Simulation-based Integrated Transportation Planning in Panelized Construction

Ahmed Zaalouk [1], Mohammed Sadiq Altaf [2] and SangHyeok Han [3]

[1] Ph.D. Candidate, Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, QC, Canada.
[2] Technical Supervisor, ACQBUILT Inc., 4303 55 Ave NW, Edmonton, AB, T6B 3S8, Canada.
[3] Associate Professor and Co-Director, Centre for Innovation in Construction and Infrastructure Engineering and Management (CICIEM), Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, QC, Canada.
Email: ahmed.zaalouk@concordia.ca, sadiq@promiserobotics.com, sanghyeok.han@concordia.ca

Abstract –

Panelized construction is an offsite construction approach that offers enhanced design flexibility and cost-effective assembly. Despite these advantages, it faces challenges due to a fragmented supply chain (SC) and transportation coordination issues that can lead to cost overruns and schedule delays. To address these challenges, this study introduces a transportation planning method that leverages Just-In-Time principles and hybrid multi-agent simulation to align factory and onsite operations across multiple projects through integrated transportation procedures. These procedures categorize SC flows into: (1) a dispatching flow, which manages trailer loading and dispatch readiness; and (2) a reverse flow, which ensures the timely retrieval of empty trailers to maintain continuous production. These flows form the core of an innovative resource coordination strategy that dynamically allocates resources, including trailers and trucks, to ensure an uninterrupted supply of panels from factory to sites. The validation results using operational data from a residential panel manufacturer illustrate the model's effectiveness in coordinating SC operations and resources. The model successfully adapts to fluctuating onsite demands and aligns transportation operations with delivery dates, matching real operational timelines. The model also manages limited production capacities efficiently and ensures precise trailer dispatch, effective truck assignments, and timely retrievals of empty trailers from different sites. The proposed simulation-based planning model provides an integrated and automated solution to improve SC performance, supporting efficient multi-production lines and multi-project operations in panelized construction.

Keywords –

Offsite Construction; Panelized Construction; Supply Chain Management; Integrated Transportation Planning; Hybrid Simulation Model; Agent-Based Modeling; Discrete-event Simulation; Just-In-Time Delivery.

1 Introduction

In panelized construction, floor, wall, and roof panels are produced in a factory-controlled environment and then transported to project sites for final assembly [1]. This approach provides several advantages compared to volumetric modular construction, such as easier handling of prefabricated components (since the components are smaller and lighter), a higher degree design flexibility, and reduced crane capacity required for onsite assembly [2]. However, the adoption of panelized construction faces challenges with respect to supply chain management (SCM), integrated planning, transportation logistics, and storage constraints (both at the factory and on site). These issues can disrupt the coordination between production, transportation, and onsite assembly, leading to increased project costs and extended schedules [1–3]. To address these challenges, efficient transportation planning is essential. Transportation planning facilitates the integration of factory production lines with project sites and manages the delivery of loaded trailers to sites and the return of empty trailers to the factory (i.e., distribution and reverse logistics). The transportation process bridges factory and onsite operations by ensuring the timely delivery of panels to project sites—a vital function for maintaining the continuous progress of onsite activities. Disruptions in transportation operations, such as delays in trailer distribution or inefficiencies in reverse logistics, can lead to idle resources and delays in onsite schedules. Moreover, factory production may be interrupted due to the unavailability of empty trailers (which are needed for loading manufactured panels). Thus, effective transportation planning is crucial for minimizing supply chain (SC) operational time and costs while enhancing the performance of both factory and project site operations.

Studies on offsite construction (OSC) transportation planning and logistics have primarily focused on individual aspects of the SC, often addressing either factory operations or construction site requirements [4,5]. While some studies have considered integrated planning [6], these have not accounted for the unique transportation challenges in panelized construction, particularly the coordination of individual panels produced in multiple production lines, the various trailer types, operational-level planning of SC tasks, and just-in-time (JIT) delivery (as opposed to using intermediate storage space between factory and site).

Existing studies have explored methods for optimizing transportation in OSC contexts such as ready-mixed concrete, precast components, and modular construction [7–10]. These works have addressed diverse topics related to transportation planning in OSC, including optimal vehicle routing and the development of stacking plans [11,12]. However, the unique needs of panelized construction, such as integrating distribution and reverse logistics and the treatment of trucks and trailers as separate units performing distinct tasks, have not been accommodated in these studies.

These limitations highlight the following critical gaps in the literature: (1) existing studies have not considered the needs of factory and project sites simultaneously, which is essential for integrated SC operational performance; (2) reverse logistics, a key component of panelized construction, has not received adequate attention (with this gap resulting in inefficiencies in trailer utilization and delays in production schedules, ultimately disrupting the SC flow); and (3) existing studies have typically assumed the availability of sufficient onsite storage, which is unrealistic for panelized construction projects (in which, ideally, JIT delivery is employed to address limited space and assembly sequencing requirements). Additionally, prior studies, such as Hsu et al. (2018) [6], have focused on truck-based transportation planning while overlooking the need to manage trailers separately from trucks (which, in turn, introduces additional coordination challenges, as trailers have distinct dispatching and returning operations that directly affect SC efficiency).

To address these gaps, the present study develops an integrated transportation planning framework tailored to panelized construction. The aim underlying the framework development is to coordinate factory production with onsite requirements, ensuring efficient trailer distribution and return operations while minimizing idle time for both transportation fleets and construction resources. Unlike previous approaches, this framework encompasses trailer prioritization based on onsite assembly sequencing and crane availability, ensuring efficient resource allocation and uninterrupted SC flow. By aligning transportation operations with factory production and onsite requirements, the proposed framework enhances SC performance, reduces project delays, and improves overall SCM efficiency.

2 Methodology

As illustrated in Figure 1, the proposed framework consists of the following four steps: (1) define SC operational objectives and constraints; (2) develop integrated transportation procedures; (3) design and build the simulation model; and (4) conduct model validation and output evaluation. The first step identifies goals such as synchronizing factory production with onsite schedules and minimizing delays, inventory, and inefficiencies. In the second step, a dispatching flow is established to ensure timely trailer loading and dispatch based on onsite requirements, along with a reverse flow for the efficient retrieval of empty trailers as a means of maintaining production continuity. In the third step, Agent-based Modeling (ABM) is implemented in the simulation model to represent factory production lines, trailers, trucks, and onsite operations. Moreover, discrete-event simulation (DES) is used to model workflows inside the agents, and GIS integration is used as a shared agent environment, facilitating resource agent movement (e.g., truck movement) within the SC. The model incorporates a GIS city map, enabling agents to navigate SC locations—factory and project sites—positioned using geographic coordinates. Agents move along transportation routes, with travel times determined based on real distances, speed limits, and road network constraints. This GIS functionality supports route selection and scheduling by incorporating distance-based travel times and automatically determining the shortest route for transportation resources, ensuring a realistic representation of transportation planning. Finally, the robustness and accuracy of the model are ensured through verification using artificial datasets and validation using real operational data to evaluate JIT adherence, resource utilization and efficiency, operations timelines, and synchronized SC performance.

To efficiently integrate transportation operations with other SC activities involved in the production and onsite assembly stages, integrated transportation procedures for SCM in panelized construction are first developed. These procedures constitute a systematic approach to managing a multi-unit fleet of trucks and trailers during a typical working day. This approach also defines critical decision points such as trailer prioritization, onsite sequence checks, and operational constraints (e.g., panel delivery dates, truck availability). Unlike traditional truck-based approaches, this method treats trailers as independent transportation units requiring distinct dispatching and returning operations. By dynamically prioritizing trailer dispatch based on onsite assembly sequencing and crane availability, the method enhances resource utilization and minimizes SC waste (i.e., resource idle time). By aligning transportation with production and onsite demands, these procedures ensure adherence to JIT delivery principles.

Figure 2 presents the developed pseudocode, which captures these transportation procedures in detail through two primary flows-dispatching flow and reverse flow.

(1) Dispatching flow—managing the fleet by checking loaded trailer availability and panel delivery dates, prioritizing trailers that contain panels required earlier in the onsite sequence, and ensuring trailers are assigned to sites with idle cranes to reduce waiting times. This trailer prioritization strategy prevents bottlenecks and ensures cranes remain productive, improving overall SC performance. Dispatching flow also assigns trucks for dispatch, and verifies sequence readiness at the site before delivery. Once dispatched, trucks deliver the loaded trailers to the project site and return to the factory for subsequent tasks.

(2) Reverse flow—retrieving empty trailers during a truck's return from dispatch or through an independent retrieval process triggered when the factory's trailer buffer falls below a threshold. This mechanism prevents production disruptions from trailer shortages and maintains fleet circulation, enhancing SC efficiency.

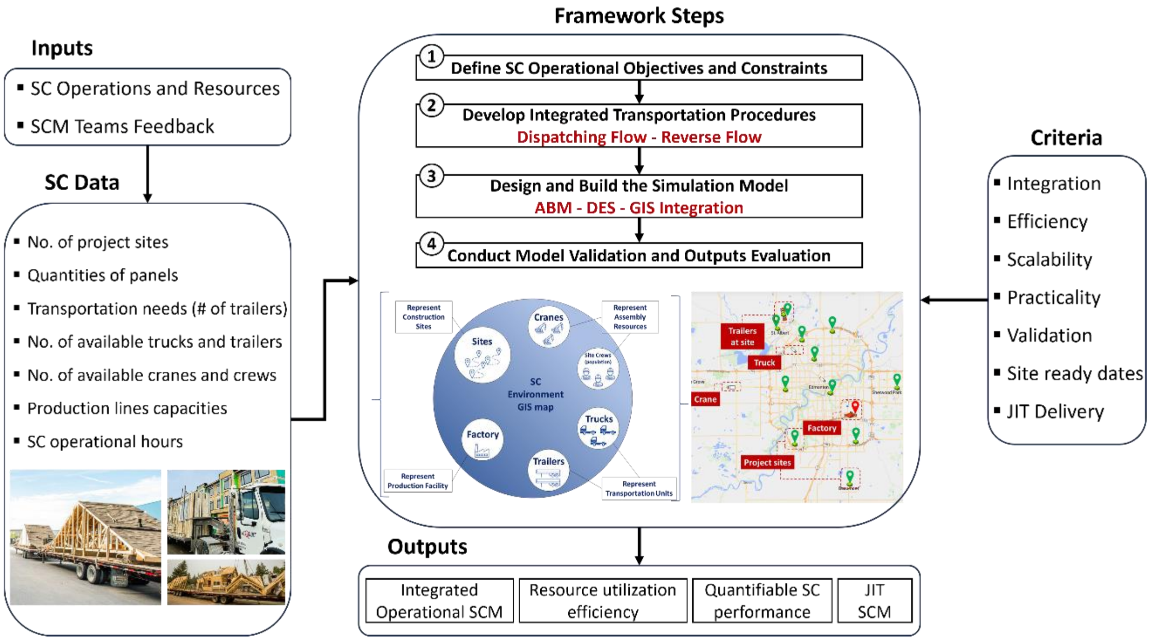

Figure 1. Overview of the research framework

The developed transportation procedures serve as the foundation for the development of the simulation's governing logic, ensuring seamless coordination between factory, transportation, and onsite operations. The simulation model integrates SC operations by leveraging ABM and DES to plan transportation-oriented panelized construction processes. This simulation models SC resources and entities as agents communicating and executing tasks based on specific production and logistics requirements within a predefined planning period. Figure 3 presents a sequence diagram illustrating the interactions among key agents: (1) the factory, which processes production and logistics requests, assigns production lines, manages trailers, trucks, cranes, and crews, and dynamically coordinates both dispatching and reverse flows; (2) the project site, which generates logistics requests, monitors deliveries, completes the onsite assembly, and manages the marking and release of empty trailers for retrieval; (3) trailer and truck, which facilitate the transportation of panels to project sites and the retrieval of empty trailers to the factory; and (4) crane and crew, which execute onsite tasks synchronized with production and transportation progress.

The simulation model outlines two primary transportation operations: (i) dispatching operations, initiated when production is completed, panels are loaded into trailers, and the panel delivery date comes due (based on the simulation time); and (ii) returning operations, activated post-onsite assembly, where trailers are marked as empty, and the factory assigns trucks for retrieval. In the developed simulation model, the factory agent plays a pivotal role in managing logistics operations to ensure the completion of all SC activities. The factory agent receives production requests (i.e., information about the quantities of panels and the location of the delivery site) and logistics requests (i.e., information about the crane type required and the number of crews) from project site agents. Based on these requests, the factory agent ensures the assignment of cranes and crews before establishing any dispatching to sites.

The factory agent processes the requests received using DES models that depict production lines and logistics workflows. These DES models actively communicate with truck and trailer agents by monitoring the behavior charts (i.e., statecharts) that show their operational status within the SC. Figure 4 illustrates the statecharts of trucks and trailers, depicting their state transitions during key operations such as loading, dispatching, and returning. These charts detail the interactions and transitions for trucks and trailers, and they are dynamically updated as the simulation progresses. Trailers progress through three primary states: (i) (AtFactory), representing empty trailers available for loading; (ii) (TrailerLoaded), indicating trailers loaded and delivered to construction sites; and (iii) (TrailerUnLoaded), referring to trailers that have completed their deliveries and are awaiting return to the factory. To minimize delays and support uninterrupted production, the factory agent ensures the prompt return of trailers, following the reverse flow procedures outlined in Figure 2.

Similarly, trucks transition between two states: (i) (TruckAvailable), indicating readiness for new transport assignments; and (ii) (TruckUnavailable), signifying active dispatch or return operations. By incorporating the transportation procedures, agent requirements, and statecharts reflecting resource operational conditions, the simulation achieves seamless and efficient transportation cycles throughout the planning horizon.

```
# Pseudocode: Integrated Transportation Procedures

# Dispatching Flow
START
WHILE working_day_active:
    IF loaded_trailers_available AND panel_delivery_date_is_due:  # Check if trailers and dates are aligned
        IF several_trailers_in_yard:  # Decision point for prioritizing trailers
            prioritize_loaded_trailers

        IF truck_available:  # Availability check for truck
            capture_truck
            select_trailer_for_dispatch_based_on_priority_rules
            IF previous_trailers_in_sequence_on_site:  # Ensure sequence is complete
                connect_trailer_and_move_to_site
            ELSE:
                wait_for_sequence

            disconnect_truck_at_site
            return_truck_to_factory  # Reverse flow logic applies during return
        ELSE:
            wait_for_truck
    ELSE:
        trailers_wait_in_yard

# Reverse Flow
    # During Dispatch
    IF empty_trailers_needed_at_factory AND truck_is_returning:  # During truck return, check for empty trailers
        IF empty_trailer_at_site after delivery:
            connect_trailer_to_truck_and_move_to_factory
            release_truck_and_trailer_at_factory
        ELSE:
            check_other_sites_for_empty_trailers
            IF empty_trailer_found:
                move_truck_to_nearest_site_and_connect_trailer_to_truck
                move_truck_to_factory
                release_truck_and_trailer_at_factory

    # If Factory Runs Out of Trailers
    # For when dispatching is done, and trailers are still needed at the factory.
    IF factory_trailer_buffer_below_threshold:  # Independent retrieval when factory is short on trailers
        check_sites_for_empty_trailers
        IF empty_trailer_found:
            capture_truck
            move_truck_to_nearest_site_and_connect_trailer_to_truck
            move_truck_to_factory
            release_truck_and_trailer_at_factory

    # End Conditions
    IF all_trailers_returned OR end_of_working_day:  # Conclude operations if no further tasks remain
        END
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Figure 2. Pseudocode for integrated transportation procedures in panelized construction

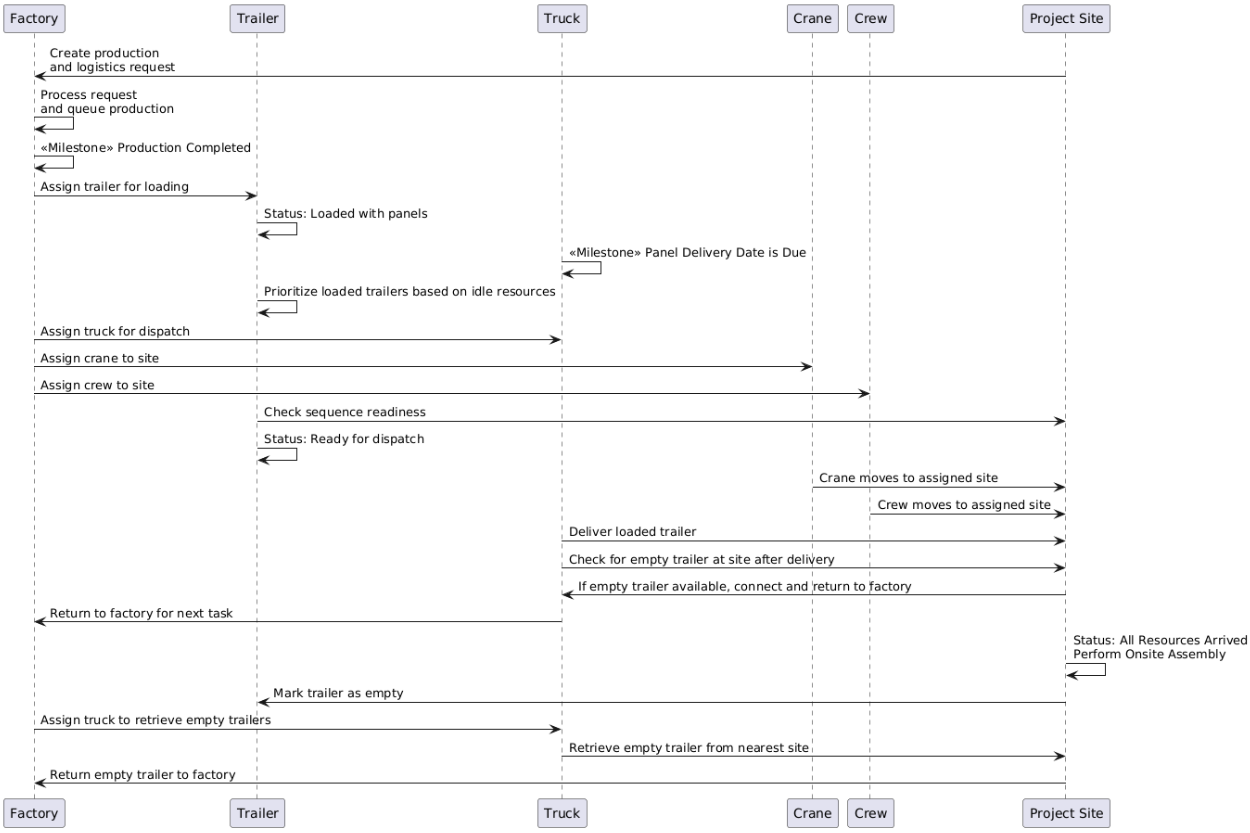

Figure 3. Sequence diagram of agent interactions in integrated SC operations

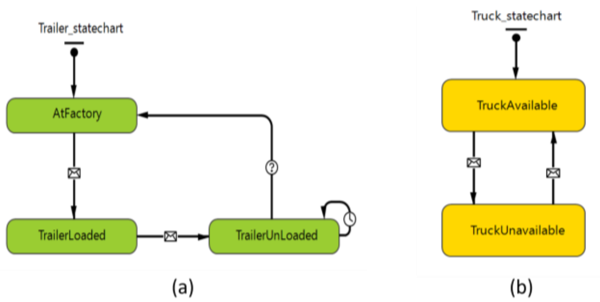

Figure 4. Statechart of the transportation agents: (a) trailer agent; (b) truck agent

3 Implementation and Results

To evaluate the proposed integrated transportation procedures, a case study was conducted using operational data from ACQBUILT, an Alberta-based prefabricated panel manufacturer. The case company produces floor, wall, and roof panels in a factory-controlled environment and transports them to project sites for assembly. Despite advancements in production automation, the case company's SCM remains manual, lacking integration between production and onsite operations. It relies on push planning, producing panels early regardless of onsite delivery dates, resulting in excess inventory and inefficiencies. The proposed transportation procedures ensure timely delivery of panels by bridging factory and onsite operations. A simulation model was developed to test the proposed procedures under realistic conditions in order to demonstrate their ability to connect factory production, transportation, and onsite assembly for efficient SC performance.

To assess the effectiveness of the proposed framework, several verification and validation steps were conducted. Test cases using artificial datasets were developed to confirm agent interactions and workflows, ensuring the procedures functioned as intended. Additionally, the movement of transportation resources on a GIS map was visually checked to verify that trucks were traveling to the required destinations while adhering to operational hours and taking the shortest available route. Real operational data and project details from April, 2021, was also used to validate the ability of the proposed framework to align with actual production progress and meet onsite requirements. During April, 2021, panels for 35 distinct home construction projects needed to be produced, transported and assembled on site. These projects varied in design complexity, panel sizes, and panel quantities, leading to differences in transportation scheduling, trailer allocation, and onsite sequencing. The proposed framework manages variations through independent project site agents, each autonomously handling its panel orders, trailer arrivals, and resource coordination based on project-specific parameters. This structure ensures that each site dynamically adapts its logistics based on actual SC conditions, supporting multi-project scalability. With respect to the case implementation, the simulation model used the same production capacities and SC resources as those established by the partner in reality for the same period (April, 2021). While predefined factory capacities, working hours, and resource availabilities serve as operational constraints in the proposed framework, the scheduling process itself is automated. The framework dynamically extracts actual job details and available resources from the enterprise resource planning system (ERP) and updates scheduling parameters accordingly. A dedicated user interface (UI) extracts data and integrates it into a built-in database (DB) within the simulation that structures SC configurations and job details. These automated updates ensure that each scheduling horizon reflects the latest available data without requiring manual intervention beyond predefined constraints. To ensure data reliability, extracted datasets undergo a structured verification process before integration into the simulation model. Before integration, extracted data is validated in structured Excel files to flag inconsistencies. Missing values either are corrected through cross-validation with ERP records or are replaced with default estimates based on historical data to maintain scheduling feasibility.

The purpose of the validation was to evaluate the performance of the proposed framework against operational data for manufacturing, delivery, and onsite assembly. Metrics such as delivery times and adherence to JIT delivery were used to assess the successful coordination of SC processes. Expert feedback further confirmed the practicality of the generated SC operational plans and the effectiveness of the developed model in minimizing delays in dispatching and returning operations and enhancing resource allocation, thus achieving integrated SC performance. It should be noted that, given its structured database architecture and ERP-based data extraction, the framework can be adapted to other OSC companies with similar SC structures, ensuring flexibility in different operational environments.

The first verification step was to ensure that the model accurately manages production operations in response to onsite demand. The factory agent should be able to receive and record all required panel quantities and then manage production according to factory procedures. Moreover, the factory agent should adhere to internal constraints (e.g., production line capacities and operational days). For instance, as shown in Figure 5, on April 15, 2021, a peak daily request of approximately 20,000 sq ft was recorded, exceeding the production line's capacity of 12,000 sq ft/day. Despite the high demand, the model ensured that production remained within capacity by deferring excess quantities to subsequent operational days. Non-operational days, such as April 11, 18, and 25, were accurately represented with zero production, reflecting compliance with predefined factory capacities. Another verification aspect was to ensure model accuracy in terms of the total quantities received from the sites being equal to the total amounts produced by the factory at the end of the planning period. As shown in Figure 5, cumulative quantities confirmed that the wall production line successfully fulfilled all orders received, with the cumulative received and produced quantities reaching the same number, 168,680 sq ft, by April 28, 2021. These results underscore the model's ability to dynamically adjust production to meet varying demands while maintaining efficiency and strict adherence to operational constraints.

After verifying the production performance, the focus shifted to evaluating the transportation procedures to confirm their effectiveness in seamlessly linking production and onsite activities. The factory uses two types of trailers: flatbed trailers for loading floor and roof panels and vertical trailers for wall panels. In the model, "TA 1-TA 35" represents flatbed trailers while "TA36-TA55" refers to vertical trailers. As shown in Table 1, the model assigns trailers based on panel type and initiates dispatching operations efficiently. For instance, Trailer 38 was loaded with Wall0 on April 12 at 10:51. However, Truck 1 was assigned (and dispatching occurred) on April 15 to ensure delivery on the same day panels were required on site, with arrival at the site on April 15 at 5:39 and assembly completed by 8:30. As this example demonstrates, the model was found to adhere to JIT principles, ensuring trailers and trucks arrive onsite before assembly begins and promptly return empty trailers after assembly. Regarding returning operations, there are two notable patterns: daytime returns to meet immediate factory needs and end-of-day returns for flexibility. Dispatching operations are prioritized to ensure timely delivery to sites and to maintain continuity in onsite assembly activities by avoiding crane idle times.

Finally, the model's ability to manage the assembly of the same number of jobs completed in reality was validated by comparing assembly quantities between actual SC performance and simulated results. Although daily assembled quantities were found to fluctuate, the model completed all assembly operations on the same day as the actual schedule (April 30, 2021). Additionally, the total cumulative quantities (58,600 sq ft) in reality were the same as in the simulation, demonstrating the model's accuracy in completing all necessary onsite tasks. These results validated the model's ability to synchronize dispatching, onsite activities, and trailer returns, ensuring JIT delivery and maintaining alignment across the SC.

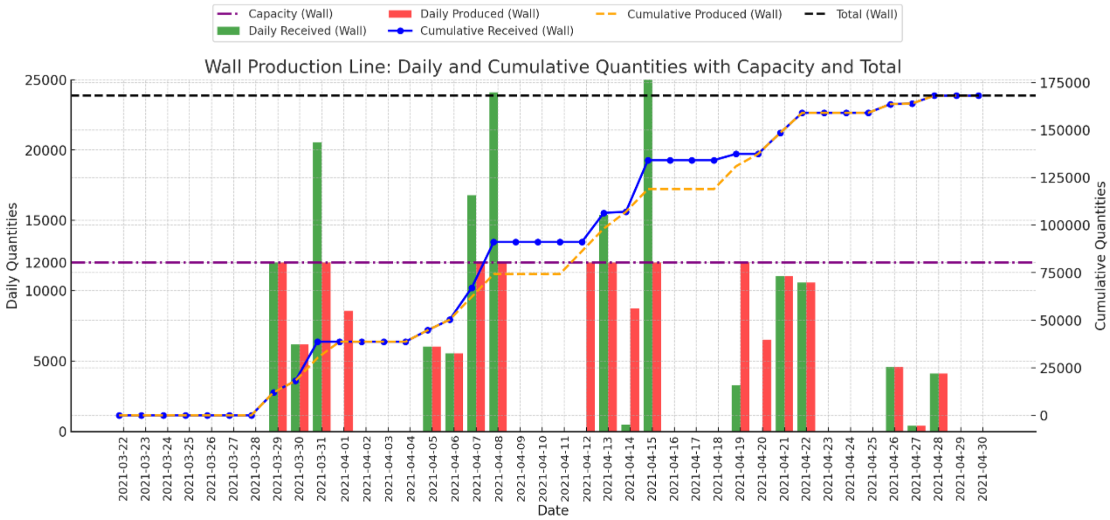

Figure 5. Simulation results for wall production line received and produced quantities

Table 1. Example of trailers and truck assignments during dispatching and returning operations

Job details			Dispatch			Onsite			Return
#	stage	PT	LC	TA #	TU #	AS	AC	TU #	RT
1	Capping	Wall0	12-04-10:51	TA 38	TU 1	15-04-5:39	15-04-8:30	TU 3	15-04-19:30
1	Capping	Floor1	12-04-13:35	TA 22	TU 3	15-04-5:51	15-04-11:01	TU 3	15-04-20:29
1	Lifting	Wall1	20-04-10:33	TA 38	TU 3	21-04-5:51	21-04-7:12	TU 2	21-04-10:14
1	Lifting	Wall1	20-04-11:55	TA 41	TU 1	21-04-6:27	21-04-8:20	TU 3	21-04-10:32
1	Lifting	Roof	19-04-13:00	TA 25	TU 2	21-04-9:39	21-04-11:01	TU 2	21-04-11:24
1	Lifting	Roof	19-04-13:30	TA 11	TU 3	21-04-9:57	21-04-12:08	TU 2	21-04-12:35
1	Lifting	Roof	19-04-14:00	TA 13	TU 1	21-04-10:31	21-04-13:16	TU 3	21-04-19:17
2	Capping	Floor1	13-04-14:05	TA 10	TU 1	16-04-5:29	16-04-11:00	TU 3	16-04-19:44
2	Lifting	Wall1	22-04-13:02	TA 53	TU 2	27-04-5:35	27-04-7:00	TU 3	27-04-7:20
2	Lifting	Floor2	23-04-12:38	TA 23	TU 2	27-04-6:25	27-04-8:01	TU 3	27-04-8:10
2	Lifting	Wall2	22-04-15:19	TA 50	TU 3	27-04-6:55	27-04-9:04	TU 1	27-04-13:20
2	Lifting	Roof	26-04-9:45	TA 26	TU 3	27-04-7:45	27-04-10:05	TU 1	27-04-14:05
2	Lifting	Roof	26-04-10:15	TA 9	TU 1	27-04-12:55	27-04-14:10	TU 1	27-04-14:55
2	Lifting	Roof	26-04-10:45	TA 16	TU 1	27-04-13:40	27-04-15:11	TU 1	27-04-18:17

*panel_type (PT); load_complete (LC); arrival_site (AS); assembly_complete (AC); return_trailer (RT); trailer (TA); truck (TU)

4 Conclusion

This study introduces a simulation-based framework designed to address the complex challenges of SCM in panelized construction. It integrates production, transportation, and onsite assembly using JIT delivery principles and hybrid multi-agent simulation, enabling synchronized SC operations. The proposed framework develops integrated transportation procedures that plan dispatching and reverse flows in the SC, emphasizing coordinated operations and resource allocation.

The contributions of this study are as follows. First, a synchronized transportation planning framework tailored to panelized construction is proposed. This framework uniquely addresses the dual objectives of improving factory and onsite operations by considering trucks and trailers as distinct entities with different tasks. By integrating distribution and reverse logistics with JIT, it resolves inefficiencies in trailer utilization, mitigates delays, and aligns transportation flows with onsite needs, enhancing overall SC performance. Second, a detailed approach to simulation of SC workflows, including dispatching and reverse logistics, is developed. The model captures interactions among trailers, trucks, cranes, and crews to address limited onsite storage and improve resource allocation. By focusing on actionable strategies, such as adhering to onsite delivery dates, the framework provides practical insights for mitigating SC disruptions. Third, a practical simulation-based SCM approach is proposed that enables the automated generation of SC plans, ensuring dynamic coordination between production, transportation, and onsite assembly. It also addresses SCM challenges such as onsite storage constraints by applying JIT, ensuring minimal waste and efficient resource utilization. Moreover, the proposed transportation planning procedures introduce an algorithmic innovation by integrating rule-based heuristics for trailer prioritization, dynamically aligning dispatching and retrieval decisions with onsite SC conditions to improve resource allocation and minimize idle time. Additionally, the framework supports operational decision-making, empowering stakeholders to test various SCM scenarios, thereby ensuring adaptability to onsite-specific challenges and constraints.

While the case study presented herein demonstrated the framework's ability to coordinate multi-project operations, handling logistics for 35 distinct sites with varying resource requirements, future research could be undertaken to further validate the model's scalability by applying it to a more diverse project environment, such as multi-manufacturer settings or projects with different types (e.g., commercial projects). Moreover, the model's application could be expanded to assess its adaptability to additional logistical constraints and SC configurations.

Furthermore, while the proposed simulation model effectively coordinates transportation and production using predefined decision rules and heuristics, further enhancements could be made by incorporating optimization-driven decision-making. The integration of metaheuristic algorithms (e.g., genetic algorithms) could further improve resource allocation by, for instance, optimizing the balance between owned and rented transportation resources, ensuring cost-effective fleet management while maintaining operational flexibility. Additionally, stochastic factors could be incorporated improve the model's ability to account for uncertainties in SC performance, particularly fluctuations in transportation availability, onsite demand variations, and operational constraints. These advancements could contribute to further reductions in operational costs and scheduling delays while improving overall SC resilience. The framework could also be extended to evaluate alternative transportation methods, such as rail, ship, or autonomous vehicles, by introducing corresponding agents into the simulation model. This extension would allow for the impact of different transportation strategies on the efficiency and cost-effectiveness of the SC to be analyzed. Furthermore, sustainability metrics could be integrated to evaluate the environmental impact of different transportation strategies, providing insights into reducing carbon emissions and improving the sustainable performance of SC operations.

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