Mode Description

		Contractor	Main supplier	Sub supplier
By components type (prefabricated degree)	**Modular Construction**	Install the entire section of the module on site, sequence is every per module	Assemble all components from sub-suppliers to a room module block	Manufacture components from customized cut steel to casted concrete/steel/wall etc.
	Panelized construction	Install floors, walls and facades etc. on site together to be an entire section, usually follows the sequence of all same type of panel in a floor and then next floor	Put sub components to designed position and cast concrete to make panels like floors, walls and facades etc.	Manufacture small components like wooden frames, windows and parts of installation.
By technology integration (digitalization degree)	**Technology Integrated**	ETO phase is rather simple due to uniform design and file support like IFC	ATO phase doesn't have lots of procedure difference, even though in panelized construction its control should be cast but it takes rather short time than sub supplier and can be deemed as ATO	Due to uniform file and assistance of robotic systems; the manufacturing can follow one piece production, but to ensure a stable production MTS is still in basis.
	Non-technology integrated	In ETO phase certain customization and transition is required due to different file format	ATO phase follows same procedures, but product have certain cast	The most of manufacturing follows batch and queue to reduce setup waste and cost.
Note: The main and sub suppliers are divided based on the function not company or location; they could be in the same location. For example, in some modular construction production, there's one factory containing all components making. The "main supplier" in this case is the final assembly station in this factory.				

4.3. General PCSC Procedures

As summarized from the literature and interviews, the coordination of the Prefabricated Construction Supply Chain (PCSC) involves multiple stages, from design to completion, as shown in Figure 4.1. The process typically begins with the client's design and government approval. Following this, the main contractor manages the engineering in collaboration with component suppliers. Once the drawings and production technical details are confirmed, and the required materials have arrived, the production of sub-components begins. These sub-components are then assembled at the main supplier's station and delivered to the construction site as needed. The design confirmation with the client and government permit approval, along with the raw material supply (marked with a dashed line in the figure), are critical but fall outside the scope of this research. The communication and coordination in these procedures are detailed below, with corresponding numbers referenced in the figure.

1. 2. Request for Engineering and Order (ETO): The process begins with the contractor initiating the confirmation of drawings and technical details with the main and sub-suppliers. This step involves several rounds of back-and-forth communication for joint confirmation and verification to ensure that the components to be produced meet the requirements set by the contractor and the client.

3. Manufacturing Components (MTS): Once the drawings are confirmed, production orders are issued to the sub-supplier. In theory, this procedure should follow a make-to-order process, as schedules are provided in advance, and production is expected to adhere to these schedules. However, in practice, because the engineering is already completed and customization is rarely needed before the production time, and due to fluctuating demand from the construction site and the need for the manu-

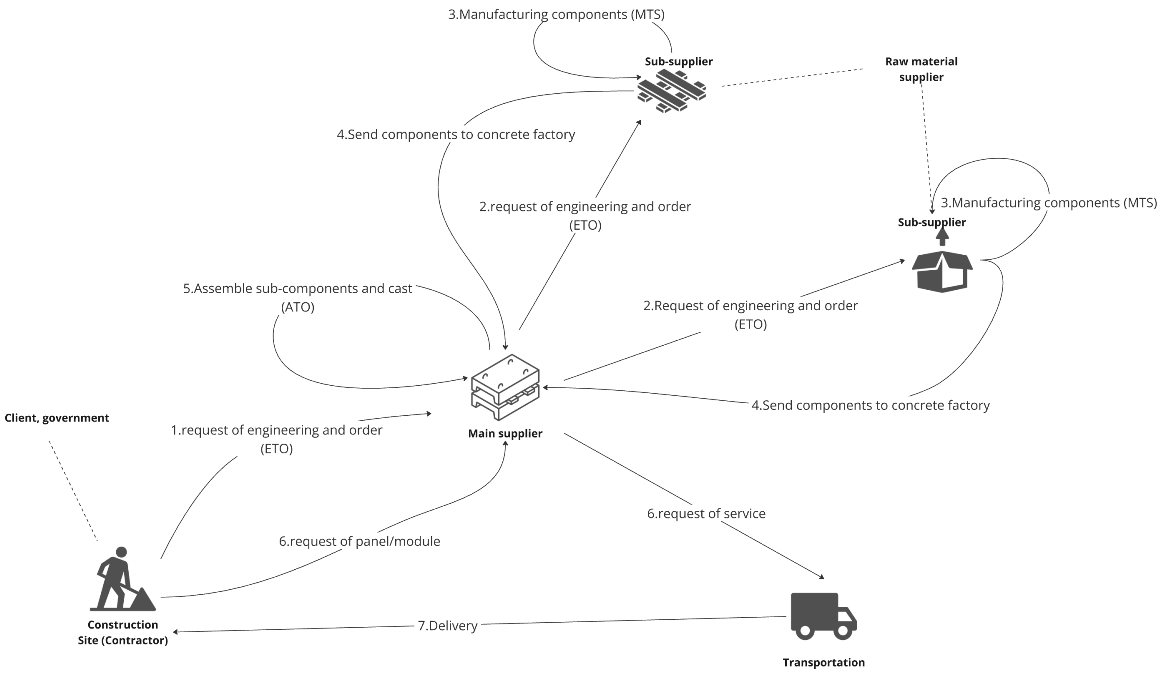

Figure 4.1: PCSC supply chain main procedures. Source: author's own elaboration

facturing factory to manage its schedule with other projects, a make-to-stock mode is most frequently used.

4. Send Components to Main Supplier: Both sub-suppliers and the main supplier have their inventory spaces. The sub-supplier maintains a certain inventory of subcomponents, while the main supplier also keeps a certain level of subcomponent stock in the factory. Whenever there is a demand from the main supplier, the subcomponents are transported accordingly. There are usually multiple sub-suppliers at this stage; however, for simplification and generalization, the diagram shows only one.

5. Assemble Sub-Components (ATO): Once all the required subcomponents have arrived at the main supplier, only a few simple steps are needed before they can be sent to the construction site. In some cases, this involves assembling windows and doors; in others, it involves integrating walls and floors into a complete model. Due to the significant uncertainty from the construction site and the large volume of the final product made in this step, and because the assembly speed is high, the final products are typically assembled based on orders.

6. 7. Request for Transportation Service and Delivery: Following the final assembly, the components are delivered by a logistics company to the construction site for installation. The delivery process varies; sometimes it involves the company's own vehicles, and sometimes it relies on a third-party service provider. Logistic hubs emerge as a new player in this stage, supporting the industrialization of the construction supply chain, similar to wholesalers in other mass production industries. These hubs use cross-docking or similar methods to ensure all materials and equipment arrive on schedule and are available as needed, playing a significant role in streamlining deliveries and managing inventory, thus reducing on-site construction time.

4.4. Verification and Validation

As described in the research methods section, the creation of the three models follows a sequential approach, with the conceptual model serving as the foundational starting point. Because the conceptual model is a summary from the data collected, it is verified by checking its logic and mainly validated together with other sub-questions. The conceptual model was developed with minimal external validation, primarily through limited engagement with the case study company. This initial validation aimed to

Table 4.4: Validation Result - Part 1

Parts	Questions	Interviewee iD	Individual Grade	Average Grade	Main Comments and Suggestions
Part 1	Overall Cnceptual Model Applicability	3	4.5	4.125	Overall, the structure is well described. All participants specifically addressed the ETO phase and the stages before it, as it remains the main focus in the construction industry today, with expectations for more emphasis on that part. For example, the engineering company and the owner could be different entities, and responsibility for engineering depends on macro factors such as knowledge and finance. Logistics from the sub-supplier to the main supplier can cover long distances in some cases, making the process quite complex. Additionally, transportation modes like shipping by sea introduce further challenges. Orders are placed much further in advance than when they are actually needed.
		4	4		
		7	4		
		8	4		

ensure that the model accurately reflects the company's operations, thereby preventing any significant discrepancies that could lead to costly issues in later phases.
After the conceptual models were established, further validation was conducted through interviews to assess the model's applicability across various stages of the supply chain. Additionally, the interviews are used to gather detailed feedback on each stage of the supply chain modeling process. The conceptual model received an average score of 4.125 out of 5, with a more detailed grades shown in Table 4.4, indicating strong agreement with its applicability and relevance to the stages being modeled. This score reflects the model's effectiveness in capturing the essential elements and requirements of the supply chain operations as perceived by the participants.

5

Hybrid Simulation Model Setting

To answer sub-question 2, a proper simulation method should be chosen. There were lots of works done on the simulation of supply chains, but firstly, most of them are not in the modular construction supply chain, and secondly, no research has used an integrated way of simulation. Even though using each simulation method can model the whole supply chain already, each of them may have different emphases on the aspects they want to express. The model built by this thesis utilized three types of simulation methods to capture both the macro and micro levels of modular construction supply chain performance: system dynamics (SD), agent-based modeling (ABM), and discrete event simulation (DES).

5.1. System Dynamics (SD) for Ordering Decision Making

System dynamics is a continuous simulation methodology that uses concepts from engineering feedback control theory to model and analyze dynamic socioeconomic systems. The mathematical description is realized with the help of ordinary differential equations. The main objective of system dynamics is to understand the structural causes that bring about the behavior of a system. Some examples of inflows in the supply chain are production and sales. Some examples of outflows in the supply chain are stocks, fill rate, and work in process. System dynamics assumes that control is carried out by varying the ratio of the variables (for instance, production and sales) which changes flows (and therefore stocks). It is also based on the feedback principle, i.e., a manager compares an objective value for a metric with the real value and takes corrective actions if required. In other words, the basic system dynamics objective is to understand the structural causes that trigger system performance. This is a long-term approach. Suitable variables selection is the most important (system elements analysis) because it is based on the analysis of internal logic and the system's structural relationships. The structure consists of multiple interacting feedback loops that depict the policies and continuous processes underlying discrete events (Belhajali & Hachicha, 2013).

In this study, SD was utilized to model the overarching flows and feedback mechanisms that characterize the supply chain dynamics. Key variables within the SD framework included aggregate inventory levels, average lead times, and overall demand rates across the supply chain. This macro perspective helps in understanding the broader impacts of strategic decisions and policy changes.

An extensive literature review was conducted first, aiming at identifying key performance indicators and dynamic factors relevant to modular construction supply chain management. Critical factors influencing supply chain performance were extracted, such as inventory levels and demand forecasting accuracy. Because the system dynamics literature is limited on prefabricated construction supply chains, and since PCSC's industrialization makes it have common features with manufacturing departments as described in the previous chapter, some general supply chain (not modular construction) feedback structure and factors are also considered, as well as some literature about modular construction feedback and performance management.

The overall system performance and equilibrium are modeled as a system dynamics model. System dynamics are capable of identifying better inventory levels using goal-seeking loops, for example, (Belhajali & Hachicha, 2013) (2013) used SD to decide safety stock in a single-stage inventory system.

Type	General supply chain	Modular Construction Case	Function
End-user	Customer	On-site assembler	Consume goods
Non-manufacturing department (ATO)	Distributor/Retailer/Wholesaler	On-site inventory/Factory inventory	Provide intermediate inventory
Manufacturing department (MTS)	Factory	Concrete/wood frame/ installation factory	Make products
Engineer (ETO)	Engineering Department	Drawing making by manufacturing department (sub-components)	Engineering products

Table 5.1: Comparison of General Supply Chain and Modular Construction Supply Chain

The basic influence diagram of the supply chain is adapted from the articles listed in the table. The reason why it is adapted is that these articles mostly describe the general supply chain or in supply chains like beer distribution, where it usually contains a supplier, manufacturer, distributor, and retailer, and some of them model only a single stage of the supply chain. However, in the modular construction context, the supply chain parties are a bit different and contain many stages, but the general causal and influence loops remain adaptable and can be adjusted to this case. The proposed new supply chain parties are based on the real case from the interview. How the parties are moved from the general supply chain to the modular case are described in Table 5.1.

5.1.1. Feedback loops identification

The aim of system dynamics is to find feedback loops and instruct balanced decisions for practice in agent-based modeling and discrete event simulation. As the main aim of system dynamics is to give macro control of the system behavior and give structure to the interdependence of the variables in the system to make the key points. Except for the buffers described in the previous chapter that influence each other in their function aspect, the supplying itself also has internal logic that forms the main feedback loops are described below and it's sorted by the difference of the working mode of PCSC, namely ETO, MTS, ATO, and MTO.

ETO department influence diagram

As PSCC is still a certain-level customized industry, the first stage in any project before product production is to make engineering work. It was also identified in the interview that in panelized construction, a very long lead time of drawing making and confirming exists before production starts, for example for a house's concrete components production, it usually takes 5-6 weeks to make and confirm the drawing back and forth among the contractor, main supplier, and sub-supplier, while actual production could be only one week once every needed material has arrived. To model this long modification and rework, dynamic Planning Methodology is identified as a potential candidate for an ETO system archetype (Zhou, Wang, Gosling, & Naim, 2023). This method has been utilized in production process research, rework simulation, and design errors analysis. One outstanding feature of this influence diagram is the feedback and loops are all positive, making there no balancing action, there are two goal-seeking loops instead. A rework rate would not influence the average output flow, but instead, rework will add to the WIP (work in progress) amount and, following Little's Law, make the cycle time of the engineering longer. The influence diagram of the ETO procedure is shown in Figure 5.1.

MTO/ ATO (without manufacturing) department influence diagram

The ATO and MTO modes share the basic logic that shipments are made based on the order amount, sometimes also called 'demand pull' in the inventory and production system (Chiang & Huang, 2021). The influence diagram of it is shown in Figure 5.2. The ATO process also includes the assembly procedure, which will be discussed in the following manufacturing department. The two balancing loops for this ATO and MTO department are inventory and backlog control loops from the upper and lower streams, respectively. The upper stream inventory control loop involves the delivery rate, inventory, and order rate. It demonstrates that as inventory increases, the order rate decreases, thereby balancing the system inventory. The lower stream backlog control loop involves the order rate, backlog, desired shipment rate, and shipment rate. It shows that as backlog increases, the desired shipment rate increases, which then affects the shipment rate and subsequently reduces the backlog. These two loops work together to reach a balance in the department's inventory level.

MTS (without manufacturing) department influence diagram

Similar as the ordering patterns with MTO and ATO, MTS system's inventory is adjusted by certain demand, but in this case, the demand is not from lower stream, instead, it is a target order book, in other terms it is also called 'capacity push' (Chiang & Huang, 2021). It represents the desired level of orders that the company aims to maintain and acts as a buffer or safety stock to meet unexpected

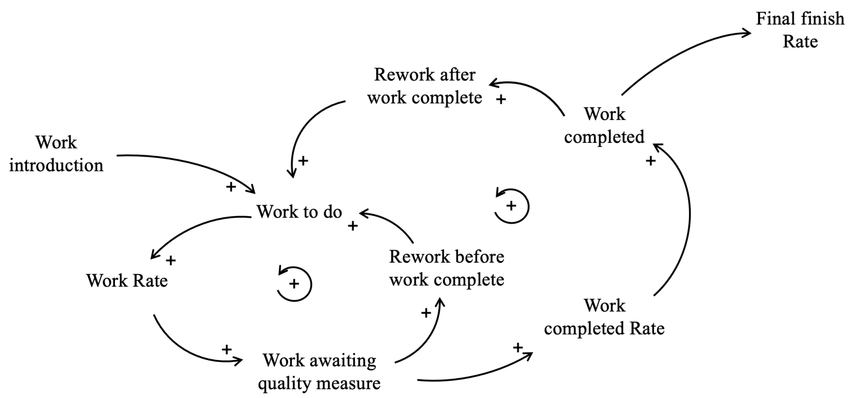

Figure 5.1: ETO system influence diagram. Source: author's own elaboration adapted from (Zhou et al., 2023)

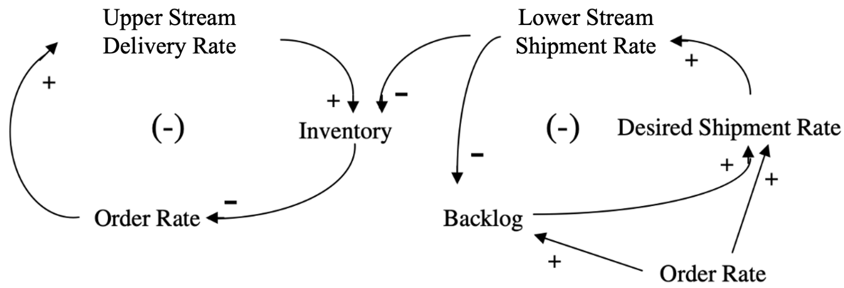

Figure 5.2: Non-manufacturing department (Make to Order) influence diagram. Source: author's own elaboration

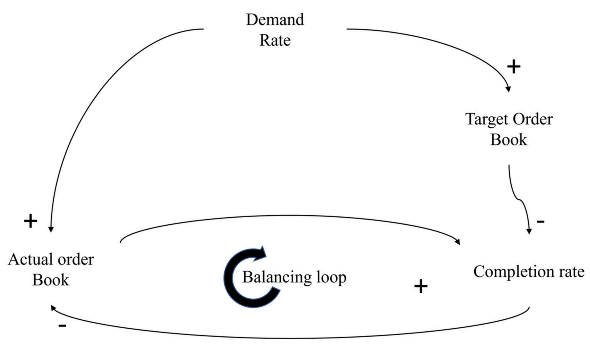

Figure 5.3: Non-manufacturing department (Make to Stock) influence diagram. Source: (Zhou et al., 2023)

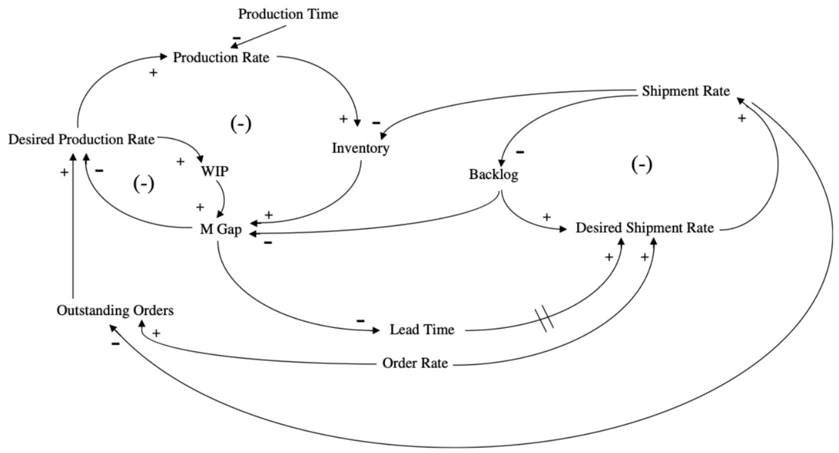

Figure 5.4: Manufacturing department influence diagram. Source: author's own elaboration adapted from (Özbayrak, Papadopoulou, & Akgun, 2007)

surges in demand or to smooth out fluctuations in order production. The loop's goal is to maintain the target order book at or near the actual order book level. When deviations occur, adjustments in the completion rate help to bring the actual order book back towards the target. Effective management of this loop allows the MTS system to adjust production rates and inventory levels dynamically and be more responsive to customer demands while maintaining efficient use of resources and minimizing excess inventory. The influence diagram of it is shown in Figure 5.3

Manufacturing department influence diagram

The manufacturing department has some different loops as the way it responds to orders is not only to check inventory and plan delivery but also to introduce production work and WIP when necessary, which will involve a long lead time and cause delays to the system, and is the main source of the bullwhip effect. The logic of the manufacturing department mainly involves three loops: A Backlog Control Loop that involves the order rate, backlog, desired shipment rate, and shipment rate, which aims to balance the backlog and shipment rate to reduce the backlog to zero. A Production Control Loop that involves the desired production rate, production rate, inventory, and manufacturing gap. It aims to adjust production to match the inventory needs and reduce the manufacturing gap to zero. A WIP Control Loop that involves the desired production rate, WIP, manufacturing gap, and production rate. It balances the WIP and production rate to control the manufacturing gap, ensuring that the production rate adjusts to the WIP level. The influence diagram is shown in Figure 5.4 .

Buffer loop

The three buffers' influence on each other, even though haven't been systematically recognized in the literature, can be roughly drawn in Figure 5.5. The inventory buffer usually represents directly or indirectly the demand side, while capacity and lead-time buffers are used to mitigate unexpected effects on the supply aspect. These feedback loops are implemented in the site ordering procedure where demand is construction site's demand and supply is the upper suppliers all producing panels to the construction site. Inventory buffer here is the safety stock on site, lead time is a performance measured from order shipment from ABM, and the capacity buffer here represents extra trucks ready for transporting wood frames and panels. This part will be described in more detail in the data integration part. Once the influence diagrams are established, the next step is to build a stock and flow diagram accordingly to quantify the relationship among all the factors and variables. Stocks and flows are two basic types of elements when doing a system dynamics simulation. Flows represent some rates about material or information at the speed they go to certain places, and stocks represent the accumulation of rates. Some typical examples of them are for example shipment rate leads to shipped goods, desired production rate leads to WIP. The SD creation is described in Figure 5.6. The variables in system dynamics are shown and their equations are provided in Appendix A.

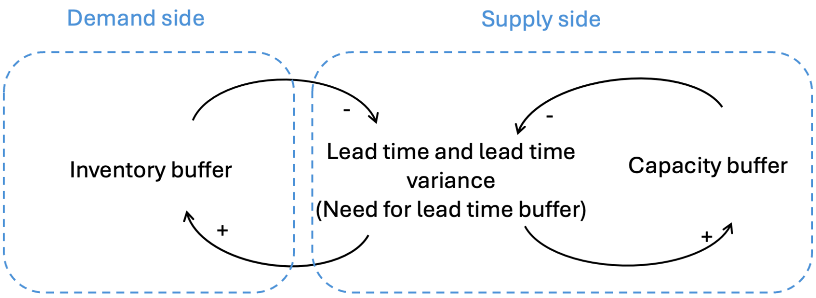

Figure 5.5: Supply chain buffer influence diagram. Source: author's own elaboration

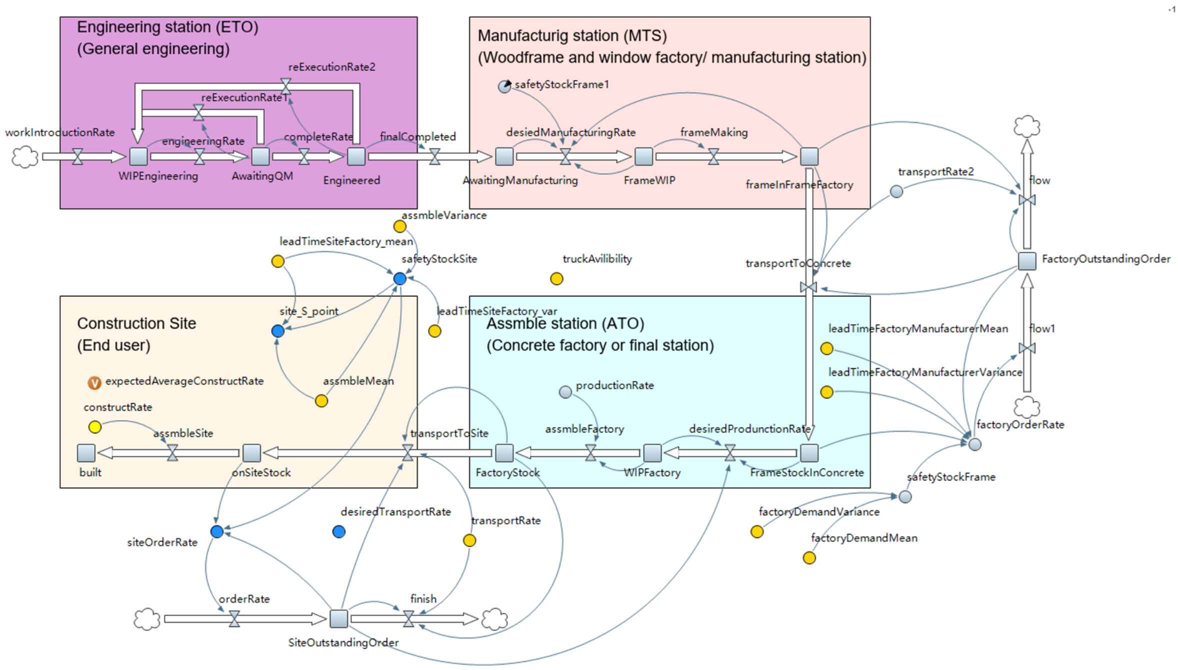

Figure 5.6: Stock-Flow Chart SD. Source: author's own work screenshot from Anylogic

5.2. Agent-Based Modeling (ABM) for Ordering/ Manufacturing/ Shipment Implementation

5.2.1. Agent identification, properties, and functions

ABM was deployed to simulate the behaviors and interactions of individual agents within the modular construction supply chain. The agents, specifically representing construction sites, factories, and logistics companies, were programmed with distinct behaviors such as inventory management strategies, production WIP release, and delivery batches. This micro-level modeling allows the exploration of how individual decisions and interactions affect the larger system performance.

This model contains three types of agent:

1) macro agent that represents different functions inside the supply chain parties: assemble, production, manufacturer, inventory, and engineer agent;

2) meso agent that represents the population of moving actors: truck agents; and

3) micro agent that contains certain information or material: order and shipment agents.

Their properties and functions are summarized in Table5.2.

Table 5.2: Agent properties and functions

Type	Name	Main Properties	Functions
On-site	Site Assemble agent	Assembler capacity, assemble workgroup utilization	assembleMaterial(), sendMaterial()
	Site inventory agent	Panel inventory, order point, inventory condition	checkInventory(), orderModule(), orderAssemble()
Main supplier	Factory Assemble agent	Assemble line capacity, assemble line utilization, WIP	sendWIP(), assembleSubComponents(), sendPanel()
	Factory inventory agent	Panel inventory, woodframe inventory, outstanding order, backlog order, inventory condition	checkInventory(), orderWoodframe(), orderAssemble()
Sub supplier	Manufacturer production agent	Assemble line capacity, assemble line utilization, WIP, manufacturing batch size	sendWIP(), produce()
	Manufacturer inventory agent	Woodframe inventory, safety stock	checkInventory(), sendWoodframe()
Engineer	Engineer	Engineer batch size, engineering WIP	sendEngineer()
Transporter	Truck	Capacity per truck, total truck numbers, speed, cost per truck, working conditions	sendOrder(), moveTo(), load(), unload()
Objects	Order	Owner, destination, amount, order time, finish production time	/
	Shipment	Owner, destination, amount, delivery time, arrival time, lead time	/

Figure5.7 (a) shows the statecharts of the inventory agents. The agent's action depends on its two inventory-related states. It decides whether to remain at the current state when inventory is sufficient or ask replenishment when inventory falls below the needed stock (namely outstanding orders in ATO, and safety stock in MTS). The state of truck agents is shown in Figure5.7 (b). The truck as a moving agent, its state transition happens when multiple kinds of messages arrive. The truck is usually provided by a third-party logistics company, so when there's no shipment requirement it stays in the truck station, and once a shipment is needed all the trucks whose state is not "isBusy" will be searched and return

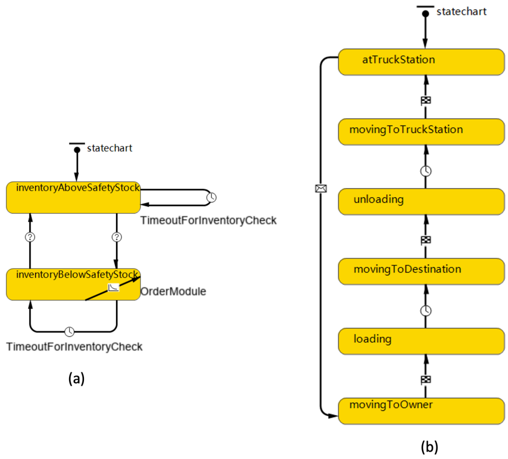

Figure 5.7: ABM state charts for (a) inventory agents, (b) truck agents. Source: author's work screenshot from Anylogic

a random one, and make the shipment from the shipment owner to shipment destination (one owner is the manufacturer, one owner is the concrete factory). And the loading/unloading state is triggered by truck arrive at a certain place, the timeout of such state depends on the shipment that it is taking's size. Once all the tasks are done and no new message of shipment is received, it will go back to the truck station.

5.2.2. Agents interaction

Besides their own attributes, the interaction among agents forms the main activity and contributor to the ABM model. The agent description and interaction is mostly based on the interview to be more case and situation-specific. The interaction among all the parties can be abstracted as in Figure5.8. The process starts from engineering decisions to define component specifications, make drawings, followed by inventory assessments at manufacturing sites to ensure resource (in this case whether the work unit has been engineered) availability before production. Once enough inventory is gathered for logistical arrangements. Related party receives order and organize shipment whenever the transportation resource is available. The decisions agents make follow the same logic as in the previous SD part under the same ETO/MTS/ATO mode. With the same logical feedback loops, the ABM facilitates dynamic responses to inventory shortages or delays, ensuring adaptability and continuity in the production and construction cycle.

5.3. DES Process for Agent Internal Behaviour

Some procedures inside the construction site and factory are modeled as discrete event simulations as it presents better with sequencing events, for example, panels waiting to be assembled and once every resource is gathered, the production can indeed start. The parts of module assembling in the concrete factory where blocks are waiting to be transported are described below in Figure5.9. The aim of DES is to present processes that must meet sequences and objects that cannot be described purely using continuous methods such as SD.
The DES process includes procedures involving Aussie agents from engineer to manufacturer to site assembler. Figure 5.9 (a) shows the engineering work of engineers as real-life engineering cannot be done one piece at a time; it is usually done in bunches of certain work units, for example in the case study it is usually a bunch of 9 to 10 houses together at least before a whole engineering process starts. The batches are used when there are certain tuned work introduced; the work introduced here represents a working introduction rate that is usually based on future work with predictions based on previous work. Figure 5.9(b) shows the manufacturing process in the sub-supplier manufacturer; the engineer here is a prerequisite for the precise manufacturing once it is engineered. The last step will be injected into this procedure, similar to the engineering manufacturing department, except for the wholly robotic integrated one, also cannot do one piece mode, starting all the machines just to do one door. The manufacture line is set up once the expected manufacturing amount is accumulated. Of

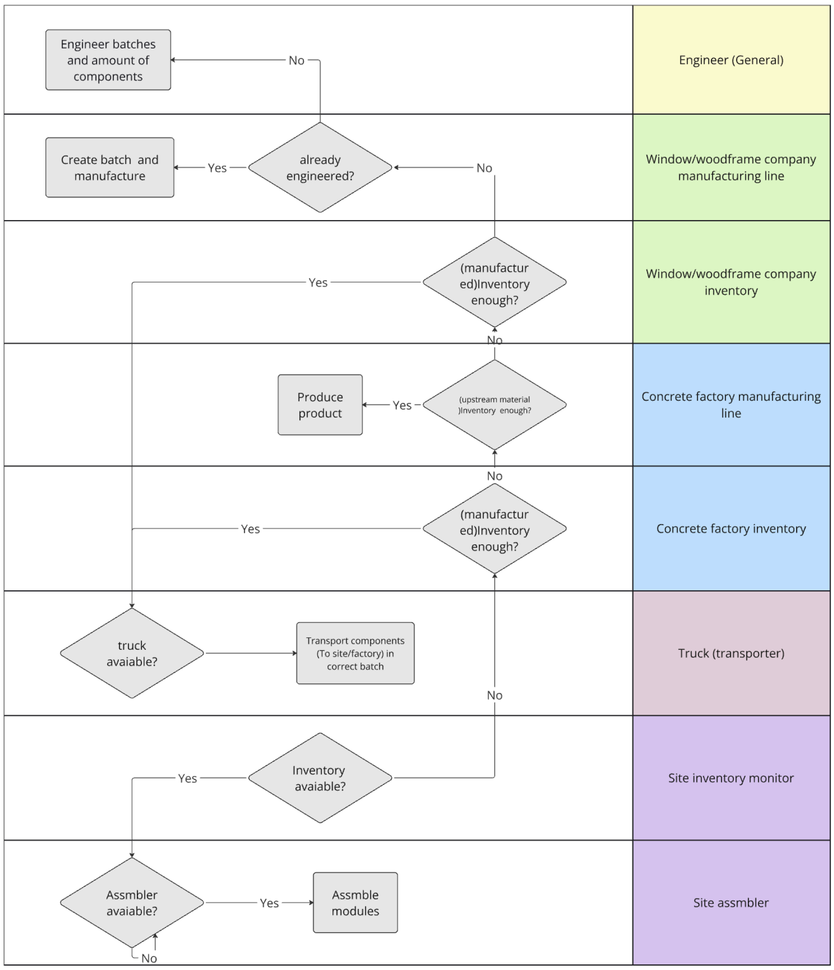

Figure 5.8: Agent Interaction. Source: author's own elaboration

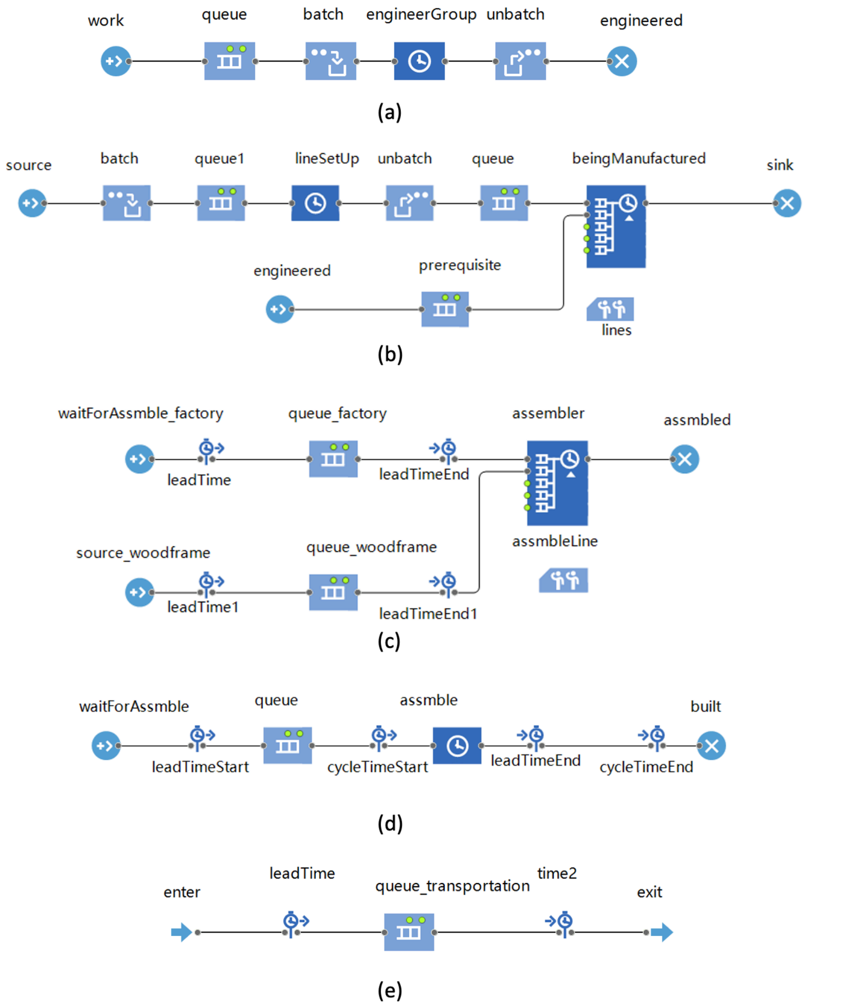

Figure 5.9: DES Processes of (a) Engineering work of components (by both main and sub supplier), (b) Sub supplier's manufacturing work of sub-components, (c) Main supplier assemble all sub components to a ready for site module/panel, (d) on-site assembler install modules/panels to build building, (e) the searching procedure for available trucks when shipment released. Source: author's work screenshot from Anylogic

course, it depends also on the manufacturing types but here we only consider one sub-supplier and we assume the subcomponents it produced will go through the same workstation but just have different processing times so it can be simplified also as a batch and unbatch; once the batch size is reached, the manufacturing will start. Figure 5.9(c) is the process in the main supplier which is to assemble all the subcomponents from sub-suppliers and make a ready item for on-site assembly and installation. It is worth noting that in this step, even though sometimes in panelized construction it needs cast concrete, the final item procedure still does not take as long as previous ones and due to the huge volume of components and unstable demand from the site, it can follow one-piece flow, and there is no batch size in this procedure. Figure 5.9(d) describes the procedure of on-site assembly and installation of modules; the delay here includes our activities from, for example, module check-up, hook installation, and final installation, etc. Figure 5.9(e) shows that once a shipment requirement is made by a certain party, the waiting procedure before finding an available truck begins.

5.4. Hybrid Simulation Integration

As discussed previously, supply chain coordination requires different strategies and tactics and constantly needs feedback to modify these decisions. To effectively address how this is applied in a real case, this research uses an integrated approach combining System Dynamics (SD) and Agent-Based Modeling (ABM) to address the complexities of the modular construction supply chain, which encom-

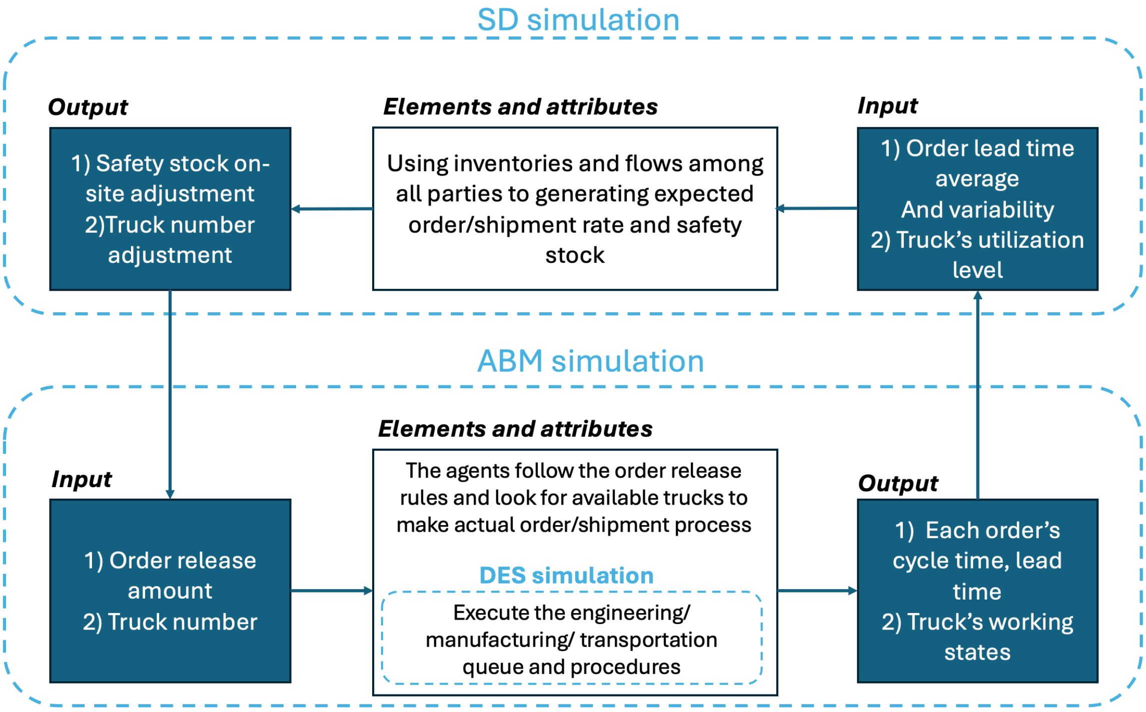

Figure 5.10: SD-ABM Integration method. Source: author's own elaboration

passes construction sites, factories, and logistics companies. The objective is to create a holistic model that captures both the macro-level flows and the micro-level agent interactions within the supply chain. Central to this modeling setting is the feedback loop, where outcomes from agent interactions (modeled through ABM) inform the macro-level dynamics in the SD model. For instance, the cumulative ordering and stocking decisions by factories influence the overall inventory levels, which are captured in the SD component of the model. Continuous data flow between the ABM and SD components ensures that changes at the micro level, such as a delay in module production at a factory, dynamically affect and are reflected in the macro-level SD model.
A clearer explanation of how ABM and SD are responsible for different parts of the model and their inputs/outputs is shown in Figure 5.10.

ABM Part

Starting from the bottom left corner in the figure, the model begins with a predefined input of safety stock amount and total check numbers, and the ordering procedure can start in agent-based modeling from the construction site to the factory. When the order agent is created, the factory agent starts seeking trucks to transport modules. When a truck is occupied, its state becomes busy and is recorded as working time. Once a truck arrives at the destination and delivers the shipment to the construction site, the order agent tracks the total lead time it spent.

DES Part

DES simulations are inside ABM, being responsible for certain procedures by the agents' functions, for example taking the queue of waiting for transportation or waiting for the minimal batch size to be fulfilled.

SD Part

Aggregated statistics are calculated using AnyLogic's embedded dataset and statistical functions, and safety stock is calculated based on the system dynamic function, considering post-demand and supply uncertainty.
The basic logic here is that by running these certain decisions, new KPI measurements from ABM and DES are generated to update the auxiliaries in the system dynamic model, creating a feedback loop and instructing the agent's behavior.
(There is an exception for engineering to order department for integration procedure, because rework if modelled as agent based modelling requires more detailed information like production sequence and

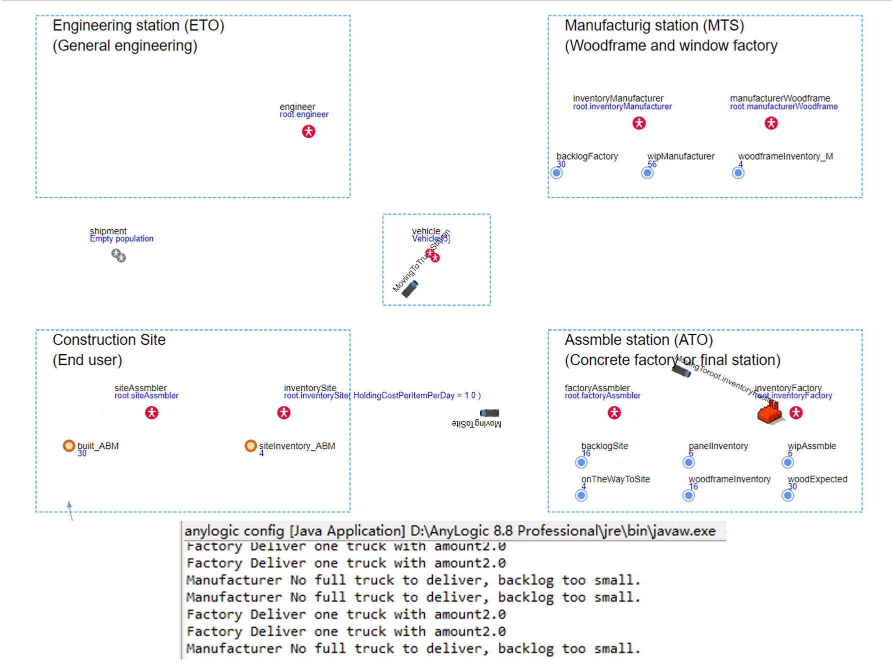

Figure 5.11: Model interface in Anylogic. Source: author's own work screenshot in Anylogic

scheduling, and is a bit out of scope of this research, so engineering to order system dynamics part serves as part of the answer to answer sub question 2 to explain the logic of ETO procedure. In the integrated model, engineering to order phase only uses discrete event simulation in the engineer agent to initiate the process with engineering batches.)

5.5. Verification and Validation

Before implementing the model in real cases, the model needs to be verified first to ensure it works as intended. In this paper, the model is verified by its integrity test and relative value test. Then the model is validated using interview.

Verification: Model Integrity

The model integrity check ensures that the model contains no data or code errors. The model is implemented in AnyLogic, which provides a well-built interface for all modeling methods. The SD part is straightforward, with all its elements in the same layer, and the values change dynamically when the simulation runs, allowing them to be observed and compared with the equations. For the ABM part, because there are macro-level agents on the same level first to represent supply chain communication among different parties and then different states and DES inside each agent with many variables, it is hard to visualize the internal working procedure directly. For moving agents like 'Truck,' an animation is used in the simulation map for its movement. For other static agents, the embedded function in AnyLogic, traceln(), is used to print out their actions when some key decisions (make order, make replenishment, and make shipment) are made. The dest.text function is used to present the state of the agent (inventory below safety stock, inventory above stock, loading, unloading, etc.). The Figure 5.11 shows the running interface of the model and printing out the key steps.

The Figure 5.12 presents the interface of the integrated simulation. At the center, the main simulation components of Agent-Based Modeling (ABM) and System Dynamics (SD) are displayed. To the left, the interface showcases the middle variables and the collected dataset, while on the right, real-time plots of inventory levels and vehicle numbers are graphically represented.

Verification: Relative Value Test

Relative value testing is another verification method used to verify a known relationship between an input and an output by changing the input in a specific way and checking if the output is as expected. In this specific model, the aim of the SD part is to produce some key decision parameters like safety stock and vehicle number for ABM and DES to run and generate KPIs and feed them back to the SD model,

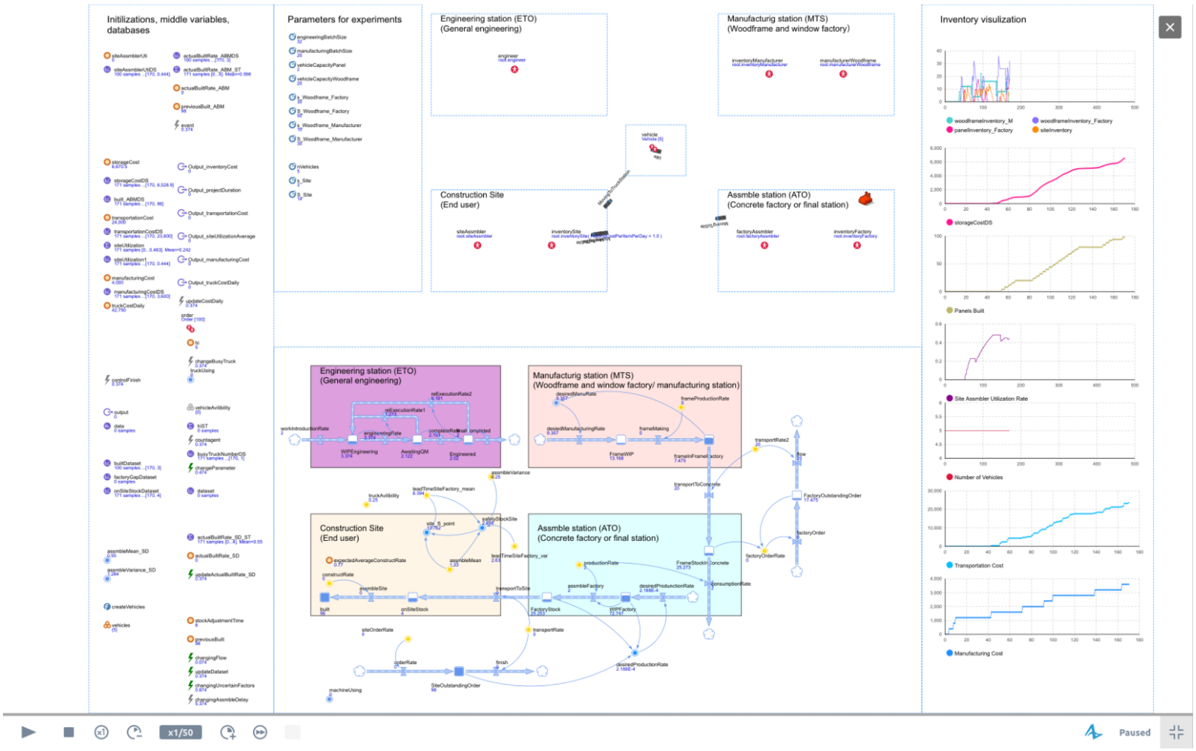

Figure 5.12: Model interface in Anylogic. Source: author's own work screenshot in Anylogic

building a dynamic feedback loop between ABM, DES, and SD. In this case, ensuring these key decision variables indeed have an influence on the ABM and DES system performance is important before being integrated into the SD model. A p-value test was conducted to test the significant impact of all the decisions on the identified KPIs. The parameter settings are provided in Table 6.2. The summary of p-values is shown in Table 5.4. Based on a 95% confidence level, the decisions of safety stock and reorder point on wood frame in the concrete factory are excluded because, in the given parameters that represent an approximation of real-life value, the transportation batch size of wood frames is usually large, around 60-80 pieces, and is transported at once early to the concrete factory waiting for production. This mitigates the proposed safety stock approach in the concrete factory. Similarly, even though an MTS system is applied to the wood frame manufacturing stage, due to its batches of production and transportation, the safety stock in the wood frame factory also doesn't significantly influence the KPIs. Other tactics, as shown in bold font with p-values smaller than 0.05, demonstrate statistical significance on the KPIs.

Validation: Interview

Table 5.3: Relative Value Test Parameters

Parameter	Type	Min Value	Max Value	Step
vehicleCapacityWoodframe	Range	30	60	30
engineeringBatchSize	Range	16	32	16
manufacturingBatchSize	Range	10	20	10
vehicleCapacityPanel	Range	1	4	4
s_Site	Range	5	15	10
S_Site	Range	20	40	20
s_Woodframe_Factory	Range	30	40	10
S_Woodframe_Factory	Range	60	80	20
s_Woodframe_Manufacturer	Range	10	20	10
S_Woodframe_Manufacturer	Range	20	40	20
nVehicles	Range	3	6	3

The simulation method was validated through an interview alongside two other sub-questions by asking

Table 5.4: P-values of tactics on KPIs

	Site Utilization	Inventory Cost	Transportation Cost	Project Duration	Manufacturing Cost
Manufacturing Batchsize	**0.002**	0.217	**0.007**	0.033	**0.000**
Safety Stock Site	**0.000**	**0.000**	**0.000**	**0.000**	0.073
Order Up To Point Site	0.605	**0.000**	0.812	0.084	0.672
Woodframe Transportation Size	**0.000**	**0.000**	**0.000**	**0.000**	**0.012**
Panel Transportation Size	**0.000**	**0.000**	**0.000**	**0.000**	0.401
Number of Vehicles	**0.000**	**0.000**	**0.000**	**0.000**	0.067
Woodframe Mnufacturer Safety Stock	0.667	0.818	**0.002**	0.865	0.919
Woodframe Mnufacturer Production Up To Point	0.434	0.254	0.293	0.165	0.739

the interviewees' considerations when making related decisions, whether they align with the structure introduced by the model. The applicability of the simulation method received an average grade of 3.75 for the overall modelling method choosing, indicating a high vadility of the model. And different sub-parts grades are shown in Table 5.5. Most of candidates agree and one indicated that the logic is correct, but the constraints in real life are far more complex. For example, truck and machine maintenance can vary, and different routes to construction sites must consider trucks that can only be used during the evening and in traffic jams. The maximum number of trucks allowed to park on construction sites is also a common issue, especially in modular construction, where module volumes are extremely large and trucks need to stay on-site until the modules are installed.

Table 5.5: Validation Result - Part 2, 3

Parts	Questions	Interviewee ID	Individual Grade	Average Grade	Main Comments and Suggestions
Part 2	SD-ETO Applicability	3	5	5	The logic is correct, but in real life, rework occurs throughout the entire supply chain. While it may be a smaller portion compared to this example, it still exists.
		4	5		
		7	5		
		8	5		
	SD-MTS Applicability	3	4	3.75	There is a connection between MTS and ATO. They represent different stock types at different stages, but in real life, they often share the same storage area in factories, without separate safety stocks. Implementation can sometimes be challenging due to varying standards across the industry.
		4	4		
		7	4		
		8	3		
	SD-ATO Applicability	3	4.5	4.875	No additional comments, as this phase occurs after the most complex ETO stage. With MTS products ready, the assembly logic is more straightforward.
		4	5		
		7	5		
		8	5		
	SD-Site Ordeing Policy Applicability	3	4	3.75	For modular integrated construction, the models are usually very large. Due to limited space on-site and the previously well-planned schedule, if there are concerns about the schedule — for example, if a module is not yet fully prepared in the factory — the module may be transported to the site first, where additional work, such as installation, is completed. In these cases, safety stock is generally not advantageous, and just-in-time delivery is preferred.
		4	3		
		7	4		
		8	4		
	ABM Applicability	3	5	4.5	Interaction is well-executed. It works better with prefabricated construction and smaller items that are easily transportable. However, if the item is large and consists of multiple parts, the planning needs to be traced back further.
		4	5		
		7	4		
		8	4		
Part 3	The Decision and Constraints Alignment with Hybrid Modelling Methods	3	5	3.75	The logic is quite clear, but the real-life constraints are much more complex than those shown in the graph. For example, truck and machinery maintenance can be more frequent, and routes to the construction site may vary due to factors like trucks being allowed only during evening hours or traffic congestion. The maximum number of trucks allowed to park on-site is also a common constraint. (For grade 2: The logic is correct, but the real-world supply chain is too complex to be fully captured by a small model.)
		4	4		
		7	2		
		8	4		

6

Case Study of Panelized Construction Buffers using Hybrid Simulation

All the modes of the supply chain described before belong to industrialized construction, where we discussed the different production modes of these settings and the possible buffers that could be involved in the process. This chapter provides a more specific case of panelized construction, focusing on the use of inventory and capacity buffers under its particular settings of different batch sizes. Batch size was also mentioned in the previous literature review when introducing what could cause emergent patterns in the supply chain and the main concerns of supply chain management. To be more specific to this case, the following section will first provide a description of batch size. The case scenario and data description that follows are mainly based on the panelized construction context, as this method is in the middle of a transition from traditional construction to the most advanced modular and integrated construction types, making it representative.

6.1. Batch size scenario selection in specific panelized construction scenarios

As discussed earlier, prefabricated construction, as a transition to industrialization, shares some attributes and concerns with manufacturing, production, and general supply chains. Among these, batch size remains a concern throughout the entire process.

A batch is a quantity that is either in production or scheduled to be produced. The concept of batch size is best defined in terms of two different concepts: the process batch and the transfer batch. A process batch is the quantity of a product processed at a work center before that work center is reset to produce a different product. A transfer batch is the quantity of units that move from one work center to the next. The transfer batch size need not, and in most cases should not, be equal to the process batch size; the process batch can be equal to or greater than the transfer batch. In synchronized or lean manufacturing systems, the transfer batch size should generally be kept as small as possible to ensure a smooth and rapid flow of materials. The process batch size should be determined by the requirements of the system and should be allowed to vary as needed over time. At bottleneck work centers, especially those with significant setup times, small transfer batches should be used with relatively large, economical process batches (Swamidass, 2000).

In prefabricated building, the process batch size reflects the fact that the manufacturing and assembly process is often carried out in large batches. A large number of basic elements from sub-suppliers are manufactured and produced before being placed together with the main supplier, increasing the amount of work in progress as well as inventory levels at each echelon. One factor that contributes to this is the large size of engineering design batches (Bulhoes & Picchi, 2008).

Another important issue related to transportation is the transfer batch size (Lair, Ayob, Baksh, & Sharoun, n.d.). Issues with batch size include decisions on whether to vary or fix the batch size and determining the appropriate batch size. Some researchers, such as Schwarz and Weng(2000), suggest varying the batch size according to order size, while others prefer fixing it. For example, Banerjee

and Kim(1995), in their study on joint optimal integrated inventory replenishment policy in a Just-in-Time (JIT) system, suggested that the delivery batch size should be fixed to develop an optimal supply chain. In the context of modular construction, due to the large bulk of modules, one truck usually holds only one or two assembled units/rooms and transports them to the site, where they wait to be assembled. However, in panelized construction, a truck can usually carry more components, making transportation batches more dynamic and influential to other procedures. These batch size-related transportation and inventory issues are both important in supply chain management. The buffers we mentioned help address these problems. The application of Just-in-Time (JIT) (no inventory buffer) to manage inventory issues in the supply chain has been investigated by various researchers. JIT requires a reliable supply and transportation system to work efficiently. Thus, reliable transportation and upper-level suppliers are necessities for a no-inventory buffer system. Reliability is usually represented by variance (Morash & Clinton, 1997). For example, (Schwarz & Weng, 2000) studied the effect of system variability (transportation and node variability) on the performance of a JIT-Basestock three-echelon supply chain and found that reducing variance can help reduce the distributor's base stock level and safety stock (which is as important as reducing demand uncertainty). In contrast, proper safety stock can help improve supply chain performance when supply chain variance is high (which could be caused by large batch size, etc.).
So we can formulate the hypothesis that proper safety stock may work well with supply variance and may even work better when variance is higher. Based on the abovementioned issues, the following case study will take batch size for engineering, manufacturing, and transportation as basic scenarios to show how hybrid simulation works with buffers.

6.2. Case Description

After the model is built, it is applied to a case study to check its performance under different scenario settings. In this research, the model is applied to a panelized construction project without technology integration. According to the supply chain mode summarized in the previous chapter, the main supplier here provides casted floors and walls, while the sub-supplier is mainly responsible for wood frames, doors, and installations. Some key assumptions are made before building the model, and these are listed below:

- The most important component in this supply chain is the wood frame and its long lead time in the previous engineering phase. Therefore, the supply chain is simplified to the following sequence: engineering—sub-supplier that provides wood frames—main supplier that casts concrete together with wood frames—contractor. The sub-supplier and the main supplier are different companies in different locations.
- The project involves building individual houses. In the typical conceptual model of a house, one house contains ten walls and six floors. Thus, it is assumed that sixteen concrete elements and approximately two concrete blocks correspond to one wood frame or door. The project consists of a total of 23 houses, and the model stops automatically when 23 houses (368 panels) are built.
- In reality, there are more suppliers that provide raw materials like concrete and wood. These suppliers are excluded from consideration, and it is assumed that all raw materials are already in place.
- In addition to the raw material supplier, there is another supplier that provides installation parts together with wood frames and sends them to the concrete factory to be assembled. However, due to the low volume of installation parts, it is difficult to implement a one-piece flow for this material, which results in less variation to test in this model. Therefore, this supplier is excluded from consideration, and it is assumed that these parts are already delivered to the factory.
- The wood frame manufacturing factory does not have a robotic system to automatically perform a one-piece flow job. Before each production run, the supply line needs to be set up, which is why batches are needed.
- Engineering batches are required due to financial factors. As described in the previous chapter, this approach is akin to engineering-to-order because of the importance of understanding the rework effect on this part of the supply chain. In the ABM model, we simplified the work introduction rate to the average rate of onsite construction.

- The wood frame manufacturing and concrete production factories usually serve multiple clients simultaneously. In the model, we do not consider any schedule conflicts with other clients; one manufacturing line is considered dedicated to this project, and the work-in-progress (WIP) also belongs exclusively to this project.
- Model running time is based on working hours.

Main parameters of the case study were obtained from interview together with similar project records, and they are approximations of historical values, which are presented in Table 6.1. Some parameters are estimated using a triangular distribution because a triangular distribution requires only three parameters (i.e., minimum, mode, and maximum). It was more practical to solicit the values of its parameters from experts in cases where historical data was unavailable, and it has frequently been used to represent construction activity durations (Hussein, Darko, Eltoukhy, & Zayed, 2022).

Table 6.1: Overview of Parameters and Values

	Parameter	**Value**	**Unit**
Construction site	Panel installation	triangular(2.5, 3, 3.5)	hour
	Parallel panel installation maximum number	2/	hour
Truck	Truck loading/unloading	triangular(5, 7, 10) number_panel	minute
		triangular(1.5, 2, 2.5)*number_window	minute
	Maximum Truck Capacity	4	panels
		80	woodframes
	Truck speed	triangular(45, 50, 55)	km/h
	Distance factory to manufacturer	60	km
	Distance factory to site	60	km
	Transportation cost	400	euro/truck
Woodframe factory	Time needed to process one unit	triangular(135, 175, 320)	minute
	Manufacturing line setup time	triangular(220, 250, 270)	minute
	Manufacturing line setup cost	500	euro/truck
Concrete factory	Casting one panel	12	hour
Engineering	Parallel panel casting maximum number	9	house
	Minimum batch of engineering	16 (1 house)	panel
	Maximum batch of engineering	15	house
	Engineering time per house	triangular(20,25,30)	hour

6.3. Tactic decision and KPIs setting

A total of four tactical decisions were initially identified based on a literature review and an interview, and five KPIs were chosen to be implemented in the model.
The tactical decisions, which are used as changing parameters in the model for testing and running, include:

1. **Batch Size of Engineering and Manufacturing**: Work in the engineering and manufacturing departments begins only after a minimum amount of work is introduced. This decision is influenced

by external factors, such as production line setup costs and the requirement for a minimum work unit.

2. **Batch Size of Material Transportation from Sub-supplier and Main Supplier (Wood Frame and Concrete Factory in the Case Study)**: Due to the limited number of trucks and the cost associated with truck use, larger batch sizes are preferred for transporting materials, particularly smaller products like wood frames. However, a one-piece flow can still be used if necessary.
3. **Safety Stock and Reorder Points for Site Contractor's Module, Wood Frames in Concrete Factory, and Wood Frames in Wood Frame Factory**: These are used as inventory buffers to mitigate uncertainties in demand and lead time.
4. **Number of Trucks**: This serves as a resource and a constraint for the key operation of transportation.

A total of five KPIs are identified:

1. **Site Resource Utilization**: The percentage of the on-site assembly workgroup's time that is being actively used for work.
2. **Total Inventory Cost**: The sum of all storage costs for both wood frames and concrete at the site, as well as at the concrete factory and wood frame factory.
3. **Transportation Cost**: This cost is based on the number of truck movements, as transportation is charged per truck.
4. **Project Duration**: The time required to build the necessary number of panels in a house based on a panelized construction project.
5. **Manufacturing Cost**: This particularly refers to the additional costs associated with setting up the manufacturing line.

6.4. Scenario setting

Different scenarios were set for model testing. In the model, safety stock levels and the number of trucks are dynamically determined by the simulation, so these factors are not included in the initial scenario settings. In panelized construction, where technology and location are not integrated, achieving a balance between the cost benefits of bulk production and the agility of a one-piece flow is a key challenge. Therefore, the scenarios were designed as a matrix, varying both transportation modes (bulk vs. one-piece flow) and the application of manufacturing and engineering batch sizes (high vs. low). The scenarios presented in this study cannot be directly applied to other real cases, such as

Table 6.2: Scenario Setting Parameters

Scenario	Engineering BatchSize	Manufacturing BatchSize	Transportation BatchSize-Panel	Transportation BatchSize-Woodframe
Big batch transportion-Small batch manufacturing	16	10	4	60
Big batch transportion-Big batch manufacturing	48	30	4	60
Small batch transportion-Small batch manufacturing	16	10	1	10
Small batch transportion-Big batch manufacturing	48	30	1	10

a technology-integrated construction project. However, the features of these scenarios are designed to reflect different levels of technology and location integration. In technology-integrated companies, it is easier to implement a one-piece flow, especially if both sub-components and main components are produced within the same factory. In such cases, safety stock is no longer necessary, and only in-factory transition stock is required.

6.5. Result

The model was run with 10 seeds under four different scenarios, both in Agent-Based Modeling (ABM) and hybrid simulation settings. The average differences in results for each Key Performance Indicator (KPI) are presented in Table 6.3. And how much the hybrid simulation result differ from pure ABM simulation are marked in both the table and Figure 6.1.These improved values align with the initial hypothesis that hybrid simulation, designed to support ABM in decision-making, would yield better results. Thus, comparing the results between the two models is crucial.

As shown in the results, the hybrid simulation consistently produced better outcomes for project duration and site utilization than pure ABM. This observation aligns with the dynamic strategies regarding safety stock on-site, especially when comparing scenario 3 to 1 and scenario 4 to 2. In the ABM simulation, scenarios 3 and 1 performed worse than 2 and 4 in terms of project duration and site utilization because the transportation batch size increases transportation variance. However, in the hybrid simulation, the dynamic safety stock improves their performance percentage. As discussed in the chapter on buffering, these strategies aim to meet customer demand. The equations governing these two decision variables do not consider financial factors like transportation cost but focus on achieving minimal local optimization rather than global optimization, which explains the results. The hybrid simulation primarily enhances demand-side management at the construction site.

Table 6.3: Hybrid Simulation and ABM Scenario KPIs

		Inventory Cost	Project Duration	Transport Cost	Site Utilization	Manufacture Cost
Hybrid	**Scenario 1**	34773.6 (+5.75%)	448 (-8.20%)	54000 (+11.57%)	0.395 (+3.67%)	18400 (0%)
	Scenario 2	34758.9 (-17.22%)	429 (-8.14%)	44880 (+2.75%)	0.358 (+1.42%)	7200 (+5.88%)
	Scenario 3	18255 (-29.07%)	410 (-39.17%)	166400 (-0.95%)	0.481 (+39.02%)	16800 (0%)
	Scenario 4	26912 (+5.92%)	483 (-45.85%)	168160 (+2.29%)	0.419 (+19.37%)	6000 (+7.14%)
ABM	**Scenario 1**	32881	488	48400	0.381	18400
	Scenario 2	41989.2	467	43680	0.353	6800
	Scenario 3	25742.4	674	168000	0.346	16800
	Scenario 4	25407.9	892	164400	0.351	5600

However, it is important to note that while the average values from the hybrid simulation do not differ significantly from the pure ABM results across most scenarios (scenarios 1, 2, and 3 are quite consistent), scenario 4 presents an outlier. In this scenario, as illustrated in Figure 6.2(d), one of the simulation seeds resulted in a significantly longer projected duration than others, as shown in Figure 6.2(c). This anomaly can be attributed to the larger batch sizes in the engineering and manufacturing stages compared to the transportation batches. This discrepancy creates a periodic pattern in inventory supply.

Furthermore, the dynamic safety stock is calculated based on the lead times of the most recent 20 orders, which introduces a delay. This delay can lead to the bullwhip effect, as mentioned in the previous chapter. In this case, the dynamic demand forecast does not accurately predict future needs, making the stable safety stock approach in pure ABM more effective. For example, in Figure 6.2(a), under scenario 3, although there is still significant uncertainty in demand and supply, the cyclic pattern is less pronounced. Thus, our simplified equation for calculating safety stock performs better in this scenario. Future research should focus on replacing this equation with a more sophisticated predictive function, although this is beyond the scope of the current study.

6.6. Validation

Internal Validation

Internal validation focuses on verifying that the model is correctly constructed and logically sound. This involves checking the internal coherence of the model's conceptual framework to ensure that the relationships between different components are clear and free from contradictions. Specifically, the research focused on demonstrating the effectiveness of the hybrid simulation approach compared to single-method simulations. This involved a comparative analysis between Agent-Based Modeling

Figure 6.1: Hybrid Simulation and ABM Scenario KPIs Comparision

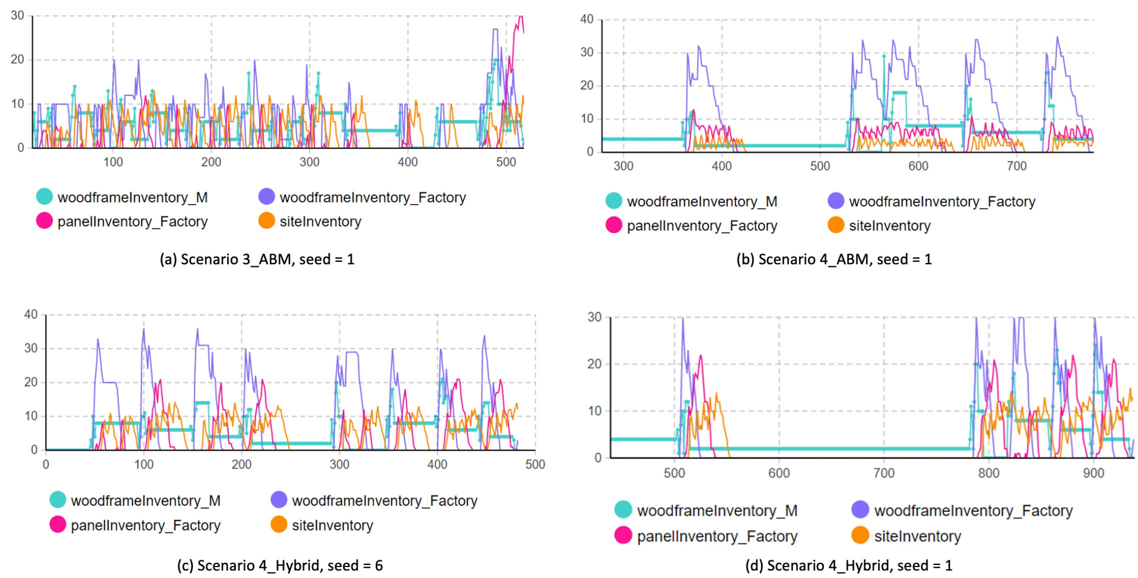

Figure 6.2: Inventory Comparison under different method and scenario. Source: author's own work screenshot in Anylogic

Table 6.4: Validation Result - Part 4

Parts	Questions	Interviewee ID	Individual Grade	Average Grade	Main Comments and Suggestions
Part 4	Batch Size and Safety Stock's Influence on KPIs	3	5	4.5	The tendency for smaller batches to offer more convenience is accurate, and dynamic safety stock should be more effective for managing inventory and utilization. This approach aligns more with prefabricated construction, where there is usually no concern about where to store trucks. However, in modular integrated construction, the module is typically kept on the truck until it is installed, and the batch size is usually just one. Therefore, transportation batching is not suitable to describe this scenario.
		4	4		

(ABM) and the hybrid simulation, as discussed in the case study section, which showed that the hybrid simulation provided more comprehensive insights and better aligned with real-world practices.

External Validation

External validation was employed to determine whether the model reflects real-world thinking and strategies. This was done through interviews. Similar to the interviews for the previous two sub-questions, the interview asked practitioners why they believe these simulated results are expected based on the scenario settings. For example, they were asked why they think a large batch of manufacturing would cause more uncertainty in inventory stock and more delays in delivery, and why small batches of transportation would cause vehicle inadequacy and introduce more transportation variance. They were also asked whether periodic reviews to decide safety stock based on historical data are useful or if they could cause trouble in certain uncertain cases. These interviews helped confirm the model's alignment with actual industry practices, validating its external applicability. This part of the model received a score of 4.5 from the interviews, indicating a high level of validity in the case study test.

7 Discussion

The discussion section compares the findings of this research with the initial literature review and identified research gaps. Its aim is to highlight the contributions and limitations in relation to the research questions and scope. The following discussion is organized into three sections, each addressing one of the sub-questions, and concludes by summarizing the study's limitations.

7.1. PCSC Mode- Physical Layer of DT

Addressing Identified Issues from Previous Research

Recent years have seen a notable increase in the trend of prefabricated construction, as highlighted by extensive literature reviews and numerous projects. This research aims to provide a general overview of the various supply chain modes within this sector. However, it has become apparent that terms such as ”modular,” ”prefabricated,” and ”panel construction” are often used interchangeably or confused, both in academic literature and industry practices when doing literature review and interviews. This lack of clear definitions in industrialized construction (Gibb & Isack, 2003) sometimes leads to misunderstandings, which is one of the motivations behind this research. When supply chain modes are not accurately understood, it becomes challenging to implement appropriate management strategies.

The industry is currently transitioning from traditional to industrialized construction. During this transition, there is an attempt to apply principles from the manufacturing industry, such as lean manufacturing, to construction practices. However, as Larsson, Eriksson, Olofsson, and Simonsson(2014) observe, due to varying maturity levels of prefabrication, the distinction between highly customized construction and highly standardized industrialization remains vague. These interconnected processes are crucial, and the shift from ETO to ATO can only be effectively strategized when their specific contexts are clearly understood.

One advantage of this new industrial construction paradigm is that preferred principles from manufacturing have been developed much earlier than those in construction. The challenge now, also as Warszawski (2003) notes, is to discern these differences between construction and manufacturing and to apply these principles accordingly. Moreover, the emergence of entities like logistic hubs, which function similarly to wholesalers and distributors in traditional manufacturing supply chains, highlights the need to differentiate the various processes and production modes within this new supply chain model. Vrijhoef and Koskela (2000) also emphasize the role of these hubs in optimizing construction logistics, mirroring traditional manufacturing systems.

Research Contributions

The research enhances the understanding of dynamic interrelationships within PCSC by providing a conceptual framework that outlines the general processes and key participants. It clarifies their roles, businesses, and interactions, offering both industry professionals and academics a comprehensive overview. This conceptual understanding serves as a foundation for analyzing how the industry operates and facilitates further exploration of its complexities and interactions. In building a digital twin, it is crucial to first identify the physical entities and processes. The ultimate aim is to develop a cyber-physical system featuring a real-time data interface and virtual layers that accurately mirror the physical system (Syed et al., 2024). The current summary and generalization of these physical processes can serve as a basis for industry to further explore what should be integrated into the virtual layer of the digital twin, and to select appropriate sensors and technologies in the physical world to reflect it accurately. One limitation of this research is the level of detail concerning the identified modes in the supply chain. As Ballard and Howell(2003) suggest, these modes require further exploration to determine at which points construction management principles are more effective, and where manufacturing principles might be better suited. The current research only provides a broad conceptualization, and a detailed examination of these specific points is necessary to fully understand the practical applications. Without this, the findings remain limited in their ability to offer precise guidance for improving construction project efficiency, adapting industrial principles to the unique challenges of the construction sector, and providing further guidance on how to gradually build information processing and virtual layers for a digital twin.

Research Limitations: Scope and Gaps

The research scope is a bit wide under the limit of time, even though the main contribution of this research is to propose a new way of using simulation methods. The chosen approach to model the overall system equilibrium makes it inevitable that system dynamics should be found, and agent-based modeling should be built. These foundational steps are not well-researched in previous literature, creating multiple research gaps. Due to time constraints, the accuracy and quality of the model itself are somehow sacrificed. For example, the first sub-question about the process could already be a qualitative research topic, but with only six interviewees participating, it could not be qualitative enough. This spared time for the whole research, similarly affecting the other two sub-questions. Overall, the research covers many aspects but does not delve deeply into a certain aspect.

7.2. Hybrid Simulation Application- Virtual Layer of DT

Addressing Identified Issues from Previous Research

The concept of hybrid simulation emerged from the goal of modeling supply chain interactions and implementing management strategies based on these models. Although previous studies often did not explicitly state their reasons for choosing specific modeling methods, they generally displayed a preference for certain types of modeling due to the different levels of abstraction offered by these methods. Initially, we employed system dynamics to model macro interactions and overall system performance. However, the scarcity of recent literature on system dynamics in supply chain applications might relate to historical computational constraints, the evolution of computational capabilities that now favor more complex models such as those used in ABM. ABM's highly descriptive nature and ease of understanding make it a preferred method in recent studies, as evidenced by North and Macal(2007), who explore how ABM enhances the adaptability of supply chain models to real-world complexities.

At first glance, SD and ABM seem to be very different techniques. While SD takes a top-down approach, ABS is a very extreme example of a bottom-up approach. Also, while ABm is stochastic, SD models tend to be deterministic. However, it can be proved that in fact the set of all SD models is a strict subset of the set of all ABM models. This is the Agency Theorem for System Dynamics (Macal, 2010), and quite simply states that every well-formulated SD model has an equivalent formulation as an ABS model. Therefore, we can model any SD model using ABS. This tends to produce results which perform at least as well as running the SD model, if not better, however, it comes at a price as ABS models are a lot more time-consuming to model and to run(Maidstone, 2012).

System dynamics, while simpler in terms of coding, demands that equations be based on established relationships among variables. On the other hand, ABM starts with straightforward agent interactions and escalates through computational power to reveal intricate relationship dynamics, supporting current research that such simulations are advantageous for digital twins (Ambra & Macharis, 2020).

Returning to system dynamics, it is crucial to note that this method is not inferior to ABM. When managing large model sizes where not every detail can be meticulously captured, system dynamics offers a valuable approach to maintaining overall system equilibrium. However, the limited recent research on system dynamics presents challenges in applying it effectively within modern contexts. This observation aligns with Malbon and Parkhurst(2022), who discuss the integration of system dynamics in complex policy environments, emphasizing its strengths in broader system analysis despite newer methods gaining popularity.

Research Contributions

This thesis provides a novel hybrid framework that integrates Agent-Based Modeling and System Dynamics, catering to diverse academic and practical needs. It not only allows for a more accurate representation of PCSC processes but also provides an exemplary framework for choosing and utilizing different simulation methods effectively. The approach is validated through the creation of a prototype, demonstrating that the hybrid method is not only applicable but also inspirational for researchers seeking to align simulation strategies with real-case planning. It serves as an experimental platform to examine how systemic changes over time relate to decision rules and to assess the impact of different inventory and capacity scenarios on supply chain performance. This dynamic perspective helps in presenting the supply chain coordination process in a more accurate and applicable manner.
In a digital twin setting, this hybrid simulation is an important part of the digital layer of the digital twin, which is an exact replication of the physical elements in a virtual model. This layer is instrumental in synthesizing data, strategies, and operational insights to optimize SC performance (Syed et al., 2024). Most authors have proposed a DT conceptual framework after investigating the particular system for integration, such as Kalaboukas, Rožanec, Košmerlj, Kiritsis, and Arampatzis who also indicates the importance of DT at the virtual level to create sub-DTs (different parts of simulations) for various SC processes to enhance the visualization and control for complex systems. The focused aspects provide detailed insights and analysis for better integration at the SCM network level. Similarly, it helps each SCM process design, test, and optimize before integration into a larger system. This layer of simulation has profound potential in offering analytical solutions that aid in decision support, predictive analytics, and the timely identification of systemic disruptions. The deployment of data analytics avails hybrid solutions conducive to continuous systemic adaptations, thereby augmenting SC performance.

Research Limitations: Decision-Making Techniques of Model

During our literature review, we considered some management policies that could mimic the control offered by system dynamics. Yet, this workaround complicates the simulation model implementation, leading us to use only the most basic safety stock models in the study's system dynamics part. There are potential alternative approaches, such as conducting more extensive reviews of management strategies. However, developing system dynamics models is a substantial topic in itself already and beyond the scope of this research. It could be left for future research to enrich this.
The system dynamics part, as described before, represents the decisions the supply chain should make. In real life, departments usually try to make their decisions more optimized based on many factors. This research only chooses the most common inventory ordering safety stock decisions and uses trucks as adjustable constraints. The end of the research is to show the feedback loop back and forth between the two simulation method results and provide more insights for understanding supply chain coordination and future research instructions on how to develop more reasonable modeling techniques based on these features. However, the hybrid simulation cannot prove its optimality compared to single method simulation, as it is beyond the research scope.

7.3. Case Study Implementation- Analytics and Service Layer of DT

Addressing Identified Issues from Previous Research

In this research, we chose a case study on panelized construction, which we previously identified as a midpoint in the continuum of prefabricated construction. This form of construction integrates diverse stages such as one-piece engineering and batch production, making it an subject for examining the complexities of prefabricated construction. The selected scenario reflects different production and transportation batches, a critical element in both the manufacturing and construction industries. This choice is underscored by feedback from industry partners interviewed, who highlighted this as a key concern, especially in relation to how the transition towards industrialization impacts decision-making processes.
The case study is hypothetical, constructed using parameters derived from existing literature and insights from our interviews, allowing for a controlled comparison of results across different scenarios. In this study, we applied two different simulation methods to assess how each would perform under varying conditions. The findings indicate that while larger batches can yield cost savings, they may disrupt the construction process. This is because not all phases of construction are suited to large batch production or traditional manufacturing strategies such as "make-to-stock," particularly in phases that require sequential engineering.
The result also revealed that the hybrid simulation approach, while not providing optimization tech-

niques, could perform effectively under scenarios where an economic ordering policy is applicable. Conversely, in scenarios where supply and demand variability is high, the hybrid simulation tended to perform less effectively.

Research Contributions

Through specific use cases, this research tests the hybrid simulation under various supply chain scenarios, thereby validating the advantages and identifying the limitations of the proposed framework. The study investigates the effects of tactic using such as and safety stock adjustments, on supply chain performance. These practical applications underscore the effectiveness of hybrid simulations in enhancing supply chain management and provide actionable insights for future strategic implementations. In a digital twin setting, it is accordingly the analytics or service layer of a digital twin, which receives real-time data from the digital layer. It performs digital analysis to support resilience using advanced tools such as simulation modeling to interpret data and generate actionable insights(Syed et al., 2024). The simulation from the last virtual layer is more targeted with specific aims and performance guidance, the analytics layer to be more specific, is reflected in this research, by doing lots of what-if analysis, giving management insights into what factors have influences on the system, what is the more suitable batch size after different scenarios simulation, and observe the emergent patterns generated by system sub-components interaction, in this specific case is dynamic inventory buffer by hybrid simulation only works better when no periodical demands fluctuation. This virtual layer also provides the foundation for the real service layer when later on added real-time data processing, cause the analytic layer gives guidance of how decisions should be made, and once it’s connected to real data system, it can instruct the system to anticipate emergent patterns, respond with a tested better solution, and recover from disruptions promptly, i.e., increase the system resilience.

Research Limitations: Model Accuracy and Additional Validation

The model proposes a way of simulation using a hypothetical case to demonstrate the idea of using different modeling and simulation approaches to better represent different parts of the supply chain. The case study is based on parameters from interview about a real-case setting and some supplementary parameters from a literature review, so it remains a hypothetical case. The validation addresses all three sub-questions, meaning it covers a wide range of aspects but does not focus on any specific aspect. In the future, the proposed simulation approach can be further explored under more scenarios and use more accurate validation, such as using an exact case and comparing it with historical data for model calibration and further validation.

Research Limitations: Tactical Modeling Part

The system dynamics part of the model aims to combine different simulation methods and use system dynamics to help decide the tactics used in PCSC. The tactics identified in this study are inventory, lead time, and capacity buffers, and there is research and interview data supporting their importance and correlation in making supply chain decisions. However, the literature that quantitatively describes the relationships among them is rarely found, and real-life decisions on them are based on more extensive factors. Even though the exactness and exhaustiveness of the system dynamics model for these three tactics are beyond this research’s contribution, it does limit the possibility of generating more diverse results by changing those parameters, which needs to be explored in the future.

8 Conclusion

To conclude this research, we addressed the primary question. To summarize, it is answered as follows:

8.1. Answering Sub Questions

Sub-question 1: *What are the general supply chain modes in the context of prefabricated construction, and how are they coordinated?*
Answer: In prefabricated construction, supply chain modes are primarily determined by the level of prefabrication—ranging from basic component assembly in Prefabricated Construction (PC) to complete modular builds in Modular Integrated Construction (MiC), and the level of technology integration like uniform files. It also differs by the specific manufacturing processes used, such as Engineer-to-Order (ETO), Make-to-Order (MTO), Make-to-Stock (MTS), and Assemble-to-Order (ATO). These modes define how components are designed, manufactured, and assembled, ensuring that each part of the construction process aligns with the overall project timelines and quality requirements. Coordination within these modes across different stakeholders, from sub-suppliers, main suppliers, and contractors to clients, is crucial for the prefabricated construction industry to effectively manage complex supply chains, adapting to various levels of product customization and technological integration to meet specific project demands.

Sub-question 2: *How can this type of coordination be modeled using the advanced simulation capabilities provided by digital twins through a hybrid simulation method?*
Answer: Integrating hybrid simulation methods—system dynamics (SD), agent-based modeling (ABM), and discrete event simulation (DES)—within a digital twin framework significantly enhances the management of prefabricated construction supply chains. By employing SD, the overarching dynamics and feedback loops of the supply chain are modeled, providing insights into material and information flows over time. ABM focuses on the individual behaviors and interactions of contractors, suppliers, and sub-suppliers, enriching the understanding of micro-level dynamics. DES complements these by simulating the sequence and timing of construction events and logistics, capturing the operational dynamics of the construction process. The digital twin serves as a dynamic virtual replica of the physical supply chain, continuously updated with real-time data from IoT devices and sensors, and provides data support to this hybrid simulation. By synthesizing data and simulations, the digital twin then provides a comprehensive, responsive tool that enhances predictive accuracy and helps make real-world decisions in complex construction projects.

Sub-question 3: *How can the proposed simulation approach aid in determining practical tactics for using different buffers in the supply chain?*
Answer: The proposed hybrid simulation approach can aid in determining practical tactics for different buffers within the prefabricated construction supply chain. By integrating the three methods, this approach allows for detailed exploration of buffer tactics across various scenario settings. Specifically, the case study model evaluates how different configurations of inventory buffer, transportation and production batch size impact key performance indicators such as project duration, inventory costs, and site

utilization. This enables the identification of better way of buffer and batch sizes and arrangements that enhance supply chain efficiency and responsiveness to fluctuations in demand and supply. Furthermore, the model's dynamic simulation capabilities provide real-time insights into the effects of tactical adjustments, supporting decision-making in complex construction projects. For example, it assesses the trade-offs between batch sizes and setup costs against inventory holding costs, and the impact of transportation logistics on delivery frequency and costs. These simulated results help supply chain managers make preferred decisions, ensuring that material flow and project timelines are managed more uniformly.

8.2. Answering Main Research Question

Main question: *How can digital twin-enabled simulation help with prefabricated construction supply chain coordination?*
Answer: Digital twins serve as a powerful tool in managing prefabricated construction supply chains by providing virtual replicas of real-world operations. These simulations are one of the aspects of digital twins from the virtual world, and allow for risk-free testing of various strategies and operational tactics in a controlled environment. The digital twin technology captures the complexity of interconnected processes across the whole prefabricated construction supply chain by different production modes, component types, and technology types, enhancing operations through informed decision-making and accurate predictions of future states. Within the simulation, multiple simulation methods capture various aspects of the supply chain, such as system dynamics (SD), agent-based modeling (ABM), and discrete event simulation (DES), to address different aspects of the supply chain. This approach provides managers with dynamic tools to effectively understand and coordinate complex interactions by observing the emergent patterns shown in front-running simulation. Integrated information sharing ensures all stakeholders have access to consistent and accurate data, promoting transparency and collaboration. In summary, digital twins offer a comprehensive, integrated approach to managing the complexities of prefabricated construction supply chains, empowering stakeholders to optimize processes and achieve project goals efficiently.

8.3. Recommendations for Future Research

8.3.1. Practical Recommendations

Based on the findings and insights from this research, several practical recommendations can be made for stakeholders in the prefabricated construction supply chain.
Ehance Coordination Among Stakeholders
To optimize supply chain management, it is essential to improve coordination among all stakeholders, including suppliers, contractors, and clients. Building integrated communication platforms in digital twins as structured by this research can facilitate real-time information sharing, ensuring that all parties are aligned on project timelines, inventory levels, and production schedules.
Utilize Advanced Simulation Techniques with DTs
Besides the information sharing basic function by DT, stakeholders can leverage the front running simulations multiple times in DT to get risk-free insights before project starts. Hybrid simulation methods, such as combining SD, ABM, DES, can be utilized to better understand the complexities of their operations. These simulations can help identify bottlenecks, optimize buffer tactics, and enhance overall supply chain efficiency, enabling proactive decision-making without disrupting physical operations
Implement Flexible Tactics
Adopting flexible tactics is crucial for managing variability in demand and supply. By analyzing the impact of different variables and KPIs, for instance, batch sizes, on inventory levels and transportation costs—as shown in the case study—organizations can identify possible configurations of these parameters and establish optimal dynamic decision-making tactics and strategies. At the same time, they should consider the interconnectedness among all system elements, which can be achieved through advanced simulations using digital twins (DTs).

8.3.2. Recommendations for Future Research

In this part, recommendations for future research are described based on research results and discussion.

More utilization of ABM

Agent-based modeling, in some application use cases, is very effective at simulating populations of agents with similar attributes and functions. This is a significant advantage when compared to discrete event simulation, which can represent separate identities and discrete time events. In this case study, the agent population is applied to the truck agent. A more effective use of ABM is to model not only a single supplier and a single manufacturer; this is important as one of the research contributions helps to understand what happens in the coordination process among a single supply chain. Additionally, due to a lack of data to support the assumption of a holistic supplier and contractor relationship, the supplier, contractor, and sub-supplier were only modeled as individuals, not as populations of individuals, based on interviews from a specific case. As introduced in the literature review, the research focuses on managing the tactics of inventory and ordering policy at a project-based level, which belongs to the tactical part. However, managing all different partners, site locations, and cross-docking logistic places belongs to strategic decision-making, and the scope for making and adjusting these kinds of decisions is usually based on the performance of many projects, and the decision will have a broader but more abstract implication. Future research can try to model different construction sites as agents and apply the same sub-agents as in this research to simulate more complex and layered models.

Increase model level of detail

As described in the discussion part, one research direction is to go deeper into the level of detail, utilizing the agent-based model's ability to simulate more detailed aspects. For example, in this research, we also modeled orders and shipments as agents but with only simple attributes like amount and didn't consider ordered material types, due dates, etc., because if considered, some scheduling techniques need to be introduced. Also, according to the interviewees, rework happens at every stage of the supply chain, making it worthwhile to research how different stages of rework will influence these orders and the construction schedule.

Capture local optimization conflict

Another aspect is the discussion about optimization in the limitations section. This research provides a perspective that these dispersed parties can be modeled and their coordination examined, but the simulation aim is quite simple, just to check the KPI level and different scenarios using an inventory policy. However, in a decentralized setting, the conflict between local optimizations and overall optimization can be another interesting phenomenon. Future research could allow different agents to perform local optimizations separately and observe the emergent behaviors of their interactions.

Adding information processing layer of Digital Twins

Data mapping is an important aspect of digital twins (DT) in which collected data is carefully organized and assigned to specific models or parameters. Current research misses the part of data processing bidirectionally between the physical world and the virtual world; future work can complete this part by exploring what information can be transferred in between and how.

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A

System dynamics variables

Type	Name	Meaning	Formula
Stock	Inventory	The inventory at this level	Inventory(t) = Inventory(t-dt) + (Shipment Rate - Delivery Rate) * dt
Stock	Back Log	The difference between the order and shipment rates	Backlog(t) = Backlog(t-dt) + (Order Rate - Shipment Rate) * dt
Stock	Outstanding Orders	The orders that need to be subtracted to ensure any parts that have been ordered but not yet received are taken into account	Outstanding Orders (t) = Outstanding Orders (t-dt) + (Delivery Rate - Order Rate + Ship) * dt
Flow	Delivery Rate	Input(from upper stream party)	DELAY3 (Retailer Order, Wholesaler Delivery Delay) (customer rate i.e. delivery rate)
Flow	Shipment Rate	Output(to lower downstream party)	Initial conditions: Delivery starts; units=outbound
Flow	Desired Shipment Rate	Desired output to lower downstream party	Desired shipment= Desired shipment rate
Flow	Desired Delivery Rate	Desired input(from upper stream party)	Same as shipment, but accounting for backlog
Variable	Safety Stock	The order goes to upper stream party	Inventory, Safety Stock = Desired Delivery Rate+consumption rate
Variable	Order Rate 1	Inputs(from the upper stream)	Summarize fixed#people on site(i.e. fixed no. on the construction site) means the real construction site by construction site)
Variable	Order Gap	The difference between inventory and backlog of orders	Delivery Delay is a backlog(missing factor); Order gap = Inventory - Backlog
Parameter	Stock	To reduce the inventory fraction, it's a predefined value	Can be varied for test
Parameter	Supply delay	production capability, supply chain efficiency (i.e. lead-time, clearance matching, distribution efficiency, raw material supply timing and resources (e.g. labor time, process/ operating time, fleet time, and any transportations)	Can be varied for test
Parameter	Delivery delay	To reduce the order rate into the stock different between inventory level and the safety stock	Can be varied for test
Function	Order policy	control policy	best value

Table A.1: Non-manufacturing department

Type	Name	Meaning	Formula
Stock	Inventory 1	The material inventory (raw material before manufacturing)	Inventory(t) = Inventory(t-dt)+(Shipment_Rate - Delivery_Rate)
Stock	Inventory 2	The product inventory (finished products after manufacturing)	Inventory(t) = Inventory(t-dt)+(Shipment_Rate - Delivery_Rate)
Stock	BackLog	The demand that needs to be satisfied either from inventory or manufacturing first	Backlog(t) = Backlog(t-dt)+(Order_Rate - Shipment_Rate)
Stock	Outstanding Orders 1	Orders that need to be subtracted to measure shipment and production network outstanding orders are produced in such a way as outstanding orders are satisfied	OutstandingOrders(t) = OutstandingOrders(t-dt) □ (OrderRate - ShipmentRate)/dt
Stock	Outstanding Orders 2	Work in progress	WIP(t) = WIP(t-dt) □ (Desired_Production_Rate - Production_Rate)□dt
Flow	Delivery Rate	Input from upper stream plant	DELAY1(Retailer_Order, Wholesale_Delivery_Delay)
Flow	Shipment Rate	The products delivered to lower downstream party	Shipment_Rate(1) = Delivery_Rate + Backlog(1) + Shipment_Ratio_backlog$_{o}rders(1)$
Flow	Desired Delivery Rate	The products delivered to lower downstream party	Shipment_Rate(2) + any backloged orders
Flow	Input	Same as delivery rate	Same as delivery rate
Flow	Output	The order gets it upper stream	Same as delivery rate
Flow	Production Rate	The real production rate by manufacturing factory	min(production capacity, WIP)
Flow	Desired Production Rate	The desired production rate by manufacturing factory	OutstandingOrder-OrderGap
Variable	Order Gap	Difference of inventory and back log of orders shipment rate	inventory - Backlog
Variable	Production Delay	log difference, standard deviation UTILITY ratio standard deviation days	Can be varied for test
Parameter	Safety Stock	To reduce the uninventory factions, eft it's	Can be varied for test
Parameter	Delivery delay	The backup delay time depending upon parameters assigned	Can be varied for test
Function	Order policy (manufacture)	To see all the fills to deficit between the inventory level and the safety stock	Not a value

Table A.2: Manufacturing Department system dynamics variables

B

Interview Questions - Initial Data Collection

Part 1: Business

1. Business Overview

- **Construction**: As a modular construction company, what is your main business (types of projects you're taking), and in these projects, what parts do you usually choose to be prefabricated?
- **Prefabrication**: As a prefabricated factory, what components do you produce? Are they wholly standardized ones, or are they customized by customers?
- **Logistics**: What is the scope of your logistics services? Are they only for the construction industry, or are they particularly tailored for modular construction?

2. Business Partner/Environment

- **Construction**: Can you describe your and your partner's relationship in the supply chain? For example, do you have a constant module supplier, or do you have different suppliers based on project types? For one project, will you choose multiple suppliers at the same time?
- **Prefabrication**: Can you give an overview of your customer and partners? Do you usually work with certain companies with a consistent frequency, or is it usually a one-time transaction? Do you use a logistics company? If yes, what is the business model with them?
- **Logistics**: Can you describe the business between you and your customers? For instance, do you have a long-term contract for transporting all goods they supply during a specific period, or is it a project-based arrangement where you are responsible for specified goods?

3. General Process Involving Different Parties

- **Construction**: Can you describe the general process of planning and executing a modular construction project from start to finish? In this process, which management departments are primarily involved? (e.g., Technical, Procurement)
- **Prefabrication**: Can you give an overview of the process in the factory, from order intake, production scheduling, to meeting client demands? Which management departments are primarily involved? (e.g., Technical, Demand Analysis)
- **Logistics**: Can you provide an overview of the process within your company, from order intake, product receiving, product storage, and delivery? Which management departments or responsible staff are mainly involved? (e.g., Warehouse, Customer)

4. Business Objectives

- **Construction**: What objectives do you aim to achieve? For example, project finish-on-time, sustainability, etc.
- **Prefabrication**: What are the objectives you aim to achieve? For example, project finish-on-time, sustainability.
- **Logistics**: What are the objectives you want to achieve? For example, maximizing machine utilization and delivering on time for all orders to maintain reliability.

5. External Decision-Making Processes

- **Construction**: What criteria do you use to select component suppliers, and how do these criteria impact project outcomes? (Or what factors do you consider when choosing them?)
- **Prefabrication**: Under what conditions would you integrate some of your components into a logistics company? How do you decide which logistics company and components should be stored there?

6. Intrinsic Uncertainties and Challenges Can you identify some uncertainties and challenges you face during your projects or operations? How do these uncertainties affect your day-to-day activities and long-term planning? Could you give examples of unexpected challenges that have arisen in past projects and how they impacted your workflow? In your view, what are the primary sources of these risks (with hints towards solutions)?

Part 2: Inventory

1. Decision-Making Processes Related to Inventory Management

- **Construction**: Considering uncertainties in the project and supply chain, how do you manage your on-site component stores?
- **Prefabrication**: Considering the uncertainties in the project and supply chain, how do you manage your storage/warehouse?
- **Logistics**: How does your company forecast the demand for logistics services and plan storage (fabrication components) and capacity (like trucks) accordingly?

2. Inventory Management Strategies

- **Construction**: Do you have any strategy to manage inventory? For example, lean construction, just-in-time delivery. Do you change your strategy at any point? What factors (internal and external) cause you to adjust your strategy (e.g., limited on-site space, weather)?
- **Prefabrication**: Do you have any strategy to manage inventory? For example, push & pull systems for production. Do you alter strategies, or do you use a hybrid system in some cases? What factors lead you to change strategy (e.g., on-site inventory, forecasted demand)?
- **Logistics**: Do you have any strategy to manage inventory? Do you change strategies at some point, using feedback loops? What factors lead you to alter strategy (e.g., on-site inventory, forecasted demand)?

3. Inventory Forecasting and Optimization

- **Construction**: How do you forecast the required inventory of prefabricated modules for upcoming projects? How do you determine the optimal level of inventory to balance storage costs with project needs?
- **Prefabrication**: How do you determine the amount of raw materials and components to keep in stock? How do you manage inventory levels to reduce waste while maintaining production efficiency?

- **Logistics**: How do you manage the inventory of transport resources, such as containers, trucks, and packing materials? What strategies do you employ to ensure that vehicle and equipment inventory meets fluctuating client demands?

4. **Supply Chain Coordination Challenges**
   - **Construction**: What are the most challenging aspects of coordinating activities within your supply chain? Can you describe a situation where supply chain coordination was particularly challenging, and what factors contributed to this? How does communication flow between your company and stakeholders in the supply chain, and what challenges arise?
   - **Prefabrication**: How do you synchronize timelines and deliveries among all stakeholders, including suppliers? What systems or technologies do you use to manage the supply chain and maintain communication with partners?
   - **Logistics**: How do you coordinate with your suppliers to manage lead times and maintain consistent supply? Can you explain the system you have in place for tracking and replenishing inventory of critical logistics supplies?

5. **Measures for Risk and Uncertainty**
   - **Construction**: How do you ensure synchronization of timelines and deliveries among all stakeholders, including suppliers? What technologies or systems do you use to manage the supply chain and maintain communication with partners?
   - **Prefabrication**: How do you manage inventory levels to ensure production efficiency while balancing storage costs? How do these measures affect the efficiency and reliability of your projects?
   - **Logistics**: What strategies do you employ to ensure your vehicle and equipment inventory meets the fluctuating demands of your clients? What technologies or systems do you use to manage risk and uncertainty in the logistics process?

6. **How Digital Twin Technology Helps with Coordination**
   - **Construction**: How are you implementing digital twin technology to help with construction processes? In what ways has digital twin technology facilitated improved communication and coordination with your supply chain partners?
   - **Prefabrication**: How does your factory use digital twin technology in the design and fabrication of prefabricated components? Can you give examples of how digital twin technology enabled your factory to adapt more quickly to changes in design or client requirements?
   - **Logistics**: How has digital twin technology aided in your response to logistical uncertainties, such as vehicle breakdowns or traffic congestion? Can you discuss the benefits of using digital twins for your warehouse operations?

C

Interview Questions- Validation

Part 1: Supply Chain Mode

- Can you describe how well the general prefabricated construction supply chain model shown in the figure reflects the operations and interactions among all parties involved?
- Are there any critical aspects or processes in the current supply chain model that you believe are missing or misrepresented?
- Can you provide a grade for the applicability and representativeness of the model (from 1 - strongly disagree to 5 - strongly agree)?

Part 2: Key Modelling Parts

- What are your usual decision-making considerations when managing inventory at different stages of the Prefabricated Construction Supply Chain?
- Do you think the marked feedback loops align with your decision-making considerations?
- Can you provide grades for different parts of the feedback loops?
- Could you provide examples of any additional feedback loops that should be considered in the model?
- Do you think the marked agents and their interactions reflect the industry case?

Part 3: Hybrid Simulation Method

- What are your thoughts on the hybrid simulation method proposed for supply chain coordination and decision-making? Does the approach, where macro aspects are modeled as system dynamics and micro aspects are modeled as agent-based modeling, align with the logic of your operations?
- Are there any challenges or limitations you foresee with the proposed simulation method?
- Can you provide a grade for how well the simulation method aligns with your own tactical management logic?

Part 4: Simulation Results

- Looking at the example results from different scenarios of batches, how realistic do you find these outcomes?
- Do you think that smaller batches causing higher transportation costs and shorter project durations is reasonable?

- Do you believe that basing safety stock and vehicle capacity on historical needs could cause a greater bullwhip effect?
- Can you provide a grade on how well the results represent real-world case under these four scenarios?