

AUTOMATED MASTER SCHEDULING FOR SUPPLY CHAIN MANAGEMENT IN PANELIZED CONSTRUCTION

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ABSTRACT: In offsite construction, the panelized method is more complex than the volumetric modular approach, as managing the production, delivery, and installation of individual panels is more demanding and time-intensive than delivering fully assembled modular units. Accordingly, effective coordination among supply chain entities is essential as a means of mitigating the risk of cost overruns and delays. To achieve effective coordination, panelized construction companies develop supply chain master schedules that integrate factory production, transportation, and onsite assembly. However, these scheduling practices remain largely manual and time-consuming, lacking a fully integrated approach to align supply chain operations. This lack of synchronization leads to unstable supply chain performance, underutilized resources, increased costs, and project delays. To address these challenges, this research proposes an automated master scheduling system comprising three core components: (i) heuristic scheduling algorithms to automate master schedule generation, reduce bottlenecks in the supply chain flow, and streamline resource allocation based on demand, availability, and operational hours; (ii) a self-adaptive, genetic algorithm-based multi-objective optimization algorithm designed to optimize key supply chain variables, such as number of resources and project priorities; and (iii) a fully integrated simulation model that represents supply chain entities as agents, defining their relationships and interactions. A prototype of the system is developed and implemented in a case study of a panelized home prefabrication facility. This research advances the automation and optimization of supply chain master schedules in panelized construction by addressing key coordination requirements for multi-line production facilities and incorporating practical considerations for transportation and onsite operations across multiple projects.

1. INTRODUCTION

Panelized construction is an offsite construction (OSC) method that is gaining popularity due to its various benefits, which include enhanced design flexibility, cost-effective logistics, and low environmental impact (Zhang et al. 2020). To achieve these benefits, though, efficient supply chain management (SCM) strategies are needed to ensure the continuous flow of individual panels between the factory and project sites. In this regard, supply chain master scheduling (SCMS) plays a crucial role in coordinating supply chain (SC) entities, particularly production, transportation, and onsite assembly, ensuring seamless SC operational integration and preventing disruptions. SCMS ensures that each panel is produced and scheduled for delivery according to onsite assembly sequences, aligning transportation and onsite assembly resource availability (e.g., trucks and cranes) (Zaalouk et al. 2023). However, developing an efficient SCMS is challenging due to the complexity of the scheduling process, which must consider several aspects: (i) interdependence between operations, leading to SC “domino effects” and bottlenecks; (ii) the need to

schedule multiple projects, production lines, and resources simultaneously while considering assembly sequences; (iii) variations in SC procedures and constraints, including differing operational hours and capacities among SC entities; (iv) the need to collect scheduling data from multiple sources (e.g., site-ready dates from the construction department and panel quantities from the estimation department); (v) panel customization, which results in differing production and assembly durations; (vi) unique resource requirements for each project; and (vii) the need to share and communicate the developed schedules with different stakeholders. Despite these complexities, current industry scheduling practice is still reliant on experience-based, manual scheduling methods that lack full SC integration. This results in bottlenecks in SC flow and resource underutilization, as manual scheduling does not fully account for internal operational procedures, scheduling constraints, and resource limitations across SC entities.

Research on planning and scheduling in panelized construction has primarily focused on improving production efficiency (Alsakka et al. 2023, 2024; Altaf et al. 2018; Zhang et al. 2020). Within this domain, studies focused on scheduling have been relatively limited, and those available often address only production operations and do not fully integrate transportation and onsite assembly (Ahn et al. 2022; Liu et al. 2015; Rahman and Han 2024). Moreover, the domain lacks a comprehensive SCMS method that synchronizes SC stages and related operations. Existing studies primarily focus on short-term, detailed scheduling rather than considering a systematic approach that optimizes SCMS and automates their generation. To address this gap, there is a need for an integrated SCMS system for panelized construction.

2. METHODOLOGY

This paper presents an automated SCMS system for panelized construction that synchronizes SC operations across production, transportation, and onsite assembly while optimizing SC configurations (e.g., the number of required SC resources). As shown in Figure 1, the developed system integrates a hybrid operations-oriented SC simulation and optimization engine, consisting of the following components: (i) Just-In-Time (JIT) SC master planning procedures; (ii) automated SCMS algorithms; (iii) self-adaptive hybrid-genetic algorithm (GA) for multi-objective optimization; and (iv) a fully integrated SC simulation model.

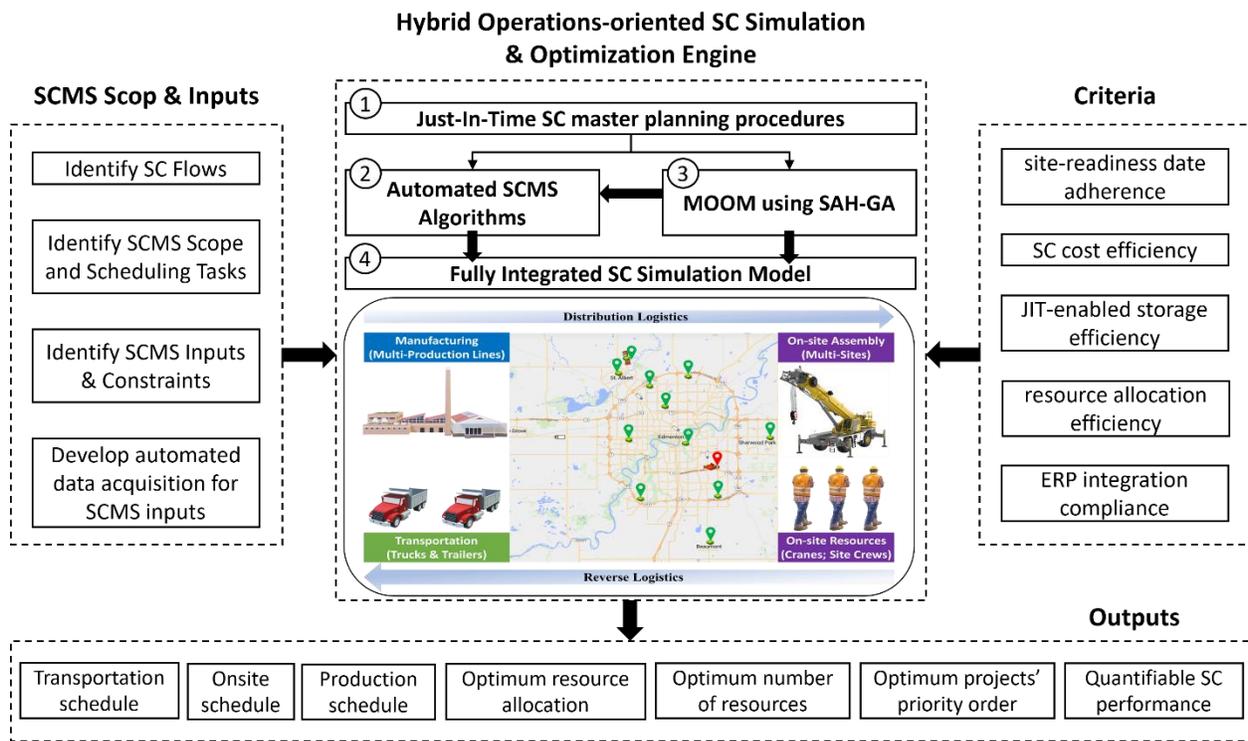


Figure 1: Automated and optimized SCMS system.

2.1 Master scheduling scope and tasks

In current practice, panelized construction follows a project-specific, customized production approach. In this approach, transportation logistics must be seamlessly integrated to ensure timely panel delivery and alignment with onsite assembly requirements. These requirements include adherence to onsite schedule (e.g., foundation work must be completed prior to onsite assembly), and the availability of assembly resources. As shown in Figure 2, this integration is achieved through a synchronized process involving four key stages: production, storage, transportation (which in turn consists of dispatching operations and returning operations), and onsite assembly (which in turn consists of capping and lifting), each involving specific operations and resource requirements. For instance, manufacturing operations involve production line crews assigned to floor, wall, and roof manufacturing tasks. These operations follow a prioritized order, resulting in the production of customized panels of various sizes. Additionally, each production line operates at a different rate and follows different operational hours, necessitating close coordination among manufacturing crews to ensure panels for the same building are produced concurrently. Following manufacturing, loading operations take place. Loading crews are responsible for placing prefabricated panels onto trailers based on panel type—flatbed trailers for floor and roof panels and vertical trailers for wall panels. Once the panels have been loaded, trucks are dispatched to transport them to project sites according to panel delivery dates and assembly sequences. Returning operations, meanwhile, involves retrieving empty trailers from sites to maintain trailer availability at the factory, ensuring uninterrupted factory operations. Onsite assembly operations refers to the installation of delivered panels using cranes and site crews. The rate of assembly operations is influenced not only by the productivity of the site crew but also by parking space constraints, as trailers arrive at the site based on parking space availability. This requires close coordination between dispatching and onsite assembly to ensure smooth operations. The assembly stage consists of capping operations and lifting operations. Capping (carried out by capping crews) involves installing basement walls and floor panels for the ground level, while lifting (carried out by lifting crews) involves erecting floor and wall panels for the upper levels and installing roof panels.

The scope of the SCMS is to integrate SC operations across these different stages by developing the following integrated schedules: production schedule, transportation schedule, and onsite assembly schedule. To develop these schedules, the master scheduler must integrate and coordinate SC operations to ensure cost- and time-efficiency. To achieve this, several key scheduling aspects must be addressed: (i) determining the number of SC resources required to complete all operations and the breakdown of rented versus owned resources to be utilized, (ii) assigning SC resources to various operations, (iii) establishing the optimal sequencing (i.e., priority order) of different projects in the SC, (iv) defining the production start date for each production line, (v) setting the start and end times for each operation in the SC, (vi) collecting necessary scheduling data from different stakeholders (e.g., the cost estimation and construction management departments), and (vii) organizing resource movement between SC entities (e.g., project sites). The goal here is to optimize operational performance by maximizing resource utilization while reducing costs (e.g., equipment rental and storage costs) and minimizing the time required to produce and assemble all panels across project sites (i.e., SC makespan). In other words, the objective is to establish SC configurations that lower SC costs and construction completion time by maximizing resources and prioritizing the use of owned assets (e.g., cranes) in order to minimize the reliance on rented assets.

2.2 Just-in-Time SC planning procedures

In the conceptual model for JIT-based SC planning, each project site represents a factory "customer" placing panel orders and requesting assembly resources. To minimize SC operational waste, particularly panel and resource waiting times, JIT delivery principles are implemented to regulate the movement of prefabricated panels through the SC, aligning factory production with onsite assembly demands. Accordingly, fluctuating site demand and production operations are synchronized by applying reverse scheduling to estimate production start dates based on site completion dates. The reverse scheduling process starts from the site completion date, i.e., the onsite milestone when the building must be fully assembled. From this endpoint, the SC flow is traced backward to determine production start dates that align the upstream portion of the SC (i.e., factory) with the downstream portion (i.e., site operations). The model also distinguishes between the two onsite assembly operations: capping and lifting. Capping operations and lifting operations are represented as two distinct panel streams in the SC,

anchoring the reverse scheduling process with two key milestones—the panel delivery date for capping and the panel delivery date for lifting—that define when panels must arrive on site for assembly at each stage. To enhance the effectiveness of the reverse scheduling, the model incorporates production line-specific time buffers to refine the generated start dates. As shown in Figure 3, these buffers prevent bottlenecks where concurrent project demands exceed production capacities. This is achieved by adjusting the start date of each production line to accommodate the required panel quantities while considering production capacity constraints, ensuring a continuous SC flow. Moreover, the buffers facilitate the coordination of operations across different production lines, accounting for varying production rates and operational hours, thereby ensuring that all of the panels required for the same given building are produced according to a coordinated schedule.

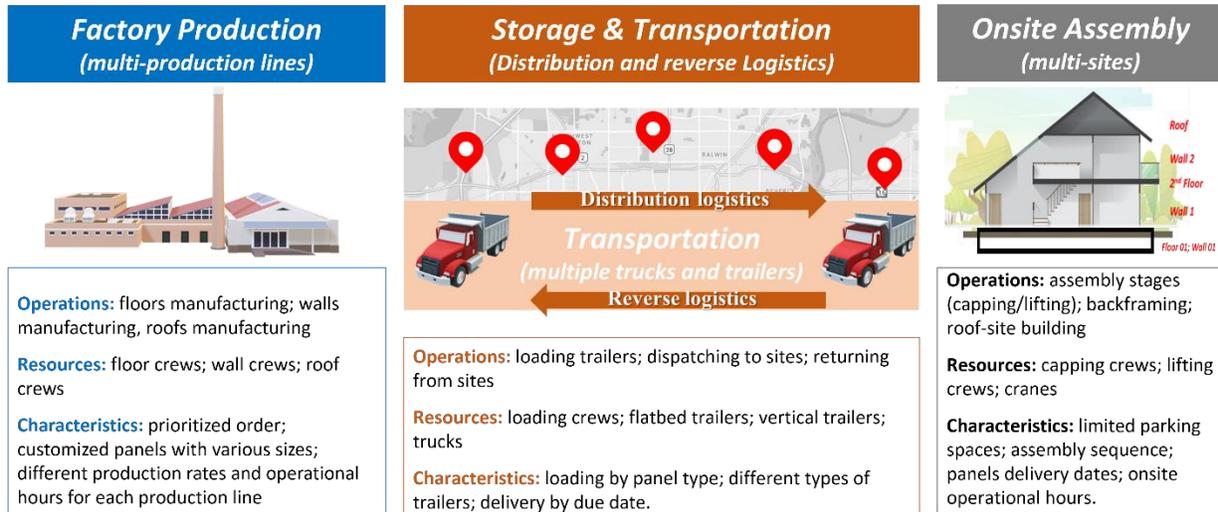


Figure 2: SC stages, operations, and resources involved.

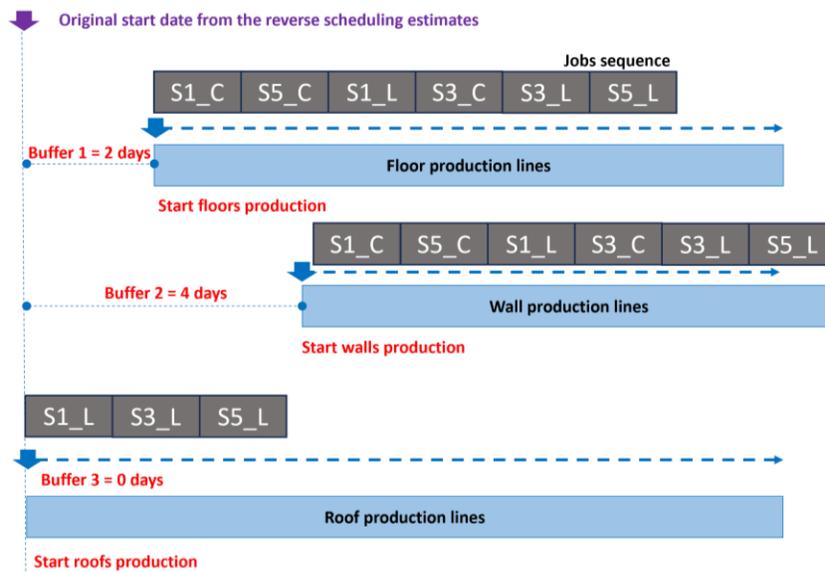


Figure 3: Time buffers for JIT SC procedures.

2.3 Automated SCMS algorithms

The JIT-based planning procedures described above serve as the foundation for establishing integrated scheduling and resource allocation for dynamic SC management. This is achieved through the development of algorithms that automate and optimize the SCMS by balancing demands, resources, and production

capacities to satisfy the panel delivery dates for each project site. There are three key algorithms: (i) a production scheduling algorithm that aligns factory outputs with JIT logic and onsite demand by dynamically estimating production start dates and managing production lines; (ii) a logistics scheduling algorithm that allocates SC logistics resources (e.g., trucks) to align with production and onsite requirements, reducing idle time and enhancing operational synchronization; and (iii) an onsite assembly scheduling algorithm that manages assembly operations according to the onsite sequence, tracking progress to ensure alignment between onsite work and other related SC operations (e.g., dispatching operations). The outputs of these algorithms serve as inputs for the simulation engine, providing the logic necessary for dynamic and automated scheduling.

Figure 4 presents the pseudo-code for the developed production scheduling algorithm as an example of the scheduling algorithms' structure and logic. The algorithm ensures that factory output aligns with onsite requirements by estimating production start dates, assigning start dates for production lines, and managing production operations. First, to estimate production start dates for each project site, the algorithm iterates through all panel types associated with the site. The required production duration is determined by dividing the total panel quantity by the factory production line capacity, and rounding up. Using a reverse estimation approach, the algorithm back-calculates the production start date by subtracting the required production days from the panel delivery date while adjusting to account for non-operational days. However, while the reverse scheduling process estimates production dates for each project site individually, the factory requires a common start date across all sites in order to synchronize production lines while meeting onsite requirements. To account for this, the second function assigns common start dates for production lines by identifying the earliest required date among all scheduled jobs for each panel type. These dates are then adjusted by incorporating production line-specific time buffers to manage potential disruptions and ensure demand levelling across multiple projects. Finally, the third function manages production operations by entering production requests into available production lines during factory operating hours. The scheduling process considers production crew availability and prioritizes requests based on project priority, assembly stage priority, and panel type priority according to the onsite assembly sequence. By integrating these steps, the production scheduling algorithm effectively synchronizes production operations with onsite requirements, ensuring a well-coordinated and efficient SC flow.

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// Estimate Production Start-Dates for Each Project Site
For each site:
  For each panel type:
    Determine required production days
    [total quantity / production line capacity, rounded up]

    Compute production start date [Reverse estimate]:
    Site-ready date - production days

    Adjust for non-operational days or holidays

// Assign Start-Dates for Production Lines
For each production line:
  Find the earliest production date among all associated panel types
  Add time buffer and assign the adjusted start date

// Enter Requests to Production Lines
For each production line:
  If line is idle during operating hours:
    Select production request with the highest priority
    Priority = project priority + stage priority + panel type priority

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Figure 4: Pseudo-code for production scheduling algorithm.

2.4 Proposed MOOM algorithm

As the next component of the developed system, a Self-Adaptive Hybrid-GA (SAH-GA) is developed for Multi-Objective Optimal Operation Management (MOOM) to optimize scheduling parameters. The parameters to be optimized in order to determine the optimal SC performance include project priorities in the SC (i.e., project sequence), the number of resources (owned versus rented) required to meet SC

demand within a specific scheduling horizon, and any time buffers required to determine the optimal production start date. SC performance is evaluated based on two key metrics: makespan and total SC cost. SC makespan represents the total time required to complete all SC operations, measured from the start of the first production operation to the completion of the last onsite assembly operation. This value is obtained dynamically based on the simulation, which captures the total elapsed time (in hours). Total SC cost, meanwhile, is computed as the sum of the various cost components associated with SC operations, including production, transportation, storage, and construction costs. As shown in Figure 5(a), the GA chromosome comprises three layers representing SCMS configurations. Layer 1 defines project priorities using integer coding, assigning two priorities to each project corresponding to the required capping operations and lifting operations. The length of this layer is determined by the number of projects in the SC, with the priority integer count being twice the number of projects (to accommodate both capping and lifting priorities). Layer 2 allocates the required number of SC logistics resources, including capping crews, lifting crews, trucks, trailers, and cranes. Real coding is applied in this layer, assigning values to resources based on their minimum and maximum availability. The minimum value represents company-owned resources, ensuring the use of owned resources is prioritized as the more cost-effective option, while the maximum value accounts for the potential to rent additional resources to expedite operations when necessary. Layer 3 represents buffer values for the start dates of each production line. These buffer values can be either negative or positive, where a negative value indicates shifting the initial production start date earlier than estimated by the production scheduling algorithm, while a positive value shifts the start date later to allow for schedule adjustments and better production line utilization (if the demand from all project sites is not high and can be accommodated in fewer production days). As shown in Figure 5(b), the GA initially generates scheduling solutions based on an initial population strategy, as the quality of the initial solution significantly influences algorithm convergence and the quality of the optimal solution. In this regard, an initial population strategy is proposed to assign project priorities based on panel delivery dates for each site. To evolve towards the optimal solution, the GA incorporates several operators specifically designed to optimize multiple SCMS configurations simultaneously: (i) rank-based crossover and mutation operators, which rank individuals in the population according to their fitness scores, with the best-performing individual receiving the highest rank and the worst-performing individual receiving the lowest rank—here, higher-ranked individuals (better fitness) are assigned higher crossover rates and lower mutation rates, whereas lower-ranked individuals (worse fitness) receive lower crossover rates and higher mutation rates; (ii) a local search operator, which is activated if no improvement is observed after n generations, allowing the algorithm to explore the solution space and potentially escape local optima; and (iii) a repair operator, which ensures logical scheduling by adjusting capping priorities so that they are always higher than lifting priorities, thereby preventing the premature loading of trailers with completed panels that cannot be delivered until the capping is complete. This approach strategically prevents bottlenecks in the SC flow.

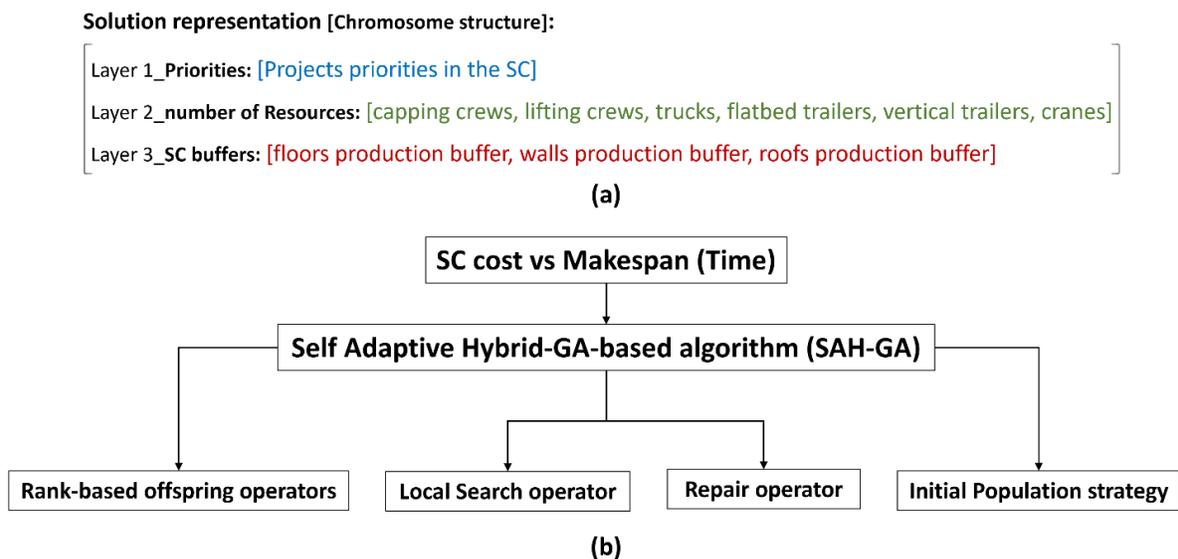


Figure 5: SAH-GA algorithm design: (a) solution representation; and (b) evolution operators.

2.5 Integrated SC simulation model

The developed simulation model integrates Agent-Based Modelling (ABM), Discrete-event Simulation (DES), and the SAH-GA to capture dynamic interactions among SC entities and generate optimized SCMS. The core component of the simulation is the scheduling agent, which evaluates onsite requirements, tracks SC operations, and dynamically allocates resources using the SCMS algorithms embedded within the simulation. These algorithms define the scheduling agent's logic for managing SC operations. Additionally, the simulation applies the SAH-GA to optimize scheduling parameters, including time buffers, number of resources, and project priorities in the SC. As shown in Figure 6, the simulation represents SC interactions through four key agents: (i) Factory Agent, which manages production operations across multiple lines, processing scheduling agent requests while adhering to working hours and operational constraints; (ii) Project Site Agents, which represent site-specific requirements, including panel delivery dates, resource needs, and assembly sequencing, ensuring efficient onsite operations; (iii) Resource Agents, which include transportation resources (trailers and trucks) and assembly resources (cranes and site crews); and (iv) Scheduling Agent, which oversees SC orders, ensuring the SCMS aligns with transportation availability and assembly needs by dynamically allocating resources and issuing logistics and production requests. This hybrid simulation–optimization approach ensures adaptive scheduling that optimizes SC performance by synchronizing production, transportation, and onsite processes under JIT principles.

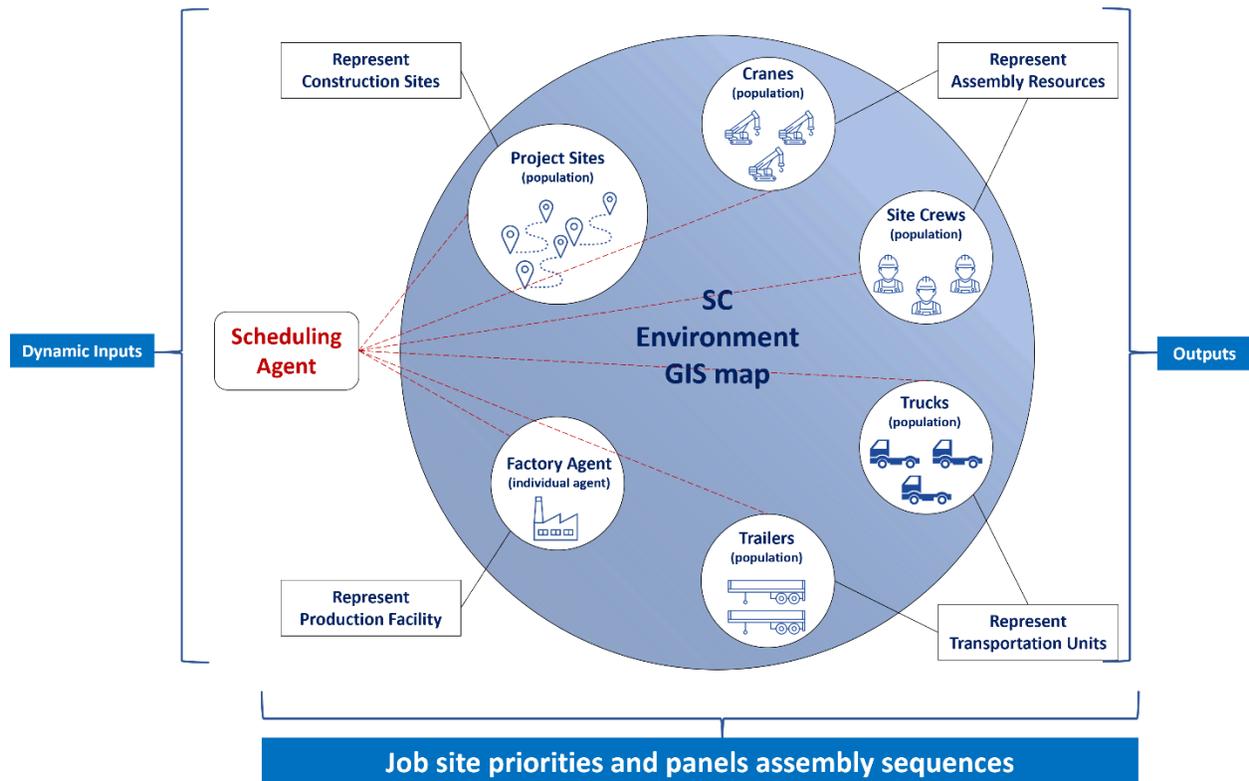


Figure 6: Simulation model structure and SC agents involved.

3. CASE STUDY

A prototype of the SCMS system, incorporating the proposed JIT-based automated SCMS approach, is developed to integrate the scheduling and optimization algorithms with the simulation model, implemented using AnyLogic software version 8.8.4. To assess the performance of the prototype, a case study is conducted using project data from ACQBUILT, a prefabricated panel manufacturer in Alberta. The case company produces floor, wall, and roof panels for panelized homes in a controlled factory environment and

transports them to construction sites for assembly. Despite advancements in production automation, its SCM remains largely manual, lacking seamless integration between production and onsite operations. The case company's production facility consists of multiple production lines: one for floor panels, one for wall panels, and three for roof panels. The case company also owns a fleet of trailers, trucks, and cranes for panel transportation and assembly. During peak demand periods, when multiple homes must be completed within a short time frame, additional equipment is rented to supplement the fleet of owned assets.

The case company utilizes an enterprise resource planning (ERP) system with a centralized database that connects all departments, including estimation and sales. To establish SCMS for multiple projects, relevant data entered by different departments must first be extracted from the ERP. The required project information includes completion dates, which are determined by the sales and contracts department based on customer needs and contractual commitments. The estimation department provides job-specific quantities, while the drafting department determines the number of required trailers based on stacking plans. The construction department, meanwhile, is responsible for setting panel delivery dates, ensuring alignment with onsite activity completion (e.g., foundation work). As shown in Figure 7, to automate the data acquisition process for SCMS, a user interface (UI) is developed for extracting the necessary information and linking it to a built-in database. This database reads SC configurations and job details and then stores them within the developed system, enabling seamless integration and efficient scheduling.

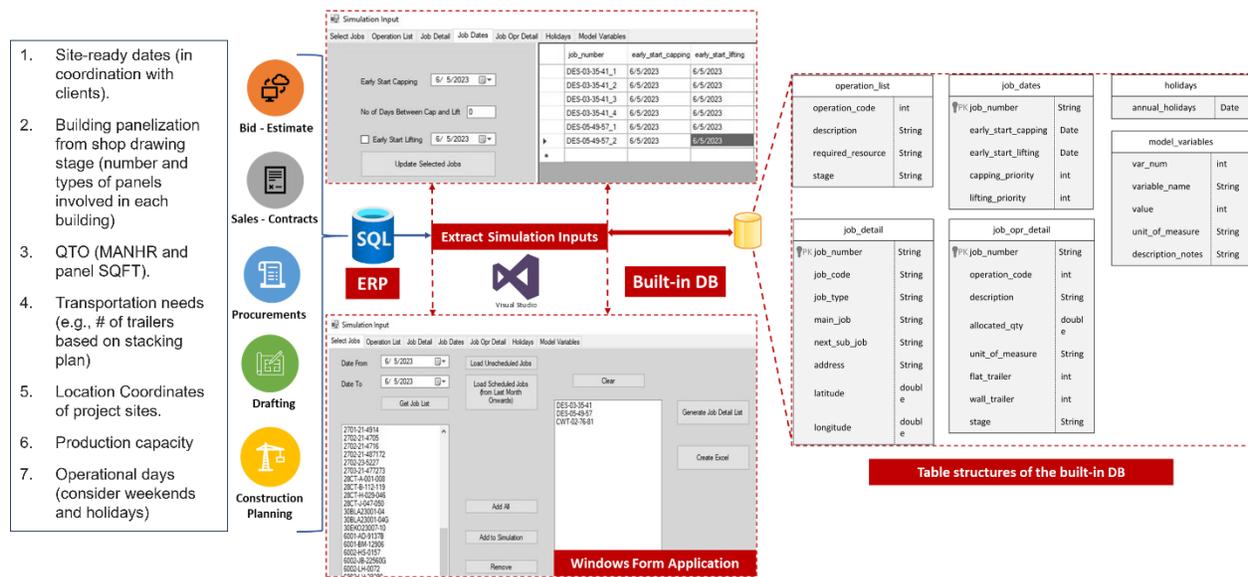


Figure 7: Developed user interface for data acquisition.

Data from 12 projects scheduled for delivery between May 12, 2022, and May 24, 2022, is extracted for SCMS. These projects consist of various two-storey homes, including single-family homes and townhomes. Once the input data has been collected, the system initializes a scheduling parameter solution by setting project priorities, determining the number of resources, and assigning time buffers using the SAH-GA with an initial population, (i.e., SAH-GA-IP). The SAH-GA-IP parameters are set as follows: 300 generations, a crossover rate ranging from 0.8 to 1, a mutation rate between 0.05 and 0.2, and a maximum of 10 generations without improvement. The generated solution is then communicated to the scheduling agent, which generates project site agents based on the input data and creates resource agents (e.g., cranes, site crews, trucks, and trailers) according to the parameters proposed by SAH-GA-IP. Subsequently, the scheduling agent applies buffer values in order to estimate production start dates for each production line. As scheduled production dates are reached (as the simulation time elapses), jobs enter the production lines based on assigned priorities, while the scheduling agent continuously applies logistics and onsite scheduling algorithms to allocate resources. The process continues until all required SC operations are complete. The SC makespan and SC cost are then calculated based on SC performance, and the values are communicated to the optimization algorithm, which proposes another solution. This iterative process continues until the predefined number of generations is reached. Finally, the optimal scheduling parameters

are reported, and the optimal schedule, which includes the start and end times of all operations, along with resource allocations, is generated. The optimized schedule is then sent to the ERP system, making it accessible to the relevant departments within the company.

Compared to the initial sequence generated based on panel delivery dates [23, 22, 21, 13, 20, 10, 24, 17, 19, 18, 15, 14, 16, 4, 12, 5, 11, 3, 9, 2, 8, 1, 7, 6], the optimal solution adjusts the project sequence in the SC to [22, 10, 21, 13, 18, 5, 23, 17, 24, 19, 15, 14, 16, 4, 11, 6, 12, 1, 9, 2, 8, 3, 20, 7]. For example, in this sequence, the capping phase of project 1 is assigned priority 22, while its lifting phase is assigned priority 10. Higher-priority jobs enter the production line first and maintain priority across all subsequent SC operations. Accordingly, project 5, which has the highest capping priority (24), is the first to enter the production line, and its lifting phase is assigned priority 19. Regarding time buffers, the optimal values are 0 for the floor production line, -1 for the wall production line, and 0 for the roof production line. The estimated production start dates determined by the scheduling algorithm are May 10 for the roof line, May 11 for the floor line, and May 12 for the wall line. Since the buffer value for both the floor and roof lines is 0, the estimated start dates for these lines remain unchanged, whereas the wall production line starts one day earlier than initially estimated. Consequently, the final production start dates are May 10 for the roof line and May 11 for both the floor and wall lines. The optimal resource allocation configuration (in terms of number of required resources) is 2 capping crews, 8 lifting crews, 4 trucks, 55 flatbed trailers, 15 vertical trailers, and 4 cranes. This configuration results in a total SC cost of CAD 718,168.31 and a makespan of 545.41 h, corresponding to a project completion date of May 24, 2022. This is the earliest possible completion date, as the last panel delivery is scheduled for May 24, and panels cannot be delivered before this date due to site readiness considerations.

To evaluate the effectiveness of the proposed optimization algorithm with the initial population strategy (SAH-GA-IP), its performance is compared to that of the basic GA and of the self-adaptive GA without the initial population strategy. As shown in Figure 8, the results demonstrate that SAH-GA-IP achieves superior performance when the algorithm starts from an initial solution based on panel delivery dates, highlighting its efficiency and robustness. Further, to comprehensively assess the practical value of the proposed SCMS, the optimal solution generated by SAH-GA-IP is compared with two manually developed schedules used in practice (referred to here as “Schedule 1” and “Schedule 2”). Schedule 1 starts earlier (May 8) to achieve the same completion date (May 24), resulting in a longer makespan (17 days) and higher total SC cost (CAD 801,497.05). Schedule 2 starts later (May 12), reducing total cost (CAD 689,260.09) but delaying project completion until May 26. In contrast, the proposed automated SCMS effectively balances cost and duration, starting on May 10, achieving timely completion (May 24) with a shorter makespan (15 days) and optimized cost (CAD 718,168.31). This clearly demonstrates the practical advantages of the proposed method over conventional manual scheduling and standard GA approaches. In this study, timely completion was prioritized to align with customer demand constraints, while still achieving acceptably low total costs.

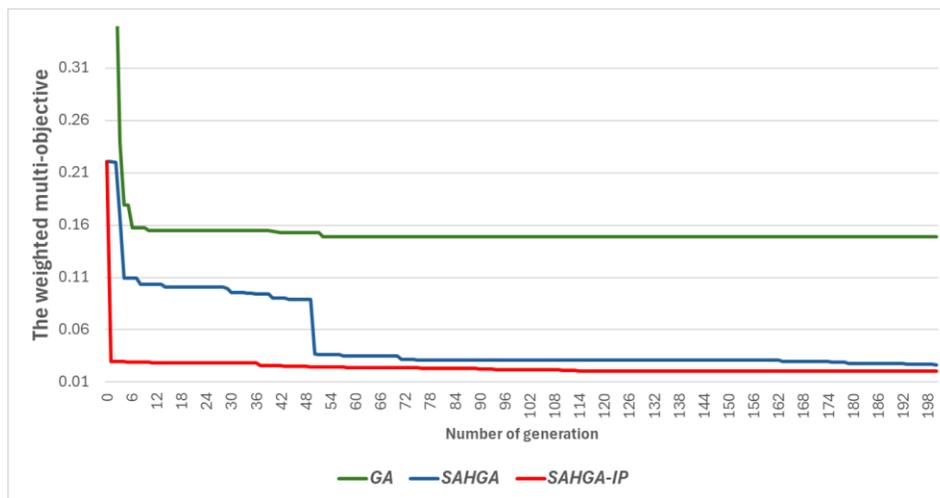


Figure 8: Comparison of convergence speed of GA, SAHGA, and SAHGA-IP.

4. CONCLUSIONS

The complexity of scheduling in panelized construction stems from the need to coordinate multiple SC entities, including multiple project sites and production lines, while optimizing resource allocation and aligning production with onsite requirements. This research presents an automated SCMS system that integrates JIT principles, optimization, and multi-agent simulation to enhance SC coordination. The proposed system incorporates automated SCMS algorithms, a self-adaptive hybrid-GA-based algorithm for multi-objective optimization, and a fully integrated SC simulation model. These components synchronize production, transportation, and onsite assembly operations while optimizing scheduling parameters to improve SC performance. The case study results demonstrate that the developed system effectively defines optimal scheduling parameters, including project priorities and the number of resources, to efficiently manage SC operations. By automating SCMS processes, this system advances scheduling practices in panelized construction, providing a scalable and adaptable solution for managing complex SC operations across different stages of the SC.

While the proposed SCMS system demonstrates effectiveness specifically in the context of panelized construction, its applicability to other OSC methods, such as modular construction, requires further exploration. Future research could evaluate the applicability of the proposed system to other OSC contexts. Additionally, it is worth noting that the complexity of implementation and initial integration costs represent practical barriers to adoption of the proposed system. Phased implementation, targeted training for SC schedulers, and pilot projects could mitigate these challenges. Future studies should include detailed cost–benefit analyses and guidelines to support smooth implementation of the system in different SCM environments. In future work, the authors plan to explore the development of a digital twin that enhances system adaptability and responsiveness to SC disruptions by integrating real-time data. Additionally, the material supply stage will be incorporated, and the model will be expanded to consider different transportation methods, such as rail and ships.

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