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Multi-Agent Simulation Approach for Modular Integrated Construction Supply Chain

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Abstract: The shift from traditional on-site to off-site construction marks a significant evolution in the construction industry, characterized by increasing levels of prefabrication. These advancements enhance construction efficiency, reduce lead times, and mitigate environmental impacts, leading to modular integrated construction (MiC). However, MiC presents complex supply chain challenges, particularly in the transportation of prefabricated components and fully integrated modules. This study addresses these challenges by employing a multi-agent simulation using AnyLogic to optimize MiC transport logistics. The simulation models the interactions of various agents involved in the MiC process to improve operational efficiency and reduce costs. Results demonstrate that using three vehicles per supplier minimizes total transport costs, effectively balancing fixed and variable expenses while eliminating penalties for project delays. The findings highlight the cost efficiency of MiC, showing potential savings due to centralized assembly and optimized logistics. These significantly reduce material transportation and related costs, contributing to the overall efficiency and sustainability of construction projects. These insights underscore the value of multi-agent simulation in addressing the complexities of MiC supply chains.

Keywords: off-site construction (OSC); modular integrated construction (MiC); multi-agent simulation; construction supply chain management; transportation optimization

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1. Introduction

The transition from traditional on-site construction methods to off-site construction signifies a pivotal evolution in the construction industry [1]. Off-site construction (OSC) encompasses several levels of prefabrication, each offering distinct advantages in terms of efficiency, delay, cost, and environmental impact [2]. The simplest form, construction based on prefabricated components (PCs), involves the off-site manufacturing of basic structural elements like beams, columns, and slabs, using materials such as reinforced concrete, steel, and wood. This method, while lessening some on-site activities, still requires significant on-site construction efforts [3]. More advanced is panelized construction, where major structural components such as walls, floors, and roofs are produced in factories as prefabricated panels [4]. These are then transported to construction sites for assembly, improving the construction process by reducing the construction timeline and on-site labor requirements. Further along the spectrum lies modular construction (MC), where entire sections of a building, such as hotel rooms or classrooms, are fully constructed off-site in a factory setting [5]. These modules are then transported to the site and assembled into the final structure. This method allows for building components to be stacked, joined side by side, or layered, depending on the architectural design. At the top of OSC technology is modular integrated construction (MiC) [3]. MiC not only employs the benefits of modular construction but also integrates mechanical, electrical, and plumbing components along with interior finishes during the factory phase. This integration significantly expedites the overall construction process and minimizes the need for on-site installation, offering the highest level of prefabrication. Given its comprehensive approach, MiC presents a unique set of logistical challenges, particularly in the transport of these fully integrated modules.

Figure 1 illustrates the distinct stages of OSC. This progression from the simplest form of prefabrication, using basic structural components, through more complex modular constructions highlights the incremental advancements in prefabrication techniques that enhance efficiency, reduce delays, and mitigate environmental impacts across the construction industry.

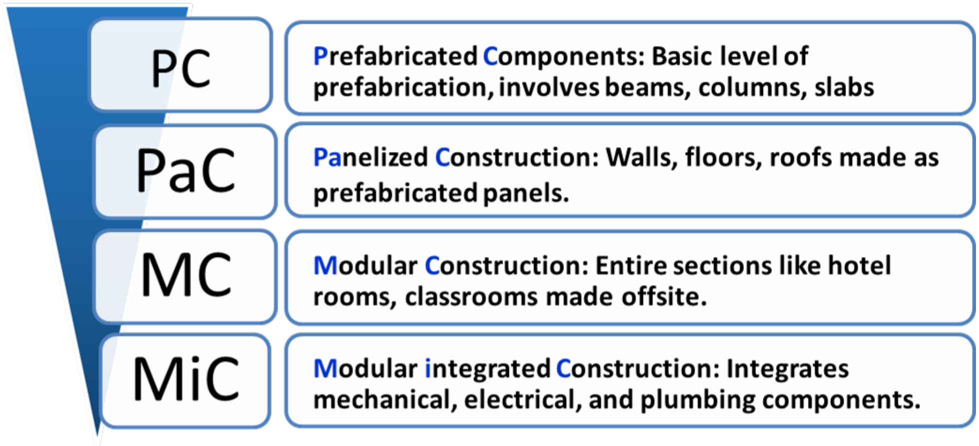

Figure 1. Progression of off-site construction techniques: evolution from basic prefabricated components to the advanced modular integrated construction (MiC).

Recent studies in MiC and construction supply chain management (CSC) have highlighted a series of significant challenges necessitating in-depth research [3,6–9]. These works underline the critical need for resilient CSC frameworks capable of mitigating impacts from disruptions, a common feature in today's dynamic construction environments [10]. Enhancing CSC resilience relies crucially on robust information sharing and collaborative efforts among all stakeholders, including suppliers, manufacturers, transporters, contractors, and project managers [6].

Advanced technologies, such as Building Information Modeling (BIM) and Internet of Things (IoT), are essential throughout the entire building lifecycle, including the design, construction, and exploitation phases [11]. BIM provides detailed digital models that enhance decision-making, coordination, and efficiency at each stage [12]. IoT complements BIM by enabling real-time data collection and communication among devices, which allows for the dynamic monitoring and control of construction processes [13]. Additionally, IoT allows for the continuous monitoring and management of building systems in the exploitation phase (e.g., energy use, environmental conditions, and equipment status), ensuring optimal performance and proactive maintenance [14]. Together, BIM and IoT support the creation of digital twins—virtual replicas of physical assets—that offer comprehensive insights and predictive analytics to optimize both construction and post-construction phases [11,13]. In the context of MiC, these technologies are particularly impactful. The detailed digital representations of BIM facilitate precise prefabrication and assembly, improving coordination and reducing errors. IoT enhances these capabilities by providing real-time data on the status and condition of components and modules during transportation and installation [15–18]. Moreover, Artificial Intelligence (AI) is recognized for its potential to significantly improve MiC operations. AI can automate complex data management tasks and improve traceability throughout the MiC supply chain, providing stakeholders with real-time visibility of logistics operations. This transparency is essential for making informed decisions quickly, improving operational efficiency and reducing delays. AI can also facilitate predictive analytics, enabling potential delays or problems to be anticipated before they occur [8].

Recent works in the literature emphasize that MiC is not only about improving efficiency and productivity but also about fostering sustainability and environmental responsibility [3]. MiC supports the principles of the circular economy by promoting resource efficiency, reducing construction waste, and enabling the reuse and recycling of building components [19]. This is achieved through design for disassembly (DfD) and the use of recycled materials, which significantly lower the environmental impact of construction projects [20,21]. By integrating circular economy strategies such as reducing, reusing, and recycling materials, MiC helps create a more sustainable and resource-efficient built environment [22]. Moreover, from a MiC supply chain perspective, optimizing components and modules logistics and adopting closed-loop supply chains can significantly minimize CO_2 emissions, as efficient transport logistics inherently reduce fuel consumption and emissions [23]. These practices align with the broader objectives of the 2030 Agenda for Sustainable Development adopted by the United Nations [24]. Despite the advancements in MiC methods, the literature reveals a notable lack of quantitative analyses concerning the cost-effectiveness and sustainability benefits of MiC [9,25]. In addition, sustainability assessments are often qualitative rather than quantitative, limiting the ability of decision-makers to make comprehensive assessments based on solid empirical data [9].

In addition to the economic and environmental considerations, the literature indicates an absence of advanced, suitable models for optimizing transport planning and supply chain configurations in the context of MiC [3,7]. In particular, there are gaps in strategies for efficiently managing the logistics of large, integrated modules requiring special handling and routing procedures. Stochastic programming appears to be a recommended method for filling these gaps [7]. This approach makes it possible to model the uncertainties and variabilities inherent in construction logistics, such as delivery delays, variable module sizes and fluctuating costs, thereby improving supply chain resilience. Moreover, the recent literature review in MiC identifies research opportunities across all phases of construction [3]. This includes the use of decision-making systems in design, and the adoption of Industry 4.0 technologies in module production for increased operational effectiveness. In module logistics, advanced models optimize the location of module fabrication centers and vehicle routes, enhancing performance while considering environmental and economical impacts. On-site, sophisticated planning models accelerate assembly and optimize project durations, demonstrating a shift towards more technologically integrated construction practices.

To address these challenges, this paper explores the potential of multi-agent simulation using AnyLogic to enhance the MiC supply chain. Multi-agent simulation offers a sophisticated approach to modeling the interactions of various agents involved in the process, such as suppliers of prefabricated components, fabrication centers for integrated modules, construction sites, and transportation vehicles [26,27]. This simulation paradigm provides a comprehensive tool for optimizing transport configurations and supply chain operations [23]. By simulating the complex behaviors and interactions within the logistics network, this approach enables the detailed analysis and optimization of MiC transport logistics. The study introduces a multi-agent-based model specifically designed to optimize transportation logistics for MiC, focusing on reducing costs and improving operational efficiency. Results from the model application demonstrate enhanced logistics performance and underscore the value of multi-agent simulation in addressing the complexities of MiC transport logistics.

Therefore, the article is structured as follows: Section 2 provides a comprehensive review of the existing literature related to MiC and simulation-based models, and examines the specific transportation challenges faced by MiC. Section 3 details the developed agent-based model and the interactions between each agent, utilizing AnyLogic to efficiently address these challenges. Section 4 analyzes the results obtained from implementing the multi-agent simulation model, focusing on Key Performance Indicators (KPIs) related to MiC transport. Finally, Section 5 concludes the paper by summarizing the key findings and discussing future research avenues and potential advancements in the MiC supply chain.

2. Related Works

This section provides an in-depth analysis of the current literature on MiC and the application of simulation models to address the transportation challenges associated with the MiC process.

2.1. Overview of Modular Integrated Construction (MiC)

As illustrated in Figure 2, the MiC process involves a series of planned steps to ensure efficiency and accuracy from design to completion [28]. The process begins with design approval and the engineering process, where the architectural design is conceptualized and refined, followed by rigorous engineering calculations to ensure structural integrity and conformity [29]. Permit applications and approvals are then required. The necessary documentation is submitted to meet local codes and standards [30]. After architectural, conceptual, and regulatory approval, the MiC process progresses to the site development and plant fabrication phase [31]. During this stage, decision-makers must carefully consider the optimal locations for these fabrication sites [32]. Key criteria for site selection include proximity to the final construction site and to the suppliers of the module components. Additionally, the size of the fabrication plant is crucial, as it influences the production rate. Accessibility is another important factor, particularly the adequacy of road networks for transporting the integrated modules to the construction site [33]. The next phase, factory production and module assembly, involves assembling the structural elements, integrating the mechanical, electrical, and plumbing (MEP) systems, and carrying out thorough quality checks. This stage is crucial, as it determines the overall quality and integrity of the modules [34]. Once the modules are ready, they are transported to the project site. Logistics are carefully planned, and the modules are transported safely and on schedule [3]. During the installation phase, the integrated modules arrive at the construction site where they are precisely assembled, and finishing touches are applied followed by a rigorous final inspection to ensure compliance with all standards. This phase requires optimal planning to ensure continuous operations. Firstly, adequate on-site storage capacity is crucial and must be aligned with the delivery schedule of the integrated modules to prevent logistical bottlenecks. Secondly, appropriate lifting and assembly resources need to be available, scaled to the size of the construction project, and designed to meet project timelines efficiently [35]. Lastly, connectivity capabilities must be robust, ensuring that all modules integrate seamlessly and function as intended once assembled, maintaining the integrity of the entire construction project. Each of these steps is crucial, requiring close coordination between the various stakeholders, ultimately resulting in an efficient construction process that takes advantage of the benefits of OSC to reduce lead times, costs, and environmental impact [28]. Furthermore, the decision-making in the MiC process is influenced by a variety of factors, ranging from logistical considerations to regulatory compliance and a skilled and experienced factory labor force. These factors are comprehensively reviewed and discussed in the review article by [34].

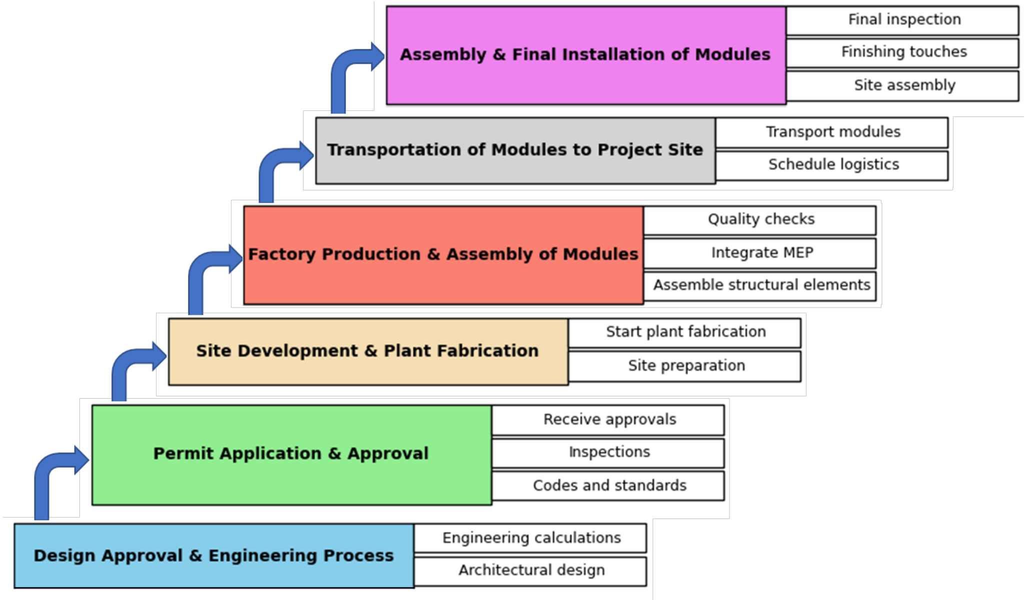

Figure 2. Steps and substeps for the modular integrated construction (MiC) process.

2.2. Simulation Applications in MiC Logistics

In the context of MiC, transporting and managing logistics presents significant challenges. These include ensuring the timely and cost-effective delivery of modules, optimizing routes to reduce transportation costs and environmental impact, coordinating large-scale prefabricated modules, and managing their transportation efficiently. Traditional logistics systems often struggle with these demands due to their inflexibility and limited adaptability to the dynamic requirements of modular construction.

Simulation techniques have emerged as crucial tools for addressing these complex logistics challenges. By leveraging simulation, researchers can model the complex interactions between all actors and stakeholders involved, including the suppliers of components, MiC manufacturers, transporters, and project managers. This modeling is essential for ensuring efficient decision-making and project execution. Three primary simulation paradigms are commonly used:

- Discrete event simulation (DES): used to model the operation of a system as a discrete sequence of events in time, effective for systems where the state changes at specific points, such as the arrival of trucks or the completion of module assembly tasks [36].
- Agent-based simulation (ABS): models the individual behaviors of agents, representing various entities in the logistics network, such as trucks, warehouses, or modules. Each agent operates based on a set of rules, and their interactions can lead to complex system behavior. This paradigm is highly suitable for capturing the dynamic and stochastic nature of MiC supply chain [23].
- System dynamics (SD): focuses on the feedback loops and time delays affecting the entire system's behavior, useful for strategic-level decision-making and long-term planning [37].

Numerous studies have addressed the challenges of logistics planning in off-site construction (OSC), including MiC. These studies have primarily addressed a single supply chain stage and have addressed issues like inventory management [38], vehicle routing [39], and integrated truck planning [40]. Some researchers have proposed optimization models that integrate various supply chain stages, such as combining production with logistics [41] and logistics with installation [42]. These integrated approaches aim to provide more holistic solutions but often ignore the uncertainties and dynamic interactions, which are critical in real-world applications. To address these limitations, some researchers have employed DES simulation [43], which allows for the modeling of complex logistics processes over time. Some studies have integrated multi-method simulation models with optimization approaches, providing a more robust framework that accounts for both dynamic interactions and stakeholder decisions [44–46]. By combining these varied approaches, the literature demonstrates significant advancements in addressing the logistical complexities of MiC supply chains. However, further research is needed to develop models that holistically integrate all stages of the supply chain while accounting for uncertainties and dynamics.

Table 1 summarizes the focus and limitations of each related study, showing how the proposed study addresses gaps in the current literature by providing a more comprehensive and integrated approach to the MiC supply chain.

Table 1. Comparison of related work.

Study	Focus	Limitations Addressed
[38]	Inventory management in OSC	Single supply chain stage, does not address dynamic interactions or uncertainties
[39]	Vehicle routing for OSC logistics	Single supply chain stage, lacks integration with other stages and consideration of real-world uncertainties
[40]	Integrated truck planning for OSC	Single supply chain stage, does not incorporate dynamic interactions between different supply chain stages
[41]	Combining production with logistics in OSC	Integrated approach, but overlooks uncertainties and dynamic interactions critical for real-world applications
[42]	Integrating logistics with installation in OSC	Holistic approach, but lacks consideration of uncertainties and stakeholder dynamics
[43]	DES simulation for OSC logistics	Models complex processes over time but does not fully integrate all supply chain stages or stakeholder dynamics
[44–46]	Multi-method simulation with optimization for MiC	Robust framework addressing dynamic interactions, but further research needed for holistic integration of all supply chain stages
This Study	Multi-agent simulation for holistic MiC logistics	Comprehensive integration of all supply chain stages, addressing dynamic interactions, uncertainties, and real-time data integration

3. Proposed Agent-Based Model

In this section, we detail the developed agent-based model. The model leverages AnyLogic's multi-agent simulation capabilities to efficiently manage and optimize the MiC process.

3.1. From Physical Process to the Multi-Agent Model

The physical process in Figure 3a begins with the suppliers who produce prefabricated components such as beams, exterior walls, and laminated boards. These components are manufactured in suppliers' plants, which are designed to handle large-scale production with high precision. Once produced, these components are transported by transporters (T_1) to the MiC factories. At these factories, the prefabricated components are assembled into integrated construction modules. This stage involves the assembly of various components into fully functional modules, including the integration of mechanical, electrical, and plumbing systems. The assembled modules are then transported by transporters (T_2) to the construction sites. Finally, at the construction site (CS), the integrated construction modules are assembled into the final structure. This on-site assembly is significantly faster than traditional construction methods, reducing overall project timelines and minimizing the impact of on-site activities.

The intermediate layer between the physical process and the multi-agent simulation model in Figure 3b is crucial for capturing real-time information and ensuring the accuracy of the simulation model. Various technologies are employed to collect and manage data:

- Inventory System: Tracks the availability and status of prefabricated components in stock at the supplier level.
- Geographic Information System (GIS) such as Global Positioning System (GPS) and Open Street Map (OSM) [47]: Provides real-time tracking of transport vehicles, ensuring efficient route planning and the timely delivery of components and modules.

- Manufacturing Execution System (MES) [48]: Manages the production process at MiC factories, integrating physical processes with automation and control systems to ensure high-quality module fabrication.
- Radio-Frequency Identification (RFID) [49]: Tracks the movement and status of components and modules throughout the supply chain.
- Building Information Modeling (BIM) [50]: Provides detailed digital representations of the construction project, enabling the precise planning and execution of the assembly operations for integrated modules.

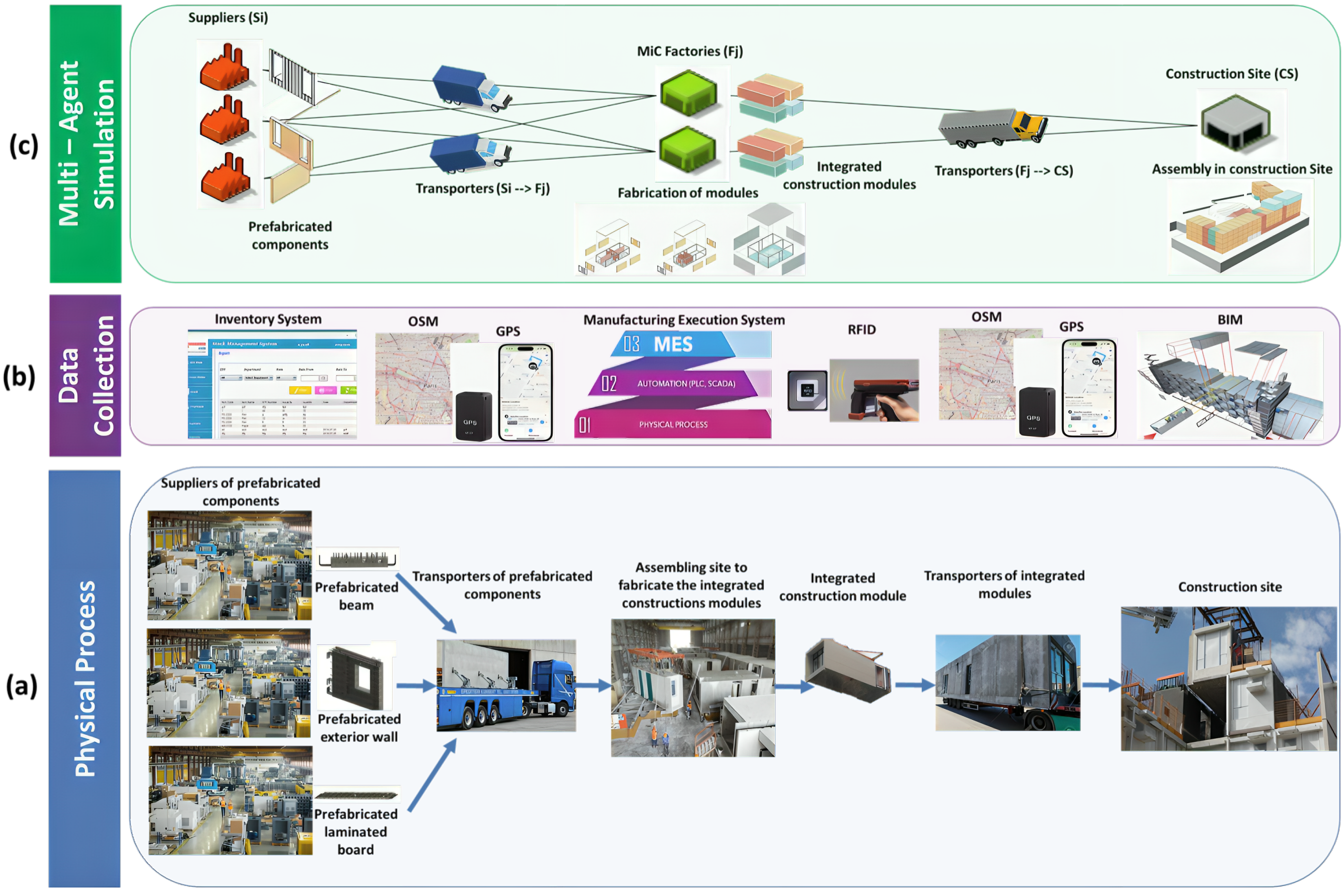

Figure 3. Integration of (**a**) physical process, (**b**) data collection, and (**c**) Multi-Agent Simulation in the MiC Supply Chain.

The multi-agent simulation model in Figure 3c uses the data collected to simulate the interactions between different agents in the MiC supply chain. Each agent represents a key entity in the supply chain, including suppliers, transporters, factories, and construction sites. The model reflects the physical processes and interactions accurately, allowing for the optimization of logistics and operational efficiency: supplier agents, transporter agents, factory agents, and construction site agent.

By accurately reflecting the physical processes and using real-time data, the multi-agent model can be extended to create a digital twin of the MiC supply chain [51]. A digital twin is a virtual representation of the physical system that can be used for real-time monitoring, predictive analysis, and decision-making.

3.2. Agent-Based Model Overview

The agent-based model developed in this study incorporates various entities involved in the MiC supply chain process. Each entity is modeled as an agent with specific behaviors and interactions. The primary agents in the model include the following:

- Suppliers (S_i): Responsible for providing prefabricated components. Each supplier agent manages the production and dispatch of components to fabrication centers (i.e., MiC factories).
- Transporters ($T_{1,k}$: S_i -> F_j and $T_{2,l}$: F_j -> CS): These agents simulate the transportation vehicles that move prefabricated components from suppliers to fabrication centers and then integrated modules from fabrication centers to construction sites.
- MiC factories (F_j): These agents represent the fabrication centers where prefabricated components are assembled into integrated construction modules.
- Construction sites (CSs): The final destination agents where the integrated modules are assembled into the final construction.

The use case diagram (see Figure 4) illustrates the interactions between various agents involved in the logistics process of MiC, ensuring that each step is clearly defined and that all agents work in coordination to achieve efficient construction logistics. Each agent performs specific functions to ensure the efficient delivery and assembly of integrated construction modules. The construction site (CS) agent initiates the process by placing orders for integrated construction modules to the MiC factories. Once the modules are fabricated and transported, the construction site agent receives and assembles them on-site. The factory (F) agent receives orders from the construction site for integrated construction modules and is responsible for fabricating the integrated modules based on these orders. To fabricate the modules, the factory agent places orders for prefabricated components to the suppliers. Once the modules are ready, the factory agent requests transportation for the modules to the construction site. The supplier (S) agent receives orders for prefabricated components from the factory. Upon receiving these orders, the supplier agent produces the required prefabricated components and then requests transportation to deliver the produced components to the MiC factories. Transporter T_1 is responsible for transporting prefabricated components from the supplier to the factory. Transporter T_2 handles the transportation of integrated modules from the factory to the construction site. Finally, the construction site (CS) receives and assembles the modules on-site, completing the construction process.

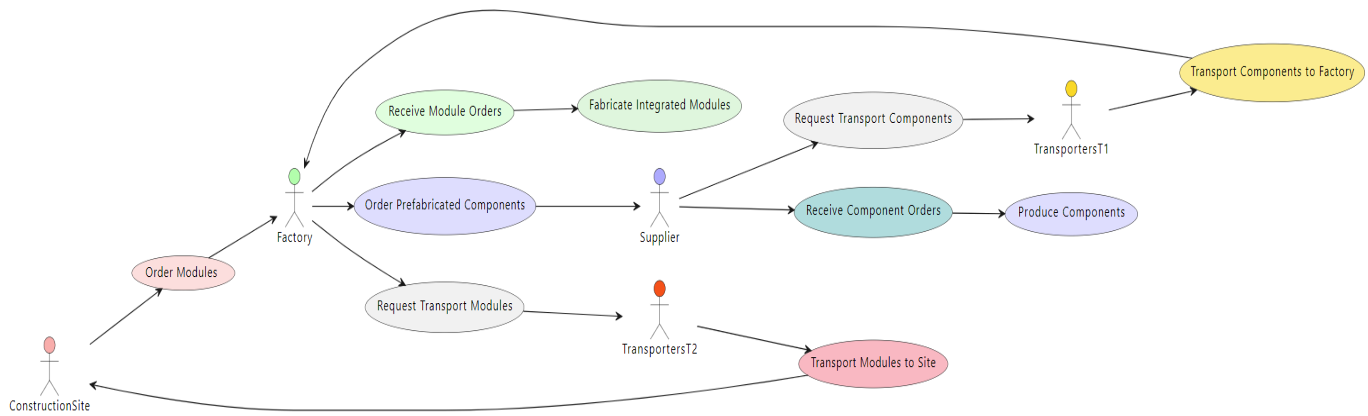

Figure 4. Multi-agent system use case diagram.

3.3. Modeling of Interactions between Agents

The interactions between different agents in the MiC supply chain are complex and require careful coordination to ensure efficiency and the timely completion of construction projects. The sequence diagram in Figure 5 illustrates a detailed view of these complex interactions, visualizing the flow of communication and activities between the various agents involved in the MiC supply chain, including the construction site, factories, suppliers, transporters T_1 and transporters T_2. It details the order and fabrication process, as well as the transport and assembly process, highlighting the communication and activities required for efficient logistics management.

The process begins with the construction site (CS) agent initiating the order for integrated construction modules from the factory (F) agent. The factory agent confirms the order and schedules the production process. To fabricate the modules, the factory agent places orders for prefabricated components with the supplier (S) agent.

Upon receiving the component orders, the supplier agent produces the required components and requests transportation from the transporter (T_1) to deliver these components to the factory. The transporter confirms the transport request, loads the components, and delivers them to the factory. Once the components arrive, the factory agent proceeds to fabricate the integrated modules.

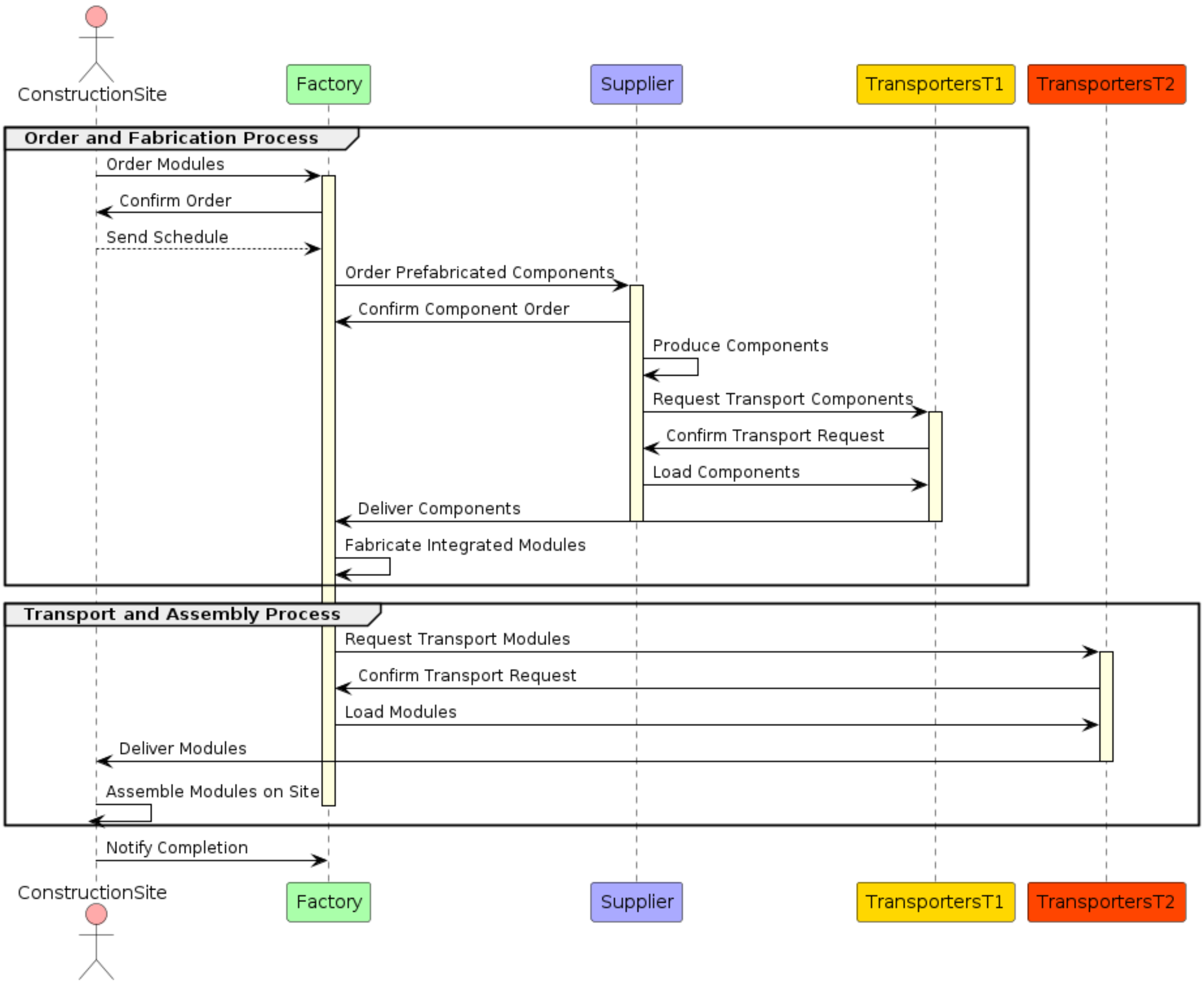

Figure 5. Sequence diagram of multi-agent system for MiC supply chain.

After the modules are fabricated, the factory agent requests transportation from the transporter (T_2) to deliver the integrated modules to the construction site. The transporter confirms the transport request, loads the modules, and delivers them to the construction site. Upon delivery, the construction site agent assembles the modules into the final structure and notifies the factory of the completion.

This sequence diagram effectively ensures that each step is clearly defined and that all agents work in coordination to achieve efficient supply chain management. The use of real-time data collected through various technologies enhances the accuracy and efficiency of the multi-agent simulation model, providing a robust framework for optimizing logistics and operational processes.

3.4. Model Implementation Using AnyLogic

In this section, we discuss the implementation of the multi-agent model in the simulation software AnyLogic 8.7.9 Personal Learning Edition (https://www.anylogic.com/, accessed on 30 May 2024).

3.4.1. Why AnyLogic?

AnyLogic is a powerful simulation software that is well suited for modeling complex systems involving multiple interacting agents, such as the MiC supply chain [23]. The choice of AnyLogic is justified by several key factors. Firstly, AnyLogic supports various simulation methods, including discrete event simulation (DES), system dynamics (SD), and agent-based modeling (ABM) [27]. This flexibility allows for the comprehensive modeling of complex systems, enabling the integration of different approaches to accurately reflect real-world processes.

Additionally, AnyLogic's robust agent-based modeling capabilities are particularly useful for simulating the interactions between different entities in the MiC supply chain. Each agent can be programmed with specific behaviors and rules, allowing for detailed and dynamic simulations of the logistics process. Moreover, AnyLogic can integrate real-time data into the simulation model, which is essential for creating an accurate and responsive digital twin of the MiC supply chain [52]. This capability ensures that the model can adapt to changing conditions and provide up-to-date insights for decision-making.

Furthermore, AnyLogic is designed to handle large-scale simulations [53], making it suitable for modeling the extensive and complex interactions within the MiC process. Its performance and scalability ensure that the model can manage the high volume of data and interactions required. AnyLogic also provides powerful visualization tools that allow users to see the simulation in action, providing valuable insights into the dynamics of the system. The ability to visualize interactions and outcomes helps in understanding the system's behavior and identifying areas for improvement. Lastly, AnyLogic can be integrated with other software and systems, such asGIS, MES, and BIM, enabling a seamless flow of information and enhancing the model's accuracy and utility [23]. This integration is crucial for creating a comprehensive and realistic simulation environment.

3.4.2. Model Implementation

The implementation of the multi-agent model using the AnyLogic 8.7.9 Personal Learning Edition involves several key steps to ensure that the simulation accurately reflects the MiC supply chain process and provides valuable insights for optimization. This section details the properties, behaviors, and parameters of each agent involved. Table 2 synthesizes these elements for each agent.

Table 2. Properties, behaviors, and parameters of each agent.

Agent	Properties and Parameters	Behaviors and Functions
Construction Site	Demand generation event based on BIM and project planning. Parameter: MiC factory associated with the demand.	Function: GenerateDemand() for integrated modules.
MiC Factory	Event to generate demand for prefabricated components from suppliers. Parameter: Supplier associated with the demand, number of vehicles assigned to transport the module.	Process: Fabrication of integrated modules (see Figure 6a). Function: FabricationTime() for module fabrication duration, GenerateDemand() to generate demand for components, ManageVehicles() to manage vehicle assignments for transportation.

Table 2. *Cont.*

Agent	Properties and Parameters	Behaviors and Functions
Supplier	Parameter: Number of vehicles assigned, capacity, ComponentsInStorage, ProductionRate.	Process: Fabrication of prefabricated components (see Figure 6b), Inventory modeling using system dynamics (see Figure 6c). Function: ProductionTime() for component production duration, ProduceComponents() to manage the production of components, ManageInventory() to manage inventory levels and storage, ScheduleTransport() to schedule transport of components to factories.
Transporter T_1	Parameter: Associated supplier and factory.	Process: State chart (see Figure 6d). Function: TransportComponents() to manage transport of components from suppliers to factories, UpdateStatus() to update transport status and availability.
Transporter T_2	Parameter: Associated factory and construction site.	Process: State chart (see Figure 6e). Functions: TransportModules() to manage transport of modules from factories to construction sites, UpdateStatus() to update transport status and availability.

Process Description for MiC Factory Agent:

The diagram in Figure 6a illustrates the process flow related to the MiC Factory agent. Each block in the diagram represents a specific step for managing orders and transporting integrated construction modules. The process begins with the "Process Order", which involves receiving orders for modules. The orders are placed in a queue, indicating that multiple orders can be managed simultaneously. The purpose of this step is to organize and prioritize incoming orders for module production and delivery. Next, the system moves to the "Wait for Module" step. After an order is processed, the system waits for the corresponding module to be ready. This includes the time required for fabricating the integrated modules in the MiC factory. The purpose of this step is to ensure that the module is fully assembled and ready for delivery. Once the module is ready, the process advances to the "Take Vehicle" bloc. In this step, a vehicle from the fleet is assigned to transport the module. This involves allocating an appropriate transport vehicle based on availability and suitability for the delivery task. Following this, the process moves to the "Delivering" step, which represents the actual transportation of the module from the MiC factory to the construction site. The module is loaded onto the vehicle and transported to its destination. After the module is delivered, the process proceeds to the "Release Vehicle" bloc. At this stage, the vehicle is released and made available for future transportation tasks. This step marks the completion of the delivery process. The final step in the process is the "Sink". This represents the stage where the order is considered complete. The purpose of this step is to close the current order loop, ensuring that the logistics process can start anew with the next set of orders. The MiC factory agent supervises the entire lifecycle of an order, from receiving the order to ensuring its delivery to the construction site.

Process Description for Supplier Agent:

The diagram in Figure 6b illustrates the process flow related to the supplier agent. The process begins with the "Process Order" step. This involves receiving and processing orders for prefabricated components. The orders are placed in a queue, indicating that multiple orders can be managed simultaneously. The purpose of this step is to organize and prioritize incoming orders for component production and delivery. Next, the system moves to the "Wait for Components" step. After an order is processed, the system waits for the corresponding components to be produced. This includes the time required for manufacturing the prefabricated components. The purpose of this step is to ensure that the components are fully produced and ready before proceeding to the next step. Once the components are ready, the process advances to the "Take Vehicle" step. In this step, a vehicle from the fleet is assigned to transport the components. This involves allocating an appropriate transport vehicle based on availability and suitability for the delivery task. Following this, the process moves to the "Delivering" step, which represents the actual transportation of the components from the supplier to the MiC factory. The components are loaded onto the vehicle and transported to their destination. After the components are delivered, the process proceeds to the "Release Vehicle" step. At this stage, the vehicle is released and made available for future transportation tasks. This step marks the completion of the delivery process. The final step in the process is the "Sink". This represents the stage where the order is considered complete, and the system is ready to handle new orders. The purpose of this step is to close the current order loop.

Storage Process in Supplier Agent:

The diagram in Figure 6c illustrates the storage process related to the supplier agent. This specific process focuses on managing the storage of prefabricated components before they are delivered to the MiC factories. The process begins with the "Production Rate" element, which controls the rate at which prefabricated components are produced. This element ensures that components are manufactured at a consistent rate. The production rate is influenced by the "Capacity" of the production facility, which defines the maximum output that the facility can handle at any given time. Once produced, the components are stored in the "Components" storage. This element represents the inventory of prefabricated components that are ready for dispatch to MiC factories. The "Components In Storage" variable tracks the number of components currently held in storage.

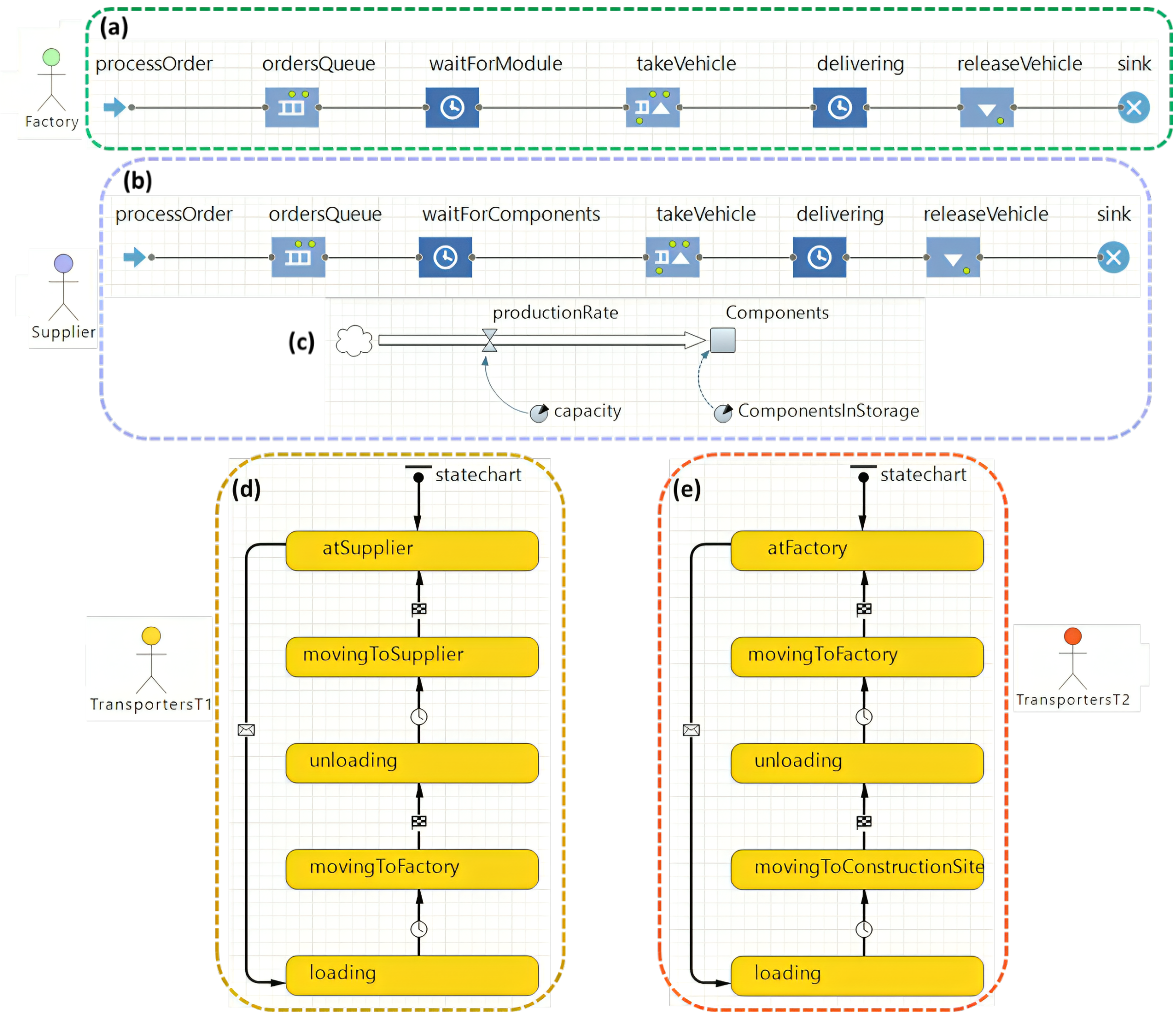

Figure 6. Process of each agent: (**a**) Fabrication of integrated modules by the MiC Factory agent, (**b**) Fabrication of prefabricated components by the Supplier agent, (**c**) Inventory process by the Supplier agent, (**d**) State chart for the transport process of the transporter T_1 agent, (**e**) State chart for the transport process of the transporter T_2 agent.

Statechart for Transporter T_1 Agent:

The statechart diagram in Figure 6d represents the various states and transitions of the transporter T_1 agent. Transporter T_1 is responsible for moving prefabricated components from suppliers to MiC factories. The initial state in the statechart marks the starting point of the process. Transporter T_1 begins in the atSupplier state, where it is initially located at the supplier's facility. In this state, transporter T_1 is waiting to receive an order and be assigned a task. Upon receiving an order, transporter T_1 transitions to the loading state. This state is triggered by a message indicating that the vehicle should load the prefabricated components. After loading the components, transporter T_1 transitions to the movingToFactory state. This state is triggered by a timeout, representing the travel time required to move from the supplier's facility to the MiC factory. Once transporter T_1 arrives at the factory, it transitions to the unloading state. This state is triggered by the arrival of the agent at the factory, where the vehicle unloads the prefabricated components. Following the unloading process, transporter T_1 moves to the movingToSupplier state. This state is also triggered by a timeout, indicating the travel time required for the vehicle to return to the supplier's location. Upon arrival at the supplier's facility, transporter T_1 transitions back to the atSupplier state. This state is triggered by the agent's arrival, marking the completion of one transportation cycle and readying the vehicle for the next order.

Statechart for Transporter T_2 Agent:

The statechart diagram in Figure 6e represents the various states and transitions of transporter T_2. This agent is responsible for moving integrated construction modules from MiC factories to construction sites. The initial state, indicated as a statechart, marks the starting point of the process. Transporter T_2 begins in the atFactory state, where it is initially located at the MiC factory. In this state, transporter T_2 is waiting to receive an order. Upon receiving an order, transporter T_2 transitions to the loading state. This state is triggered by a message indicating that the vehicle should load the integrated modules. After loading, transporter T_2 transitions to the movingToConstructionSite state. This state is triggered by a timeout, representing the travel time required to move from the MiC factory to the construction site. Once transporter T_2 arrives at the construction site, it transitions to the unloading state. This state is triggered by the arrival of the agent at the construction site, where the vehicle unloads the construction modules. Following the unloading process, transporter T_2 moves to the movingToFactory state. This state is also triggered by a timeout, indicating the travel time required for the vehicle to return to the MiC factory. Upon arrival at the factory, transporter T_2 transitions back to the atFactory state. This state is triggered by the agent's arrival, marking the completion of one transportation cycle.

Main Agent Implementation:

The Main Agent in the AnyLogic model integrates all other agents and manages the overall simulation environment which is set up to reflect the real-world logistics network, including geographical locations, transportation routes, and factory and construction site locations. A key feature of the Main Agent is the incorporation of a GIS Map, which locates all agents based on their latitude and longitude coordinates. This GIS Map uses data from the OpenStreetMap (OSM) server and is configured to utilize road types, ensuring accurate route planning and transportation simulation [54]. OSM has aimed to build a detailed, freely accessible map of the world, offering precise and constantly updated geographic data for applications like traffic information, navigation, geospatial analysis, and travel urban planning [55]. In the context of the MiC supply chain, OSM plays a significant role by providing open, collaborative mapping data that help improve operational efficiency, reduce costs, and ensure the timely and reliable deliveries of both prefabricated components and integrated modules. Using the OSM server by the transporter T_1 and T_2 agents ensures the use of open standards and compatible data formats for easier interoperability and data exchange. Moreover, by integrating sensors and IoT devices (e.g., GPS devices) for delivery, transporter T_1 and T_2 agents can send real-time data on the location, vehicle status, and environmental conditions. This information enables the effective monitoring and control of logistics operations, allowing for the anticipation of delays and disruptions, and making proactive decisions to optimize the flow of goods. For example, using IoT devices to track the location and status of transport vehicles ensures the timely deliveries of prefabricated components and integrated modules, maintaining the efficiency and reliability of the entire supply chain.

3.4.3. Model Validation

To ensure the accuracy and reliability of the multi-agent model, we conducted a comprehensive validation process. Firstly, we verified the logical correctness of the model by ensuring that each agent—suppliers, MiC factories, transporters, and the construction site—accurately represented the physical processes and interactions within the MiC supply chain. Each agent's behavior and interactions were examined to confirm they operated as intended. Additionally, we compared the model's outputs with historical data from similar MiC projects, such as the CHU Bastion De Bercy project [56], to ensure that the model's predictions aligned with real-world observations. Key Performance Indicators (KPIs) like transportation costs, project completion times, and resource utilization rates were compared and used to adjust the model parameters accordingly.

Moreover, sensitivity analysis was performed to determine how changes in the model parameters affected the outcomes. This involved varying key parameters such as the number of vehicles (see Section 4) and production rates to observe their impact on total cost and project completion time. Additionally, the model was tested under different scenarios (see Section 4) to evaluate its performance under varying conditions. The results from these scenarios were compared to ensure that the model produced reasonable and consistent outcomes across different conditions.

4. Results and Discussion

In this section, we present the results of the proposed multi-agent simulation model and provide an analysis of the findings.

4.1. Study Scenarios

To evaluate the efficiency and effectiveness of logistics in MiC, we consider two construction configurations: prefabricated component construction without MiC factories, and fully MiC process.

We chose parameters that reflect the typical mid-sized project, logistics capacities, and operational constraints encountered in the construction industry. The number of suppliers, vehicles, production capacities, and cost elements were chosen based on common practices and the literature to ensure the model's relevance and accuracy. For instance, the numbers of suppliers and vehicles were determined to capture the logistical complexity to maintain a steady flow of components to the construction site, while the cost parameters were based on standard economic considerations to reflect the financial implications of logistics decisions (e.g., https://www.truckingdive.com/ (accessed on 30 May 2024)). Additionally, incorporating stochastic elements such as vehicle speed and production rates helps simulate the variability and uncertainty inherent in real-world scenarios.

4.1.1. Scenario 1: Prefabricated Component Construction without MiC Factories

In this scenario, prefabricated components are supplied directly to the construction site by a number of suppliers. This represents traditional prefabricated construction rather than MiC. In this scenario, we consider the following parameters:

- Number of suppliers: For a mid-sized project, we assume five suppliers to provide different components such as beams, columns, slabs, and exterior panels. These components are crucial for the structural integrity of the construction.

- Number of vehicles: Each supplier uses vehicles to deliver components to the construction site, based on the typical logistics capacity required to maintain a steady flow of components. We will conduct a sensitivity analysis by varying the number of vehicles per supplier from one to five to find the optimal number that minimizes the total cost.
- Demand generation: The demand for components is deterministic and based on project management derived from BIM, with an average of 60 orders per day. This demand is influenced by the construction schedule and project planning, ensuring that the supply chain remains responsive to the dynamic needs of the construction project.
- Initial components in storage: Each supplier starts with an initial inventory between 5 and 10 components, providing a buffer to meet the immediate demand.
- Production capacity/rate: Each supplier has a stochastic production capacity, with an average of 10–15 components per day depending on the complexity and type of component, with a production rate that ensures steady output to meet the ongoing demand.
- Cost Parameters:
  - Fixed cost per vehicle per day (=EUR 150):This cost per vehicle per day is a set amount that must be paid to maintain the vehicle in the fleet, regardless of whether it is actively used for transportation on that day. It is incurred regardless of the level of activity and the distance traveled. For examples, this includes costs such as vehicle leasing or rental fees, insurance, permits, and salaries for drivers and staff.
  - Variable cost per kilometer (=EUR 2): This cost reflects the additional expenses incurred for every kilometer the vehicle travels. This includes fuel consumption, wear and tear, and other distance-dependent costs.
  - Project delay penalty per day (=EUR 500): Refers to a financial penalty that is imposed for each day a project extends beyond its scheduled completion date. For instance, if a construction project is supposed to be completed in 120 days but takes 130 days to finish, a penalty of EUR 500 will be charged for each of the 10 extra days, resulting in a total penalty of EUR 5000. This penalty is intended to incentivize timely project completion and to compensate for the additional costs and potential losses incurred due to the delay.
- Vehicle speed: The speed of the vehicles is stochastic, with an average speed of 50–70 km/h.
- Geo-locations:
  - Construction site is located in Paris, France;
  - Supplier 1 is 85 km from the construction site;
  - Supplier 2 is 130 km from the construction site;
  - Supplier 3 is 145 km from the construction site;
  - Supplier 4 is 75 km from the construction site;
  - Supplier 5 is 135 km from the construction site.
- The normal project completion time for this scenario is set at 120 days. Any delays beyond this period will incur a project delay penalty as mentioned in the cost parameters.

4.1.2. Scenario 2: Fully MiC Process

In this scenario, suppliers provide prefabricated components to MiC factories, which then supply integrated construction modules to the construction site. This configuration leverages the benefits of MiC to enhance efficiency and reduce the on-site construction time. The parameters for this scenario are as follows:

- Number of Suppliers: Similar to Scenario 1, we assume five suppliers providing different components required for the modules. This allows for a diverse range of components, ensuring that all necessary parts are available for the integrated modules.

- Number of MiC Factories: We assume one MiC factory responsible for assembling the integrated modules from the supplied components. Centralized assembly at a single factory can improve efficiency and reduce complexity in logistics.
- Number of Vehicles:
  - Transporter 1 (T_1) for components: Similar to Scenario 1, each supplier uses vehicles for transportation of prefabricated components to the factories. We will conduct a sensitivity analysis by varying the number of vehicles per supplier from one to five to find the optimal number that minimizes the total cost.
  - Transporter 2 (T_2) for modules: The MiC factory uses one vehicle for module delivery to the construction site. This is based on the need to maintain a steady flow of modules while minimizing transportation costs.
- Demand generation: The demand for components and modules is deterministic and based on project management derived from BIM, with an average of 60 component requests per day by the MiC factory and three integrated module requests per day by the construction site.
- Initial components in storage: Each supplier starts with an initial inventory between 5 and 10 components, providing a buffer to meet the immediate demand for construction components.
- Production Capacity/Rate:
  - Each supplier has a stochastic production capacity, with an average of 10–15 components per day depending on the complexity and type of component.
  - Each factory has a production capacity of three modules per day. This rate ensures a continuous supply of modules to the construction site while maintaining high-quality standards.
- Cost Parameters:
  - Fixed cost per vehicle per day: EUR 150 for T_1, EUR 200 for T_2. The higher cost for T_2 reflects the more complex logistics and handling required for transporting integrated modules.
  - Variable cost per kilometer: EUR 2 for T_1, EUR 3 for T_2. Transporting integrated modules incurs higher variable costs due to their size and weight.
  - Project delay penalty per day: EUR 500. This penalty is consistent across both scenarios, incentivizing timely project completion and compensating for potential financial losses due to delays.
- Vehicle Speed: The speed of the vehicles is stochastic, with an average speed of 50–70 km/h for T_1 and 40–60 km/h for T_2. The lower speed for T_2 reflects the additional care and slower speeds required for transporting larger, more delicate modules.
- Geo-locations:
  - Construction site is located in Paris, France;
  - MiC factory is 20 km from the construction site;
  - Supplier 1 is 70 km from the MiC factory;
  - Supplier 2 is 125 km from the MiC factory;
  - Supplier 3 is 155 km from the MiC factory;
  - Supplier 4 is 75 km from the MiC factory;
  - Supplier 5 is 125 km from the MiC factory.
- The normal project completion time for this scenario is set at 120 days. Any delays beyond this period will incur a project delay penalty.

Table 3 provides a summary of the parameters for both scenarios.

Table 3. Summary of parameters for study scenarios.

Parameter	Scenario 1	Scenario 2	Unit
Number of Suppliers	5	5	-
Number of MiC Factories	-	1	-
Number of Vehicles (T_1) per Supplier	[1, 2, 3, 4, 5]	[1, 2, 3, 4, 5]	-
Number of Vehicles (T_2) per Factory	-	1	-
Average Requests per Day	60 C by the construction site	60 C by the MiC Factory, 3 M by the construction site	C: Components, M: Modules
Fixed Cost per Vehicle per Day	150	150 for T_1, 200 for T_2	EUR
Variable Cost per km	2	2 for T_1, 3 for T_2	EUR
Project Delay Penalty per Day	500	500	EUR
Initial Components In Storage per supplier	uniform(5, 10)	uniform(5, 10)	Components
Production Capacity per Day	uniform(10, 15) C per supplier	uniform(10, 15) C per supplier, 3 M per factory	C: Components, M: Modules
Vehicle Speed	uniform(50, 70)	uniform(50, 70) for T_1, uniform(40, 60) for T_2	km/h
Supplier Locations (from the construction site)	Supplier 1: 85, Supplier 2: 130, Supplier 3: 145, Supplier 4: 75, Supplier 5: 135	Supplier 1: 85, Supplier 2: 130, Supplier 3: 145, Supplier 4: 75, Supplier 5: 135	km
Supplier Locations (from the MiC factory)	-	Supplier 1: 70, Supplier 2: 125, Supplier 3: 155, Supplier 4: 75, Supplier 5: 125	km
MiC Factory Location (from the construction site)	-	20	km
Construction Site Location	Paris, France		-
Normal Project Completion Time	120		days

4.2. Results

In this section, we introduce the Key Performance Indicators (KPIs) used to evaluate the logistics performance in each scenario. The KPIs considered are total variable cost, total fixed cost, total penalty, and total cost. We will also present the results of the simulations for both scenarios.

Total variable cost (CV): This cost is calculated using the following formula:

$$\begin{aligned} \text{CV} = &(\text{Total distance traveled by all vehicles of } T_1 \times \text{Variable cost per km for } T_1) \\ &+ (\text{Total distance traveled by all vehicles of } T_2 \times \text{Variable cost per km for } T_2) \end{aligned} \quad (1)$$

Total fixed cost (CF): This cost is calculated as follows:

$$\begin{aligned} \text{CF} = &(\text{Number of days to transport all components by } T_1 \times \text{Fixed cost per day per vehicle for } T_1 \\ &\times \text{Number of vehicles } T_1 \text{ used by all suppliers}) + (\text{Number of days to transport all modules by } T_2 \\ &\times \text{Fixed cost per day per vehicle for } T_2 \times \text{Number of vehicles } T_2 \text{ used by all MiC factories}) \end{aligned} \quad (2)$$

Total penalty (P): This is the financial penalty imposed for each delay day to complete the project. It is calculated as follows:

$$\text{P} = \text{Number of delay days to complete the project} \times \text{Project delay penalty per day} \quad (3)$$

Total cost (CT): This is the sum of the total variable cost, total fixed cost, and total penalty:

$$\text{CT} = \text{CV} + \text{CF} + \text{P}$$

4.2.1. Results of Scenario 1

In this scenario, prefabricated components are supplied directly to the construction site by five suppliers. Figure 7 presents the GIS map from AnyLogic's simulation showing the locations of each supplier and construction site.

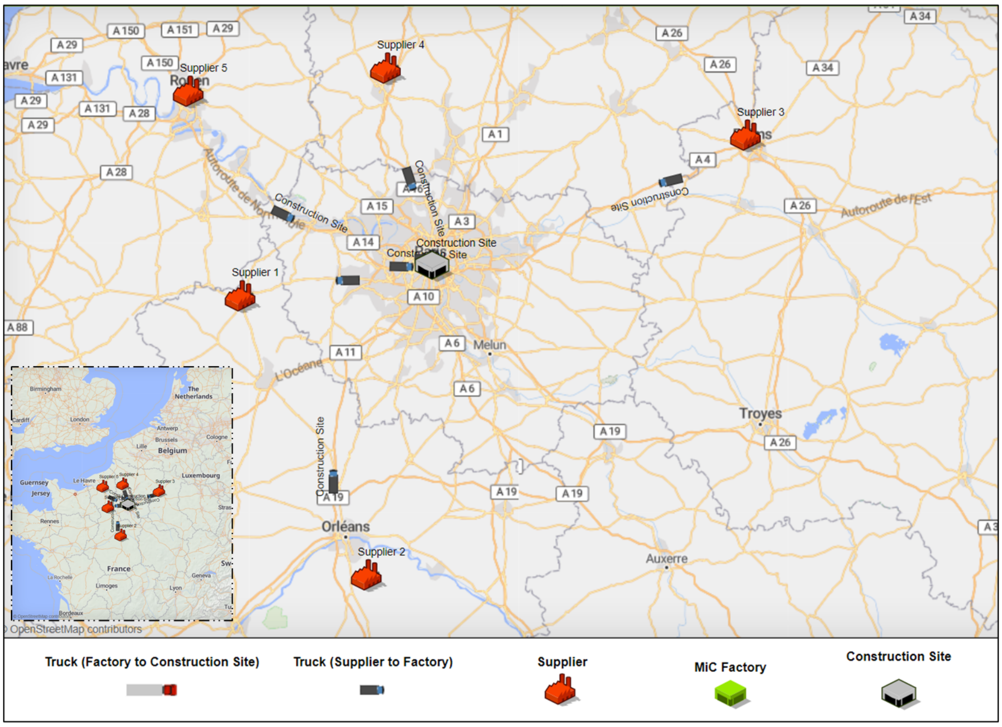

Figure 7. Scenario 1: locations of each supplier and construction site.

The results for Scenario 1 are presented in Table 4.

In Scenario 1, we analyze the costs associated with the delivery of prefabricated components. Table 4 shows how the total cost varies with the number of vehicles used by each supplier.

Table 4. Results of Scenario 1.

Number of Vehicles per Supplier	Total Variable Cost (EUR)	Total Fixed Cost (EUR)	Penalty (EUR)	Total Cost (EUR)
1	1,938,540	237,000	98,000	2,273,540
2	1,938,540	238,500	19,500	2,196,540
3	1,938,540	238,500	0	2,177,040
4	1,938,540	258,000	0	2,196,540
5	1,938,540	322,500	0	2,261,040

The variable cost remains constant at EUR 1,938,540 across all configurations. This indicates that the total distance traveled by all vehicles does not change with the number of vehicles, suggesting a stable demand and consistent routing efficiency.

The fixed cost increases with the number of vehicles. For instance, with one vehicle per supplier, the total fixed cost is EUR 237,000, which rises to EUR 322,500 when five vehicles are used per supplier.

Penalties are incurred due to project delays. When only one vehicle per supplier is used, the delay costs EUR 98,000, reflecting significant delays. As the number of vehicles increases, the penalty decreases, eventually reaching zero when three or more vehicles are used. This demonstrates that having more vehicles reduces the likelihood of project delays, ensuring the timely delivery of components.

The optimal number of vehicles appears to be three, as this configuration has the lowest total cost of EUR 2,177,040, with no penalty costs and balanced fixed costs. Adding more vehicles increases the fixed costs without further reducing penalties, leading to higher total costs.

4.2.2. Results of Scenario 2

In this scenario, suppliers provide prefabricated components to MiC factories, which then supply integrated construction modules to the construction site. Figure 8 presents the GIS map from AnyLogic's simulation showing the locations of each supplier, MiC factory, and construction site.

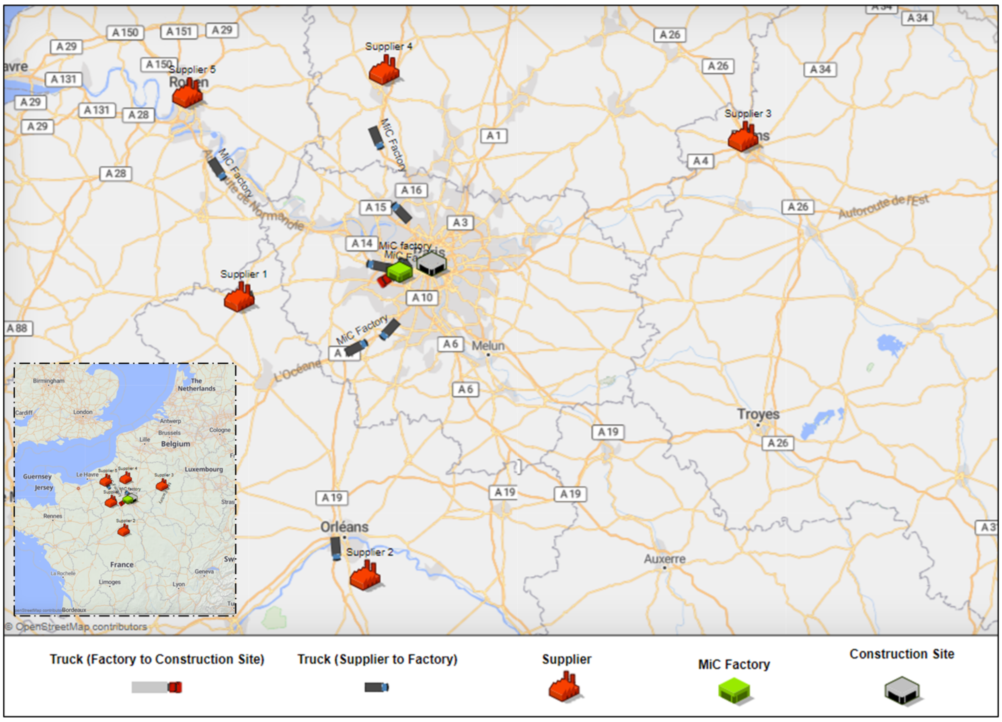

Figure 8. Scenario 2: locations of each supplier, MiC factory, and construction site.

The results for Scenario 2 are presented in Table 5.

Table 5. Results for Scenario 2.

Number of Vehicles per Supplier	Total Variable Cost for T_1 (EUR)	Total Variable Cost for T_2 (EUR)	Total Fixed Cost for T_1 (EUR)	Total Fixed Cost for T_2 (EUR)	Penalty (EUR)	Total Cost (EUR)
1	1,870,500	43,320	220,500	58,800	87,000	2,280,120
2	1,870,500	43,320	220,500	29,400	13,500	2,177,220
3	1,870,500	43,320	220,500	19,600	0	2,153,920
4	1,870,500	43,320	258,000	17,200	0	2,189,020
5	1,870,500	43,320	322,500	17,200	0	2,253,520

In Scenario 2, we analyze the costs associated with the delivery of prefabricated components to the MiC factory and the subsequent delivery of integrated construction modules from the factory to the construction site. Table 5 shows how the total cost varies with the number of vehicles used by each supplier.

The total variable cost includes the variable costs for both T_1 and T_2. For example, with one vehicle per supplier, the variable cost for T_1 is EUR 1,870,500, and for T_2, it is EUR 43,320. This cost remains stable for T_1 and T_2 across all configurations, indicating consistent routing efficiency.

The fixed cost comprises the fixed costs for both T_1 and T_2. As the number of vehicles T_1 increases, the total fixed cost for T_1 rises from EUR 220,500 to EUR 322,500, and the reverse with respect to fixed costs for T_2, which varies between EUR 58,800 and EUR 17,200, because in all configurations, we use one T_2 vehicle, and so the fixed costs depend only on days of use of this vehicle.

Related to penalties, with 1 vehicle per supplier, the delay costs EUR 87,000, reflecting significant delays. As the number of vehicles increases, the penalty decreases, eventually reaching zero when three or more vehicles by each supplier are used.

The optimal number of vehicles appears to be three, as this configuration has the lowest total cost of EUR 2,153,920.

4.3. Discussion

In this section, we compare the results obtained for the two scenarios. The analysis of the results as shown in Figure 9 from both scenarios highlights several key points.

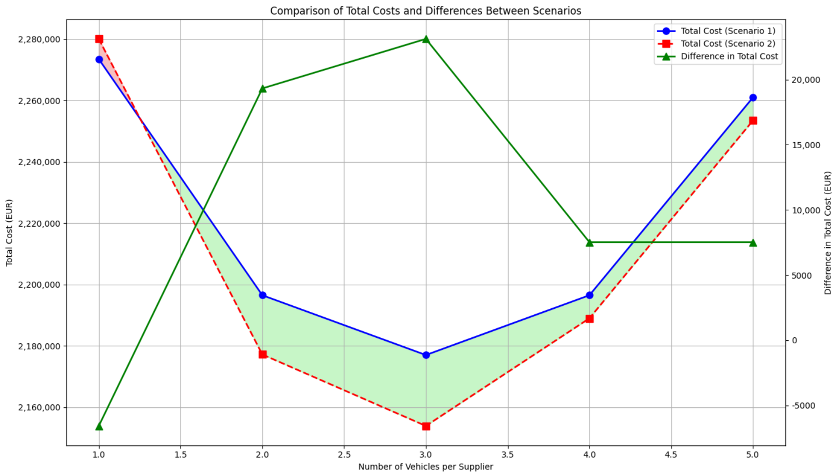

Figure 9. Comparison of the total costs for different numbers of vehicles per supplier.

In both scenarios, the total cost initially decreases as the number of vehicles per supplier increases, reaching a minimum at three vehicles per supplier. Beyond this point, further increasing the number of vehicles leads to higher total costs. This trend suggests that there is an optimal number of vehicles for each supplier that balances the fixed and variable costs while minimizing penalties. Using three vehicles per supplier is the optimal configuration. This setup achieves the lowest total cost by eliminating penalties. This result underscores the importance of optimizing the number of logistical resources to ensure cost efficiency and timely project completion. This finding aligns with the work of [57], which highlights the significance of optimal vehicle allocation in prefabricated construction logistics. Their study demonstrates that an automated approach to vehicle allocation can substantially reduce the transportation costs associated with inefficient vehicle use.

Moreover, we can observe that Scenario 2 with the fully MiC process generally results in lower total costs compared to Scenario 1 across various vehicle configurations. This indicates that the MiC approach offers better cost savings due to centralized assembly and optimized transportation logistics. This finding aligns with the results of comparative studies which highlight that modular construction can lead to a 10–25% decrease in construction costs. One of the primary factors contributing to these cost savings is reduced material transportation, as components are produced off-site and then assembled on-site, leading to more efficient logistics and lower overall expenses [58].

On the other side, the presence of penalties significantly affects the total cost when the number of vehicles is insufficient to meet demand promptly. In both scenarios, configurations with fewer than three vehicles per supplier incur penalties, which substantially increase the total cost. This highlights the critical impact of ensuring adequate logistical capacity to avoid project delays. This observation is consistent with findings in the literature, which identify poor supply chain capacity, including delays in the delivery of modular components, as critical risk factors that can derail the success of MiC projects [59].

A notable observation is that the difference in total costs between the two scenarios becomes constant beyond the optimal number of vehicles. This phenomenon can be attributed to several factors. Once the number of vehicles per supplier reaches the optimal point of three vehicles, penalties for delays are eliminated in both scenarios. This means that any additional vehicles do not contribute to reducing penalties further, as there are no penalties left to reduce. Furthermore, the variable costs, which depend on the distance traveled and the number of trips, stabilize once the logistics operations reach optimal efficiency. Both scenarios achieve a similar level of efficiency in terms of transportation distance and frequency, leading to a constant difference in variable costs. Additionally, beyond the optimal point, the additional fixed costs of deploying more vehicles dominate the total cost structure. These fixed costs are similar in both scenarios, leading to a constant difference in total costs. The fixed costs per vehicle per day become the primary factor of increased costs, and since they are applied uniformly across both scenarios, the difference remains constant.

The findings from this study provide valuable insights for construction project managers and logistics planners in the MiC industry. Understanding the optimal number of vehicles per supplier helps in making informed decisions about resource allocation, ultimately leading to cost savings and timely project completion. The comparison between Scenario 1 and Scenario 2 demonstrates the potential cost-efficiency benefits of adopting MiC over prefabricated component construction [58]. The centralized assembly in MiC allows for more efficient transportation logistics, reducing the total cost [60]. While the MiC approach shows significant advantages, Scenario 1 may still be preferable for projects with simpler logistics requirements and fewer components.

4.4. Limitations and Future Research Directions

While this study offers valuable insights, several limitations must be acknowledged. The model assumes a fixed demand for both modules and components, which does not fully capture the variability and uncertainty present in real-world scenarios. Additionally, it does not consider real-time traffic data or weather conditions, both of which significantly impact transportation logistics. Ignoring these elements can lead to less accurate simulations and suboptimal logistical planning. Also, in this model, we have not taken into account multi-modal transport (e.g., train, air, river and sea, and vehicles) which could optimize logistics. Furthermore, the current model does not evaluate the environmental impact of different scenarios, thus ignoring important sustainability factors such as carbon emissions and energy consumption. Lastly, the simulation is based on a specific geographic area, which may not be representative of other regions with different logistical challenges, regulatory environments, and infrastructure conditions.

Building on the insights gained from this study, several avenues for future research and practical advancements in the MiC supply chain can be identified. Future studies should incorporate real-time traffic data, weather conditions, and dynamic demand variations to enhance the accuracy and responsiveness of logistics models. Leveraging real-time information can help anticipate and mitigate disruptions, ensuring smoother supply chain operations. Additionally, incorporating environmental impact assessments into the logistics models can provide a more holistic evaluation of the benefits of MiC. Moreover, utilizing advanced optimization techniques, such as machine learning algorithms and genetic algorithms, can further refine logistics planning. These methods can identify the most efficient routes, schedules, and resource allocations under various constraints and uncertainties. The integration of IoT and blockchain technologies can enhance transparency, traceability, and coordination among stakeholders. IoT devices can provide the real-time tracking and monitoring of logistics operations, while blockchain can ensure secure and immutable data sharing across the supply chain. Finally, developing digital twin models of the MiC supply chain can enable real-time simulation and predictive analytics. Digital twins can provide a virtual replica of the physical supply chain, allowing stakeholders to test different scenarios, optimize processes, and make informed decisions.

5. Conclusions

This study has explored the MiC supply chain through a multi-agent simulation approach, comparing it with prefabricated component construction. The findings highlight the significant cost-efficiency benefits of MiC, driven by centralized assembly and optimized transportation logistics. Specifically, the analysis reveals that using three vehicles per supplier is the optimal configuration, in relation to the considered case study, minimizing total costs by balancing fixed and variable costs while eliminating penalties for project delays. The comparison between the two scenarios underscores the superior performance of MiC in terms of cost savings and operational efficiency. The centralized nature of MiC facilitates streamlined logistics, reducing transportation complexity, and ensuring the timely delivery of integrated modules. This advantage is critical in mitigating project delays and associated penalties, which significantly impact overall project costs.

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Abbreviations

The following abbreviations are used in this manuscript:

CSC	Construction Supply Chain
OSC	Off-Site Construction
PC	Prefabricated Components
MC	Modular Construction
MiC	Modular Integrated Construction
DES	Discrete Event Simulation
SD	System Dynamics
ABM	Agent-Based Modeling
OSM	OpenStreetMap
BIM	Building Information Modeling
IoT	Internet of Things
S	Set of suppliers to produce the prefabricated components of modules, indexed by i
F	Set of MiC factories to fabricate the integrated modules, indexed by j
T_1	Set of transporters from suppliers to MiC factories, indexed by k
T_2	Set of transporters from MiC factories to the construction site, indexed by l
CS	Final construction site

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