Optimal Transportation Fleet Scheduling in Panelized Construction

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Abstract

Optimal Transportation Fleet Scheduling in Panelized Construction

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Optimal transportation scheduling is crucial to improve the performance of the panelized construction supply chain. Previous studies lack transportation scheduling approaches for distribution and reverse logistics in panelized construction as a bridge to balance factory and site operations. To address the current gaps, this research proposes a genetic algorithm-based optimization framework to generate optimal distribution and reverse transportation schedules and on-site unloading schedules, considering a diverse transportation fleet (trucks and trailers), multiple sites, multiple panel types, on-site parking limitations, and assembly sequence while ensuring continuity of factory production and on-site operations. The proposed model extends and improves the existing transportation models by considering the distribution and reverse transportation operations and introducing design constraints in the transportation practices of the panelized construction. Results demonstrated that the method achieves transportation fleet efficiency of 98.8% and ensures seamless on-site operations, offering an invaluable planning tool for project managers and enhancing resource allocation for factory and construction sites.

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
Const.	Constraint
CS	Construction Site
DES	Discrete Event Simulation
GA	Genetic Algorithm
GPS	Global Positioning System
IABCA	Improved Artificial Bee Colony Algorithm
ID	Identification
IHDFA	Improved Hybrid Difference Firefly Algorithm
ILP	Integer Linear Programming
JIT	Just-In-Time
MBI	Modular Building Institute
MILP	Mixed-Integer Linear Programming
NP	Non-deterministic Polynomial-time
PMC	Permanent Modular Construction
PMX	Partially Mapped Crossover
PSO	Particle Swarm Optimizer
RFID	Radio Frequency Identification
TSP	Traveling Salesman Problem
VRP	Vehicle Scheduling Problems

Chapter 1: Introduction

1.1 Background

Off-site construction has received increasing attention from researchers and industry experts in recent years, due to its numerous benefits over traditional construction. These benefits include reduced construction time, early return on investment, improved workplace safety, lower construction costs, improved worker productivity, and compatibility with the circular economy [[1]–[4]]. Modular construction represents an advanced level of off-site construction, with state-of-the-art manufacturing and logistics technologies, resulting in fully factory-finished volumetric modular 3D units that can be rapidly assembled on site. In panelized construction, another type of off-site construction, individual 2D panels (i.e., floor, wall, and roof panels) are manufactured, that are smaller in size compared to modular (volumetric) units and therefore offer ease of transportation and handling. Panelized construction is getting more popular as an off-site construction technique [5] due to its design flexibility, reduced construction equipment capacities (e.g., cranes), and trailer requirements (i.e., size and capacity) [6]. However, despite these benefits, the adoption rate of the panelized construction supply chain remains low based on the PMC market shares obtained from MBI as presented in Fig. 1 [7]. Panelized construction supply chain is the process of manufacturing building panels from raw materials in a factory and delivering the finished panels to the end users (i.e., construction sites) for the onsite assembly. Recent literature has explored many aspects of modular and panelized off-site construction, such as construction manufacturing planning [8], construction logistics [[1], [9], [10]], factory workstation ergonomics [[11], [12]], and production planning and control [13]. The body of knowledge on off-site construction is increasing rapidly due to the pressing demand for efficient construction methods to meet rising housing demand. Existing literature has identified some challenges hindering the adoption of panelized construction such as inefficient supply chain planning and scheduling and resource allocation planning [[13], [14]], highly diversified building designs, skilled workers shortage [15], inventory control [16], on-site storage limitations [17], and requirement of proper logistics and transportation operations [6]. To overcome the challenges related to on-site storage, logistics management, and transportation of panels from factory to site, and increase the adoption of panelized construction, it is crucial to establish an efficient transportation scheduling system as a bridge to link the factory and construction sites in the panelized construction supply chain taking into considerations the distribution and reverse logistic operations (i.e., delivery of loaded trailers from factory to construction sites, and return of empty trailers from construction sites to the factory).

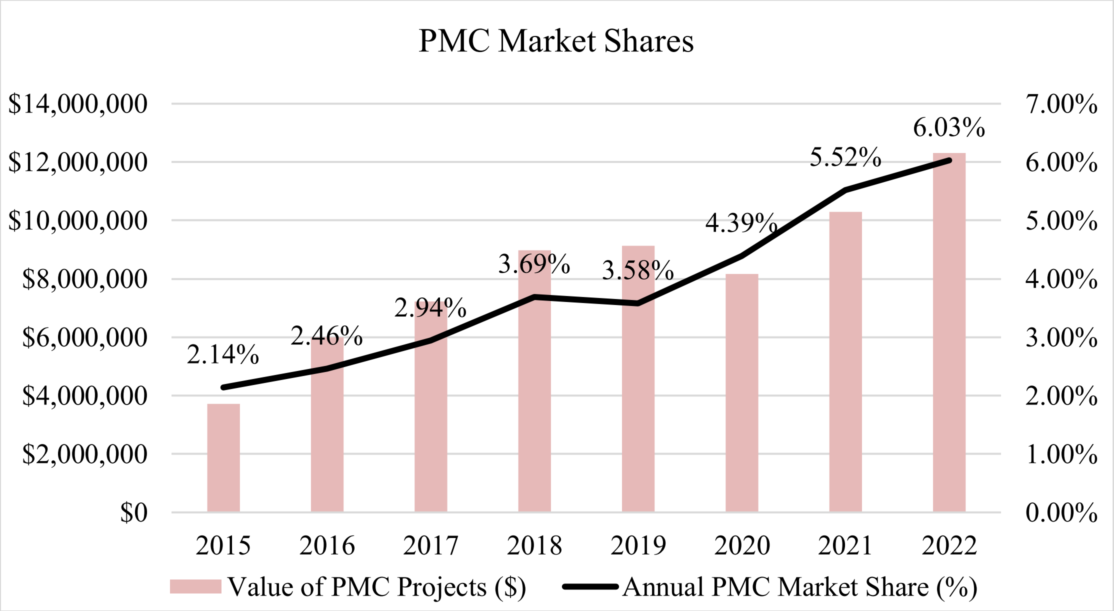


Fig. 1. PMC market shares as per MBI [7]

The transportation process in panelized construction bridges factory production and on-site assembly since it delivers produced panels to construction sites for onsite assembly and accomplish projects. Therefore, disruptions of transportation operations may impact both the factory and construction site operations, leading to additional supply chain costs and losses to the transportation fleet and factory operations. For instance, inefficient route planning and delivery sequencing can lead to longer waiting times for trucks, extended transportation durations, and delays in returning empty trailers to the factory, which increases the operational costs of the fleet and impacts the capacity of the factory to undertake subsequent projects due to non-availability of empty trailers. In this respect, delays in the distribution of loaded trailers can lead to increase idle time for the construction resources, and delays in on-site activities, particularly if panels do not arrive as scheduled, or if the delivery sequence is not in line with the on-site assembly progress. Furthermore, the return of empty trailers is a key operation in panelized construction logistics since it may affect the productivity of the factory production line. More specifically, if empty trailers are not returned to the factory on time, the production line will be stopped with prefabricated panels that cannot be loaded into trailers due to the non-availability of empty trailers. Moreover, empty trailers that are idle at construction sites will occupy the available parking spots limiting the ability of those sites to accommodate new deliveries. Thus, due to the interdependency between the factory, sites, and transportation fleets, efficient transportation planning of distribution and reverse logistics is vital for the success of panelized construction projects.

Recently, transportation planning has increasingly had attention from academia. However, many of the research efforts related to transportation and logistics scheduling overlooked the integrated form of the supply chain entities and often favored one entity of the supply chain (i.e. the factory or construction site) [[1], [9], [18], [19]]. Specifically, the fulfillment of site demands has been one of the main objectives of logistics scheduling studies [20]. In fact, the factory and construction sites tend to have different objectives where the factory aims to fulfill construction site demands while optimizing its production and transportation, whereas construction sites focus on meeting schedule milestones and minimizing delays. The review of previous literature reveals a gap in addressing the transportation process to benefit the factory and construction sites simultaneously. Moreover, although many methods have been proposed for transportation scheduling in various areas, such as ready-mixed concrete, precast concrete, and prefabricated component [[1], [9], [18], [21]–[26]], these studies do not suit the unique nature of panelized construction where two key phases are involved in the process; dispatching loaded trailers from the factory to construction sites, and the reverse logistics where empty trailers are returned to the factory after completion of unloading on-site. The other gap is that the transportation scheduling in the previous literature treated trucks and trailers as one unit rather than two separate units performing different tasks, overlooking the reverse logistics aspect. This oversight, with little attention given to the transportation process as a crucial link between the factory operations and the site, the potential benefits of panelized and off-site construction (e.g., improved productivity, minimized idle time of transportation and on-site resources, and reduced construction duration) have yet to be fully realized. In this regard, the successful management of panelized construction supply chain requires enhancing the performance of the whole supply chain and aligning the transportation process with the goals of the factory and construction sites to ensure efficient production line operations, optimal transportation operations, on-time delivery and return of trailers, and minimum idle time of transportation fleet and construction crews (cranes and workers).

1.2 Problem statement

The growing popularity of panelized construction due to its advantages over conventional construction methods, necessitates an efficient approach for the planning and scheduling of transportation operations to replace current scheduling techniques that primarily rely on priority and/or experience-based rules. The transportation operations in panelized construction involves not only delivering loaded trailers from the factory to multiple construction sites, but also returning empty trailers from sites to the factory after completing the unloading of panels on-site.

Present methods and studies in offsite logistics and transportation scheduling treated trucks and trailers as a single unit, instead of independent units performing different tasks. This oversight neglects the reverse logistics operations of trucks and trailers, specifically the return of empty trailers from construction sites to the factory. Moreover, the current scheduling techniques lack optimizing the transportation process in a manner that simultaneously benefits both factory operations and on-site construction activities.

1.3 Objective and scope

To address the gaps in transportation scheduling of panelized construction and overcome the aforementioned limitations of previous studies, this research proposes an optimal transportation scheduling framework for panelized construction as a bridge to link the factory and construction sites operations considering the following criteria:

i. Considering trucks and trailers as independent units, hence addressing distribution and reverse logistics of loaded and empty trailers.

ii. Operating in a multi-site environment (i.e., from the factory to multiple sites).

iii. Improving the transportation fleet operations by minimizing the transportation duration and maximizing the fleet efficiency.

iv. Improving the production line operations by ensuring the availability of empty trailers at the factory.

v. Ensuring continuous operations of the on-site assembly by minimizing the waiting time of onsite resources (e.g., cranes) while delivering panels.

In this respect, the proposed method involves a genetic algorithm (GA)-based optimization model capitalizing on the mathematical optimization concepts (i.e., the vehicle routing problem (VRP)) to determine the optimal distribution and reverse transportation schedules as well as onsite unloading and assembly schedules rather than simply relying on priority and/or experience-based rules. The proposed framework will improve the existing transportation planning models by incorporating the following features:

i. Reverse logistic operations.

ii. A diverse transportation fleet (multiple trucks and trailers).

iii. Multiple panel types (floor, wall, and roof panels).

iv. On-site parking limitations.

v. Sequence of delivery and assembly based on panel installation sequence onsite.

Moreover, the proposed framework will form the basis for transportation planning and scheduling as one component of the panelized construction supply chain network by benefiting the factory and construction sites simultaneously. To examine the performance of the proposed framework, an actual case study from a panelized construction factory in Canada is presented.

1.4 Research assumptions

The following research assumptions are considered in the development of the present work. These assumptions provide the basis for the proposed methodology and contribute to the overall research scope.

i. Cranes are available at each construction site for the unloading of prefabricated panels from loaded trailers. The optimal dispatching of cranes is not considered in the present study.

ii. The dispatching priority of loaded trailers to construction sites is based on the number of loaded trailers required by each site, where the site that requires the highest number of loaded trailers has the highest priority.

iii. All construction sites require the delivery of loaded trailers by the start of the day; hence the actual start time of onsite activities is not considered.

iv. Traffic status of the selected routes is not considered in the travel time calculation.

v. The dimensions of trailer parking spots at construction sites are sufficient to accommodate all types of trailers in this study.

vi. Time durations to unload the panels from loaded trailers onsite are considered from existing literature based on the type of panels in the loaded trailer.

vii. A minimum of 10 trailers per type should be available at the factory to ensure no impact on the factory's production operations.

Chapter 2: Literature Review

2.1 Transportation and logistics planning of modular and panelized construction

The panelized construction supply chain consists of three main stages; namely, the production stage, where panels are prefabricated in a factory-controlled environment, the transportation stage which includes the distribution of panels to construction sites and the return of empty trailers to the factory, and the on-site assembly stage where panels are assembled to form the building. This demonstrates that the transportation stage is the most critical as it connects the factory to the construction sites. In other terms, it bridges the factory operations (i.e., the production line) and construction site progress, where delays in the transportation process can lead to significant setbacks that can adversely affect the quality, schedule, and cost performance of both off-site and on-site operations. Factors in the transportation scheduling such as route planning, fleet availability, delivery, and pick-up schedules must be comprehensively considered to improve the efficiency of the overall supply chain operations and ensure the continuity of production line and on-site operations. In panelized construction, it should be noted, panels are manufactured in a factory using industrialized manufacturing processes, and they are then transported to the construction site where they are installed on site using a crane or other mobile lifting equipment to create the finished product. Transportation scheduling requires a specific set of skills and expertise (e.g., dispatch planning, managing the order of delivery to sites, awareness of on-site construction activities and sequence, fleet allocation, and management) to ensure that the process is conducted efficiently. Therefore, the transportation schedule should be developed based on careful coordination between the factory production schedule, the demands of construction sites and onsite installation sequences. That is, well-planned and efficiently managed transportation operations lead to cost savings, reduced project timelines, and increased overall project efficiency.

Numerous studies have attempted to address the one-to-one transportation scheduling, which refers to transportation between one factory and one site [[1], [10], [20], [21], [27]], or the many-to-one problem, where a single construction site requires deliveries from multiple factories [[19], [22], [25]], but these have tended to focus on improving the construction site operations. For instance, Almashaqbeh & El-Rayes [1] developed a mixed-integer linear programming (MILP) model to minimize the total costs of transportation and storage of modules at one site. Their model provided the optimal module assigment on trucks and the optimal delivery to the site. The developed model was solved using Pyomo solver, and was applied to a case study involving one factory, and one site with five types of prefabricated steel modular units. Yi et al. [21] proposed a MILP model to optimize the transportation planning of prefabricated products. The model was solved using CPLEX and was applied to a case study of a two-storey house comprising 15 prefabricated components, with the case project involving a construction site and a factory. Zhang and Yu [19], meanwhile, developed a framework for optimizing the transportation planning process in prefabricated projects by improving efficiency and reducing costs. Their methodology involved the development of a dynamic transportation planning framework that integrated mathematical modeling, simulation techniques, and particle swarm optimization algorithm based on the just-in-time (JIT) strategy and considering various elements including supplier selection, transportation planning for intermodal transportation from multiple suppliers to one site, site layout planning, and transportation plan adjustment. Moreover, Hsu et al. [20] noted that schedule deviations are triggered by construction site delays, implementing two-stage stochastic programming to solve the developed mathematical model in order to optimize the logistics in modular construction across different stages (manufacturing, storage, and assembly of modules) considering potential demand variations. Whereas, Shi et al. [27] studied the substitution of factory delivery vehicles with the general contractor vehicles to maximize the degree of transportation completion and improve the performance of the project. To achieve this objective, they developed an integer programming model and solved it using the branch-and-bound technique. Si et al. [10] noted that existing literature has focused on static compensation mechanisms that require factories to manage demand fluctuations while overlooking the general contractor's role. To address this gap, they introduced a dynamic compensation mechanism to control schedule variations and achieve JIT delivery of prefabricated components.

On the other hand, other researchers have studied the many-to-many relationship between multiple factories, and construction sites [[9], [24], [28]], but relatively few have studied the one-to-many transportation logistics between a single factory and multiple sites [[18], [23]]. However, most of these studies are related to ready-mixed concrete, precast concrete, or prefabricated systems which have a different nature from panelized construction. For instance, Liu et al. [23] proposed an approach to solve the integrated scheduling problem for ready-mixed concrete production and delivery using a network flow method solved by GA. The problem considered trucks, pumps, and site schedules, and was applied to a case study of a plant with one mixer. They subsequently expanded their work to include multiple mixers using a time–space network model and applied a heuristic algorithm with a set of conjoint priority rules for production scheduling, truck and pump dispatching, and mixer scheduling to solve the problem [24]. Moreover, Li et al. [18] developed an optimization model for the transportation of prefabricated systems with time windows and synchronized visits and implemented an improved artificial bee colony algorithm

(IABC). They studied the relationship between a single prefabricated supplier and several sites classified into two categories: sites that require a special vehicle to accompany the delivery of prefabricated elements (i.e., synchronized visits) and sites that only require the delivery vehicle, where the delivery vehicle used visits multiple sites before it returns to the supplier. Zou et al. [9], meanwhile, addressed the transportation scheduling of prefabricated components across multiple factories in such a way as to minimize transportation costs and distance, taking into account traffic impedance. They developed a linear programming model for the transportation problem between multiple factories and sites and solved the model using a newly developed hybrid algorithm, the improved hybrid difference firefly algorithm (IHDFA). However, in previously formulated problems, the truck and trailer were considered as a single unit whereas in panelized construction trucks and trailers are two individual units performing different tasks [14].

The transportation process in panelized construction involves distribution and reverse logistics where a truck usually drops the loaded trailer at the construction site (distribution phase), and leaves to carry out the next task, before returning empty trailers to the factory after the completion of on-site unloading (reverse logistics phase). The reverse logistic operations of panelized construction were not addressed in previous literature. On-site assembly sequence and on-site parking availability are unique constraints in panelized construction that make transportation scheduling more challenging compared to previous studies. The sequence of delivery to each construction site is another aspect that needs to be considered in the optimal transportation scheduling to improve the on-site logistics. In this respect, Liu et al. [25] have focused on optimizing the on-site transportation and storage of precast concrete components to minimize unnecessary on-site relocations by utilizing the 4D building information modeling to extract the real-time schedules and the radio frequency identification (RFID) technology to track the position of components on-site. Their research emphasized the importance of considering the onsite assembly sequence to minimize relocation waste, where the ideal situation is on-site assembly after delivery without the need for on-site storage [29]. Generating optimal transportation schedules with a sequence of delivery that follows the anticipated sequence of on-site assembly (e.g., 1st level floor panels, then 1st level wall panels) in panelized construction, combined with the just-in-time delivery approach is the key to addressing the limited on-site storage, which is a major concern, especially for construction sites that are located within the city. This approach will ensure that the panels are assembled as soon as the trailer arrives at the construction site, and accordingly eliminate the unnecessary crane operations associated with the movement of panels from the storage area to the assembly location, hence minimizing the storage waste, and on-site damages as a result of double handling [25].

The research efforts in the transportation scheduling and logistics of panelized and offsite construction are summarized in Table 1. The table highlights the nature of each study and illustrates the considerations of the proposed research objectives with respect to previous efforts.

Table 1. Summary of Literature Efforts in Offsite Construction Logistics

Author(s)	**Transportation relationship (Factory - Sites)** n: multiple				**Distribution and reverse logistics (Trucks and trailers separate unit)**	**Lookahead transportation scheduling to multiple sites**	**Intermediate / onsite storage**	**Site parking**	**Method / Algorithm**
	1-1	**1-n**	**n-1**	**n-n**					
Liu et al. [23]	x	✓	x	x	x	✓	x	x	MILP / GA (Meta-heuristic)
Liu et al. [24]	x	x	x	✓	x	✓	x	x	MILP / Scheduling algorithm (Heuristic)
Hsu et al. [20]	✓	x	x	x	x	x	✓	x	MILP / CPLEX Optimizer (Exact algorithm)
Zhang & Yu [19]	x	x	✓	x	x	x	✓	x	MILP / PSO (Meta-heuristic)
Yi et al. [21]	✓	x	x	x	x	x	✓	x	MILP / CPLEX Optimizer (Exact algorithm)
Li et al. [18]	x	✓	x	x	x	✓	x	x	MILP / IABCA (Meta-heuristic)
Almashaqbeh & El-Rayes [1]	✓	x	x	x	x	x	✓	x	MILP / Pyomo solver (Exact algorithm)
Zou et al. [9]	x	x	x	✓	x	✓	x	x	MILP / IHDFA (Meta-heuristic)
Ahn et al. [6]	x	✓	x	x	✓	x	x	✓	DES
This work	**x**	**✓**	**x**	**x**	**✓**	**✓**	**x**	**✓**	**MILP / GA (Meta-heuristic), to generate optimal transportation schedules**

A review of research efforts in this area points to the lack of attention given to the distribution and reverse logistics of panelized construction. It should be mentioned that Ahn et al. [6] studied a similar case in their research, developing a framework for optimizing the truck dispatching schedules for a panelized construction factory and construction sites using discrete-event simulation (DES). Their framework used actual GPS data for the transportation fleet, with pre-planned schedules from construction sites and the factory serving as inputs to the DES model to enhance the operational side of off-site construction scheduling.

Nevertheless, there remains a gap concerning the development of optimal transportation schedules for panelized construction supply chain that benefit the factory and onsite operations while considering the delivery of loaded trailers to sites, the return of trucks and empty trailers to the factory after unloading at the site, the sequence of onsite assembly, and on-site trailer parking availability.

2.2 Optimization of transportation scheduling

The transportation planning and scheduling of panelized construction has been characterized as non-deterministic polynomial-time (NP) hard problem in previous studies, notably those examining the prefabricated component delivery [21] and the concrete delivery problem [30]. Because the transportation scheduling of panelized construction presented in this research involves delivery and pick up of trailers to and from sites, the complexity of the scheduling increases compared to other transportation studies. Moreover, the classical form of vehicle scheduling problems (VRP) was also proven to be NP-hard [31].

Transportation planning and scheduling optimization problems are based on the concept of the traveling salesman problem [32] and the VRP introduced by Dantzig and Ramser [33]. According to Toth and Vigo [34], problems related to the delivery of goods and products originating from a depot to different customers within a given period fall within the scope of VRP. These problems usually consist of a depot (a factory or supplier), a set of customers located at various locations (in this case, construction sites), a set of delivery vehicles (trucks), and a set of possible routes or arcs, with other constraints that vary depending on the nature of the problem being studied. The basic rules of VRP are (i) each customer is visited once per day, (ii) the truck that visits one location should leave from the visited location, (iii) all trips should start and terminate at the depot, and (iv) each customer should be visited. However, the transportation scheduling of panelized construction differs from the basic VRP as each site is visited more than once a day to deliver loaded trailers and pick up empty trailers. Transportation scheduling problems are typically solved using operations research techniques to determine the optimal transportation schedules by minimizing the total cost, time, and distance or maximizing profits.

MILP and ILP are the most commonly used mathematical programming techniques for formulating transportation scheduling problems in off-site construction supply chain management [1], [20], [21], [23], [25], as well as in other application domains of supply chain management as identified in the review by Díaz-Madroñero et al. [35]. Optimization problems are usually solved using exact, heuristic, or meta-heuristic approaches. Each of these approaches has advantages and disadvantages depending on the type of optimization case. Tan and Yeh [36] reported that exact optimization methods (such as branch and bound, branch and cut [37], branch-price and cut [38] algorithms, etc.) provide superior solutions compared to heuristics and meta-heuristics, which provide the near-optimal solution. Exact methods perform well on small-size problems with a small number of instances, but become computationally burdensome for large problems, while heuristic and meta-heuristic optimizations outperform exact optimization techniques, in terms of solution time, in the case of larger VRPs. In other words, the performance of exact methods in solving VRPs depends on the number of constraints and the size of the problem. Since VRPs and vehicle scheduling problems are NP-hard, the larger the problem is, the more time-consuming exact methods will be in reaching the optimal solution. Heuristic algorithms, on the other hand, are designed to solve a specific problem and focus on finding the near-optimal solution systematically through a limited number of iterations, while meta-heuristic algorithms represent an advanced form of heuristics that can be applied to a wider range of problems [39]. Meta-heuristic algorithms are inspired by nature and include a variety of types, such as GA, Ant Colony Optimizer, Particle Swarm Optimization, and Differential Evolution Algorithm. These algorithms are capable of obtaining the near-optimal solution for any optimization problem. Because the performance of these algorithms varies depending on the type and nature of the problem, there is no general rule for selecting the best algorithm.

Considering the advantages of meta-heuristic algorithms over the exact algorithm, a meta-heuristic approach is used in the present study.

2.3 Genetic Algorithm and applications in scheduling

GA is an evolutionary algorithm, used in optimization and artificial intelligence, that was invented by Holland in 1960 [40]. The GA mimics the process of natural selection and genetic inheritance to solve complex optimization problems. In GA optimization, potential solutions are represented as individuals in a population. Individuals are evaluated based on their scores in solving the problem. Individuals with better scores have a higher chance of being selected, mimicking the "survival of the fittest" concept in natural selection. The best individuals are selected based on their fitness score through the selection process to reproduce through crossover and mutation operations and generate new individuals. The crossover process occurs by exchanging parts of the genetic information between two individuals to produce two new individuals (offspring), while the mutation process is applied to an individual by introducing random changes to the genetic information or “genes” to increase the diversity of the population.

GA has been widely applied in optimization and artificial intelligence fields, including modular construction production line optimization [41], reinforced concrete [42], ready-mixed concrete [23], manufacturing [43], workplace design[11], flow shop scheduling [[44], [45]], TSP and VRP; [[46], [47]]. There is no specific rule for the selection of a meta-heuristic algorithm to solve a problem since the performance of each algorithm differs based on the type of the problem or optimization case. The no-free lunch theorem developed by Wolpert and Macready [48] states that no algorithm outperforms all other algorithms when tested under all circumstances, hence one can perform better than another in a specific problem but can perform worse in other problems.

GA can be used to explore a large solution space simultaneously and provide multiple near-optimal solutions. The advantages of GA, as reported in the literature, are that:

i. It does not depend on the initial solution [49].

ii. It is capable of obtaining the global optimum in complex problems [49].

iii. It operates in a population of solutions and not only one solution [50].

iv. The initial population is created randomly [51].

v. It has yielded the most stable results when applied to traveling salesman problems [52].

However, GA may require high computational time, depending on the type of the problem, meaning that it may become computationally expensive and require careful tuning of parameters [[49], [52]].

In off-site logistics optimization and scheduling, many researchers have used GA to solve different types of problems [[10], [23], [25], [26], [41]], where it was proven that GA has outperformed other optimization techniques, which proves the capabilities of GA in solving complex scheduling problems. However, the following research gaps were identified from previous literature for the applications of GA in scheduling that are worth addressing.

i. Current applications of GA did not explore the transportation scheduling of panelized construction, which is an advanced form of VRP, and

ii. GA was not applied to complex scheduling problems that contain specific constraints similar to the ones that will be addressed in this research.

To address these gaps, a genetic algorithm-based approach will be implemented to generate the transportation schedules of panelized construction. The proposed GA will include problem-specific operators (the repair stage) to address the gap related to implementing complex constraints.

2.4 Summary of literature review and identified research gaps

As summary, a review of the literature reveals the following research gaps that will be addressed in the present work.

i. Existing studies in this area consider the delivery truck and trailer as one single unit, but do not consider the pick-up of empty trailers from sites (reverse logistics) in optimal transportation scheduling models.

ii. Most studies have addressed transportation scheduling from a one-site perspective rather than considering multiple sites.

iii. Most studies assume the availability of storage at construction sites, but this may not be the case in panelized construction, where a just-in-time approach is required to overcome the limited storage and/or parking spots for transportation fleets.

iv. The existing literature lacks a comprehensive method to generate optimal transportation schedules that considers the benefits of both entities of the supply chain (i.e., the factory and the construction site)

v. GA was not explored in the transportation scheduling of panelized construction which involves the complex design constraints described in detail below.

Chapter 3: Proposed Methodology

This research proposes a transportation scheduling framework for the distribution and reverse logistic operations in the panelized construction. The proposed framework incorporates the dispatching of loaded trailers from a single factory to multiple construction sites and the pick-up and return of empty trailers from construction sites to the factory after unloading the panels on-site. The purpose of the proposed framework is to optimize transportation schedules as a linkage between the factory production line operations and the on-site assembly operations in the panelized construction supply chain. The proposed model is built on the basic concepts of the vehicle routing problem (VRP) and covers the specific design constraints such as sequence of loaded trailer delivery, pickup of empty trailers from sites, availability of empty trailers at the factory, and on-site parking availability.

Fig. 2 presents the proposed methodology to achieve the objectives of this study. The input data into the proposed framework consist of:

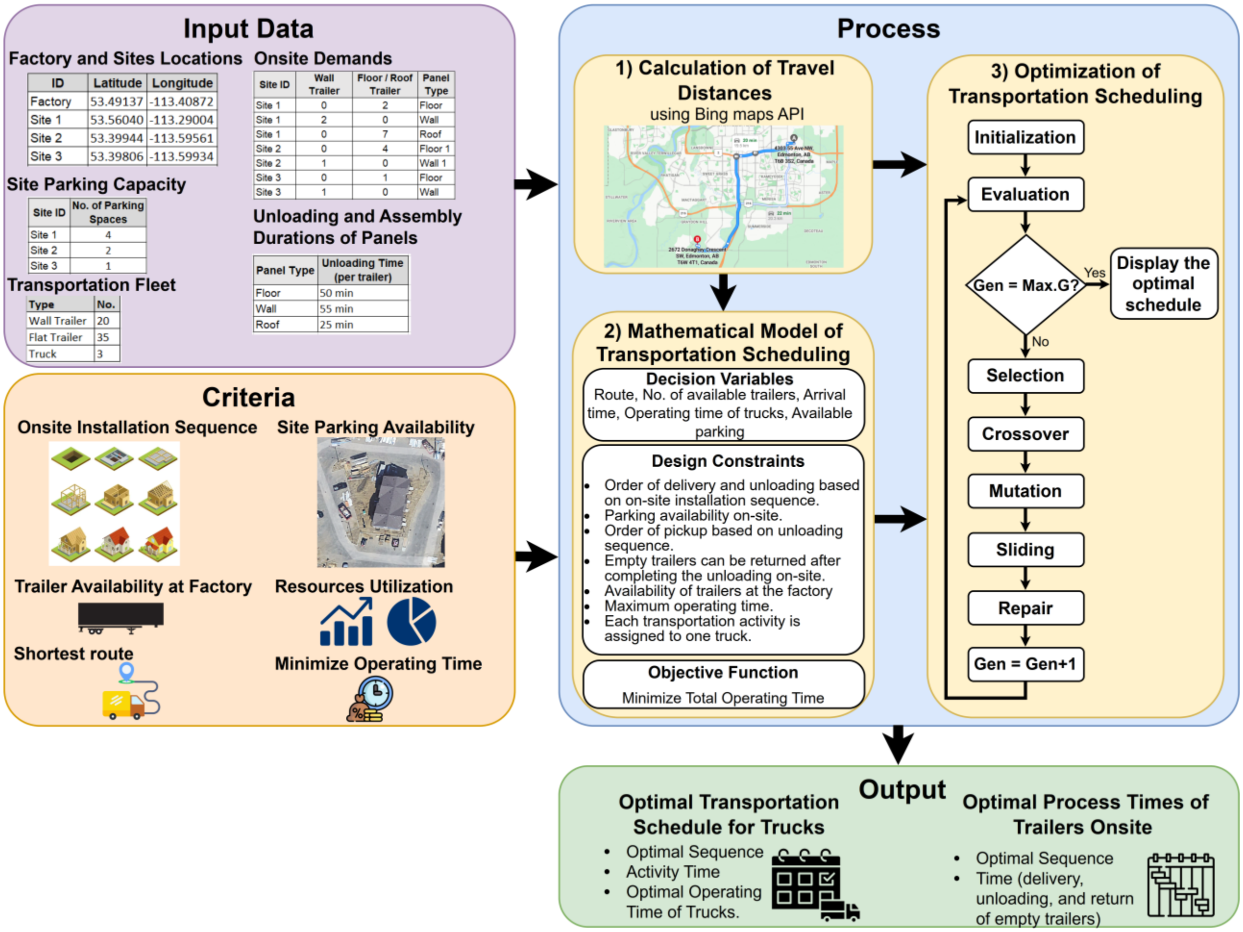
i. Factory and construction site locations

ii. Construction site demands which include required panel types and installation level, the number of loaded trailers for each panel type, and the type of trailer (wall or flat trailer).

iii. The trailer parking capacity of each construction site

iv. Durations of unloading and assembly of panels from loaded trailers

v. Transportation fleet information (i.e., number of trucks and trailers)



ID	Latitude	Longitude
Factory	53.49137	-113.40872
Site 1	53.56040	-113.29004
Site 2	53.39944	-113.59561
Site 3	53.39806	-113.59934

Site ID	Wall Trailer	Floor / Roof Trailer	Panel Type
Site 1	0	2	Floor
Site 1	2	0	Wall
Site 1	0	7	Roof
Site 2	0	4	Floor 1
Site 2	1	0	Wall 1
Site 3	0	1	Floor
Site 3	1	0	Wall

Site ID	No. of Parking Spaces
Site 1	4
Site 2	2
Site 3	1

Type	No.
Wall Trailer	20
Flat Trailer	35
Truck	3

Panel Type	Unloading Time (per trailer)
Floor	50 min
Wall	55 min
Roof	25 min

Route, No. of available trailers, Arrival time, Operating time of trucks, Available parking

- Order of delivery and unloading based on on-site installation sequence.
- Parking availability on-site.
- Order of pickup based on unloading sequence.
- Empty trailers can be returned after completing the unloading on-site.
- Availability of trailers at the factory
- Maximum operating time.
- Each transportation activity is assigned to one truck.

Minimize Total Operating Time

- Optimal Sequence
- Activity Time
- Optimal Operating Time of Trucks.

- Optimal Sequence
- Time (delivery, unloading, and return of empty trailers)

Fig. 2. Proposed research methodology

To achieve the aim of the proposed framework, the following criteria is considered:

i. Onsite installation sequence of panels.

ii. Availability of parking spots onsite to accommodate the delivery of loaded trailers.

iii. Maintaining sufficient empty trailers at the factory to ensure continuity of production line operations.

iv. Maximizing the resources utilization, and efficiency of the transportation fleet.

v. Considering the most optimum and shortest route to minimize the transportation costs.

vi. Minimizing the operating time of the transportation fleet while completing all transportation activities.

The proposed frameworks consist of three main processes:

i. Calculation of travel distances and developing the distance matrix that contains the travel distances between a factory location and site locations using Bing Maps API [53];

ii. Developing the mathematical formulation of the transportation scheduling which contains the decision variables, the objective function (fitness function) and design constraints based on the basic VRP rules.

iii. Developing a GA-based optimization model to obtain the optimal transportation schedules considering trucks and trailers as independent transportation fleet and multiple site locations with minimum interruptions of the factory and onsite operations.

3.1 Development of dispatching process in panelized construction

In general, transportation operations in the panelized construction involve distribution and reverse logistic operations for trucks and trailers leading to increase the complexity of the transportation which is the main reason to make project managers difficult to develop optimal transportation schedules. As illustrated in Fig. 3, the dispatching process of the panelized construction used as a fundamental sequences of transportation operation in this research is developed based on the practical rules identified with industrial partners. These rules are defined as design constraints in the optimal transportation problems. The dispatching process begins with the factory calculating the number of loaded trailers assigned to each construction site to establish a priority list of the sites for delivery. In this respect, a site which requires the highest number of loaded trailers, is selected as an initial delivery site. Based on considering general sequences of onsite installation in panelized construction, a loaded trailer with wall or floor panels is selected (constraint 1). At this junction, it should be noted that the sequences of onsite installation for one single house, as represented in Fig. 4, are to assemble floors and walls on 1st level, floors and walls on 2nd level, and roofs. In addition, there are two types of trailers which are wall-type for wall panels and flat-type trailers for floor and roof panels. Therefore, as an initial delivery to the selected site, a truck dispatches the flat-type trailers with floors on 1st level. However, before delivering the loaded trailers, a project manager should identify if the site has sufficient parking space to accommodate the loaded trailers (constraint 2). When the parking spots are available on the selected site, the loaded trailer is dispatched to the site. Otherwise, the next priority site is considered for the delivery. Upon the truck's arrival with the loaded trailer at the site, travel times of trucks between the factory and sites are recorded for further analysis in the optimization. Once the truck unloads the trailer, it identifies the number of empty trailers on the site, which just completed the delivery, to determine whether or not an empty trailer can be returned to the factory (constraint 3). When the empty trailer is available, the truck collects the empty trailer and returns to the factory. It is worthy to be noted that first come and first serve concept is applied (constraint 4) when there is more than one empty trailer on the site. That is, the trailer that the panels are initially unloaded is returned first. Otherwise, the truck investigates the number of available empty trailers at the factory which must be more than the minimum number of the empty trailers (i.e., 10 trailers per type in this study) to ensure continuous production line operations (constraint 5). In this respect, the truck picks up and dispatches an empty trailer on a site, which has minimum distance from the site completed the delivery, to the factory to satisfy the constraint 5. Otherwise, as a way to maintain constraint 2 (available parking spots on a site), the truck picks up an empty trailer from a site, which requires to make available parking spots for next delivery, and travel with it to the factory. This site is determined by the lowest number of parking spots among sites. If there is more than one site with occupied parking, the nearest site which has empty trailer is selected. Upon returning to the factory, the sequences of onsite installation at each site, arrival times of trucks, and number of loaded trailers at each site are recorded.

The delivery of the loaded trailers to sites continues until all loaded trailers required to the sites are delivered. In addition, as security of trailers and panels on sites, all empty trailers must be returned to the factory by the end of working hours per day (ten working hours per day defined in this study). It should be noted that this study considers the priority of delivery among sites based on the number of trailers required by each site.

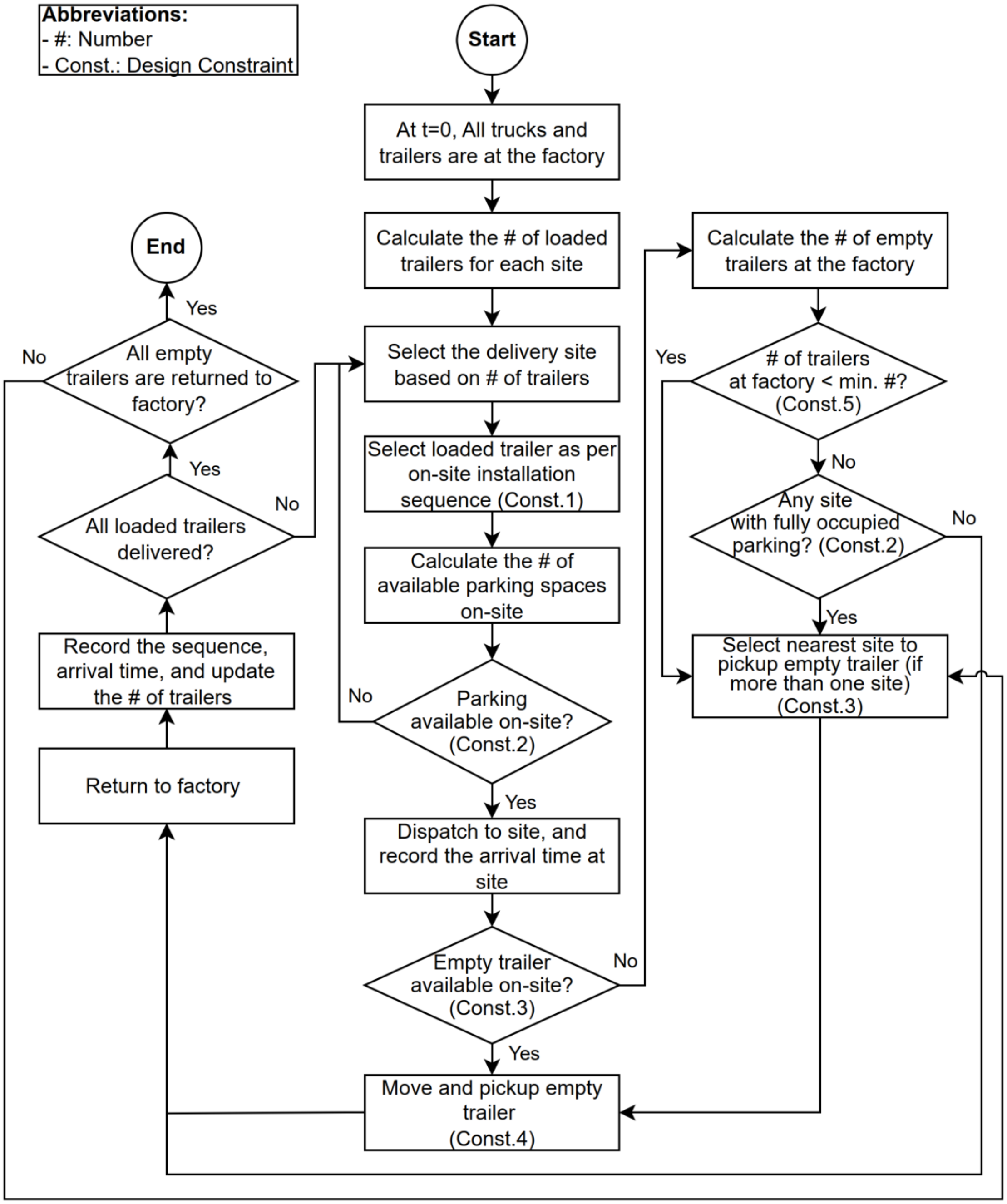


Fig. 3. Dispatching Process

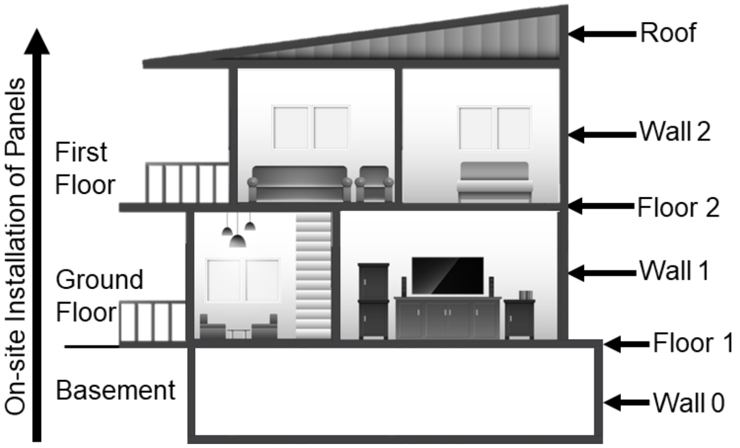


Fig. 4. Typical panel arrangement of a residential house

3.2 Calculation of travel distances

The collected factory and site locations are input into the Bing Maps API to calculate the travel distances representing per kilometer not only from the factory location to multiple site locations but also between site locations. These distances are stored as a matrix which represents an *N* x *N* where *N* is the sum of the number of construction sites and the factory as shown in Fig. 5 (e.g., in the case of 4 construction sites and one factory, the size of the distance matrix would be 5x5). The first (left) column of the matrix represents the origins and contains the factory and construction sites in consecutive order (e.g., factory, site 1, site 2), while the top row represents the destinations which are presented in the same consecutive order. The diagonal cells in the distance matrix starting from the top left are always set to zero since the distance from and to the same location is zero (e.g., factory to factory). The travel distances are used in the proposed transportation model to determine the travel times of routes which influence the dispatching decision along with the other constraints such as the pickup of empty trailer from the nearest site in case more than one empty trailer is available. The travel time is calculated based on considering a speed of 45 km/h and 55 km/h for a truck with a loaded trailer and an empty trailer, respectively. At this junction, it should be noted that the travel time in this study does not consider the status of the traffic on routes.

Travel Distance Matrix (in km)						
		Destination (to)				
		Factory	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Origin (from)	**Factory**	0.0	19.4	8.7	6.7	29.5
	Site 1	19.8	0.0	19.5	23.5	46.9
	Site 2	9.6	18.5	0.0	6.4	32.3
	Site 3	6.5	25.9	6.4	0.0	28.8
	Site 4	30.7	47.4	32.8	28.7	0.0

Fig. 5. Example of Travel Distance Matrix (in km)

3.3 Mathematical model of transportation scheduling

This research considers distribution and reverse logistics as a transportation schedule with a set of trucks and trailers from one single factory to several construction sites. That is, trucks are dispatched from the factory to deliver loaded trailers to construction sites, pick up empty trailers from construction sites and then return to the factory for other delivery tasks. Due to these complex constraints and resources in the transportation schedule of panelized construction, this research proposes a mathematical model as a metaheuristic approach to develop an optimal transportation schedule using GA instead of exact algorithms as the problem is non-deterministic polynomial-time (NP) hard which is mainly the classification for simpler transportation problems [[21], [30], [31]]. In this respect, the proposed optimization model supports to reduce the computational cost of finding an optimal transportation schedule. The transportation scheduling of panelized construction belongs to the directed graph $G = (N, E)$, as presented in Fig. 6, where $N = \{1, \dots, n\}$ is the set of factory and site locations in which 1 represents the panelized construction factory, and $2, \dots, n$ represent the construction sites, where loaded trailers are delivered to and empty trailers are picked up from, whereas the set of edges $E = \{(i, j) : i, j \in N, i \neq j\}$ represents the direction of visits for a truck from location i to location j (e.g., (1,2),(2,1),(1,3)) and $V = \{1, \dots, n\}$ is the set of available trucks in the transportation fleet. The edges are represented as black, brown, and blue arrows, where a truck with a loaded trailer travels on one of the four directions represented by the black arrow, while a truck returning to the factory with or without empty trailer travels on one of the directions presented in brown arrows, and a truck dispatched to pick up empty trailer travels on one of the blue color directions. It should be noted that since sites require more than one visit (to deliver loaded trailers and pick up empty trailers), the set of locations N includes the trailer numbers representing sites. As such, the transportation problem in this study differs from the basic VRP where each site is visited once per day.

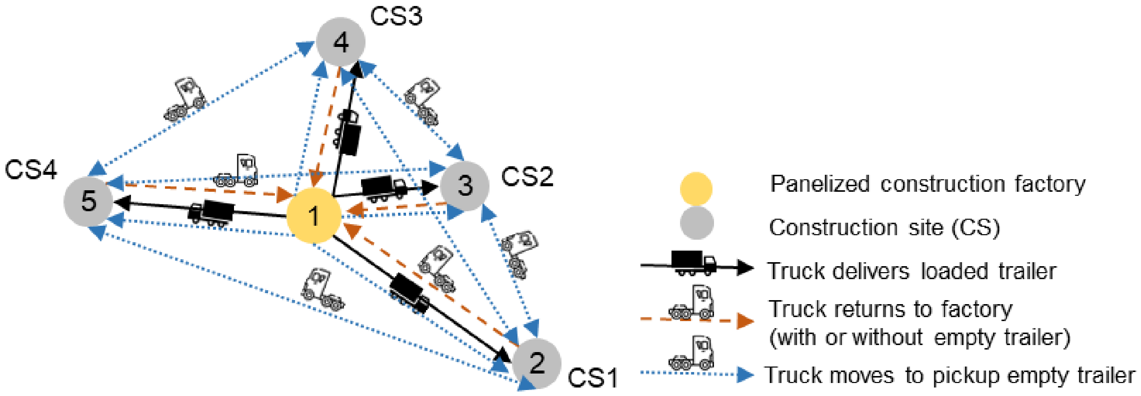


Fig. 6. Directed graph G of transportation in panelized construction

The mathematical notations used in the present work are presented in Table 2.

Table 2. Notation of proposed mathematical formulation

Symbol	**Description**
$CT_{w(k)}$	The completion time of unloading all panels from trailer k onsite
N	Set of locations (factory, delivery, and pickup locations)
Pn	Number of available parking spots at site n
Pn_{total}	Parking capacity of site n
RF_i ,$\forall\, i = Factory$	Number of available flat-type trailers at the factory
RF_{min}	Minimum number of flat-type trailers required at the factory
RF_{Total}	Total number of flat-type trailers as one of the resources
RW_i ,$\forall\, i = Factory$	Number of available wall-type trailers at the factory
RW_{min}	Minimum number of wall-type trailers required at the factory
RW_{Total}	Total number of wall-type trailers as one of the resources
S_n	Set of loaded trailer deliveries to site n corresponding to site demands (subset from N)
$T_{i,v}$,$\forall\, i \in N,\ \ v \in V$	Arrival time of truck v at location i
$T_{k,v}$,$\forall\, k \in S_n,\ \ v \in V$	Arrival time of truck v with the loaded trailer k at site
$T_{w(k),v}$,$\forall\, k \in S_n,\ \ v \in V$	Arrival time of truck v to pick up empty trailer $w(k)$ at site
TT_v ,$\forall\, v \in V$	Total operational time for truck v
UT_k	Duration of unloading and assembly of panels onsite from trailer k
V	Set of all available trucks at the factory
WH	Working hours per day defined by the user
$w(k)$	Empty trailer corresponding to loaded trailer k
$X_{i,j,v} = [0,1]$,$\forall\, i,j \in N,\ \ v \in V$	Indicates the direction of the visit (from location i to j by truck v)

3.3.1 Decision variables

To minimize the transportation times of trucks, the decision variables of the proposed mathematical model are determined based on the VRP concept and the dispatching process described above. As a result, the proposed decision variables are:

i. $X_{i,j,v}$, representing the truck route or direction of visit, is a binary variable that is equal to 1 if truck v travels from location i to j, otherwise it is 0 if that route is not visited by the truck.

ii. $T_{i,v}$ is an integer variable representing the arrival time of the truck at location i in seconds.

iii. TT_v is an integer variable representing the total operating time of a truck in seconds.

iv. RF_i and RW_i are integer variables representing the number of available flat- and wall-type trailers, respectively, at the factory.

v. P_n is an integer variable representing the number of available parking spots at site n.

3.3.2 Design constraints and objective function

Based on the dispatching process described above, constraint 1 guarantees that all deliveries to a given site follow the sequences of panels installation onsite as outlined in Eq. (1), in other words; the arrival time of truck with the loaded trailer $T_{(k+1),v}$ in the succeeding delivery must be greater than or equal to the arrival time of truck with the loaded trailer $T_{k,v}$ in the preceding delivery. This ensures that the loaded trailers are delivered in a sequential order to avoid unnecessary occupying space at the site and maintain the sequences of panel assembly on-site.

$$\sum_{v \in V} T_{(k+1),v} \geq \sum_{v \in V} T_{k,v} \quad \forall\, k \in S_{\mathrm{n}} \qquad (1)$$

Constraint 2 representing in Eq. (2) ensures that there are sufficient available parking spaces on-site before delivering loaded trailers to the site by evaluating the number of available parking spaces with respect to the parking capacity of the site. In the event that all parking spaces onsite are occupied, this constraint necessitates the return of empty trailers from the site to the factory before delivering the loaded trailers to the site. The number of available parking spots onsite is determined using Eq. (3), and is calculated by deducting the total number of loaded trailers dispatched to the site, from the site's parking capacity and then adding the total number of empty trailers returned to the factory. For instance, if site 1 has a total capacity of 5 parking spaces and received a total of 6 loaded trailers of which 3 are emptied and returned to the factory, the number of available parking spaces onsite is 2.

$$0 \leq \ Pn \leq \ Pn_{total} \tag{2}$$

$$Pn = Pn_{total} - \sum_{k \in \mathrm{S_n}} \sum_{v \in V} X_{i,k,v} + \sum_{k \in \mathrm{S_n}} \sum_{v \in V} X_{w(k),i,v} \quad \forall \ i \in Factory, n \ is \ the \ site \ \text{no.} \tag{3}$$

Eq. (4) represents constraint 3 which ensures that the arrival time of the truck at a site to pick up an empty trailer $T_{w(k),v}$ occurs after the completion time of unloading all panels from the trailer $CT_{w(k)}$ which is calculated by Eq. (5) and (6). In Eq. (5), the unloading completion time is calculated by the sum of arrival time of truck with the loaded trailer at the site and the unloading duration of panels from the trailer, whereas Eq. (6) indicates that the unloading time of the loaded trailer commence after completing the unloading from preceding loaded trailer on-site, hence following the precedence relationship (finish to start) and ensuring that only one trailer is unloaded at a time since only one crane is operated on a site. For instance, the completion time of unloading panels from the first trailer is calculated by Eq. (5) while the completion time of unloading panels from the second trailer must satisfy Eq. (5) and (6) since the unloading of panels from the second trailer can only start after completing the unloading of panels in the first trailer.

$$\sum_{v \in V} T_{w(k),v} \geq \ CT_{w(k)} \tag{4}$$

$$CT_{w(k)} \geq \sum_{v \in V} T_{k,v} + \mathrm{U}T_k \quad \forall\, k \in \mathrm{S_n} \tag{5}$$

$$CT_{w(k)} \geq \; CT_{w(k-1)} + \mathrm{U}T_k \quad \forall\, k \in \mathrm{S_n}, \qquad k > 1 \tag{6}$$

As represented in Eq. (7), constraint 4 is to pick up an empty trailer from a site in a consecutive order following the sequence of panels unloading onsite. Hence, the arrival time of the truck at site to pick up empty trailer $T_{w(k+1),v}$ in the succeeding pickup must be greater than or equal to the arrival time of the truck to pick up empty trailer $T_{w(k),v}$ in the preceding pickup activity.

$$\sum_{v \in V} T_{w(\mathrm{k}+1),v} \; \geq \sum_{v \in V} T_{w(k),v} \quad \forall \;\; \mathrm{k} \in S_{\mathrm{n}} \tag{7}$$

Constraint 5 representing in Eq. (8) and (9) ensures that sufficient number of empty flat- and wall-type trailers are available at the factory by comparing the number of available trailers at the factory with the minimum number of trailers that should maintain at the factory in order to ensure continuity of production line operations, which forces the return of empty trailers from sites to the factory as soon as the number of available trailers at the factory reaches below the limit (RF_{min} or RW_{min}). For example, if the factory has 20 trailers, in which at least 10 trailers need to be maintained at the factory, once the number of available trailers at the factory reaches below 10, the return of empty trailers from sites to the factory is immediately considered.

$$RF_{min} \leq RF_i \leq RF_{total} \quad \forall\, i \in Factory \tag{8}$$

$$RW_{min} \leq RW_i \leq RW_{total} \quad \forall\, i \in Factory \tag{9}$$

Although the dispatching process section describes five constraints, as optimal transportation scheduling problems, two more constraints are defined. Constraint 6, as formulated by Eq. (10), ensures that the total operating time of any truck does not exceed the working hours per day defined by the user (WH). This constraint guarantees that the transportation activities are distributed evenly among available trucks without exceeding the operating time of the transportation fleet. Constraint 7 using Eq. (11) ensures that each transportation activity (e.g., delivery of a loaded trailer to site 1) is assigned to only one truck at a time to prevent any repetitive activities into different trucks. Constraint 7 also provides flexibility to select the suitable direction of visit to complete a loaded trailer delivery to site or a pickup of empty trailer from site. For example, consider that an empty trailer at site 2 in Fig. 6 needs to be returned to the factory. The truck has the option to either travel directly from the factory to site 2 or move from site 1,3 or 4 to site 2 to collect the empty trailer, depending on where the truck is located. Therefore, in this scenario of picking up an empty trailer, only one direction of visit is necessary.

$$TT_v \leq WH \quad \forall\, v \in V \tag{10}$$

$$\sum_{v \in V} X_{i,j,v} \leq 1 \quad \forall\, i, j \in N, i \neq j \tag{11}$$

Based on the design constraints, the objective function is to minimize the total operational time of all trucks formulated by Eq. (12). This accounts for the travel times of trucks involving delivering loaded trailers to construction sites and return empty trailers from sites to the factory as well as any waiting times that the trucks may encounter throughout the transportation cycle.

$$f = Min. \sum_{v \in V} TT_v \tag{12}$$

The efficiency of the transportation fleet is defined as the ratio of truck productive time to the total operating time and is calculated using Eq. (13).

$$Efficiency = \frac{\sum_{v \in V} TT_v - total\ waiting\ time}{\sum_{v \in V} TT_v}\ x100\% \tag{13}$$

3.4 Optimization of transportation scheduling

The proposed mathematical model is applied into GA to optimize the transportation schedules of trucks and process times of the trailers onsite consisting of waiting times before, after and during unloading. Although GA is one of the meta-heuristic algorithms which is widely used in solving optimization problems including planning and scheduling [[10], [23], [25]], it is not explored yet in solving the transportation scheduling of panelized construction which includes distribution and reverse logistics and associated design constraints among multiple construction sites and one single factory. To reflect the transportation problems in the panelized construction, a GA-based approach is proposed within additional operators described in detail below compared to the conventional GA. As shown in Fig. 7, the proposed GA model consists of eight steps:

i. Randomly generating a number of transportation schedules as an initial population by randomly sorting the delivery and pickup loaded and empty trailers among all sites.

ii. Applying all design constraints into the initial population.

iii. Calculating the fitness score of the chromosomes in the population.

iv. Performing the selection process to identify potential parents that is used to produce the offspring (i.e., new schedules).

v. Implementing the crossover to produce new offspring that represents new distribution and reverse transportation schedules.

vi. Mutating the new offspring to increase the diversity of the population.

vii. Applying the sliding operator to increase the diversity of the population by moving one transportation activities from a truck schedule to another truck schedule; and

viii. Executing the repair operator to ensure that constraints 1 and 4 are satisfied.

It should be noted that steps (7) and (8) are the new operators added to the GA algorithm to reflect the nature of the transportation scheduling problem defined in this study (multi-trucks and trailers operating in multi-sites with distribution and reverse transportation operations).

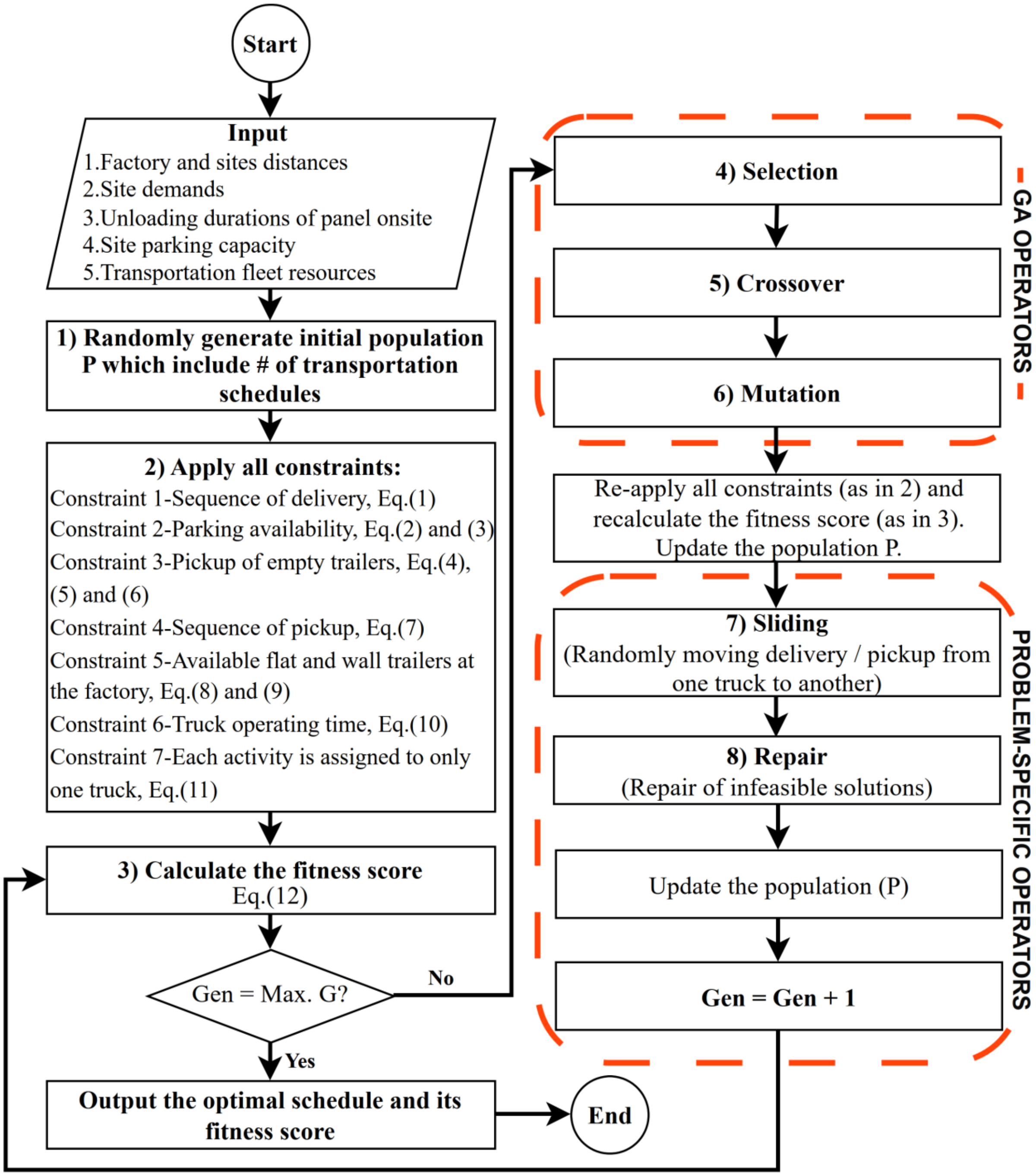


Fig. 7. Proposed GA framework flow chart

As shown in Fig. 8, the structure of the generated chromosome, which represents a potential solution (i.e., multiple trucks schedule), is broken down in accordance with the number of available trucks at the factory. The number of chromosomes (or schedules) in a population is determined depending on the population size defined by users.

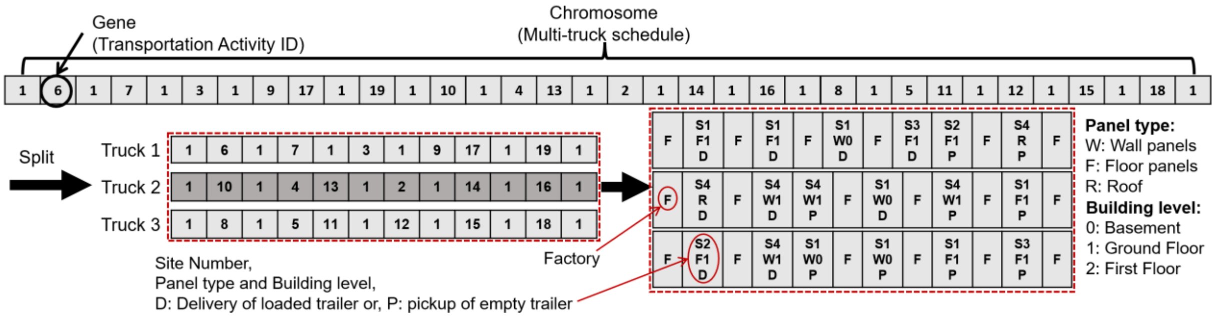


Fig. 8. An example of a chromosome for multiple trucks

Each chromosome in the population contains several genes, where a gene represents a transportation activity in the overall schedule. As represented in Fig. 9, each delivery (i.e., loaded trailer) is assigned into a distinct number starting from 2 and linked to the relevant site while the number 1 is exclusively assigned to the factory. Similarly, the return or pickup of empty trailers are assigned by numbers commencing immediately after the last delivery number. For instance, the factory is scheduled to deliver 9 loaded trailers involving 4 wall-type and 5 flat-type to two sites. Site 1 requires 3 wall-type trailers and 3 flat-type trailers while the rest goes to site 2. The loaded wall-type and flat-type trailers are defined from IDs 2 to 5 and from IDs 6 to 10, respectively. These trailers are assigned to the relevant sites consecutively (e.g., wall-type trailers 2,3,4 and flat-type trailers 6,7,8 are assigned to site 1, then wall-type trailer 5 and flat type trailers 9 and 10 to site 2). The corresponding empty trailers follow the same system, and their IDs start after the last loaded trailer (i.e., from 11 to 19). The relation between the unique number (ID) assigned to a loaded trailer k and its corresponding empty trailer $w(k)$ is given by Eq. (14), where

ND is the sum of all loaded trailers to be delivered. This structured approach allows identification and tracking of each trailer (loaded or empty) to its corresponding site, panel type, and trailer type.

$$w(k) = k + ND \tag{14}$$

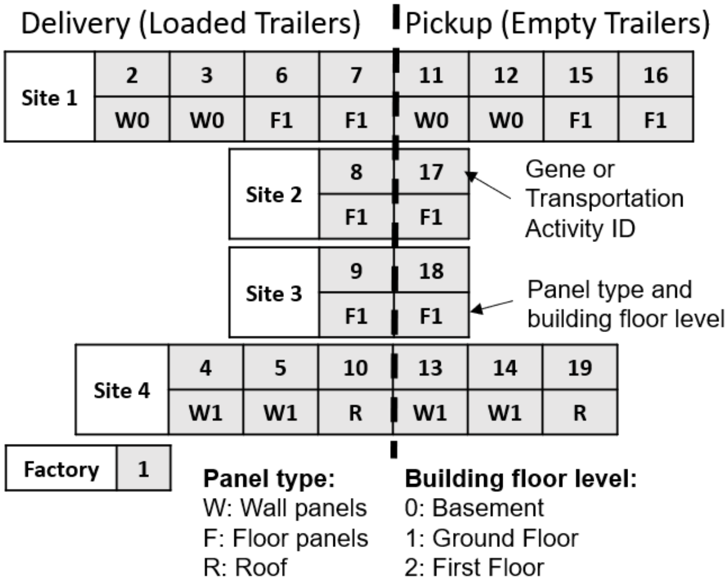


Fig. 9. Details of genes in the chromosome

Given the randomness of initial population generation, chromosomes (i.e., schedule) initially violate the design constraints. Therefore, chromosomes in the population are updated to ensure all constraints are satisfied. Then, the fitness score (objective function) of each chromosome is calculated and used in the selection process. In the proposed GA algorithm, the tournament selection [54] method is implemented to select the potential parents (chromosomes) that produce the offspring (i.e., new schedules) and the next generation of the population.

Following the selection of two parents, partially mapped crossover (PMX) is employed to produce the offspring of the next generation. PMX, introduced by Goldberg and Lingle [54], is one of the effective crossover techniques implemented in vehicle routing problems [[55], [56]]. In this method, a subsection is chosen randomly from the first parent and then swapped with the corresponding subsection from the second parent to create the offspring. The mapping relation between both subsections is determined to replace the repeated genes in each chromosome with corresponding genes to ensure no duplication of genes with identical values. Through the crossover process, offspring inherit some characteristics from their parents which may improve the quality of the solution. The PMX process is illustrated in Fig. 10. As shown in the figure, genes 5,7,4,6 from the first chromosome (parent 1) are exchanged with genes 3,2,4,8 from the second chromosome (parent 1) to generate the two new offspring, and the mapping relation between the genes in the two subsections (presented by the arrows in the same figure) is identified to replace the duplicate genes in the offspring chromosomes as shown in red color (e.g.; in offspring 1 the second gene (2) is replaced with (7) as per the mapping relation since the crossover has resulted in two genes of the same number/sequence (2)).

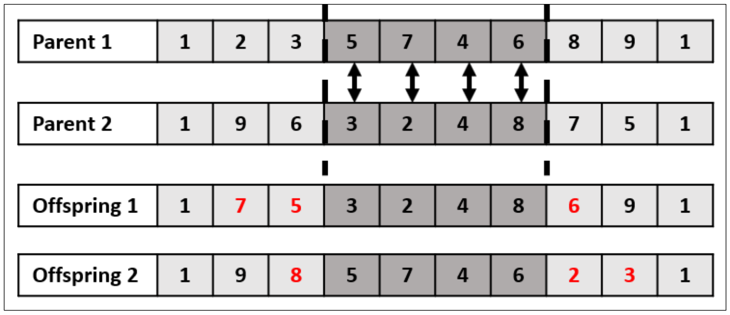


Fig. 10. Partially Mapped Crossover (PMX).

Then, swap mutation is applied to the offspring upon meeting mutation probability to increase the diversity of the population and allow exploration of the search space [54]. Mutation occurs by randomly selecting two genes in a chromosome and swapping their position as illustrated in Fig. 11, where the positions of genes 11 & 15 are swapped. Mutation can occur only if the mutation rate is met. A well-tuned mutation rate contributes to the effectiveness of the GA, where a low rate may not provide sufficient diversity in the population, and a high rate increases the diversity but will also increase the running cost of the GA.

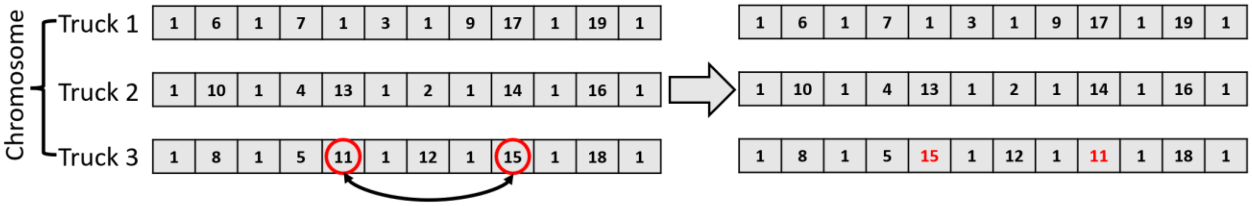


Fig. 11. Representation of swap mutation

3.4.1 Sliding

After generating new schedules using crossover and mutation, a sliding technique is introduced to further diversify the population. This technique involves randomly selecting two truck schedules within a single chromosome (which represents multiple trucks schedule), and then transferring a randomly chosen gene (activity) from one truck's schedule to the other. For instance, as illustrated in Fig. 12, the schedules of truck 1 and truck 2 are chosen, then a gene (2) from truck 2 schedule is chosen randomly and moved to truck 1's schedule resulting in a longer sequence for truck 1 schedule. This differs from mutation, which typically involves swapping two genes within the same truck schedule, keeping the same count of genes among truck schedules within one single chromosome. Whereas sliding varies the number of genes among the truck schedules within a chromosome, resulting in a broader range of potential solutions which increases the chances of finding an optimal solution. The sliding operator is applied more frequently than mutation to increase the diversity of the population. The fitness score of the modified chromosome is calculated and compared with that of the original chromosome, and the chromosome with the better fitness score is retained.

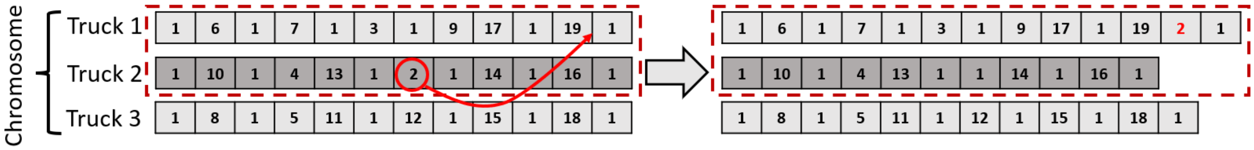


Fig. 12. Representation of sliding operator

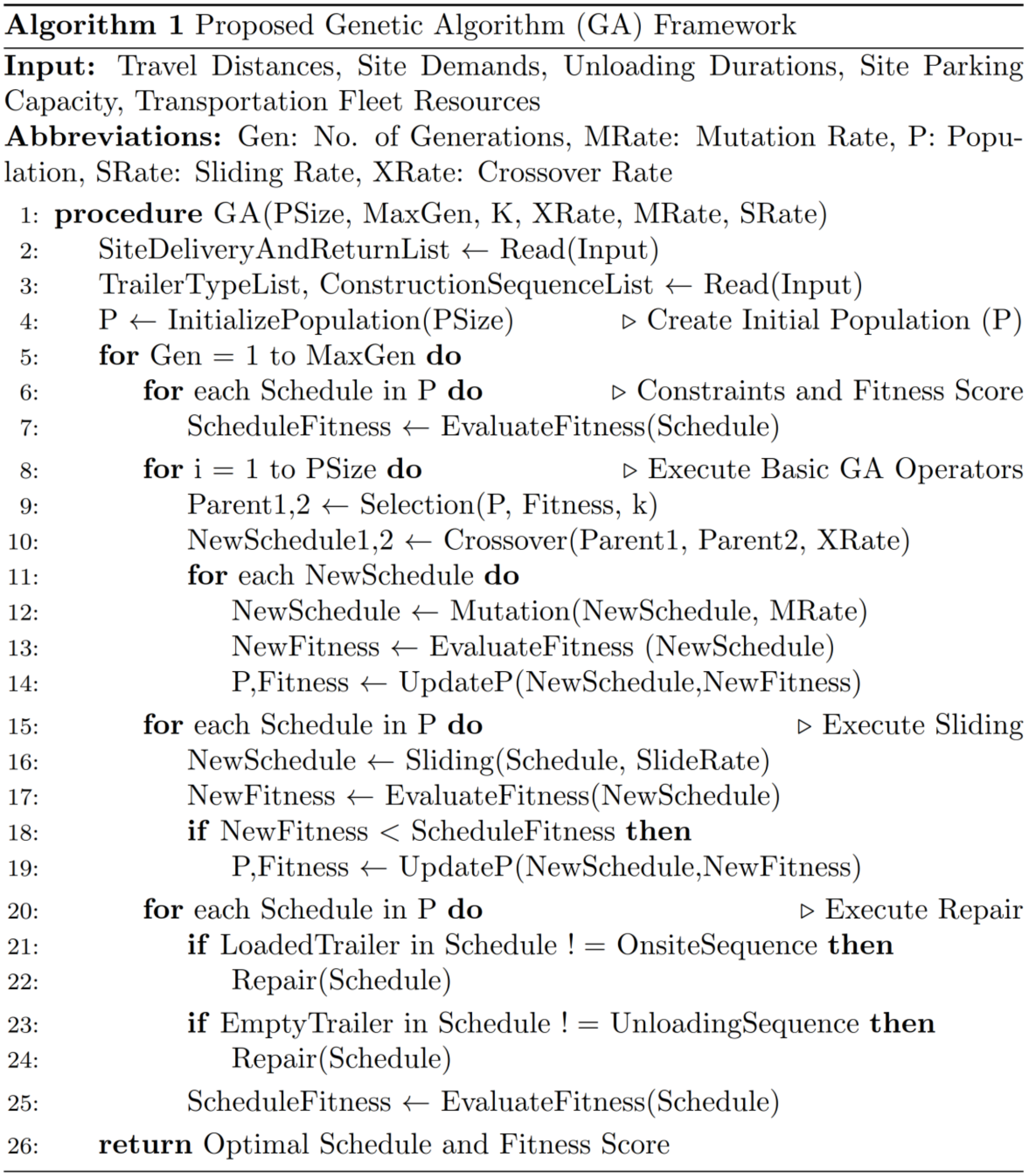
3.4.2 Repair

The final step in the proposed algorithm is to repair any solution where design constraints 1 and 4 are not satisfied. The repair is mainly used to ensure:

i. Delivery of loaded trailers to sites based on the sequence of onsite installation; and

ii. First come and first serve concept (i.e., first trailer emptied, is the first to be returned).

The repair operation verifies the sequence of loaded trailer delivery to sites and empty trailer pickup from sites, then swaps the activities that have the wrong sequence in the schedule until the correct sequence is achieved. As a result, this repair process is important to ensure that the final transportation schedules comply with the defined design constraints. The detailed steps of the proposed GA, including the repair and sliding operators, are explained in the pseudo-code presented in Fig. 13.



Algorithm 1 Proposed Genetic Algorithm (GA) Framework

Input: Travel Distances, Site Demands, Unloading Durations, Site Parking Capacity, Transportation Fleet Resources

Abbreviations: Gen: No. of Generations, MRate: Mutation Rate, P: Population, SRate: Sliding Rate, XRate: Crossover Rate

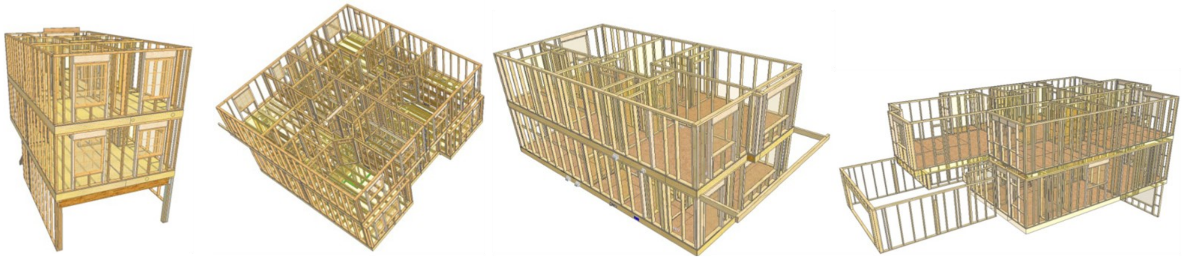
```
procedure GA(PSize, MaxGen, K, XRate, MRate, SRate)
    SiteDeliveryAndReturnList ← Read(Input)
    TrailerTypeList, ConstructionSequenceList ← Read(Input)
    P ← InitializePopulation(PSize)            ▷ Create Initial Population (P)
    for Gen = 1 to MaxGen do
        for each Schedule in P do              ▷ Constraints and Fitness Score
            ScheduleFitness ← EvaluateFitness(Schedule)
        for i = 1 to PSize do                  ▷ Execute Basic GA Operators
            Parent1,2 ← Selection(P, Fitness, k)
            NewSchedule1,2 ← Crossover(Parent1, Parent2, XRate)
            for each NewSchedule do
                NewSchedule ← Mutation(NewSchedule, MRate)
                NewFitness ← EvaluateFitness (NewSchedule)
                P,Fitness ← UpdateP(NewSchedule,NewFitness)
        for each Schedule in P do                        ▷ Execute Sliding
            NewSchedule ← Sliding(Schedule, SlideRate)
            NewFitness ← EvaluateFitness(NewSchedule)
            if NewFitness < ScheduleFitness then
                P,Fitness ← UpdateP(NewSchedule,NewFitness)
        for each Schedule in P do                        ▷ Execute Repair
            if LoadedTrailer in Schedule ! = OnsiteSequence then
                Repair(Schedule)
            if EmptyTrailer in Schedule ! = UnloadingSequence then
                Repair(Schedule)
            ScheduleFitness ← EvaluateFitness(Schedule)
    return Optimal Schedule and Fitness Score
```

Fig. 13. Pseudo code of proposed algorithm

Chapter 4: Case Study

4.1 Overview and input information

The framework is applied on data collected from a panelized construction factory, in Edmonton, Alberta, Canada to validate its efficiency to develop optimal transportation schedules for the distribution and reverse logistics of panelized construction. There are 3 trucks, 20 wall-type trailers for wall panels, and 35 flat-type trailers for floor and roof panels as the transportation fleet. The factory produces prefabricated panels (walls, floors, and roofs) for various residential projects, including duplex, townhome, single family home, and bungalow as shown in Fig. 14. Based on the site demands, panels at the factory are produced at least one day before the intended delivery date and loaded into trailers. Loaded trailers are dispatched to relevant sites on the planned installation day to achieve just-in-time delivery and minimize any on-site storage. Upon delivery of the loaded trailers, the unloading and onsite assembly of panels may begin immediately if a crane is on standby. Otherwise, the trailer waits until all panels from the previous trailer are unloaded and assembled. Therefore, it is important to deliver the loaded trailers involving panels in accordance with the site demands so that the limited number of parking spots are used efficiently and effectively. Once a trailer is emptied, it becomes ready to be returned to the factory. The timely return of empty trailers to the factory is vital to maintain the continuity of production operations at the factory and prevent potential bottlenecks due to the absence of empty trailers to load the finished panels at the factory. Moreover, the pickup of empty trailers from sites provides vacant parking spaces for the loaded trailers delivered from the factory. Typically, at the end of the day, trucks are dispatched to return empty trailers from sites to the factory. The factory operates for 10 hours daily, and 5 days per week.



Townhome **Duplex** **Single family home with detached garage** **Single family home with attached garage**

Fig. 14. Types of houses [57]

To validate the effectiveness of the proposed methodology, this study uses four construction sites (CS). Each site constructs different types of houses which require various number of trailers. For example, site 1 needs a total of eleven trailers consisting of two wall-type and nine flat-type trailers but site 3 requires five trailers consisting of one wall-type and four flat-type trailers. Table 3 represents the panel types, number of trailers and associated types, and types of houses at each site. The onsite unloading and assembly duration of panels, the duration required for a truck to pick up a loaded trailer at the factory and the duration needed for a truck to locate and pick up an empty trailer onsite (Table 4) are obtained from Ahn et al. [6]

Table 3. On-site demands

Site No.	Panel type and level	No. of trailers	Trailer type	Model type	Dispatching Priority
CS 1	Wall 1	1	Wall Trailer	Single family home with attached garage	1
CS 1	Floor 2	2	Flat Trailer		
CS 1	Wall 2	1	Wall Trailer		
CS 1	Roof	7	Flat Trailer		
CS 2	Floor 1	1	Flat Trailer	Single family home with attached garage	3
CS 3	Wall 1 and Wall 2	1	Wall Trailer	Bungalow	2
CS 3	Floor 2	1	Flat Trailer		
CS 3	Roof	3	Flat Trailer		
CS 4	Floor 1	1	Flat Trailer	Single family home	3

Table 4. Pick up and unloading durations

Activity	Avg. duration (min.)
Unload floor panels from trailer	50
Unload wall panels from trailer	55
Unload roof panels from trailer	25
Pick up of loaded trailer at the factory	10
Locate and pick up of empty trailer from site	18

Factory and site coordinates were obtained from the given addresses and are added into the Bing Maps API spreadsheet to calculate the driving distance matrix between the factory, CS, and all CSs. Fig. 15 illustrates the factory and site locations, travel distance matrix, and routes from the factory to sites.

Input
Factory and Site Coordinates

	Latitude	Longitude
Factory	53.49137	-113.40872
CS1	53.401159	-113.554400
CS2	53.438850	-113.376119
CS3	53.476628	-113.346907
CS4	53.561915	-113.141187

Calculate

Output
Travel Distance Matrix

Origin \ Destination	Factory	CS1	CS2	CS3	CS4
Factory	0.0	19.4	8.7	6.7	29.5
CS1	19.8	0.0	19.5	23.5	46.9
CS2	9.6	18.5	0.0	6.4	32.3
CS3	6.5	25.9	6.4	0.0	28.8
CS4	30.7	47.4	32.8	28.7	0.0

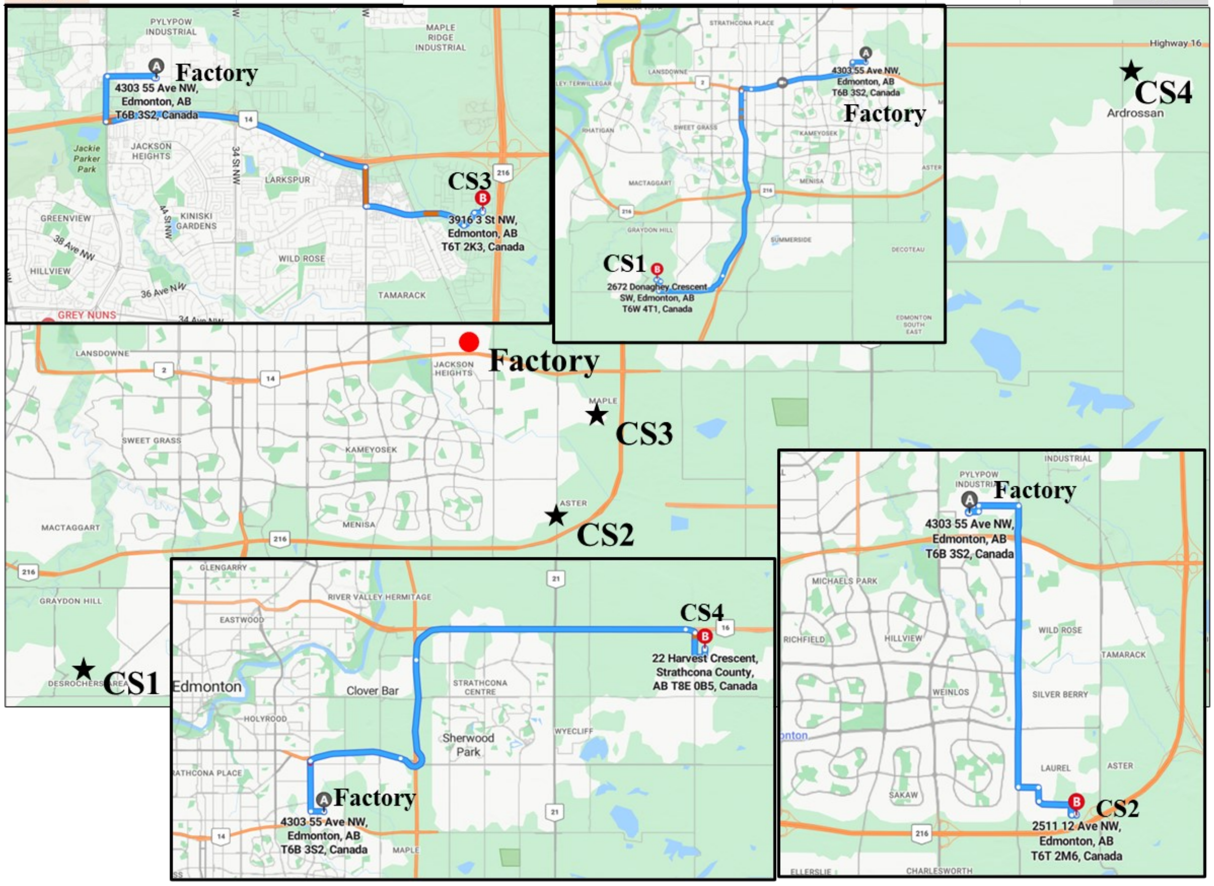


Fig. 15. Locations, travel distance matrix and travel routes

4.2 Results and discussions

All input data are added into the developed mathematical optimization model in GA to determine the optimal schedule for the distribution and reverse transportation operations of trucks and process times of trailers on-site. The convergence of the proposed GA, illustrated in Fig. 16, indicates that the developed model was able to achieve the optimal schedule within a generation size of 1000, population size of 50 chromosomes (i.e., schedules), tournament selection size of 3 chromosomes, crossover, mutation, and sliding rates of 0.7, 0.1, and 0.7 respectively.

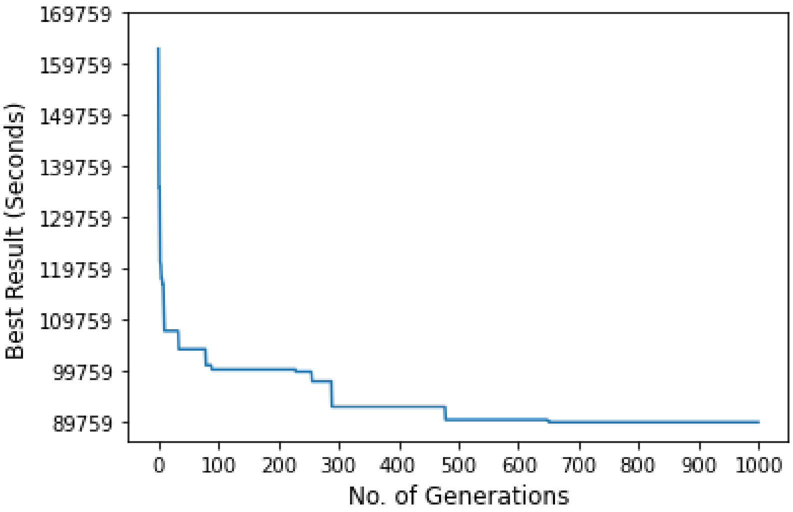


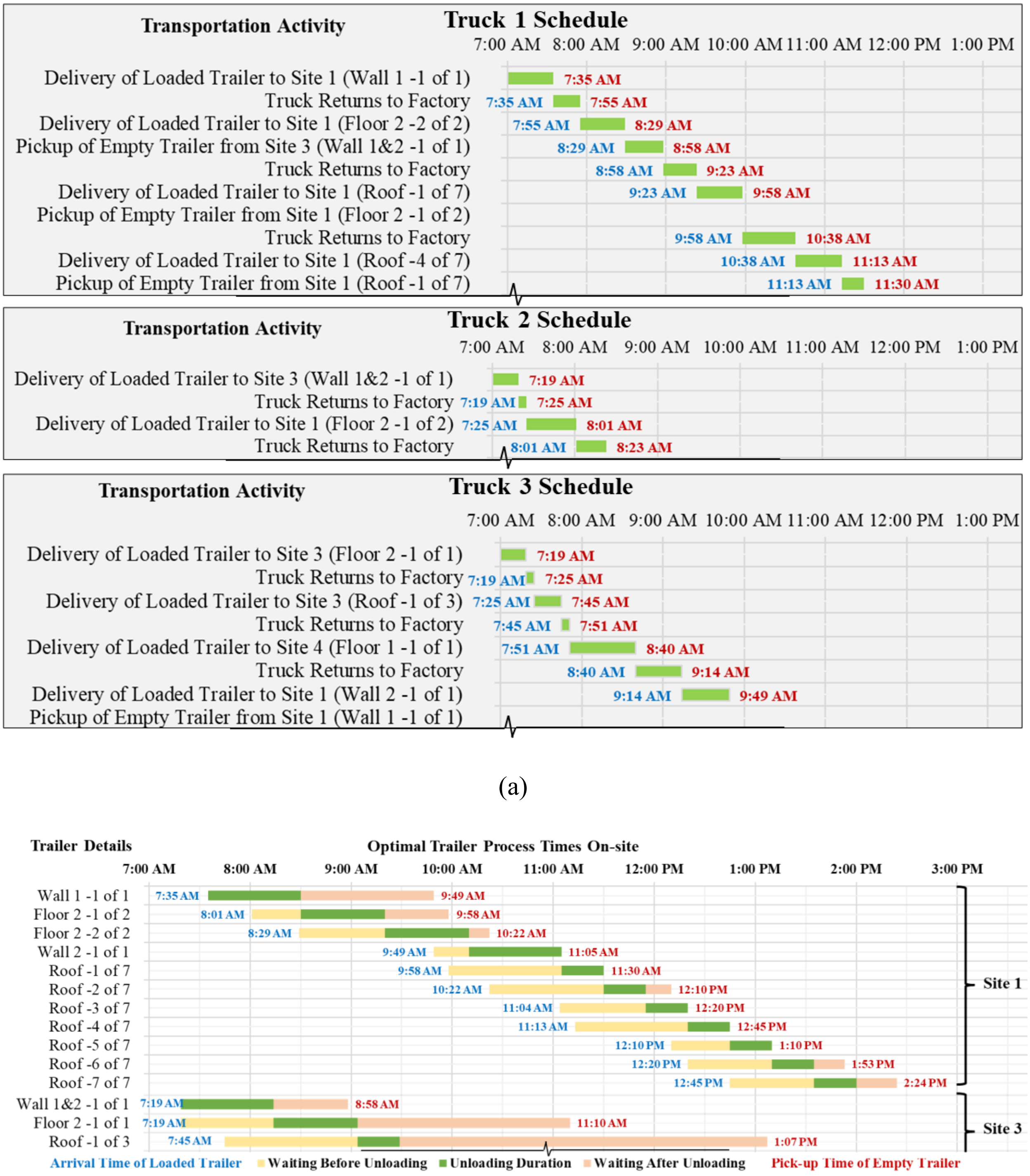
Fig. 16. Genetic algorithm convergence

To verify the outcomes of the developed optimization model, the optimal transportation schedules were evaluated based on the sequences of the dispatching process and the seven design constraints presented in the mathematical model section. According to the dispatching process, the delivery of loaded trailers begins with establishing the dispatching priority list based on number of loaded trailers required at each site. For example, as shown in Table 3, site 1 is the first priority since it requires 11 loaded trailers, followed by site 3 as the second priority with 5 trailers, then sites 2 and 4 in the third place. The sequences of on-site installation (see Fig. 4) at site 1 are wall panels on 1st level, floor panels on 2nd level, wall panels on 2nd level, and roof panels. Based on the information shown in Table 5 and Fig. 17(a), Truck 1 begins its operations at 7:00 am and dispatches the wall-type trailer with wall panels of 1st level to site 1 (Wall 1 -1 of 1) based on the onsite installation sequence. Concurrently, truck 2 dispatches the first loaded wall-type trailer carrying the wall panels for 1st and 2nd levels to site 3 based on the on-site installation sequence at site 3. Before dispatching any loaded trailer from the factory, the project manager confirms the availability of on-site parking spots as presented in Table 5, which shows that four parking spots are available before the first loaded trailer is dispatched to site 1. Upon the arrival of truck 1 with the loaded trailer at site 1 at 7:35 am, the travel time of truck 1 is recorded in Table 5. Once truck 1 unloads the trailer, it returns to the factory since there is no empty trailer on site 1 considering that this is the first delivery, as well as the count of empty trailers on the factory is above 10 trailers per type which is the minimum number of trailers. Upon arrival of truck 1 at the factory at 7:55 am, the project manager confirms that two parking spots are still available at site 1, then the dispatches the second batch of the 2nd level floor panels (Floor 2 -2 of 2) with truck 1 to site 1 since the previous batch (Floor 2 -1 of 2) was dispatched at 7:25 am by truck 2. Upon arrival of truck 1 with the loaded trailer at site 1 at 8:29 am, it records the arrival time, unloads the trailer and identifies that the unloading of panels from the first trailer at site 1 (Wall 1 -1 of 1) is not completed, but there is an empty wall-type trailer (Wall 1&2 -1 of 1) located at site 3 as illustrated in Fig. 17(b) which represents the process times of trailers onsite (i.e., arrival time of loaded trailer at site, unloading time, and pick up time of empty trailers from site). The count of empty trailers per type at the factory is still above the limit indicating that the factory does not require urgent return of empty trailers. However, as the parking spots on site 3 are occupied, while site 1 still have available spots, truck 1 moves to site 3 and arrives at 8:58 am to pick up and return the empty trailer to make available parking spots on site 3 for the next delivery. While truck 1 is on the way to the factory with the empty trailer, truck 3 dispatches the loaded wall-type trailer with 2nd level wall panels (Wall 2 -1 of 1) from the factory to site 1 at 9:14 am, arrives at site 1 at 9:49 am, then picks up the first empty wall-type trailer (Wall 1 -1 of 1) from site 1 complying with the first come and first serve concept and to clear parking spots for the next delivery. After truck 1 returns to the factory with the empty trailer from site 3, truck 1 dispatches the loaded flat-type trailer with roof panels (Roof – 1 of 7) to site 1 at 9:23 am after confirming the availability of one parking spot on site 1. Upon arrival at site 1 at 9:58 am, truck 1 records the travel time, unloads the trailer, and collects the identified empty trailer flat-type trailer at site 1 (Floor 2 -1 of 2), to make available parking spot for the next delivery. The number of available parking spots at site 1 ranges between 1 to 4 as shown in Table 5 which satisfies design constraint 2. The operations for trucks 1, 2 and 3 continue until all loaded trailers are delivered to sites and empty trailers are returned to the factory at the end of the working day as shown in the detailed schedules provided in Appendix A. Throughout the distribution and reverse transportation operations, the arrival time of loaded trailers at site 1, and the completion time of unloading the panels from loaded trailers onsite are based on the onsite installation sequence which proves the compliance with design constraints 1 and 3 respectively. The pickup time of empty trailer from site 1 satisfies the first come and first serve concept (i.e., design constraint 4). It should be noted that the total number of flat-type and wall type trailers were considered as 25 and 15 respectively which is slightly lower than the declared factory resources given that, in reality some trailers some trailers maybe in-use by the production line for other projects. At any given time, the number of available flat-type and wall-type empty trailers at the factory is above the minimum number of trailers, which complies with design constraint 5 as demonstrated in Table 5.

The total operational time of each truck as obtained from the optimal schedules are $TT_1 = 31{,}003$, $TT_2 = 26{,}569$ and $TT_3 = 32{,}187$ seconds, which satisfies design constraint 6 considering 10 work hours per day (36,000 sec) for the transportation fleet, and each truck performs its own unique transportation activities as per constraint 7, as illustrated in Fig. 17(a) representing the optimal distribution and reverse transportation schedules of trucks.

Table 5. Examples of design constraints 1 through 5 at site 1

Loaded trailer details **panel type, level - trailer#**	**Arrival time of truck with the loaded trailer at site, in second** $T_{k,v}$	**Number of available parking spots at site** $P1$	**Completion time of unloading all panels from trailer, in second** $CT_{w(k)}$	**Arrival time of truck to pick up empty trailer, in second** $T_{w(k),v}$	**Number of available flat-type trailers at the factory** RF_i	**Number of available wall-type trailers at the factory** RW_i
Wall 1 -1 of 1	2120	4	5420	10173	22	13
Floor 2 -1 of 2	3672	3	8420	10711	20	13
Floor 2 -2 of 2	5340	2	11420	12179	19	13
Wall 2 -1 of 1	10173	1	14720	14720	15	13
Roof -1 of 7	10711	1	16220	16220	15	13
Roof -2 of 7	12179	1	17720	18618	15	13
Roof -3 of 7	14682	1	19220	19229	14	14
Roof -4 of 7	15220	1	20720	20729	14	14
Roof -5 of 7	18618	1	22220	22250	12	15
Roof -6 of 7	19229	1	23720	24791	12	15
Roof -7 of 7	20729	1	25220	26684	12	15



(b)

Fig. 17. Example of (a) optimal transportation schedules, (b) process times of trailers onsite

Based on the arrival time of loaded trailers at sites, and pickup time of empty trailers from sites, , Fig. 18 is developed to represent the compliance the onsite parking capacity, where the orange line represents the trailer parking capacity of each site while the black solid line represents the count of trailers onsite at any given time. Given that each site can accommodate a limited number of trailers at any time depending on the available space onsite and location of the site, it is important to consider the on-time delivery with the available parking spots onsite when generating the optimal schedules to prevent unnecessary trailer relocations and associated delays resulting from the delivery of loaded trailers that are not immediately required onsite. The figure also demonstrates achieving a 100% completion rate for the return of empty trailers from sites to the factory.

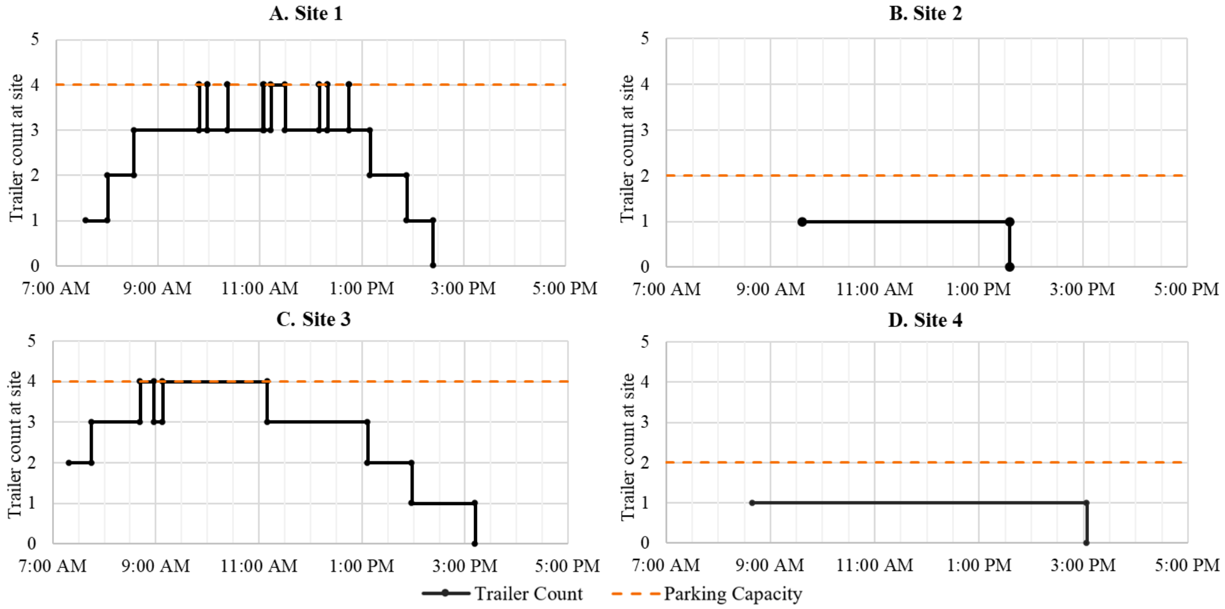


Fig. 18. Trailer count and parking capacity at construction sites

The optimal transportation activities for each truck, direction of visit ($X_{i,j,v}$) and arrival times ($T_{i,v}$) are illustrated in Fig. 19. The sequence of activities shows the uninterrupted fleet operations throughout the distribution and reverse transportation operations leading to minimized total fleet operation time of 89,759 seconds (i.e., the objective function of the optimization). The efficiency of the transportation fleet was calculated from the optimal transportation schedules as 98.8% which proves the model's capabilities in generating optimal schedules. The reduction in efficiency is due to waiting time (shown as a horizontal line) encountered by truck 1 (17 min) at site 1 after completing the loaded trailer delivery until the unloading of panels from the flat-type trailer (Roof -1 of 7) is completed. The timely pickup of the empty trailer is crucial to avoid impacting the next loaded trailer deliveries to site 1 since all parking spots.

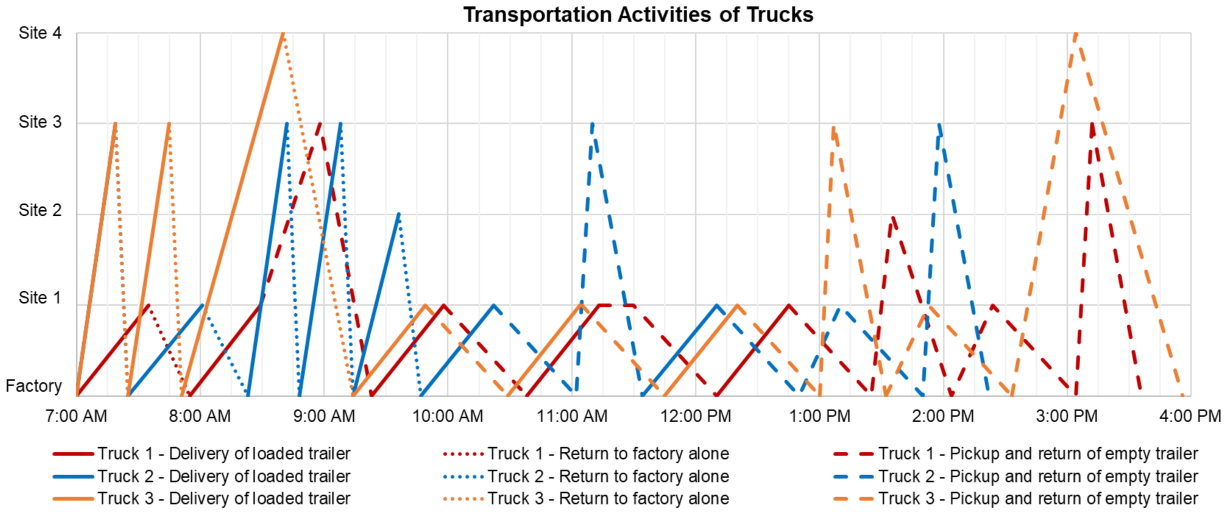


Fig. 19. Optimal transportation activities for trucks

The results of the developed framework prove that the model effectively generates the optimal schedules of distribution and reverse transportation operations benefiting the factory and construction sites simultaneously. On one hand, it ensures continuous factory operations through a seamless transportation process and by ensuring availability of empty trailers, which allows the production team to load finished panels in a timely manner, thereby preventing potential production line bottlenecks due to a shortage of empty trailers. On the other hand, it ensures continuous crane and panels assembly operations onsite by eliminating the waiting time between deliveries and delivering loaded trailers as per the site requirements. The generated process times of trailers onsite provide detailed information related to the delivery of loaded trailers to each site which helps the construction team plan the on-site activities and their resources efficiently.

Chapter 5: Conclusion

5.1 Summary and contributions

In panelized construction, several types of panels are manufactured in an indoor controlled environment and then transported to construction sites using trucks and trailers, where panels are unloaded directly from the trailers via cranes and immediately installed on-site due to limited storage space and parking spots for trailers. Once panels are unloaded, empty trailers must be returned to the factory that relies on loading manufactured panels on empty trailers to avoid production bottlenecks. This unique nature of panelized construction creates a unique distribution and reverse transportation logistics in which trucks and trailers have different operational processes. Current industry practices in developing transportation schedules still rely on manual and perception-based approaches, necessitating the need for an optimal scheduling method to ensure effective and seamless transportation operations and on-site assembly processes. In light of this, we propose a transportation scheduling framework for the distribution and reverse logistic operations in the panelized construction using genetic algorithm. The developed method minimizes the operational time of the transportation fleet, thereby increasing the fleet's efficiency and ultimately improving the productivity of the factory and construction sites.

The proposed framework contributes to the body of knowledge in the following three respects. First, it proposes a logistics optimization method that takes into consideration the unique features of transportation operations in panelized construction. With respect to the incorporated features, this model considers: (i) the distribution and reveres transportation operations to multiple sites in the supply chain; (ii) trucks and trailers as individual units performing different tasks; (iii) limited parking spots available in construction sites; and (iv) dispatching of loaded trailers to sites and the unloading of panels onsite based on the required installation sequence of panels. Second, the framework develops a mathematical model that simulates the dispatching processes for transportation operations in offsite construction, considering various constraints imposed by onsite assembly progress and fleet availability during panelized construction operations. This model links factory and onsite assembly operations, overcoming the challenge of scattered supply chain parts in offsite construction. Third, the framework proves the applicability of adopting the GA in solving transportation optimization problems in panelized construction based on developing a GA-based model that adopts additional GA operators compared to the conventional GA.

Moreover, this research introduces a practical transportation scheduling optimization method that suits the needs of the offsite construction domain, and panelized construction companies, in implementing the proposed framework, can expect the following benefits: (i) reduced production line bottlenecks and ensuring continuous on-site operations based on balancing the dispatching of loaded trailers and the availability of empty trailers on the factory; (ii) effective transportation process that replaces current experience-based transportation scheduling frequently leading to error-prone with low productivity in transportation; (iii) efficient implementation of just-in-time (JIT) delivery approach that minimizes the operating time of the transportation fleet, leading to reduced transportation costs; and (iv) better operations planning based on generating detailed transportation schedules for all trucks and trailers, which allows master planners to efficiently plan other supply chain resources (e.g., site crews and cranes) in order to ensure continuous panels installation. A case study of a panelized construction factory is presented to validate the effectiveness of the developed transportation scheduling methodology.

5.2 Future works

In the proposed transportation scheduling framework, each construction site will secure the mobile crane to carry out the unloading of panels from loaded trailers and complete the onsite assembly, hence the optimal dispatching schedules crane was not considered. However, in some cases, the factory may provide the construction sites with cranes along with the dispatched loaded trailers. Moreover, the unloading and onsite assembly durations considered in this study are based on the type of panels (i.e.: floor, walls, and roof), and were taken from historical data in the literature. However, this may differ based on other factors such as the availability of on-site resources, size of panels, and other constraints onsite. The traffic conditions and status of selected routes were not considered in this study, which may slightly impact the calculated travel times. In addition, the priority of dispatching of loaded trailers that was considered in the developed dispatching process was based on total number of loaded trailers required by the site, where the site requiring the highest number of loaded trailers was given the first priority. Furthermore, while the proposed framework tests the capabilities of genetic algorithms in solving complex optimization and scheduling problems that involves multiple specific constraints, and addresses the existing limitations related to genetic algorithms, other meta-heuristic algorithms or hybrid approaches can be still applied to analyze the overall performance of the model.

Hence, further research efforts need to be made to address the following issues:

i. The availability of cranes and their optimum dispatching schedules can be linked to the transportation schedules, thereby optimizing the lifting resources given that, in reality, the number of cranes available to unload the panels on-site may be limited.

ii. Dynamic on-site assembly rate could be taken into account based on the load size of each trailer, and the availability of on-site resources rather than merely relying on available historical data.

iii. Traffic status of the selected routes can be incorporated in the model to increase the efficiency of the fleet.

iv. The dispatching of loaded trailers to sites can be considered based on actual priorities such as site requirements instead of the number of loaded trailers per site.

v. Different meta-heuristic algorithms can be tested in order to compare the performance of the developed algorithm to that of other algorithms.

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Appendix A Results

A.1 Design constraints 1 through 5

A. Design constraints at site 1

Loaded trailer details panel type, level - trailer#	Arrival time of truck with the loaded trailer at site, in second $T_{k,v}$	Number of available parking spots at site $P1$	Completion time of unloading all panels from trailer, in second $CT_{w(k)}$	Arrival time of truck to pick up empty trailer, in second $T_{w(k),v}$	Number of available flat-type trailers at the factory RF_i	Number of available wall-type trailers at the factory RW_i
Wall 1 -1 of 1	2120	4	5420	10173	22	13
Floor 2 -1 of 2	3672	3	8420	10711	20	13
Floor 2 -2 of 2	5340	2	11420	12179	19	13
Wall 2 -1 of 1	10173	1	14720	14720	15	13
Roof -1 of 7	10711	1	16220	16220	15	13
Roof -2 of 7	12179	1	17720	18618	15	13
Roof -3 of 7	14682	1	19220	19229	14	14
Roof -4 of 7	15220	1	20720	20729	14	14
Roof -5 of 7	18618	1	22220	22250	12	15
Roof -6 of 7	19229	1	23720	24791	12	15
Roof -7 of 7	20729	1	25220	26684	12	15

B. Design constraints at site 2

Loaded trailer details panel type, level - trailer#	Arrival time of truck with the loaded trailer at site, in second $T_{k,v}$	Number of available parking spots at site $P1$	Completion time of unloading all panels from trailer, in second $CT_{w(k)}$	Arrival time of truck to pick up empty trailer, in second $T_{w(k),v}$	Number of available flat-type trailers at the factory RF_i	Number of available wall-type trailers at the factory RW_i
Floor 1 -1 of 1	9405	2	12405	23707	16	13

C. Design constraints at site 3

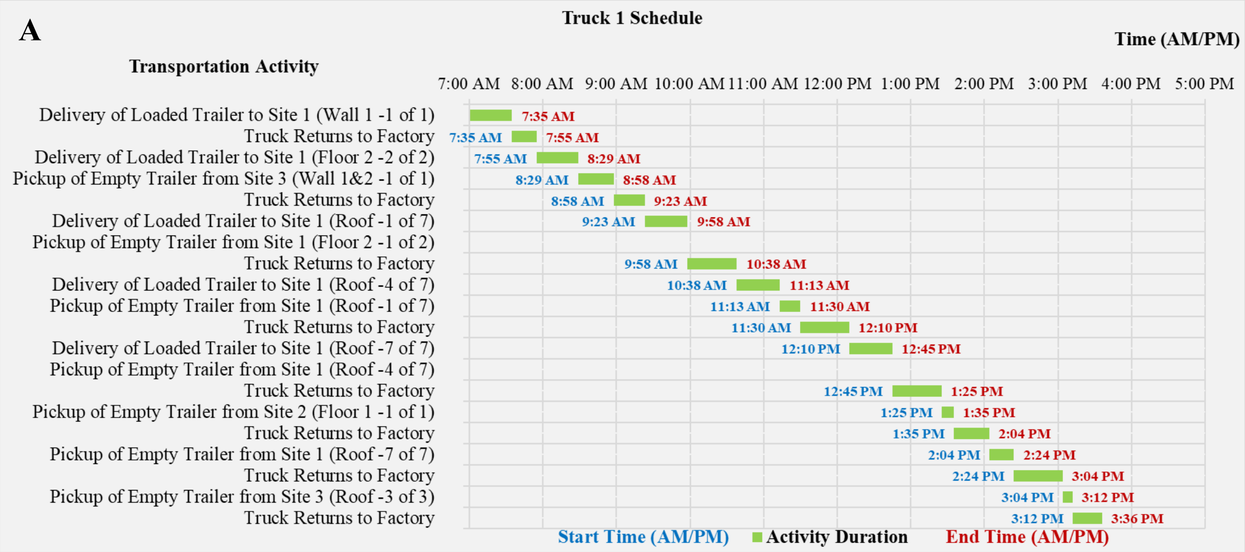
Loaded trailer details **panel type, level - trailer#**	**Arrival time of truck with the loaded trailer at site, in second** $T_{k,v}$	**Number of available parking spots at site** $P1$	**Completion time of unloading all panels from trailer, in second** $CT_{w(k)}$	**Arrival time of truck to pick up empty trailer, in second** $T_{w(k),v}$	**Number of available flat-type trailers at the factory** RF_i	**Number of available wall-type trailers at the factory** RW_i
Wall 1&2 -1 of 1	1160	4	4460	7119	24	13
Floor 2 -1 of 1	1160	3	7460	15026	24	13
Roof -1 of 3	2712	2	8960	22076	22	13
Roof -2 of 3	6141	1	10460	25097	19	13
Roof -3 of 3	7693	1	11960	29531	18	13

D. Design constraints at site 4

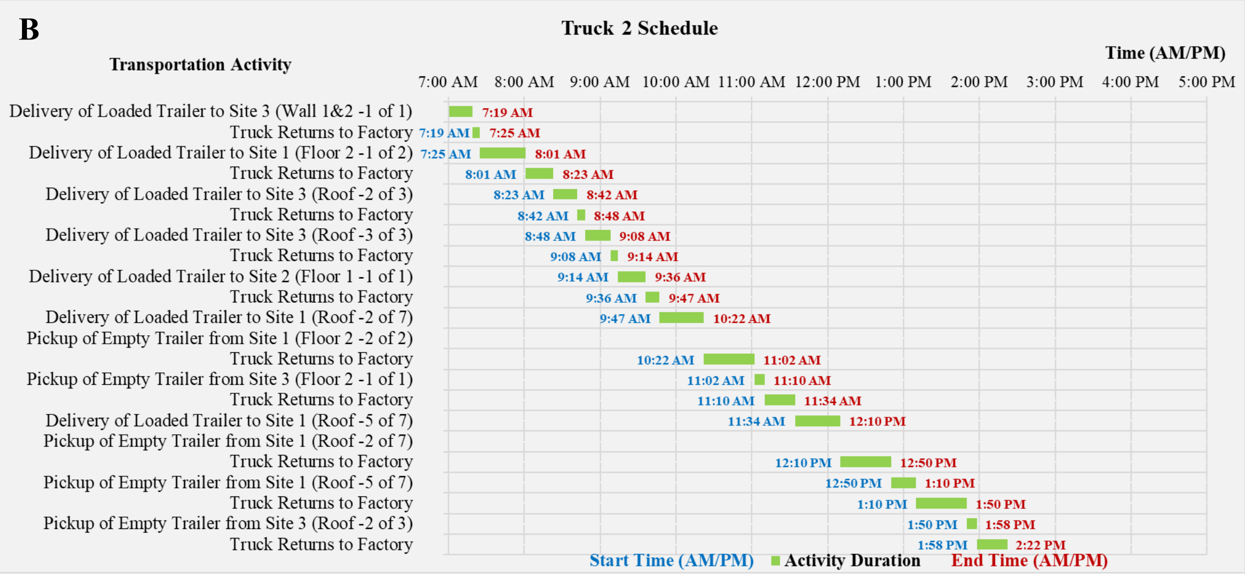
Loaded trailer details **panel type, level - trailer#**	**Arrival time of truck with the loaded trailer at site, in second** $T_{k,v}$	**Number of available parking spots at site** $P1$	**Completion time of unloading all panels from trailer, in second** $CT_{w(k)}$	**Arrival time of truck to pick up empty trailer, in second** $T_{w(k),v}$	**Number of available flat-type trailers at the factory** RF_i	**Number of available wall-type trailers at the factory** RW_i
Floor 1 -1 of 1	6024	2	9024	29078	19	13

A.2 Optimal distribution and reverse transportation schedules of trucks

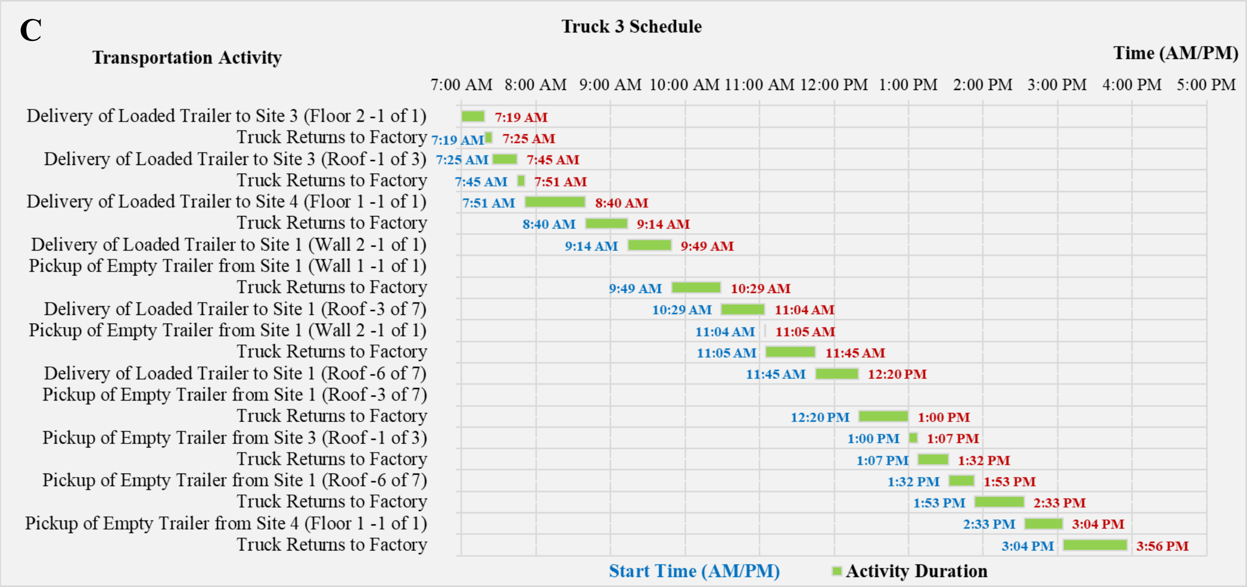
A. Optimal transportation schedule for Truck 1



B. Optimal transportation schedule for Truck 2



C. Optimal transportation schedule for Truck 3



A.3 Onsite trailer process times