Off-site and On-site Construction Scheduling:

Integrated Panelized Construction Management Using Pull Planning

by

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Abstract

In off-site construction, factory-site coordination is critically important for achieving the benefits over traditional construction, such as reduced project makespan and better resource utilization efficiency. However, current off-site construction management treats the factory schedule and site schedule separately. Additionally, off-site construction planning is done manually and ad hoc based on the manager's empirical estimation. The lack of sound decision-making results in constant schedule changes during construction and delivery delays. This research proposes a Pull Planning framework spanning the entire construction process using a combined Discrete-Event Simulation (DES) and Agent-Based Modeling (ABM) technique. The research also proves the feasibility and benefits of Pull Planning applied to multi-project scheduling in panelized construction through comparison and analysis between two simulation models using the Push and Pull planning approaches, respectively. The simulation models are built based on real factory and site operations. The Pull planning method results in a 12.6 % reduction in all project completion time and a 80.2% reduction in panel waiting time. Thus, the Pull Planning approach optimizes scheduling decisions on multi-project off-site construction planning.

Dedication

To my mother, who has always supported me with all her love.

To my father, who I highly admire with love and respect.

Acknowledgements

I would like to thank my supervisor, Dr. Zhen Lei, for his counseling and encouragement throughout my MScE program. His dedication and support largely contributed to the completion of this degree and research work.

I would also like to thank my industry partner representative, Dr. Altaf Sadiq, for his guidance and information on this research. Without his support, this research work would have been impossible.

Table of Contents

List of Tables

List of Figures

List of Symbols, Nomenclature, or Abbreviations

BIM – Building Information Modelling

DES – Discrete Event Simulation

ABM – Agent Based Modelling

PLS – Pull Planning Simulation

PSS – Push Planning Simulation

JIT – Just-in-Time Delivery

RFID – Radio Frequency Identification

PDF – Probability Density Function

SDESA – Simplified Discrete-Event-Simulation Approach

RMC – Ready Mixed Concrete

1. Introduction

The construction industry has seen a shift from the traditional stick-built method to the off-site construction method with a combined process of off-site fabrication and on-site installation (Gerth et al. 2013). Off-site construction has become increasingly popular because it offers benefits including a reduced number of contractors, better coordination, high-quality elements at higher productivity in the controlled environment factories, reduced construction time and cost, and a smaller environmental footprint (Gibb 1999). Off-site construction is inspired and developed by the manufacturing industry, whereas technological advancement and management principles have boosted the manufacturing productivity (Groover 2010). However, while manufacturing productivity has nearly doubled since 1994, construction productivity has been almost flat in the same period (Changali et al. 2015). This report has identified eight factors that account for poor productivity and high cost, all are related to project management (Changali et al. 2015). Concerning this problem, there has been increasing research interest concerning off-site construction management (Alvanchi et al. 2012, Arashpour et al. 2016, Gbadamosi et al. 2019, Gao et al. 2020, Salari et al. 2022). While some manufacturing principles can apply to off-site construction (Arashpour et al. 2016), construction-specific management problems need further research attention, such as construction resource distribution, dispatch logistics, and multitask production/ installation scheduling.

There are three types of off-site construction: prefabricated component construction, panelized construction, and full modular construction (Innella et al. 2019). Among the three off-site construction methods, panelized construction has gained more popularity because of its advantages over prefabricated-component construction and modular construction in terms of high-level standardization, design versatility, and transportation requirements (Hamdan et al. 2015). Unlike modular construction, panelized construction defines prefabricated elements with simple data such as dimensions and material, therefore further facilitating production standardization (Figure [1] and Figure [2]). In addition, two-dimensional panelized elements require minimum handling demand and fabrication sophistication. Modular construction, however, requires a higher fabrication accuracy and transportation resource capacity (e.g., trailers, cranes) for the three-dimensional elements. Panelized construction has been proven to bring benefits, including on-time delivery, reduced cost, minimum ecological footprint, and construction safety (Wang et al. 2015, Tam et al. 2015, Altaf et al. 2018).

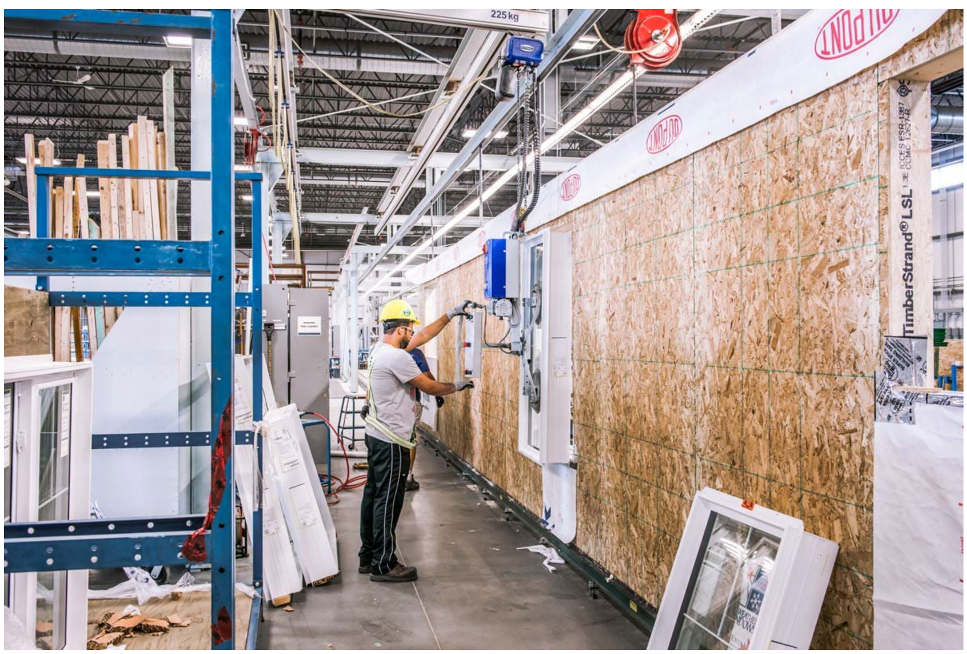

Figure [1]: wood panelized construction: factory production (photo is courtesy of ACQBuilt Edmonton, AB, Canada)

Figure [2]: wood panelized construction: site installation (photo is courtesy of ACQBuilt Edmonton, AB, Canada)

Despite the benefits, the market share of panelized construction is still small in Northern America (Goulding et al. 2015). Recent statistics show that less than 2% of new single-family homes are built using an off-site construction approach (US Census Bureau n.d.). One of the main reasons for this low adoption rate is the lack of advanced management tools (Salama et al. 2018). In particular, poor coordination between construction site demand and factory production is held accountable, resulting in failure to deliver the project on time (Boyd et al. 2013). In practice, off-site construction is usually understood as a dichotomy of two parts: off-site panel fabrication and on-site installation, which are scheduled separately. The ad-hoc handling of operation logistics has caused significant waste in terms of massive resource idle time, project delay, high cost, larger environmental footprint, etc. Effective logistics planning is the key to fulfilling off-site construction benefits. For example, vehicles transporting panels from the factory to construction sites are limited. Without a coordinated logistics flow, finished panels at the factory may have to wait for trailers. Considering the limited factory storage area, the waiting panels can result in production line stoppage. It is also impossible to fabricate panels beforehand because the panels are customized for each project, and the factory can only process the orders according to site requisition. On-site panel delivery delay caused by poor logistics management results in crane idle time, which increases cost. Additionally, trailer parking space is also limited on each site. Therefore, the empty trailers need to get transported back to the factory as soon as possible for a continuous workflow, or it may result in installation stoppage because construction materials cannot be transported to the site. This research collaborates with a panelized construction company to study and address such problems using real construction processes and operation data.

This research integrates the logistics details with factory production and site installation for an integrated simulation model based on which improvement options are explored. The simulation deploys a combined modeling technique of DES (discrete event simulation) and ABM (agent-based modeling) to represent sequential activities such as factory production lines and autonomous entity behaviors such as trucks. The model is implemented in the AnyLogic modeling environment because it supports both modeling techniques and visualizes the model structure and result.

The improvement approach is generated from the Pull Planning theory. Pull planning "pulls" resources selectively according to the requirements and works backward. This stays in contrast with the traditional Push Planning approach that always plans ahead for future events. Pull Planning is an approach grounded in the theory of Lean Construction, to minimize the waste of materials, time, and effort while maximizing the outcome value (Brioso 2015). Pull Planning has proven effective at the project level (Slack 2015, Ghosh et al. 2017, Killian et al. 2020), such as human resource management and multi-contractor coordination, but has not been applied to planning at the operation level (Ng and Hall 2019).

The research is important to designers, engineers, and construction managers who work in the off-site construction industry. It is also relevant to the research community that is interested in construction innovations. The research provides insight into one of the main obstacles in achieving off-site construction benefits by proposing an alternative planning approach. This research serves academia as a starting point to streamline panelized construction management.

2. Research Mission

2.1 Research Goal

Considering the proven theoretical benefits of panelized construction and the difficulty in achieving the benefits in practice, this research is motivated by implementing off-site construction philosophies to achieve the potential of panelized construction. A coordinated workflow is crucial to the effectiveness of panelized construction because resource limitations hamper productivity and project delivery speed. The main obstacle to a coordinated workflow is poor logistics management when handling multiple construction sites. The goal of this study is to tackle the challenge of logistics planning and resource distribution (e.g., workforce, crane, truck, trailer, etc.) in a multi-project scenario. This goal is achieved by developing a Pull Planning simulation model. This model is to be compared to traditional planning model to measure the effectiveness. To better understand panelized construction coordination problems and effectively optimize panelized construction management, this research collaborates with a panelized construction company in Edmonton, Canada, and uses real logistic details and operation data for simulations and solution validation.

2.2 Research Questions

Poor logistics management can negatively affect the industry in multiple domains, such as project delivery time, cost, and excessive inventory (Salama et al. 2018). Current major planning problems include: (1) the lack of a holistic model that simulates all procedures from factory production to site installation and (2) the lack of a coordinated workflow to optimize resource distribution and scheduling. Pull Planning is a tool developed to solve this coordination problem by scheduling backward from the finish day. However, this approach has not been applied to the operation level, so the effectiveness of this approach in logistics planning needs to be quantified and compared with the traditional Push Planning approach. Therefore, the research goal can be achieved by answering the below research question:

What are the advantages and disadvantages of the Pull Planning approach in panelized construction logistics planning in comparison to the traditional Push Planning approach?

Hypothesis: Pull Planning approach improves panelized construction logistics planning by minimizing resource idle time, just-in-time project delivery, and reducing inventory. An effective comparison should be based on an integrated simulation model that includes both factory production and site installation.

2.3 Research Objectives

Coordination between off-site and on-site activities requires a holistic simulation model. Considering current research models are oversimplified in terms of treating off-site fabrication and on-site installation as two independent processes (Abourizk et al. 2011, Alvanchi et al. 2012, Altaf et al. 2018), the first research objective is to build an accurate, integrated simulation model that includes both factory production and site installation. This model uses the traditional Push Planning approach. In addition, the model emphasizes resource state change because most waste happens at resource state transition. For example, when a trailer waits for trucks to pick it up or panels wait for empty trailers at the factory storage area, the time are counted as idle time. This objective will be achieved through (1) a literature review on the potential modeling strategies and techniques; and (2) Interviews with the industry partner for detailed panelized construction processes based on real operations.

Based on the simulation model, the second objective is to build an alternative simulation model using the Pull Planning approach. To make effective comparisons, the number of operation details and data input should be the same. This objective is achieved by: (1) a literature review on Pull Planning approach and (2) reviewing the first simulation model and building this one based on the first model's operation details and inputs.

The final objective is to compare the two models and propose optimization possibilities for future research. This objective is achieved by: (1) identifying criteria for efficiency evaluation. The criteria are generated from simulation output, such as resource waiting time and project completion time. (2) analyzing the results, comparing the two different scheduling approaches, and proposing optimization directions such as adjusting resource configuration and modifying the due date according to empirical experience to help the managers make decisions.

2.4 Research Scope and Limitations

The research scope is the entire panelized construction processes from raw material fabrication to installation completion. The design phase is not included in this research. Another limitation is set by the number of details this model can capture. Successful simulation models rely significantly on simplifying real situations while capturing the most important conditions that affects the situation the most. To focus on the logistics planning, the models stay at a higher level of abstraction at factory and site processes without going into details such as individual factory fabrication workstations, site installation workers, etc. Therefore, this simulation model cannot be a digital replica of the real processes, and the data collected may only partially reflect the actual situation. Additionally, this research works with one off-site construction company for fabrication and construction processes. While all the procedures and data are based on real situations which may not apply to all off-site construction situations. Even though many operations and management logistics can be generalized to other working scenarios, some simulation model settings may be case specific and require bigger data sets for validation. To fully validate the model, it would require the industry to make such optimization changes in real operations for a solid conclusion. Furthermore, consider current panelized construction management is done manually as an empirical combination of the Push Planning decisions and Pull Planning execution, and the past three years are significantly impacted by the outbreak of Covid-19, after discussion with the industry partner, the real operation log is not suitable for comparison and validation for this research. This research focuses on the comparison between the two different planning approaches.

Also, before extracting data from the models and analyzing the results, the criteria for evaluating the models need to be established. The objectives of construction management include reduced makespan, reduced cost, reduced resource idle time, and reduced inventory. Among these criteria, the quantification of environmental footprint and cost is not suitable for this research because: (1) the quantification of the environmental footprint is still controversial. Plus, the simulation models of this research stay at the higher management level, while environmental footprints are mostly related to operations. Additionally, environmental waste caused at the management level can be quantified resource usage efficiency. (2) the two models share the same cases; therefore, the material cost, working man hours, and resources usages cost of both models are the same. Apart from that, the idle time cost is proportional to the amount of idle time. As a result, three criteria are used for efficiency measurement: idle time, makespan, and inventory level.

3. Literature Review

This chapter consists of four sections: (1) Scheduling problems in off-site construction, (2) Discrete-event simulation and Agent-based modeling, (3) Push and Pull Planning, and (4) Literature review conclusion and research gaps. The literature review sections are organized to support different research objectives. Section 3.1 lays a foundation for the panelized construction scheduling problem and contextualizes the information extracted from the interviews with the industry partner. Section 3.2 reviews the two modeling methods and their application to validate the hypothesis that a combined modeling method is suitable for this research problem. Section 3.3 reviews the Pull Planning approach applied to construction planning in comparison to the Pull Planning to prepare for the simulation models with different modeling techniques. The last section is a review and summary of the literature review chapter.

3.1 Planning Problems in Off-site Construction

Research on off-site construction planning can be categorized by construction phases. Generally, there are three phases of panelized construction: factory fabrication, transportation, and site installation. Abundant research has been done on each topic. This section first reviews studies on planning for each phase then reviews studies that integrate all three phases to form a detailed yet holistic understanding of the panelized construction planning problem.

For factory fabrication planning, research topics include factory scheduling, resource allocation, and quality management. (LEU and HWANG 2001) uses a genetic algorithm-based searching to develop a resource-constrained production scheduling system, to optimize production sequences for minimum makespan and maximize resource utilization; (Altaf et al. 2018) deploys radio frequency identification (RFID), data mining, and simulation-based optimization to develop a production scheduling and quality control system. The challenges include handling data with noise and using clean data to build a Probability Density Function (PDF), which is crucial to building a discrete-event simulation (DES) model to help stimulate production procedures and automatically make optimizations. (Arashpour et al. 2016) builds a model to help define product sequencing using optimization-based metaheuristics for minimized machine setting-up time. (Arashpour et al. 2015) studies the impact of multi-skill resources on off-site construction results. The result is compared and validated using data generated by DES models.

For factory-site dispatch, research directions include fleet scheduling and just-in-time delivery (JIT). This research also emphasized this phase of panelized construction because the logistics stage lies at the core of coordination between the production and the construction phases (Ahn et al. 2022). (Ahn et al. 2022) proposes a framework to optimize the truck-dispatching schedule using a discrete-event simulation (DES) model. The result sees significant improvement in comparison to historical data. (Kong et al. 2018) applies the JIT strategy to time-dependent delivery considering on-site assembly time. The validation considers both economic and environmental impacts. (Yi et al. 2020) proposes a mathematical programming model to optimize transportation planning for minimized transportation costs and inventory. However, the model is not based on real operations where a lot more details could affect the workflow, such as the fact that there are multiple types of vehicles used for transportation and the panels are of customized dimensions and weights. There is a limited number of studies on this topic.

For site planning, topics include crane scheduling, construction scheduling, as-built modeling, and progress monitoring (Hussein et al. 2021). (Wang et al. 2021) uses video recording for object identification as exact site monitoring information. The installation activities are later sent to the building information model (BIM) to update the information digitally. (Dai and Lu 2013) also uses visual data from site photos to produce three-dimensional modeling of site elements. (Chan and Lu 2008) applies a simplified discrete-event-simulation approach (SDESA) to simulate material flow on construction sites. (Shewchuk and Guo 2012) proposes a lean approach to on-site panel handling, including stacking, locating, and sequencing with no site shape restrictions. (Shewchuk et al. 2017) develops new methods for modeling multi-worker physical processes within a discrete-event simulation environment for ergonomic assessment.

This section reveals a variety of research questions for each panelized construction phase; however, the coordination problem concentrates on handling construction material which is the only object that participates in all processes from start to finish. Therefore, all the panelized construction phases regarding the handling of construction materials should be considered to form an integrated and holistic simulation for this research.

The following paragraphs review studies on higher-level planning with the scope of holistic off-site construction processes. There are few pieces of literature on this topic, so the literature review is not restricted to the domain of panelized construction. (Wang et al. 2019) conduct a literature review for the precast supply chain. The review reveals research gaps in the following four topics: precast production, storage & inventory, delivery & transportation, and performance of the entire supply chain. The research gaps related to this topic are: resource allocation, including equipment, workers, and cranes; synthesis of resource assignment and production scheduling; solutions to pursue JIT delivery were constricted to the production phase; transportation management was not studied within an integrated process framework, etc.

(Lu and Olofsson 2014) develop a framework combining BIM with DES for easier simulation model maintenance in case changes are required. This combination reinforces both sides by providing additional information to each site. (Liu et al. 2014) uses a genetic algorithm (GA) approach to optimize the production and delivery schedules in ready-mixed concrete (RMC) plants. The delivery process considers the entire process of concrete handling: production, loading, delivery, unloading/ casting, and vehicle return, whereas the sites generate demands in specific time windows. The study also considers real operation details such as RMC hardening time, pump and truck arrival precedence constraints, etc. However, it only considers one mixer in one plant for the modeling, while the situation is more complex with multiple factory machines and even multiple plants. The study is inspiring in terms of how to model off-site construction processes. (Wang and Hu 2017) uses a genetic algorithm (GA) to integrate multiple processes of prefabricated components (PC): mold manufacturing, casting, curing, PC storing, and transportation into the model, which is validated with two real cases. Each process is represented as a chromosome. However, the model overlooks many details and needs to consider on-site assembly sequences, which directly impact on production sequences. (Ahn et al. 2022) proposes a framework to improve the truck-dispatching schedule using discrete-event simulation (DES) based on real fleeting data. Dispatching decisions are made using a decision-making matrix considering transportation cost, distance, and site priority factors. However, there is a site schedule input before running the simulation model. One of the criteria is the in-time delivery rate compared to the schedule, which is made to ensure continuous operation. In this case, the site schedule can be impossible to meet. Additionally, the model only considers the continuous operation of vehicles, not the factory operation or site operation.

Vehicle logistics is critically important to bridge site installation and factory production. However, the number of articles studying vehicle logistics is minimal, revealing a significant research gap on this topic. Also, the only simulation model that uses real operation data and workflow is done by (Ahn et al. 2022), which reveals many important operation logistics. For example, in a multiple-site job scenario, idle trucks that are disconnected from trailers on a construction site must fetch empty trailers on other sites, if any, which is ignored in other studies. Therefore, this research will also work closely with the industry partner to build the simulation model based on real operation data.

3.2 Discrete-Event Simulation and Agent-Based modeling

Discrete-event simulation (DES) has been mentioned a few times in the previous literature review sections, mainly used to simulate the overall logic of various activities required for an integrated operation (such as component production, vehicle dispatching, etc.). Despite continual new developments in the construction simulation field, DES has been the prevailing approach for construction simulation for over 40 years (Abourizk et al. 2011). Generally, there are three types of simulation modeling techniques, system dynamics (SD), discrete event simulation (DES), and agent-based modeling (ABM) (Siebers et al. 2010). While SD is the oldest type of simulation with the highest level of abstraction, recent discussions have been focused on the comparison and integration between DES and ABM (Dubiel and Tsimhoni 2005, Siebers et al. 2010, Chan et al. 2010). Inevitably, this research also starts with a construction simulation model based on real operation from a wood panelized-construction company based in Edmonton, Canada. Real details bring up new challenges; for example, while many simulation models consider the vehicle as one type of resource, Truck and Trailer have different logistics. Additionally, trailers usually have two types: flat and pole, and different sizes for different components. Many other constraints need to be considered for a more accurate model. Therefore, this literature review section is dedicated to the simulation modeling framework to explore possible solutions for this research.

DES requires complete independencies between activities and resources, making it suitable for sequential construction operations and supply chain simulation problems (Alvanchi et al. 2012). However, the requirement of independencies also sets limitations to its capacity. (Dubiel and Tsimhoni 2005) has summarized three limitations of DES: 1. the primary limitation of DES lies in the "generality of movement and function of entities," making it challenging to implement non-preprogrammed activities such as human movement; 2. Decision-making at small time increments requires many decision points with preprogrammed logic, making the model slow and hard to validate; 3. Processing is done at user-defined decision points and is not autonomous to the flowing entities. This has an impact on entity interactions. However, these challenges can be addressed using DES and clever programming, but that does not negate the fact that DES is not the best choice for modeling individual activities. Agent-based modeling (ABM) is a more straightforward way of tackling challenges arising from individual activities and interactions. (Dubiel and Tsimhoni 2005) proposes a framework to integrate DES and ABM to simulate a tourist circulation path in a theme park where people move from one point to another in one of two ways: tram or walk. For this study, the tram is modeled using DES, while human walking is modeled using ABM. (Siebers et al. 2010) has listed the differences between DES models and ABM models. DES is process-oriented, uses a top-down approach with an emphasis on system modeling. At the same time, ABM is individual-oriented and uses a bottom-up approach with emphasis on individual entity modeling. In DES models, the sequence of jobs is a critical element, but in ABM, there is no concept of sequences. Instead, each entity responds to the simulated environment by making micro-decisions. The features of both modeling techniques will be discussed again in later sections, combined with real operation constraints.

3.3 Push and Pull planning

The previous literature review section has mentioned two simulation modeling techniques. The previous section also brings up the top-down and bottom-up philosophical contrast of the modeling technique, which brings up another concept in construction scheduling: Pull Planning vs. Push Planning. The study of Push Planning and Pull Planning has a similar discussion and comparison of their approach. Pull Planning approach is grounded in lean construction, which stays in line with the idea that an integrated, holistic approach to the entire workflow is a prerequisite to all production improvement. This section of the literature review is dedicated to the existing discussions on Push Planning and Pull Planning, indicating the possibility of improving the wood panelized construction with the Pull Planning approach.

The concept of Pull Planning stands in contrast to its twin concept, the traditional "Push" planning approach (Ghosh et al. 2017). Current simulation models use the push planning method, where the planning process starts with identifying the operations, resources, and their dependencies. The algorithm model for this method is called the Critical Path Method (CPM) (Killian et al. 2020). The work center "pushes" out resource usage and operation status as a situation for the subsequent operations of the work, regardless of whether the situation works out for the succeeding operations (Slack 2015). Thus, the subsequent operation will likely wait for resources to become available before proceeding. Additionally, push planning seeks the earliest possible start date during execution to avoid delaying later activities. Therefore, even though waiting time and inventory can be reduced by providing the optimum resource configuration, the waste production mechanism lies in the planning approach.

Pull planning is developed to address the above-listed challenges. Instead of pushing out the situation and leaving the succeeding activities with a set of incomplete resources to start with, which leads to in-process inventory and resource/ product waiting time, pull planning means each activity draws resources from its preceding activity whose required resources can be further tracked upstream (Ghosh et al. 2017). Additionally, instead of the earliest possible start date, this outcome using the pull method is the latest possible start date, given the due date of the projects. This reduces the end product inventory and reserves the earlier dates for more urgent jobs.

Currently, pull planning is usually brought up in the context of human resource management, where the challenge can be coordinating the subcontractors/ multiple disciplinary teams who traditionally treat their tasks independently, disregarding the interdependencies of their contract, leading to waste of hours and cost on coordination (Ballard 2000, Sivaraman and Varghese 2016, Ghosh et al. 2017). So far, there are few attempts made to introduce a pull planning approach to off-site construction logistics. The later chapters discuss the possibility of enlarging the scope of pull planning to panelized construction scheduling logistics for a smooth flow of resources.

3.4 Literature review conclusion and research gaps

There are several research gaps identified in this literature review: lack of synthesis of resource assignment, production scheduling, and installation scheduling; solutions to pursue JIT delivery were constricted to the production phase; transportation management was not studied within an integrated process framework; real operation details were not represented in simulations. All these issues directly or indirectly lead to off-site construction transportation planning. Study on this topic within an integrated process framework is minimal yet crucial to improve factory and site schedule, which are usually done separately. Apart from transportation management, most studies on construction planning focus on simulation modeling, real data collection, and optimization, few have discussed planning methodologies. This research hypothesis is that Pull Planning with a scope of an integrated process would improve the level of coordination in off-site construction. Section 3.4 has supported the idea and revealed Pull Planning's potential and feasibility in improving off-site construction management. Simulation models are required to validate the research hypothesis. Section 3.3 introduced DES and ABM as valuable tools for different simulation modeling problems. Even though ABM has not been mentioned in construction process simulation, this technique is suitable for modeling autonomous entities in off-site construction transportation logistics. Multiple software packages can be used to build simulation models, such as AnyLogic, Adaptive Modeler, RePast, and Swarm. AnyLogic is chosen for this research purpose because the author has some experience regarding with AnyLogic, and it supports both ABM and DES.

4. Research Methodology

Before modeling the simulation models, a holistic understanding of the panelized construction is required. The first research objective is to develop an integrated problem statement to address the separated handling of off-site production, factory-site transportation, and on-site assembly. Following the problem statement, a simulation module consisting of two simulation models using different modeling approaches are built for analysis and comparison. Traditionally, supply chain problems are modeled with DES because the technique is natural for modeling queueing problems and can capture uncertainty through data inputs, such as stochastic distributions and normal distributions. However, the ABM technique is more suitable for individual behavior-related problems such as truck dispatch decisions. Considering that panelized construction is a complicated process that covers both problems, this research combines DES and ABM for more accurate models. Figure [3] shows the proposed research methodology framework, which consists of two main modules: the problem statement module and the simulation module.

The problem statement is dedicated to representing the panelized construction processes at a higher level of abstraction with a focus on integrating the entire supply chain from the factory to the site. This part is done through interviews with the industry partner and workflow flowcharts based on the interview information. Thus, this research does not go into details like independent factory workstations or single panel installation. The models deploy both DES and ABM modeling techniques to model processes in off-site construction based on real operation data from a wood-panelized construction company based in Edmonton, Canada. Based on the problem statement, the author builds two models using different planning methods in the simulation module: Push Planning and Pull Planning. For effective comparison, the two models include the same processes. A case study with multiple project sites generates results for analysis and comparison. Evaluation criteria include resource idle time, project makespan, and inventory level.

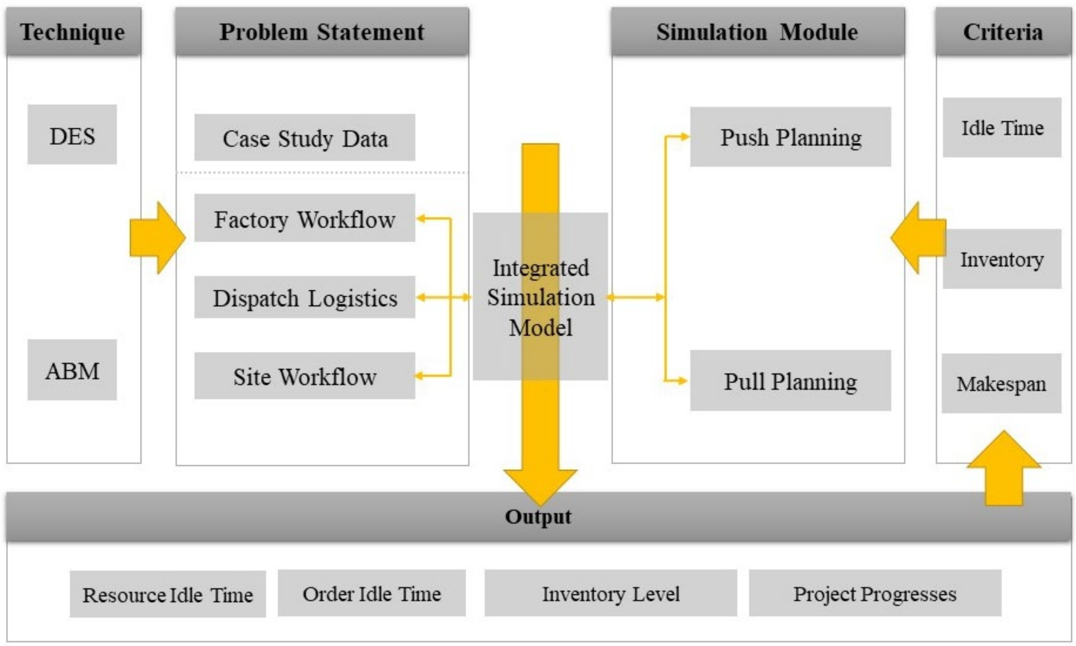

Figure [3]: methodology framework

4.1 Problem Statement

4.1.1 Overall Approach

There are two inputs in the problem statement module: (1) case study data input and (2) panelized construction workflow extracted from real operations. The scope of this work remains on a higher level of abstraction with an emphasis on integrating all off-site construction phases. Some construction processes are irrelevant to coordination, such as production line workstations. Once the material enters the line, it goes through a sequence of workstations non-stop until the end, with no effect on coordination. Therefore, one production line is considered as one process in this model. However, other details are highly relevant. For example, the three types of panels require different trailer sizes for transportation. The simulation models should be simplified to include the most relevant details of project coordination. A holistic understanding of panelized construction workflow and operations is necessary to decide what details to include. This step is achieved by interviews with the industry partner AcqBuilt Inc. The information generated from the interviews is organized in flowcharts that show the processes, constraints, and resources. Following the flowcharts, the following section translates the flowcharts into simulation models in the AnyLogic modeling environment (Figure [4]).

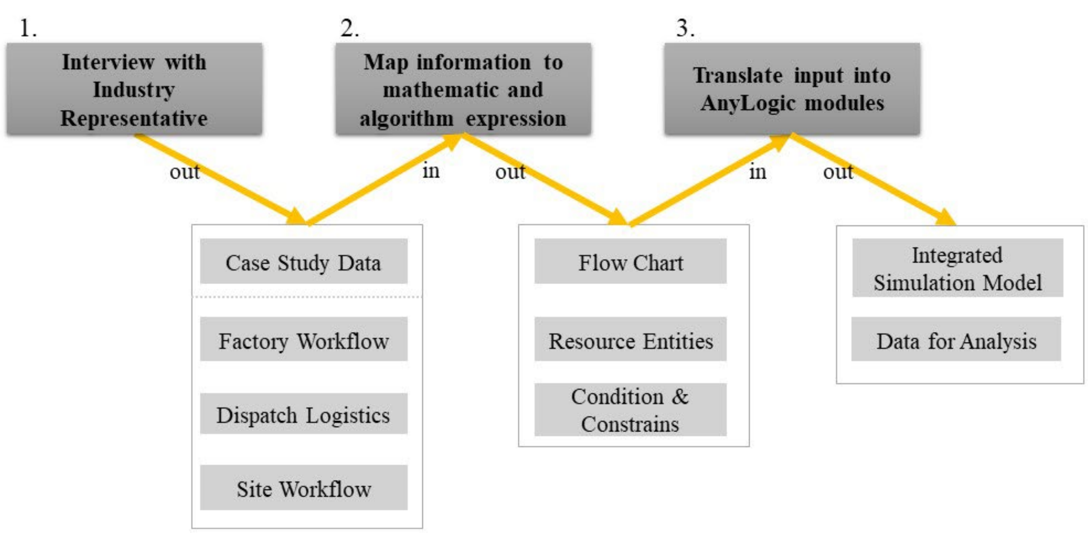

Figure [4]: simulation methodology

To summarize, the modeling methodology is broken down into three steps: (1) Interview with AcqBuilt Inc. Research & Development representative and list out the as-is operations and logistics; (2) Based on the interviews, map out the required data, model constraints, and phases using flowcharts; (3) Translate the flowcharts and data input to AnyLogic language and extract data for analysis from the model.

4.1.2 Wood panelized construction operations and workflows

This subsection is a report of the interviews with the industry partner. It is broken down into two parts: Job Environment and Resource Environment. Job Environment is a briefing about residential housing projects, including the types of panels, the housing types, and installation requirements. Resource Environment describes the available resources (truck, trailer, workstation, etc.), factory settings, site settings, and logistics processes.

For the job environment, two types of housing are considered in this research: one-story bungalows and two-story single-family houses. The problem considers multiple building projects; each consists of three types of prefabricated panel components: wall, floor, and roof. The three prefabricated component types are calculated in different units: walls are calculated in wallsqf, floors in floorsqf, and roofs in man-hours spent on the roofs. All the panels go through the following procedures: (1) fabricated in the factory, (2) loaded onto a trailer, (3) transported to the construction site, (4) unloaded by a crane, and (5) installed on site. Each procedure requires specific resources shown in (Figure [5]). When installed on site, the panels must follow a sequence from bottom to up. For example, the installation order for bungalows is as follows: level 1 floor – level 1 wall – roof. The installation order for a two-story single-family house is level 1 floor – level 1 wall – level 2 floor – level 2 wall – roof. Additionally, the installation of the first floor is called capping, while others are called lifting. Capping involves ground condition treatment. After capping, the site needs to wait before any lifting starts. According to AcqBuilt, the waiting period is usually around 10 days. The installation sequence is diagramed in Figure [6].

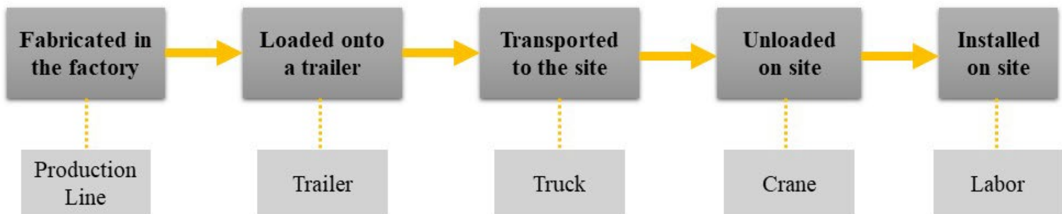

Figure [5]: panel procedures (upper row) and resources required (lower row)

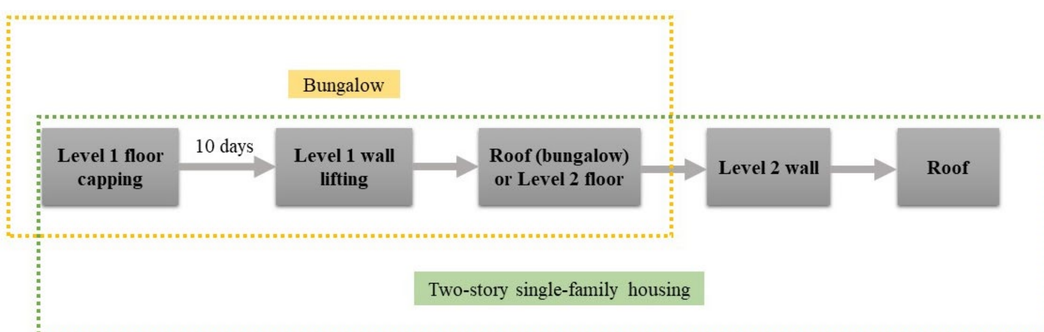

Figure [6]: panels: site procedures

Resource Environment includes three parts: (1) Factory resources, (2) Supply chain resources, and (3) Site resources. All resources work 10 hours a day from 8:00 a.m. to 6:00 p.m. Ending at 6:00 p.m. means no new tasks will be initiated after 6:00 p.m. However, tasks have already started before this time would be finished anyway even if it would pass the end time upon completion. There are three production lines in the factory: wall line, roof line, and floor line, operating independently at different production speeds. Each line involves a series of steps to turn the raw material into off-site construction panels. Take the wall line as an example; wall line involves framing, sheathing, insulation, window, and door installation, and loading operation (Figure [7]). The floor line and roof line also follow similar fabrication procedures. The factory production line layout is shown in Figure [8].

Figure [7]: wall production workstations and processes

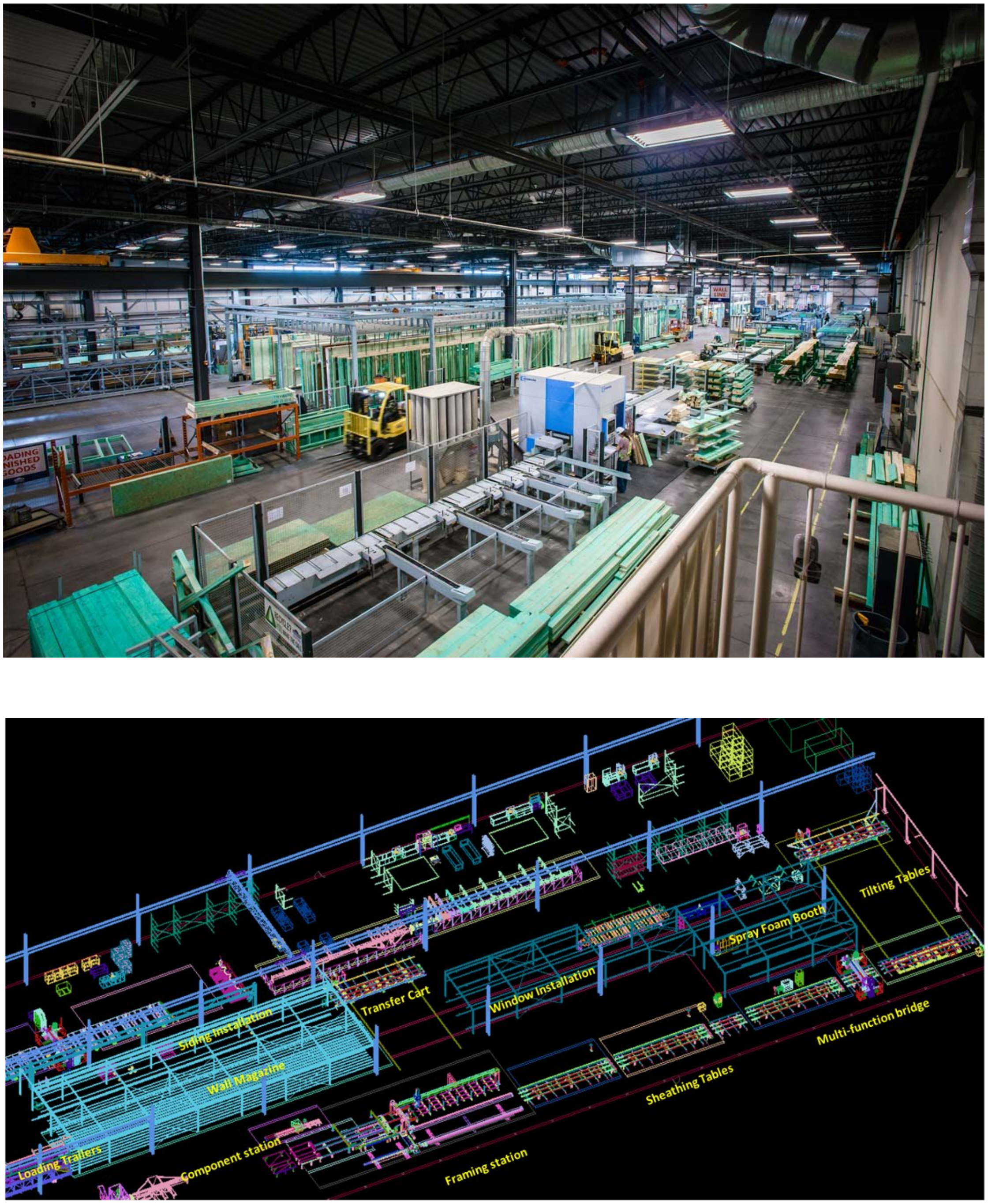

Figure [8]: factory production layout (courtesy of AcqBuilt.Inc.)

However, the production line processes are irrelevant to the factory-site coordination and is considered as one process with a normal distribution of general speed in this model. According to AcqBuilt, the wall line operates approximately at the speed of 1400 wallsqf/ hr; floor line at 350 floorsqf/ hr; and the roof line at 15 workerhr/ hr. Following factory production, the panels are loaded onto trailers. The three types of materials are shape specific: walls need to be kept vertical, with no stacking; floors can be stacked; roofs are usually of irregular shapes, leading to the requirement of different types of trailers (Figure [9]). Three types of trailers are considered in this problem: wall trailer, floor trailer, and roof trailer. After panel loading, trailers need to connect to a truck. Trucks travel between sites and the factory to transport empty/ full trailers. Additionally, unloaded trailers on sites must be moved back to the factory at the earliest to allow continuous workflow. Therefore, when on-site, trucks also travel between construction sites looking for empty trailers if the current site has no empty trailers or head back to the factory alone if no site has empty trailers. While the trailers are specified for panel-type usage, trucks carry any trailer. On site, cranes and human labor are used to unload and install the panels from trailers. The resources required for each off-site construction part are summarized in Figure [10].

Figure [9]: from left to right, roof trailer, floor trailer, and wall trailer (courtesy of AcqBuilt.Inc.)

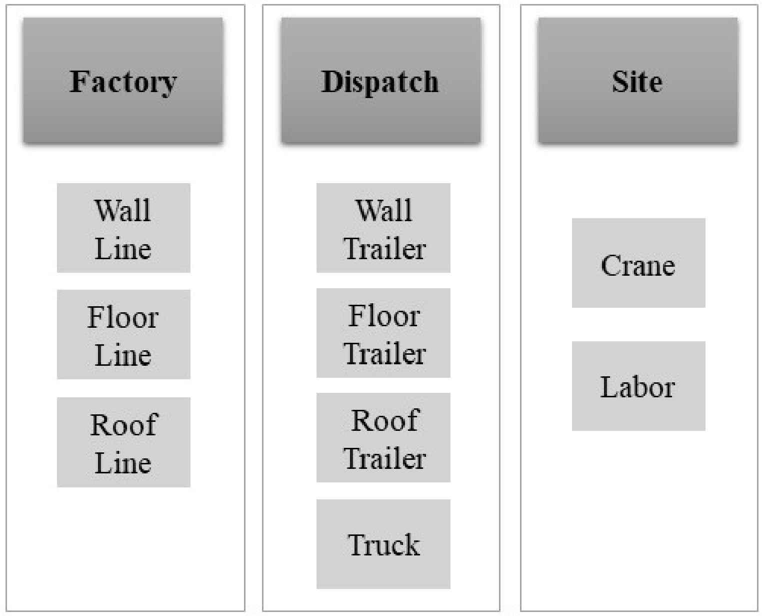

Figure [10]: resource layout

4.1.3 Problem Statement

This study considers an integrated on- and off-site construction multi-jobs scheduling problem with the objectives to reduce resource idle time, inventory, and minimize the project makespan. Reduced cost is not considered one of the objectives in this research because the amount of work (e.g., hours of production line operating, hours of installation, etc.) is not changed during the running of the simulation model under the assumption that the cost is calculated by the rate per resource operating hour. Therefore, the increasing resource idle time would increase resource usage cost proportionally. The real-world situation includes many such details, and considering all the details would make a model too sophisticated to draw conclusions. Successful models rely significantly on simplifying conditions and assumptions that emphasize the most relevant parts. Subsection 4.1.2 has also mentioned some assumptions made in the first place in the interviews to emphasize the focus on the system's primary attributes. These assumptions are summarized as follows:

(1) The three production lines, including the wall line, floor line, and roof line, are operating at an estimated speed based on real-world situations.

(2) The number of suborders/ trailers required for each job site is estimated by panel units.

(3) Travel time between the factory and the site depends on the distance.

(4) Site installation time depends on the panel units.

(5) In a real-world situation, a crane stays on the site until the job is finished. Therefore, crane supply is considered enough for all job sites.

(6) The time required to connect a trailer and a truck is ignored in this model.

The scheduling problem is stated as follows:

Given n housing projects $H_1, H_2, \ldots, H_n$ of varying panel requirements, each job consists of 3 types of panels P_w, P_f, P_r, representing wall panel, floor panel, and roof panel, respectively. The panel amount required for job H_j is P_{wj}, P_{fj}, P_{rj}. There are two types of housing: one-story bungalows and two-story single-family housing. The installation order must go from bottom to up. It is considered a parallel precedence-constrained problem, as all the steps need to be completed in a sequence that certain tasks must be completed before other tasks are begun. Additionally, each site has different trailer parking spaces A_j, which can affect the system efficiency when the parking is full. Housing project H_j can be described as:

$$H_j = \{A_j, P_{fj1}, P_{wj1}, P_{rj1}, P_{fj2}, P_{wj2}, P_{rj2}\} \tag{1}$$

If H_j is a bungalow, then level two panel quantities $P_{fj2} = P_{wj2} = P_{rj2} = 0$. Else if H_j is a two-story single-family housing, Level 1 roof panel quantity $P_{rj1} = 0$.

There are three production lines in the factory, $L_{\mathrm{w}}, L_{\mathrm{f}}, L_r$, representing wall line, floor line, roof line, each operating at a speed $S_{\mathrm{w}}, S_{\mathrm{f}}, S_r$, respectively. Truck can connect any types of trailers. Truck T consists of n identical trucks:

$$T = \{T_1, T_2, \dots, T_n\} \tag{2}$$

Trailer R consists of three types of trailers: R_w, R_f, R_r, representing wall trailer, floor trailer, roof trailer, respectively. Each type consists of n, k, i identical trailers:

$$R_w = \{R_{w1}, R_{w2}, \dots, R_{wn}\} \tag{3}$$

$$R_f = \{R_{f1}, R_{f2}, \dots, R_{fk}\} \tag{4}$$

$$R_r = \{R_{r1}, R_{r2}, \dots, R_{ri}\} \tag{5}$$

Trailers of the same type hold the same amount of panel units. The capacity of wall trailers, floor trailers, and roof trailers are C_w, C_f, C_r, respectively. The criteria of evaluating the efficiency of the model are the makespan (MS) from start to finish, resource idle time, and inventory level. There are three types of idle time: trailer idle time I_r, truck waiting time I_t, and panel waiting time I_p. The idle time is an accumulative amount of time that each piece of resource waited during the process.

Subsection 4.1.2 has covered the Job environment and Resource environment in the factory, on sites, and in transit. Based on this operation information extracted from the interviews, the rest of this subsection starts by drawing the flowchart based on the most relevant conditions that function to integrate all the phases. The overall flow chart is shown in Figure [11]. The flowchart shows overlap among all three parts: except for the transition from the factory to the site, dispatch logistics overlaps with both factory and site procedures, which brings up one of the challenges in building the simulation models: agent and discrete event identification. As mentioned in section 3.3, DES is suitable for sequential events that happen independently, while ABM is more suitable for modeling autonomous individual entities. The flowchart shown in Figure [11] has identified two autonomous and independent systems: Factory and Site. Within their own system, the factory and construction sites include a series of discrete events that is suitable for DES method modeling. In contrast, the factory procedures and site procedures could be designed as two autonomous Agents. Therefore, the model can be simplified to Figure [12], where red circles represent Agents. The factory is a single agent, while Site is a group of agents that share the same operations.

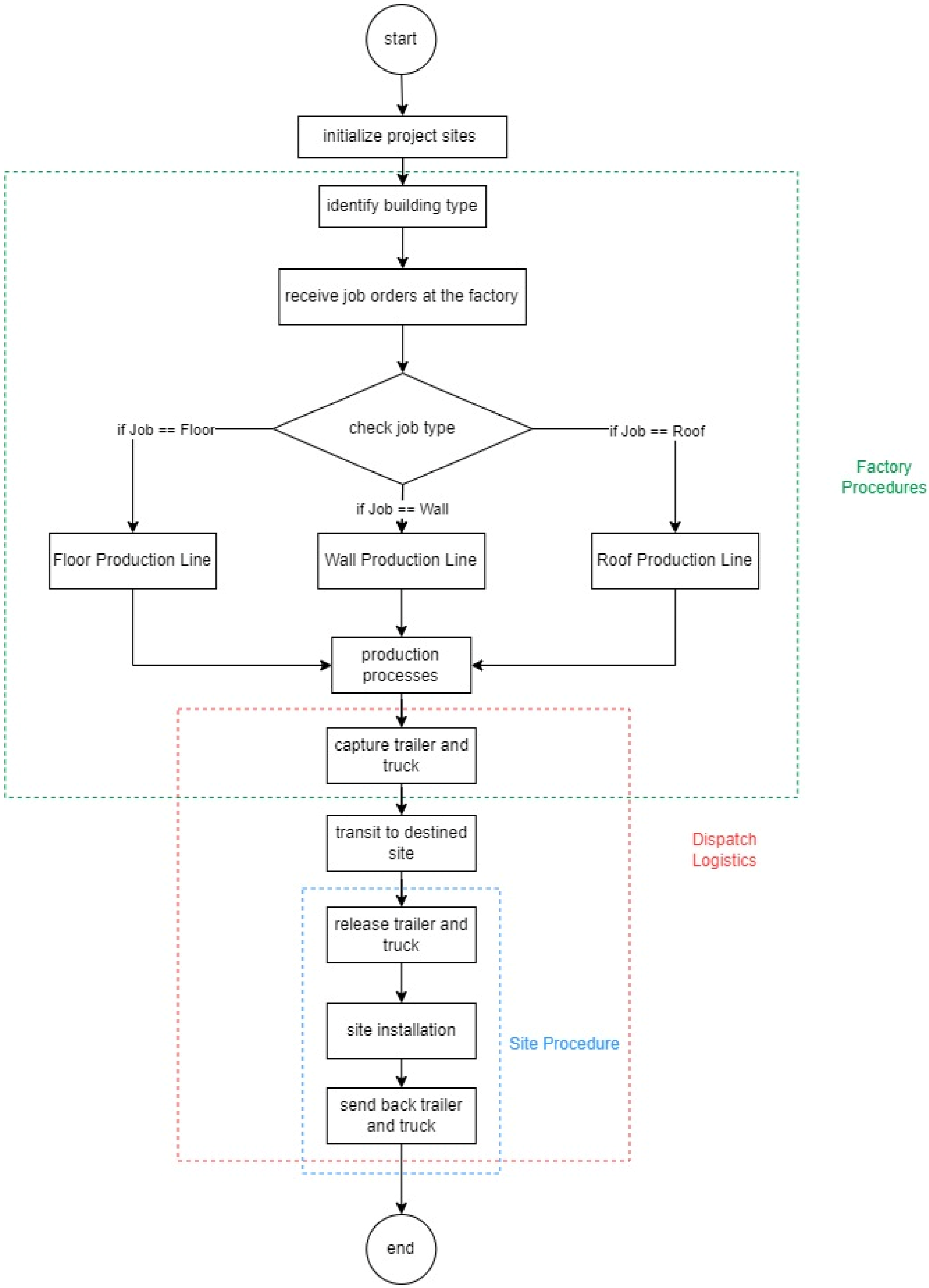

Figure [11]: supply chain overview

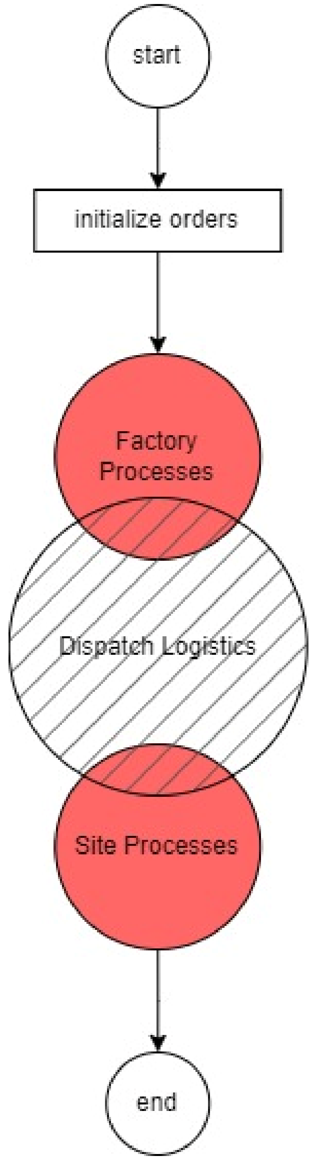

Figure [12]: system abstraction

There are three entities in Dispatch logistics: (1) trailer, (2) truck, and (3) the panels one trailer can carry, also called a suborder. One suborder consists of a single type of panel of one site. The three entities can be grouped into two categories: passive element and active element. Passive elements do not initiate events. Instead, it is controlled by systems or other entities. The Suborder is a passive element. Suborders are created at the initialization phase and flow through the factory system, dispatch logistics, and site system. In the factory, the production lines and factory constraints (e.g., storage space) control suborders; in dispatch logistics, a suborder is always paired with a trailer; in the site system, a suborder is controlled by installation speed. Thus, Suborder is not suitable to be modeled as Agent. Trailer is also a passive element. Trailer has two types of statuses: (1) connected and lead by a truck, (2) disconnected and sit at either factory or a site. At state (2), trailers follow the factory/ site system logic to operate loading or unloading. Therefore, all trailer behaviors are controlled by other entities, and Trailer is not suitable to be modeled as Agent either. While the passive elements will respond to requests from their controllers, Truck is an active element that may or may not respond to requests. For example, consider an empty trailer R_s at site, requesting a truck pick up, and an idle truck T at the factory. T will decide between a loaded trailer R_f at the factory and R_s. In this case, R_s 's request is not responded to, instead, T prioritizes tasks, in this case, picking up R_f , according to its own algorithm. Therefore, Truck operation is suitable to be modeled as Agent. The three Agents identified so far (Factory, Site, and Truck) per the three main bodies identified in Figure [12] (Factory, Site, Dispatch Logistics) are explained in the following paragraphs. The rest of this subsection is organized into three parts, as follows: (1) truck operating logic, (2) Factory Processes, and (3) Site Processes.

This paragraph elaborates on vehicle operation logic. Figures [11] and [12] have shown that dispatch logistics is a crucial element that could affect harmony between the factory and sites. Dispatch logistics is more complex than factory and construction site procedures because some vehicle operations overlap with factory and site operations. As mentioned in the previous paragraph, a truck transports between sites and the factory, with or without a trailer. Trucks and Trailers' behavior is similar in terms of commuting between the factory and different sites. Apart from that, all trailer operations happen either in the factory (e.g., loading panels to the trailer, trailer waiting for truck, etc.) or on sites (e.g., disconnection with the truck, unloading, empty trailer waiting for a truck, etc.). Truck, however, other than commuting between sites, also search for empty trailers and take them back to the factory. In this system, Truck could be considered an autonomous element that takes the initiative in its own algorithm. The operation algorithm is stated in Figure [13]. By default, all trucks are initialized at the factory. There are five different types of tasks: (1) at the factory, transport loaded trailer to the destined site; (2) at the site, transport empty trailer back to the factory, (3) at a site with no empty trailer, go to another site with empty trailers; (4) at the site, go back to the factory alone, (5) at the factory, go to a site with an empty trailer.

Factory processes and site processes are elaborated in Figure [14] and Figure [15]. The two flowcharts explain the procedures respectively, and the relationship between the three agents: the factory, site, and truck, all presented as the red circle in the flowcharts. At the factory, production lines would push all orders through as soon as possible. There are two constraints that could pause the production line: factory storage space and work hours. If the storage space is filled, the production line will wait until space is available. Otherwise, the production lines would work no stop until off the clock. Loading Trailer and connection to Truck is also part of the factory processes controlled by the factory system and truck logistics. For a batch of panels to load onto a trailer, the factory would search for empty, idle trailers at the factory. Once loaded, the loaded trailer would wait until a truck has decided to pick it up.

When a connected trailer and truck arrive at the site, the first step is to disconnect the trailer and the truck. However, trailer parking space on site is limited. If parking space is filled, the vehicle must wait at the factory until parking spaces are available. Following disconnection, the site process is divided into two streams: the trailer stream and the suborder stream. The trailer steam is part of dispatch logistics, where a trailer waits for a truck to pick it up and move back to the factory; the suborder stream is controlled by the panel type, installation speed, and panel installation sequence. For example, a trailer of wall panels has arrived on site. Even though the site has generated orders in the installation sequence (from bottom to up, the roof should be installed at last), due to different factory production speeds, roof panels may arrive earlier than this wall panel batch. In this case, the roof panels must wait on site until the walls have been installed.

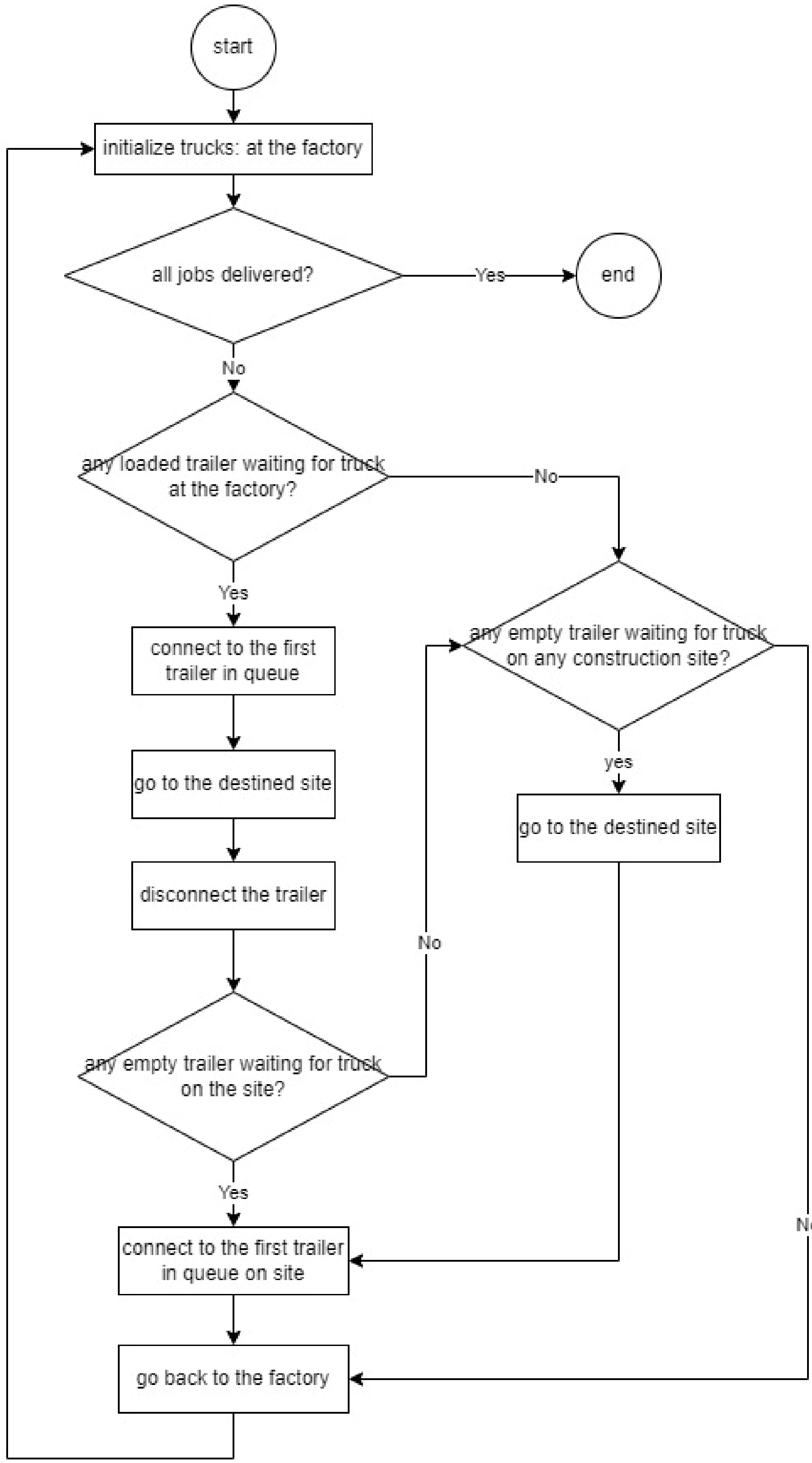

Figure [13]: truck operation logic

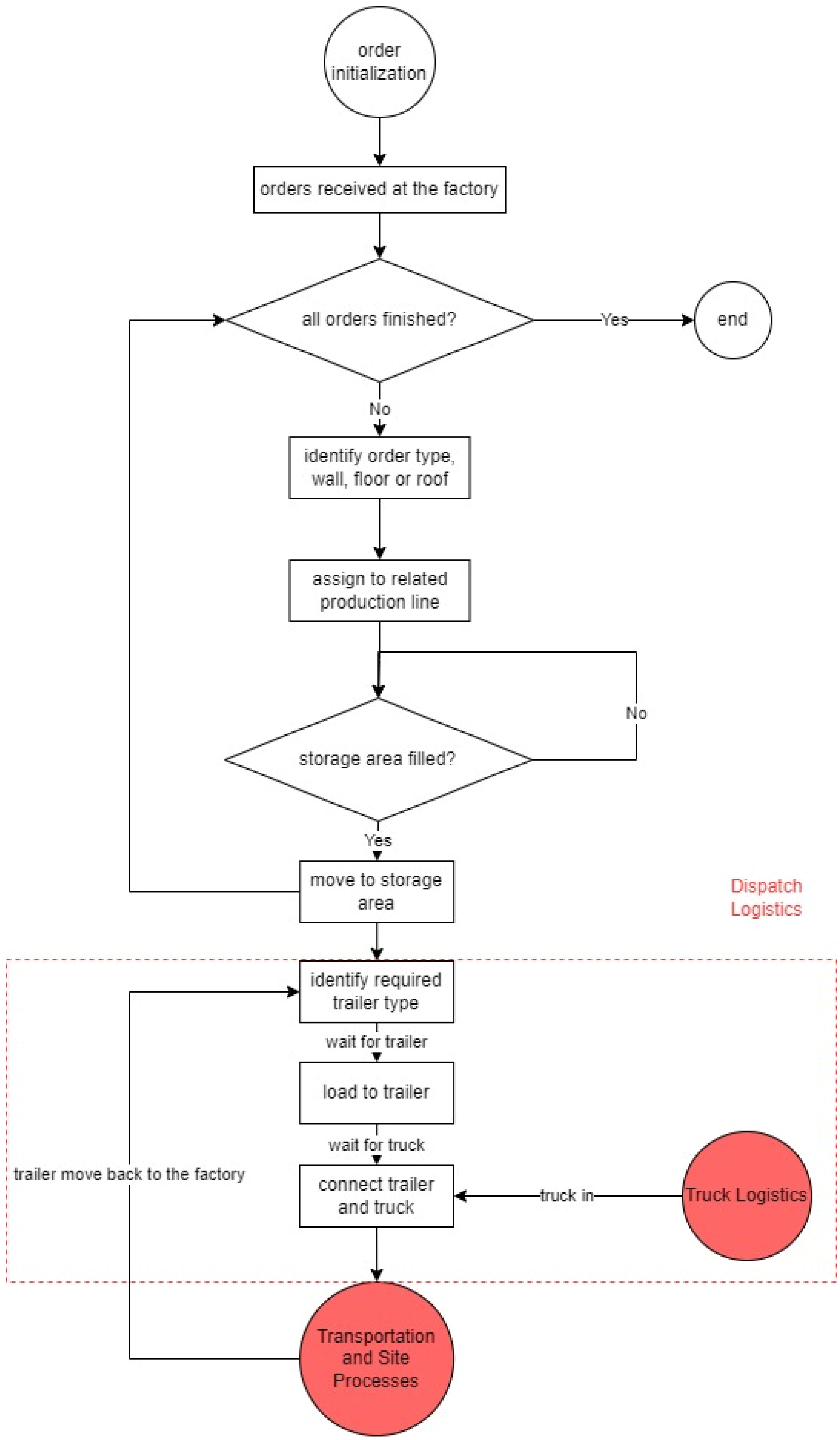

Figure [14]: factory processes

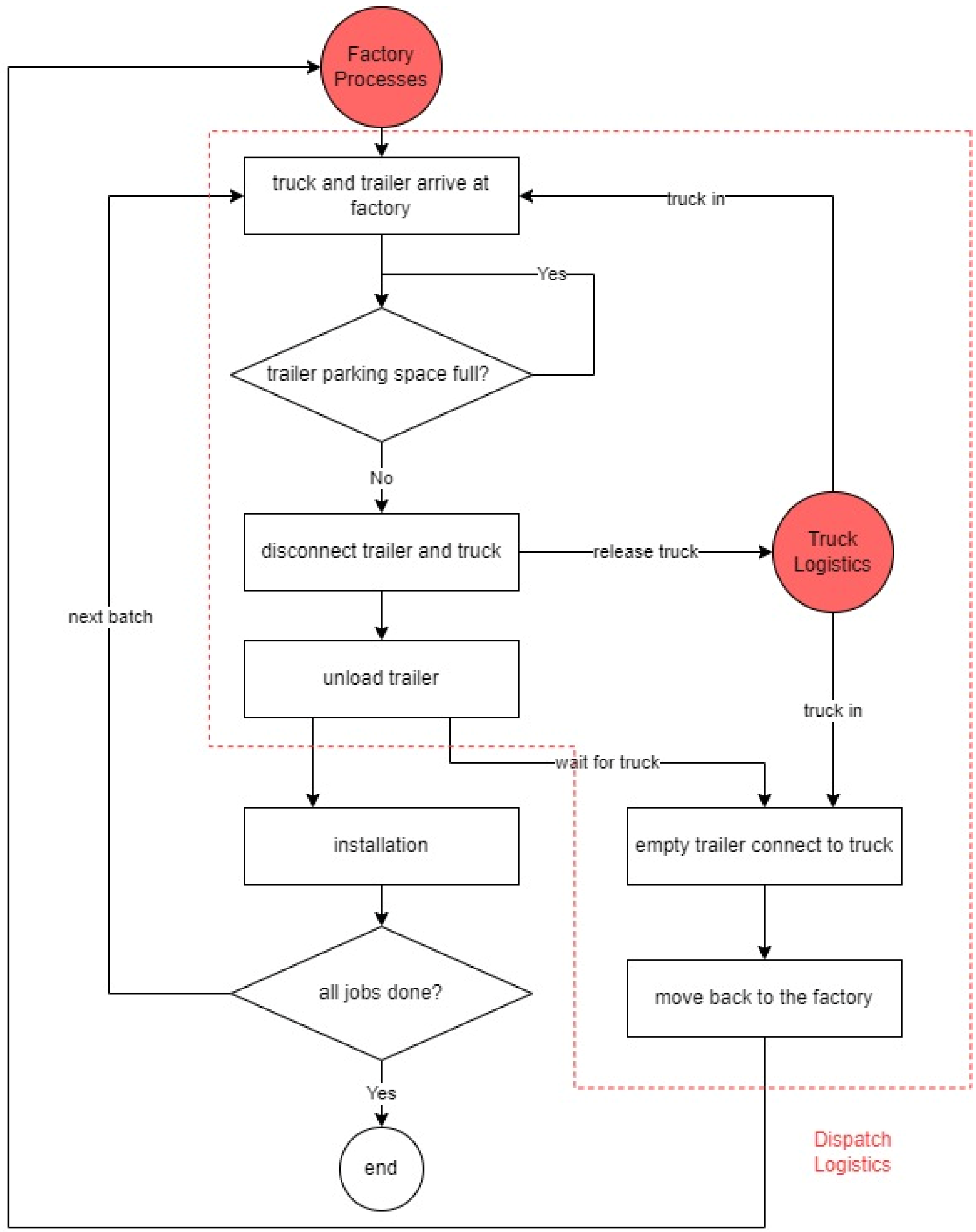

Figure [15]: site processes

4.2 Simulation Module: Push and Pull Planning

4.2.1 Push Planning Simulation

Section 4.1.3 has described the Push Planning design for a supply chain system using a combined method of ABM and DES. This subsection translates the design into an AnyLogic modeling environment where the flowcharts are further elaborated and implemented. The first step is a global environment definition that defines the suborders and initiates the model. In AnyLogic, the global environment is called *Main*. *Main* sets up the model by reading the input data sheets, defining global parameters such as working hours, trailer numbers, etc., and defining agents. There are three types of project information in the input data sheet: (1) site name, (2) location (longitude and latitude), (3) panel breakdown schedule (capping floor, lifting wall, lifting floor, and lifting roof), and (4) site trailer parking space. An input example is shown in table [1].

Table [1]: input spread sheet example

SiteName	Longitude	Latitude	CappingFloor (floorsqf)	LiftingWall (wallsqf)	LiftingFloor (floorsqf)	LiftingRoof (workerhr)	Parking
A	53	-113	1600	4000	1600	100	3
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Global parameters are not changed during the simulation. Global parameters include (1) working hours, (2) trailer and truck number, (3) trailer capacity, (4) factory location (longitude and latitude), and (5) truck speed. The model is initiated by sites generating all orders in sequence and sending them to the factory. The order initialization considers orders of two stages: capping and lifting (Figure [16]). In the case of two-story single-family housing, wall lifting needs to be divided into two batches.

Capping Floor Initialization

```
a = capingfloor;
while(a > 0){
    double b = Math.min(a , get_Main().floorpertrailer);
    get_Main().add_order(2, 1, b, this);
    a -= get_Main().floorpertrailer;
}
```

Lifting Initialization

```
double a = liftingwall;
while(a > 0){
    double b = Math.min(a , get_Main().wallpertrailer);
    get_Main().add_order(1, 2, b, this);
    a -= get_Main().wallpertrailer;
}

a = liftingfloor;
while(a > 0){
    double b = Math.min(a , get_Main().floorpertrailer);
    get_Main().add_order(2, 2, b, this);
    a -= get_Main().floorpertrailer;
}

a = liftingroof;
while(a > 0){
    double b = Math.min(a , get_Main().roofpertrailer);
    get_Main().add_order(3, 2, b, this);
    a -= get_Main().roofpertrailer;
}
```

Figure [16]: suborder initialization

Section 4.1.3 has identified three agents in this model: (1) factory model, (2) truck model, and (3) site model. While Factory is modeled as an Agent because of its autonomy, within the Factory, the procedures are a series of sequential discrete events suitable for DES modeling. There are three production lines, and each take suborders according to the suborder type. In the factory model, the subject is suborders. In other words, the system is designed to control suborders. Trailer and truck paired with this suborder are modeled as suborder variables (Figure [17]). The factory procedures are initiated by receiving orders from the sites, represented as blue right arrows in Figure

[18]. The suborders flow through a series of discrete events represented in blue rectangles and finally exit the factory system. Production line speeds are defined in the three production modules respectively.

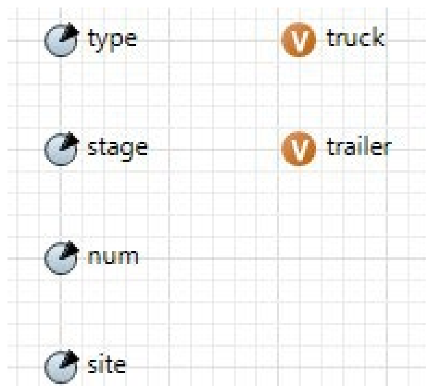

Figure [17]: order variables and parameters

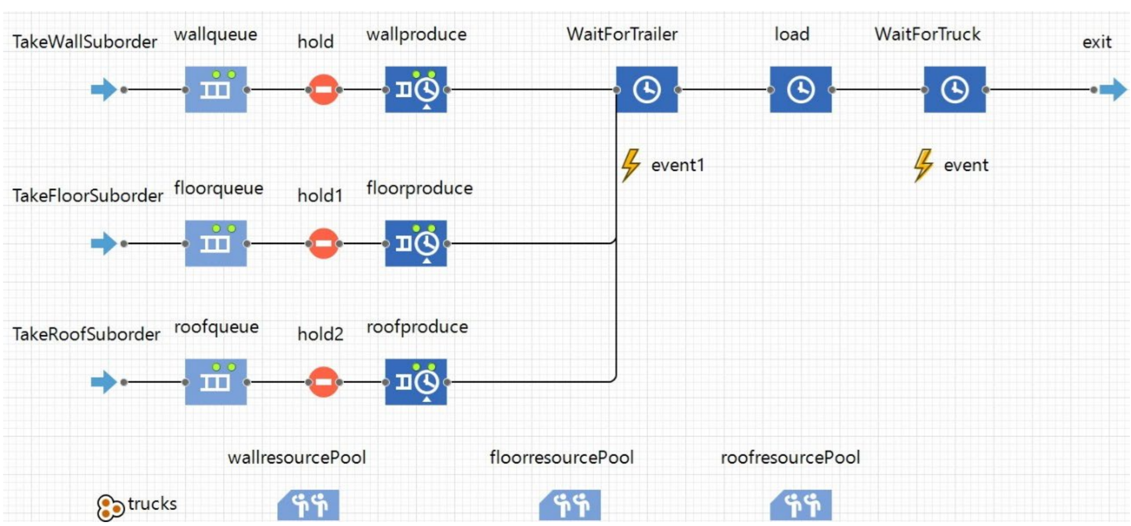

Figure [18]: factory model

As mentioned in the previous subsection, Factory Processes consist of two parts: factory production and dispatch logistics. The three modules at the left of Figure [18]: wall production, floor production, and roof production, are production modules, while the three on the right: wait for Trailer, load, and wait for Truck, are dispatch logistics. The production modules delay the exact amount of time t based on production speed S and order amount O_i:

$$t = \frac{O_\mathrm{i}}{S} \tag{6}$$

Even though the orders go to different production lines according to the order type, upon reaching the end of each production line, all orders enter the exact dispatch logistics in the factory. The dispatch logistics are initiated by suborders waiting for trailers to load. The condition for a suborder to exit the module "WaitForTrailer" and start loading is an empty trailer available at the factory. The trailer searching code regarding wall type suborder is shown in Figure [19]. Next, the suborder is loaded onto the empty trailer and wait for truck connection. This step is executed recursively every minute until a truck is paired with a trailer. Truck's availability at the factory is controlled by truck logistics.

```
trailer t = null;
order o = null;
if(waitorder.size() > 0){
    if(load.size() + WaitForTruck.size() < capacity){
        int s = 0;
        l1:for(order i : waitorder){
            if(i.type == 1){
                if(walltrailer.size() > 0){
                    o = i;
                    t = walltrailer.get(0);
                    //t.order = o;
                    o.trailer = t;
                    walltrailer.remove(t);
                    WaitForTrailer.stopDelay(o);
                    waitorder.remove(o);
                    o.time = time() - o.time;
                    s++;
                    break l1;
                }
            }
        }
```

Figure [19]: suborder loading condition example

According to subsection 4.1.3, Truck has five operations: (1) at the factory, transport loaded trailer to the destined site; (2) at a site, transport empty trailer back to the factory, (3) at a site with no empty trailer, go to another site with empty trailers; (4) at a site, go back to the factory alone, (5) at the factory, go to a site with an empty trailer. The Truck always operates the task that is nearest to it. In the AnyLogic environment, Truck algorithm is implemented with the state chart shown in Figure [16]. Based on the five tasks, six states are identified: (1) idle at the factory, (2) connect to a loaded trailer and move from the factory to a site, (3) move directly from the factory to a site for an empty trailer, (4) find an empty trailer at a site, (5) move from one site to another site, and (6) Move from a site back to the factory, with an empty trailer. The relationship between the states is shown in Figure [20]. In the state chart, the action of moving back, with or without a trailer, is abstracted as one state: state (6). It is the core state that connects most of the other states. The implementation of each state is described in java code. Take state (1) as an example, the truck is at the factory. Here, two conditions need to be considered: (1) there are loaded trailers at the factory, and (2) there is no loaded trailer at the factory. Under condition (1), if there is enough parking space on the site, the truck would connect to this trailer and move to the destined site. The example code regarding wall panels is shown in Figure [21]. Under condition (2), the truck would search other sites for empty trailers on sites; if any, the system would send the truck to retrieve the empty trailer on the site. The code implementing this condition is shown in Figure [22].

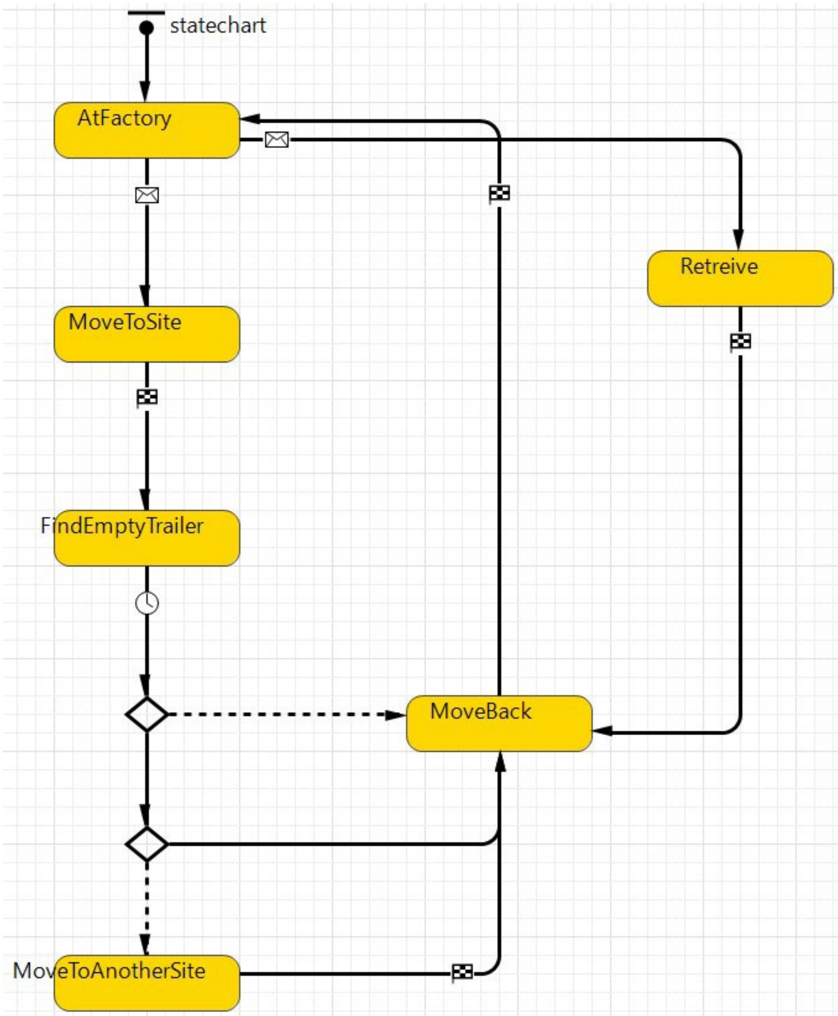

Figure [20]: truck state chart

```
if(trucks.size() > 0){
    if(finishorder.size() > 0){
        order k = null;
        trailer m = null;
        l1:for(order l : finishorder){
            if(get_Main().countsitetrailer(l.site) && l.type == 1 && (l.site.wallstore1 + l.num) <= l.site.wallstore){
                k = l;
                for(trailer tt : waittrailer){
                    if(get_Main().walltrailer.contains(tt)){
                        m = tt;
                    }
                }
                l.site.wallstore1 += l.num;
                break l1;
```

Figure [21]: truck at factory connect to loaded trailer example code

```
else{
    l3:for(site i : get_Main().site){
        if(i.emptytrailer.size() > 0){
            trucks.get(0).trailer1 = i.emptytrailer.get(0);
            trucks.get(0).site = i;
            i.emptytrailer.get(0).truck = trucks.get(0);
            trucks.get(0).receive("retreive");
            i.emptytrailer.remove(0);
            trucks.remove(0);
            break l3;
        }
    }
}
```

Figure [22]: truck at factory head to a site and retrieve an empty trailer implementation code

Subsection 4.1.3 has identified two streams for site processes: installation and dispatch logistics (Figure [15]). The upper stream of Figure [23] is a series of discrete events regarding the general installation procedures: capping, waiting, and lifting. Capping includes ground condition treatment; therefore usually requires the site to sit still for around ten days before any lifting. The condition to exit the module Capping is that the capped floor amount is equal to the total capping floor amount, then the installation process would proceed to wait. The factory keeps producing panels during this waiting time. Additionally, the panels must be installed in a particular sequence depending on the project type (Figure [6]). This is modeled as a constraint separately from the two streams (Figure [24]). The construction sequence needs to be controlled because even though the orders are created in the correct sequence, the three production lines operate at different speeds, resulting in a shuffled arrival sequence. This part of the model creates a queue for the suborders to ensure installation in the correct sequence. The example code regarding the wall panels is shown in Figure [25]. The bottom half of Figure [23] is the site dispatch logistics. In this stream, the Trailer is the subject that documents the trailer and order state changes, then waits until the stop delay command is called by an idle truck at this site (Truck state (4): find an empty trailer). The example code for this stop delay condition is shown in Figure [26].

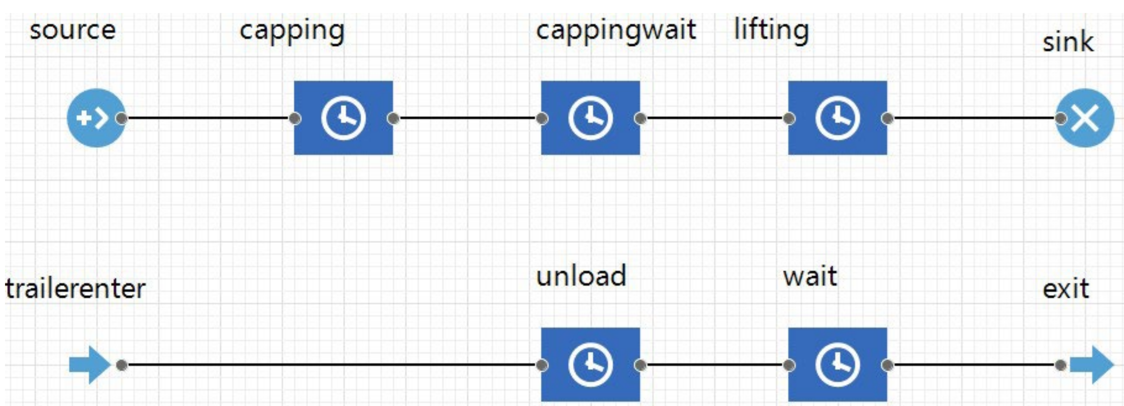

Figure [23]: site processes

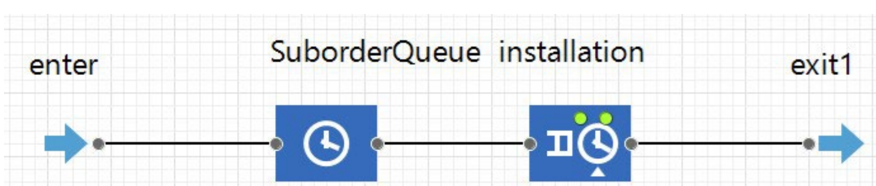

Figure [24]: site installation

```
else if( leve == 2 && finishliftingwall1 < liftingwall/2.0 && caping.size() == 0){
    l4:for(sqf i : collection){
        if(i.type == 1){
            delay.stopDelay(i);
            finishliftingwall1++;
            break l4;
        }
    }
}
```

Figure [25]: site installation sequence wall panels example

```
if(t != null){
    if(s == s1){
        change = false;
        site = s;
        site.wait.stopDelay(site.emptytrailer.get(0));
        trailer = site.emptytrailer.get(0);
        site.emptytrailer.remove(0);
    }
    else{
        change = true;
        site = s1;
        trailer1 = site.emptytrailer.get(0);
        site.emptytrailer.remove(0);
    }
}
```

Figure [26]: site trailer stop delay condition

4.2.2 Pull Planning Algorithm

Section 4.2.1 has modeled the integrated supply chain system based on real operations using the Push Planning method. While this model pushes orders through as soon as possible, there are two major problems: (1) even though the orders are sent to the factory in installation sequence, the three production lines operate at different speeds, resulting in a shuffled sequence of arrival orders. To ensure the correct sequence to be installed on the site, the suborders that arrived on site need to be reorganized in the installation sequence (Figure [24]), resulting in an excessive site inventory. The second problem is: (2) in the real world, jobs are rarely completed way earlier than the due date. Instead, the earlier dates are reserved for more urgent projects, and the ideal situation is to complete a project right before the due date. Section 3.4 has reviewed studies on pull and push approaches in construction management, with a general result that pull planning can reduce inventory and resource waste. However, there is no study applying pull planning philosophy to off-site construction logistics. This section is an attempt to remodel the simulation model based on the same operations using the Pull Planning approach. The resulting comparison and analysis are discussed in the next Chapter.

Pull planning requires the simulation to start from the model end time and proceed backward to generate the proper starting time and order sequence. Instead of starting with the site sending orders in the installation sequence to the factory and ending with the project completion time, the Pull-Planning Simulation (PLS) starts with the ideal project completion time and ends with the proper order generation sequence and the start time. The key to this model is the reversed workflow. The simulation starts with all jobs completed. Imagine deconstructing the houses and breaking them down into panels, the panels being uninstalled, loaded onto trailers, connected to trucks, transported to the factory, unloaded, put on the production lines, and restored to raw materials. The procedures and duration are based on Push Planning Simulation (PSS) data.

Considering AnyLogic built-in clock is a regular clock, the first step of this pull planning model is to build a reverse clock (Figure [27]). The clock reduces minutes instead of adding them. Therefore, the completion time of a day becomes one of the required inputs for model initiation (Table [2]).

▾ Action

```
startminute--;
if(startminute < 0){
    startminute = 59;
    starthour--;
    if(starthour < 0){
        starthour = 23;
        day--;
    }
}
```

Figure [27]: reverse clock

Table [2]: input completion time example

SiteName	Year	Month	Day	Hour	Minute
A	2022	Sep	15	17	30
⋮	⋮	⋮	⋮	⋮	⋮

There are two steps in applying the Pull Planning approach to the new model: (1) remake the flowchart based on the same problem statement referring to subsection 4.1.3, and (2) remodel the simulation model based on the flowcharts. The old flowcharts and model are referenced throughout the following subsection to (1) construct the PLS and (2) compare and discuss the different approaches to pave the way for the case study and result discussion. For clarity purposes, the flowchart for PLS describes the processes of deconstructing housings and restoring them to raw materials because it flows naturally with the arrow direction and distinguishes itself from PSS.

4.2.2 Push and Pull Planning Simulation Flowcharts

The two models share many features. The flowchart's structure remains the same as shown in Figure [12], with three main Agents: Truck, Site, and Factory. While the Site and Factory are autonomous systems in the global environment, activities within the Factory and the Site Agents are modeled with DES. The flowchart of overall procedures in reversed order is shown in Figure [28]. The main body still consists of three parts: (1) site procedures, (2) dispatch logistics, and (3) factory procedures. Same as PSS, the integration is also implemented at the overlapping part where the Trailer is disconnected from the Truck, and trailer activities are modeled along with Factory/Site procedures. For the truck algorithm, even though the start state may be different between the two models (e.g., in the push planning approach, the start state of a truck is idle at the factory (Figure [20]), while in the new model, the start state is at one of the sites), both truck logic loops between states for both models. Hence, the truck logistics shown in Figure [13] still apply to the new model.

For Factory and Site, revising the order has changed the modeling logic. Factory procedures in PSS consist of two independent parts: factory production and dispatch logistics. In PSS, Factory production lines always operate at their full capacity unless constraints such as the filled factory storage area can pause the production lines. Once a suborder leaves the production line, production lines keep producing the next suborder, if any (Figure [14]). At the end of the production line, the flow diverges; the finished order flows to dispatch logistics and considers vehicle problems, while the production line returns to the beginning of the production line to start and produce the latest order in the queue. In PSS, the production line is an active entity. All orders are sent to the production lines upon model initiation, and the production lines work at their maximum capacity until completion. PLS, however, orders are sent to the production lines only when they can smoothly flow through the entire procedure and get installed on site. Therefore, the factory production lines in PLS are passive entities that only operate upon receiving the suborders (Figure [29]).

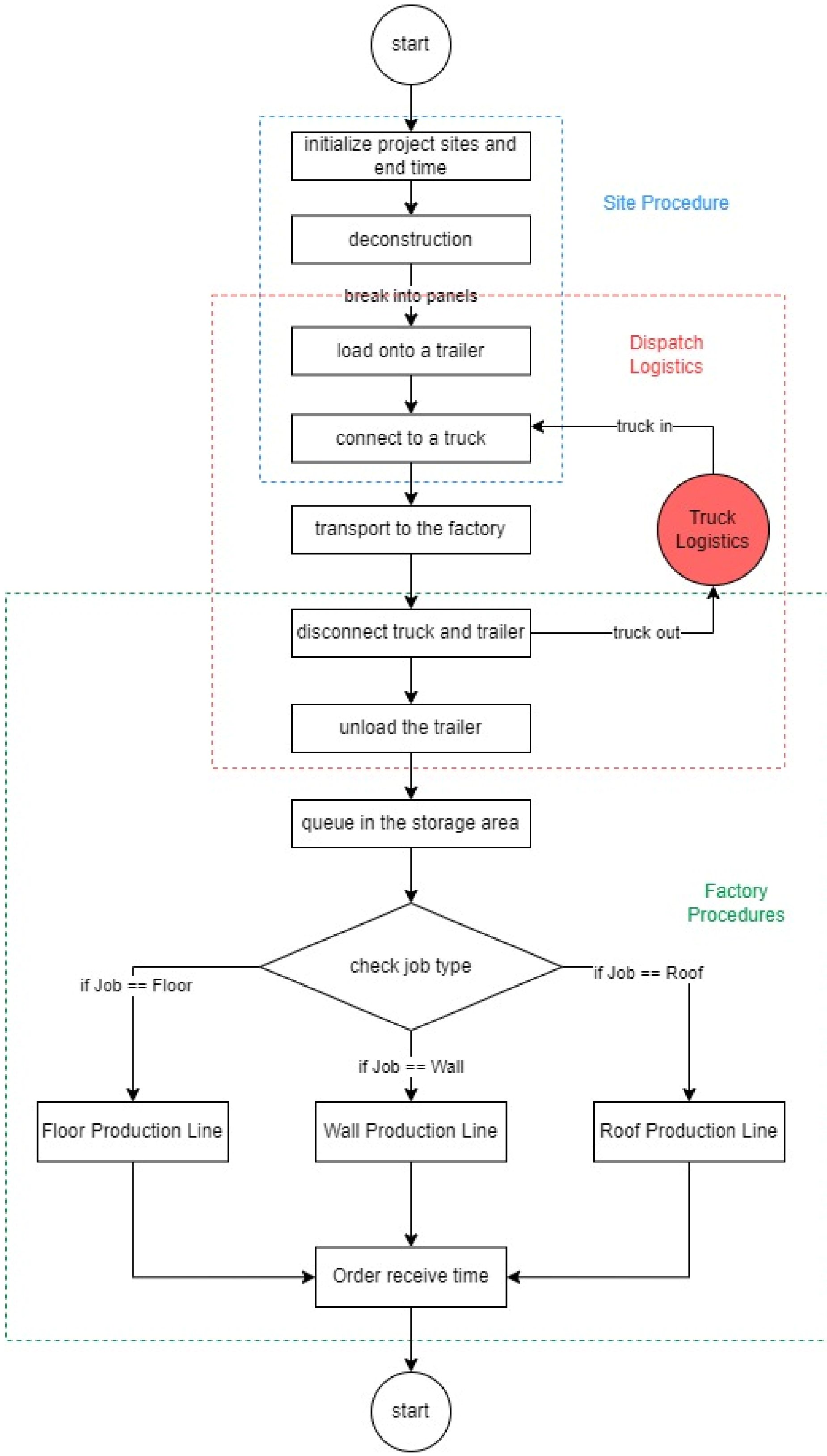

Figure [28]: overall flowchart using pull planning approach

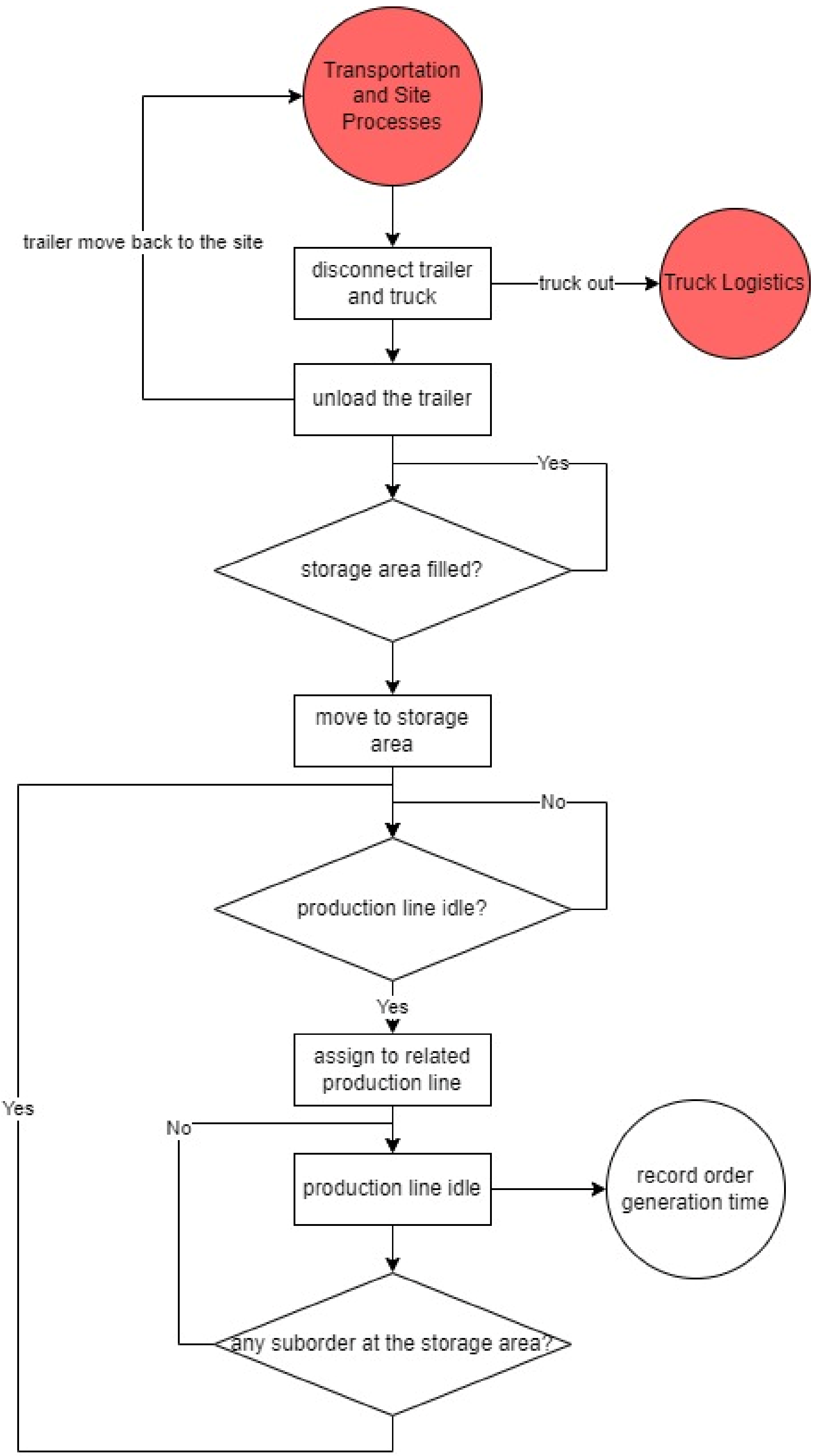

Figure [29]: PLM factory procedures

The PLS site processes also consist of site installation (deconstruct) processes and dispatch logistics, but the sequence is reversed. The main challenge in drawing the site flowcharts is handling the two parallel flows regarding different objects: trailer and suborder. In the previous model (Figure [15]), after unloading a trailer, the flowchart diverges to a trailer-oriented stream and a suborder-oriented stream. The former is part of the dispatch logistics, where the empty trailer keeps searching for a truck to transport it back to the factory, and the latter proceeds to site installation processes. In PLS, after deconstructing, the two streams converge into one module: loading onto a trailer requires an empty trailer and one suborder (Figure [30]). As mentioned before, truck logistics is a loop that is constantly changing between statuses until the model ends. Among all the truck tasks, transporting an empty trailer back to the factory is considered the loop connection point that is modeled at the end of the trailer stream in PSS. In PLS, this activity is inserted between deconstruct completion and loading to Trailer. Additionally, the site installation (deconstructing) process is an active entity that keeps operating unless paused by constraints, such as limited site parking space. Pull planning, therefore, swaps the role of site installation and factory production compared to the push planning approach.

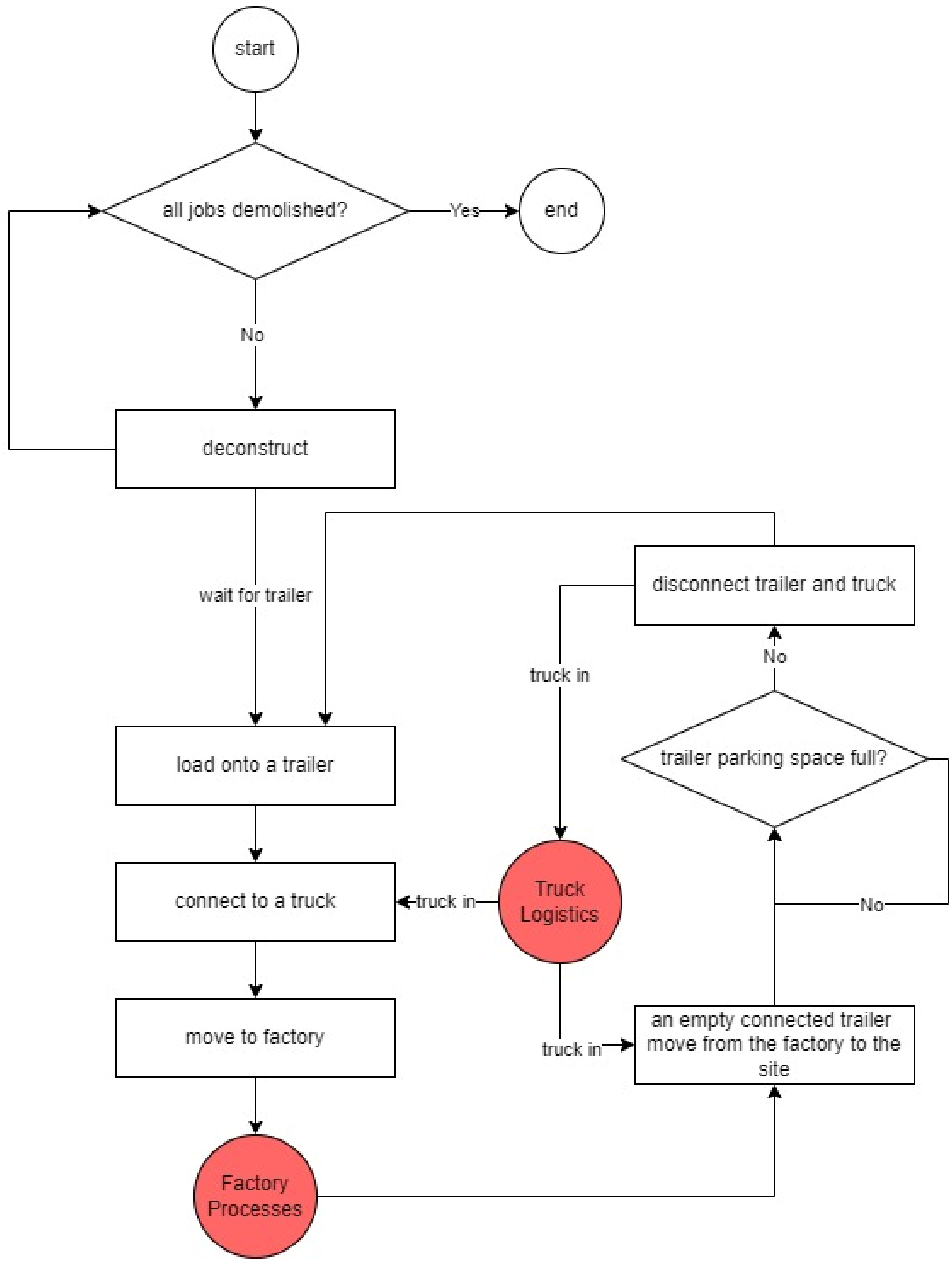

Figure [30]: PLS site procedures

4.2.3 Pull Planning Simulation (PLS) Model Implementation

The previous subsection has drawn PLS flowcharts based on the problem statement and PSS. One of the main differences is that in PLS, instead of factory production lines, the site is the active entity that generates requests and pulls the resources selectively from the system. When implementing the Site agent, suborder (the amount of same-type panels that can be carried in a trailer) is the executor of this active role that keeps requesting resources and initiating events. It is also the core element that flows through most parts of the system and carries all the related information, such as the trailer instance, truck instance, and site information. The only event that suborder is not involved in is that truck transporting empty trailers from the factory to the site. In order to model it as an agent that actively searches for Truck/ Trailer throughout the model, a Batch is created to represent the abstract idea of suborder that circulates back to the site. Therefore, based on the previous model, apart from the agents that are inherited from the PSS (Factory, Site, and Truck), the suborder is modeled as the Batch agent in PLS. All suborder events are modeled either in the Site agent or Factory agent. In other words, Batch does not have its own events. Instead, Batch is defined with a series of variables, parameters, and most importantly, the function that lets it actively find trucks and trailers. The function is called as soon as the batch instance is created. A Batch keeps searching for a Trailer and Truck until it is paired with both. Figure [31] shows the constructor of a batch, its variables, and the truck/ trailer finding function. There are four parameters to define a batch instance: (1) type, whether this batch of suborder is wall, floor, or roof; (2) num, the quantity of this batch, (3) state is the parameter to record whether this batch is a capping batch or a lifting batch; (4) from_site records the site where this batch is generated. Apart from the four instances that are not changed during simulation, there are four variables: (1) a trailer that carries this batch, if any; (2) a truck that connects to the trailer, if any; (3) the current time, which is calculated by a reverse clock, and (4) moving state. There are two moving states in this model: moving state one means to move from the site to the factory and moving state two means to move from the factory to the site. The searching behavior implementation considers the two moving states separately, shown in Figures [32] and [33]. For moving state one, the batch searches a trailer that matches its panel type at the factory. Once paired to a trailer, it searches for an idle truck at the factory and pairs it to this truck. For moving state two, the trailer is already paired in moving state one, so this part only searches for the nearest idle truck, which can be anywhere, at the factory, at any site, or on the road. This function is called in site processes when batches have finished deconstructing.

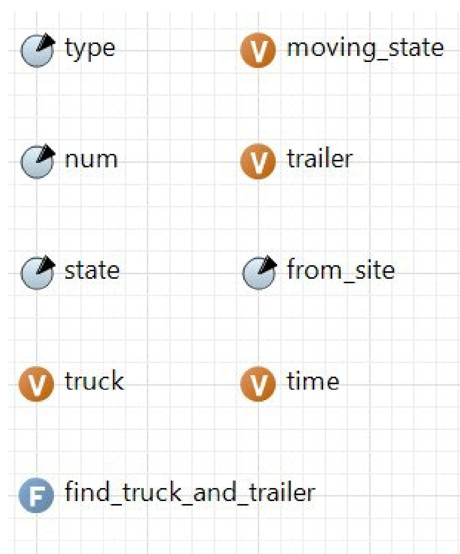

Figure [31]: batch agent

```java
if(moving_state == 1){
    if(get_Main().factory.trucks.size() > 0){
        if(type == 1 && get_Main().factory.walltrailer.size() > 0){
            truck = get_Main().factory.trucks.get(0);
            truck.batch = this;
            truck.trailer = get_Main().factory.walltrailer.get(0);
            truck.trailer.truck = truck;
            truck.receive("send");
        }
        else if(type == 2 && get_Main().factory.floortrailer.size() > 0){
            truck = get_Main().factory.trucks.get(0);
            truck.batch = this;
            truck.trailer = get_Main().factory.floortrailer.get(0);
            truck.trailer.truck = truck;
            truck.receive("send");
        }
        else if(type == 3 && get_Main().factory.rooftrailer.size() > 0){
            truck = get_Main().factory.trucks.get(0);
            truck.batch = this;
            truck.trailer = get_Main().factory.rooftrailer.get(0);
            truck.trailer.truck = truck;
            truck.receive("send");
        }
    }
}
```

Figure [32]: moving state one searching implementation

```java
if(moving_state == 2){
    List<truck> list1 = new LinkedList();
    for(truck i : get_Main().truck){
        if(i.idle == 0){
            list1.add(i);
        }
    }
    if(list1.size() > 0){
        truck k = null;
        double dis = 999999.0*999999.0;
        for(truck i : list1){
            if(i.distanceTo(this) < dis){
                k = i;
                dis = i.distanceTo(this);
            }
        }
        truck = k;
        truck.batch = this;
        truck.trailer = trailer;
        truck.trailer.truck = truck;
        truck.receive("send back");
    }
}
```

Figure [33]: moving state two searching implementation

The rest of this subsection implements the model design referencing subsection 4.2.2 in the following sequence: (1) Site agent implementation, (2) Factory agent implementation, and (3) Truck agent implementation. PLS implementation challenges mainly appear where state changes and constraints apply, such as the management of trucks in transit and the parking space limit on sites. The following paragraphs elaborate on how to manage state changes and constraints.

For site processes, as mentioned in subsection 4.1.4, the flowchart diverges after unloading a trailer from the factory. The model is separated into two parts in the previous model: trailer-centered discrete events and suborder-centered discrete events. This situation is naturally modeled separately, presented as two streams with independent entrances and exits (Figure [23, 24]). In PLS, however, the flow turns around at Factory Processes and converges into the module "load onto a trailer" (Figure [30]). In AnyLogic implementation, trailer arrival breaks at the connection with factory processes and gets inserted into suborder-oriented discrete events as the modules "trailer Arrival", "wait", and "trailer Departure" (Figure [34]). Disconnection with a truck is also inserted in the same place, but the time used for this event is merged into the trailer waiting time before vehicle departure, the "wait" module. The blue brackets control the site parking space constraint before trailer arrival and after trailer departure. If the parking space is full, the batch will wait in the "queue" module before the blue bracket until there is at least one trailer parking space. Like site installation in PSS, the module "deconstruct" has a specific deconstruct sequence to follow. The sequence for the module "deconstruct" is shown in Figure [35], which is the reversed order of the upper half of Figure [23]. The deconstructing (installation) process starts with lifting (all the panels except for the first level floor), then waiting for a period before any capping (the first level floor). This stream controls the “deconstruct” module in Figure [34]. During the waiting time (usually around ten days), the “deconstruct” module is disabled.

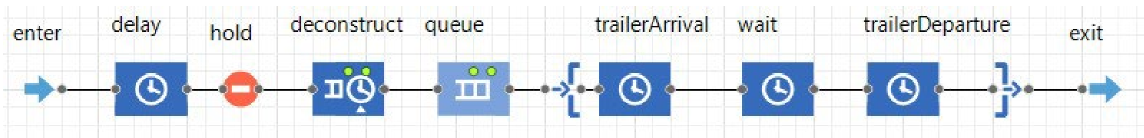

Figure [34]: PLS site processes

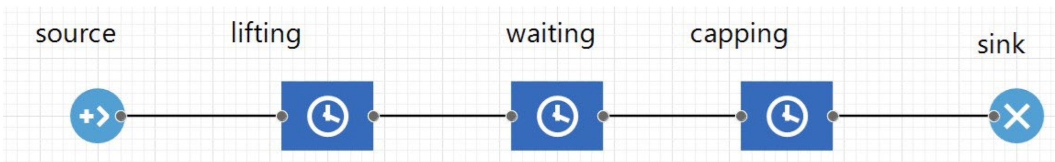

Figure [35]: PLS deconstruct module elaboration

For factory procedures, the model is a direct translation from the flowchart shown in Figure [29]. A Batch enters the factory procedures, queue if the factory parking space is full (usually factory parking is more than enough for all vehicles), and proceed to disconnect with the truck and unload, then wait if the production line is serving the previous batches (Figure [36]). For example, if two wall batches arrive at the factory, the one that arrives earlier would also enter the wall production line earlier. When the wall production line is servicing the earlier Batch, the later Batch would have to wait until the wall production line is idle. Factory entry and exit also use Batch to carry information such as the paired trailer and truck. Therefore, in the PLS, besides the abstraction of suborders, Batch also serves as the simulation tracker to record the simulation progress.

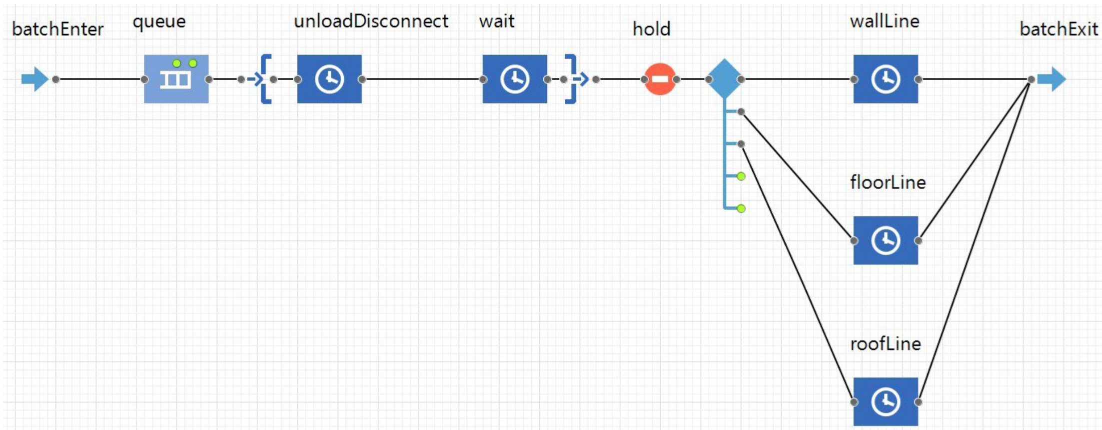

Figure [36]: PLS factory procedures

The truck logistics flowchart has listed the truck states and their relationship (Figure [13]). However, when implementing the model, the actual state is not limited to the ones shown in the flowchart. The situation is complicated by Trailer and Batch behavior. When searching for an idle truck, the truck can be at the factory, at one of the sites, or in transit. When paired to a trailer, the truck can also be at factory, at one of the sites, resulting in many transition states, such as the truck is moving from a site back to the factory, not connected to a trailer, but during the road time, it gets paired to a trailer at a site. The truck should now turn around and head to the paired site. Therefore, the truck status is modeled based on the Batch's trailer and truck finding function. As mentioned before, Batch considers two conditions when searching for vehicles: moving state one, finding a vehicle to transport this batch from the factory to the site, and moving state two, finding a truck to transport this batch from the site to the factory. Both moving states would search for the nearest idle truck, regardless of the truck's location. Thus, the state chart of truck logistics starts with the state idle, which depends on the command truck receives to decide which condition to take. The condition of successfully pairing to a truck is that the batch has already paired with a trailer. If the batch is at moving state one at the factory and requires a truck to transport the batch to the site, an idle truck at the factory will receive the command “send”. The truck would then move the batch and its trailer to the destined site, disconnect and return to the idle state. If the batch is at moving state two, the request would be to transport the batch from the site to the factory. Considering a truck is not necessary at this site, this condition would let the truck move to the current site before moving to the factory, then return to the idle state (Figure [37]).

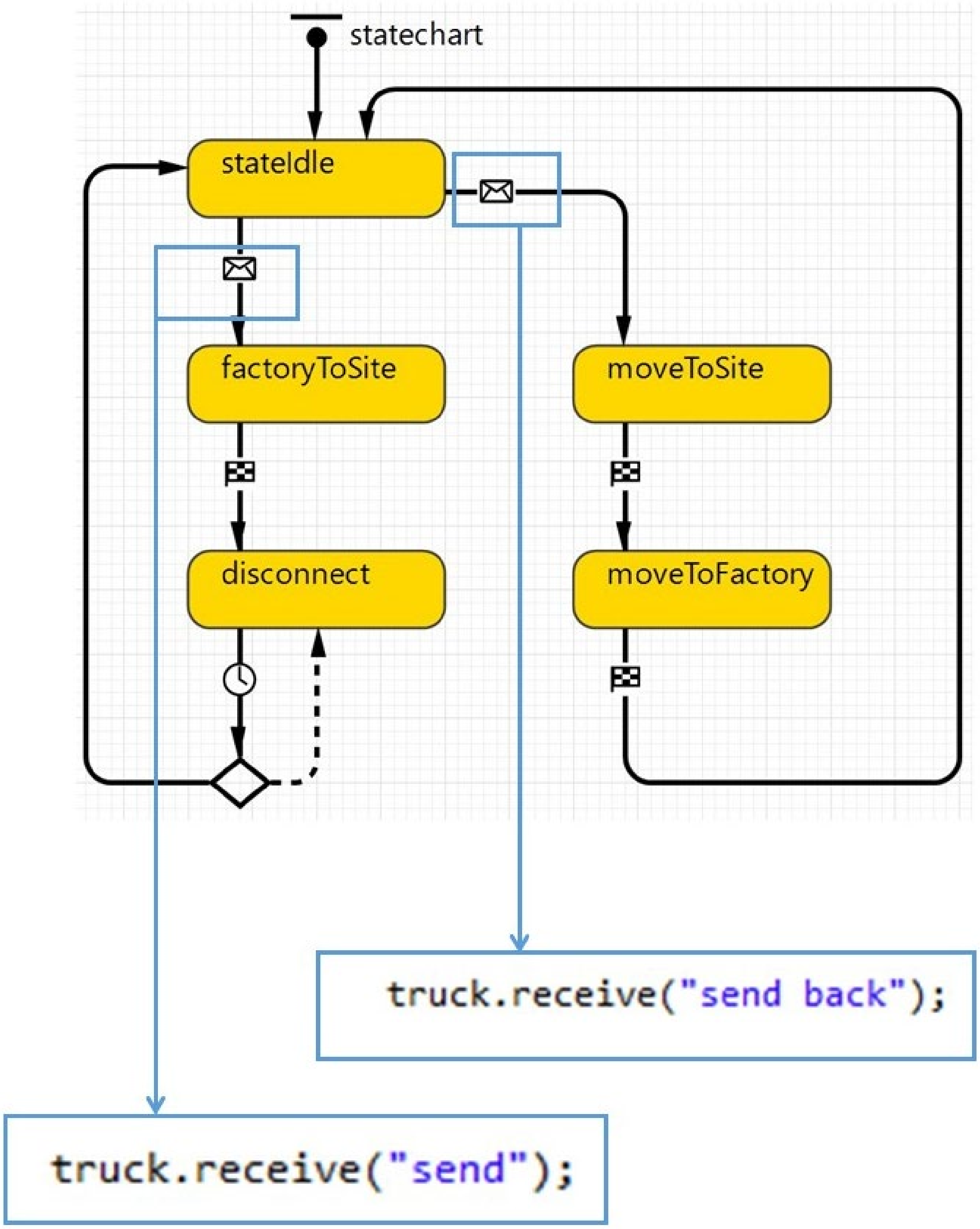

Figure [37]: PLS truck state chart

5. Case Study

5.1 Case Study Evaluation Criteria

Chapter 4 presents two models using push planning and pull planning, respectively. To compare the efficiency of the two approaches, the two models share the same set of data input and procedures. This chapter compares the two approaches by analyzing results generated from real-world case data. As mentioned in subsection 2.4, three criteria are used for efficiency measurement: idle time, makespan, and inventory level (Figure [3]). The three criteria are defined as follows:

(1) Idle time. Idle time is the time between two entity states, where the entity is ready to transit from the former state to the latter but cannot proceed because of system constraints. For example, when a loaded trailer at the factory waits for a truck, the time should be counted as trailer idle time because "loaded" means the trailer is ready to connect; however, at that time, an idle truck at the factory is not available. Idle time can happen at any of the three parts: Factory, Site, and Dispatch Logistics. As mentioned in Chapter 4, the PSS identifies the factory as the active entity that fabricates the panels at their maximum capacity. The site takes the panels with site constraints, resulting in a possible situation where sites are idle with no task to be done. In PLS, the situation is the opposite. The factory can possibly be idle with no tasks queuing. These situations are caused by the modeling approach. These idle times do not reflect the schedule efficiency. Only when resources are forced to pause because of constraints such as the storage space is full/ not enough vehicles, the idle time should be counted. Considering the factory and the site

are constantly processing suborders when getting paused by constraints, suborder is used for calculating the factory production line and installation idle time. Suborder (panel) idle time I_p is the sum of all suborder idle time at the factory and on sites, including the time waiting for production and the time waiting for installation. Besides the factory and sites, truck and trailer idle time also indicate the scheduling efficiency. Trailer idle time I_r happens when a loaded trailer (1) waits for a truck, (2) waits to be loaded, (3) is on the site, waiting to be unloaded, and (4) is on a site, waiting for a truck to take it back to the factory. Truck idle time I_t happens when a truck at the factory is waiting for a loaded trailer, or at the site searching for an empty trailer. Three types of idle time are considered: trailer idle time I_r, truck waiting time I_t, and panel waiting time I_p.

(2) Makespan. Makespan MS is the total time used from job initiation to completion. Considering the system processes multiple jobs, and the jobs are unlikely to be completed simultaneously, the result also records each job's start time and completion time for evaluation. In addition, the industry partners have emphasized the importance of the lifting date for the crane schedule, so the result also records the completion time of capping and the start time of lifting.

(3) Inventory Level. Inventory level is the number of panels waiting at the storage area. The inventory level is included in suborder idle time because inventories happen when the suborders are waiting to be loaded/ installed. However, inventory level only happens at the connection point of the three

parts: Factory Processes, Dispatch Logistics, and Site Processes. Therefore, the inventory level is still recorded for all three types of panels because it indicates the level of coordination of the system's three parts (Figure [9]). There are two types of inventories: factory inventory and site inventory. All three types of panel inventories are recorded throughout the simulation.

5.2 Case Study Input and Results

There are two types of case study inputs: global parameters and case parameters. Global parameters are related to the system settings, such as work hours, vehicle numbers, etc. Case parameters are related to each job, such as wall panel amount and housing type.

Global parameters include: (1) the number and capacity of trailers and trucks (Table [3]). The factory now has 5 wall trailers, 5 floor trailers, 4 roof trailers, and 2 trucks. Real-world trailer capacity depends on both square footage and panel shape. Considering the level of standardization of the panels, the impact of panel shape on trailer capacity can be ignored. In the simulation model definition, the unit of panels each wall, floor, and roof trailer can carry is: 2500 wallsqf, 1500 floorsqf, 20 workerhr, respectively. (2) factory storage space capacity. The storage space for wall panels is 6000 wallsqf, floor storage 3800 floorsqf, and roof 150 workerhr (Table [4]). According to the industry partner, the factory has no buffer area for floor and roof. (3) factory production speed. Factory production speed uses the normal distribution to represent the sum of small, independent errors that happen in the production line. Production speed mean and standard deviation are provided by the industry partner (Table [5]). Factory production speed means for wall, floor, and roof lines are: 1400 wallsqf/hr, 350 floorsqf

/ hr, and 35 workerhr/hr. (4) site installation speed. Like factory production, installation speed also uses the normal distribution to represent the speed range. The speed mean and standard deviation are also provided by the industry partner. Site installation speed means for walls, floors, and roofs are: 1000 wallsqf/hr, 500 floorsqf/hr, and 20 workerhr/hr. (5) other global parameters include work hour, truck speed, factory loading bay number, factory loading time, site unloading time, and factory location. Work hours are Monday to Friday, 8:00 a.m. to 6:00 p.m., ten hours a day, reflecting typical working hours in Canada's construction industry. Truck speed also uses the normal distribution to represent the continuous speed change, with the mean speed set to 80 km/hr. Factory loading time and site unloading time use triangular distribution because insufficient data is available for the two items. Both minimum and maximum are set to 0.5 and 1.5 hours, respectively. The most likely value is 1 hour. The factory location is described with latitude and longitude.

Table [3]: vehicle numbers and capacity

	wall trailer	**floor trailer**	**roof trailer**	**truck**
number	5	5	4	2
capacity	2500 wallsqf	3500 floorsqf	20 workerhr	1 trailer

Table [4]: factory storage space

	wall	**floor**	**roof**
factory storage	6000	3800	150

Table [5]: factory production speed

factory production speed	
wall	Normal (σ_{wf}, μ_{wf}), where $\sigma_{wf} = 140, \mu_{wf}$ = 1400 wallsqf/hr
floor	Normal (σ_{ff}, μ_{ff}), where $\sigma_{ff} = 35, \mu_{ff}$ = 350 floorsqf/hr,
roof	Normal (σ_{rf}, μ_{rf}), where $\sigma_{rf} = 1.5, \mu_{rf}$ = 15 workerhr/hr,

Table [6]: site installation speed

site installation speed	
wall	Normal (σ_{ws}, μ_{ws}), where $\sigma_{ws} = 100, \mu_{ws}$ = 1000 wallsqf/hr
floor	Normal (σ_{fs}, μ_{fs}), where $\sigma_{fs} = 50, \mu_{fs}$ = 500 floorsqf/hr
roof	Normal (σ_{rs}, μ_{rs}), where $\sigma_{rs} = 2, \mu_{rs}$ = 20 workerhr/hr,

Table [7]: other global parameters

work hour	Mon – Fri, 8:00 a.m. – 6:00 p.m.
truck speed	Normal (σ_t, μ_t), where $\sigma_t = 10, \mu_t$ = 80 km/h,
factory loading bay	3
factory loading time	triangular (0.5, 1, 1.5) hours

site unloading time	triangular (0.5, 1, 1.5) hours
factory latitude	53.49134
factory longitude	-113.40903

On average, the company does 6 to 10 single-family houses each month. Therefore, the case study considers 10 projects based on one month's production. The location information, site parking space, and storage space are defined in Table [8]. Case study data include: (1) project number, the actual project number is replaced by an English letter due to confidentiality concerns; (2) project type: bungalow or two-story single-family housing; (3) wall, floor, and roof amount (Table [8]), (4) project location, and (5) site parking space (Table [9]).

Table [8]: site type and panel amount breakdown

site	**type**	**Capping floor (floor sq. ft)**	**Liftingwall (wallsqf)**	**Liftingfloor (floorsqf)**	**Liftingroof (workerhr)**
A	2	1603	3983	1603	100
B	2	912	2976	912	86
C	2	3406	11000	3406	300
D	1	1057	2200	0	50
E	1	1825	3495	0	89

F	1	1360	3524	0	63
G	1	1770	4633	0	92
H	2	1323	5368	1323	123
I	2	1120	5222	1120	167
J	2	1220	5445	1220	138

Table [9]: site location and parking space

site	latitude	longitude	parking space
A	53.45364	-113.6232	3
B	53.53637	-113.59883	3
C	53.47271	-113.50131	3
D	53.5367	-113.59528	3
E	53.50072	-113.47336	2
F	53.55416	-113.50622	2
G	53.56121	-113.39605	3
H	53.50584	-113.50564	3

I	53.58554	-113.53629	3
J	53.55242	-113.48803	3

The results are generated from the above-listed inputs. As mentioned in section 5.1, there are three simulation model outputs: idle time, each project makespan, and inventory level. The idle time and makespan data are also written in Excel and sorted into tables for clarity. Data such as inventory level are recorded as line charts to visualize the dynamic inventory level throughout the simulation. Considering many inputs are stochastically varied parameters, such as the factory production speed, both models run 1000 times. Figure [38] has shown an example of site makespan result in the PLS. In this case, the project makespan mean is 303.66 hours, with the upper bound 345.705 hours and the lower bound 273.801 hours.

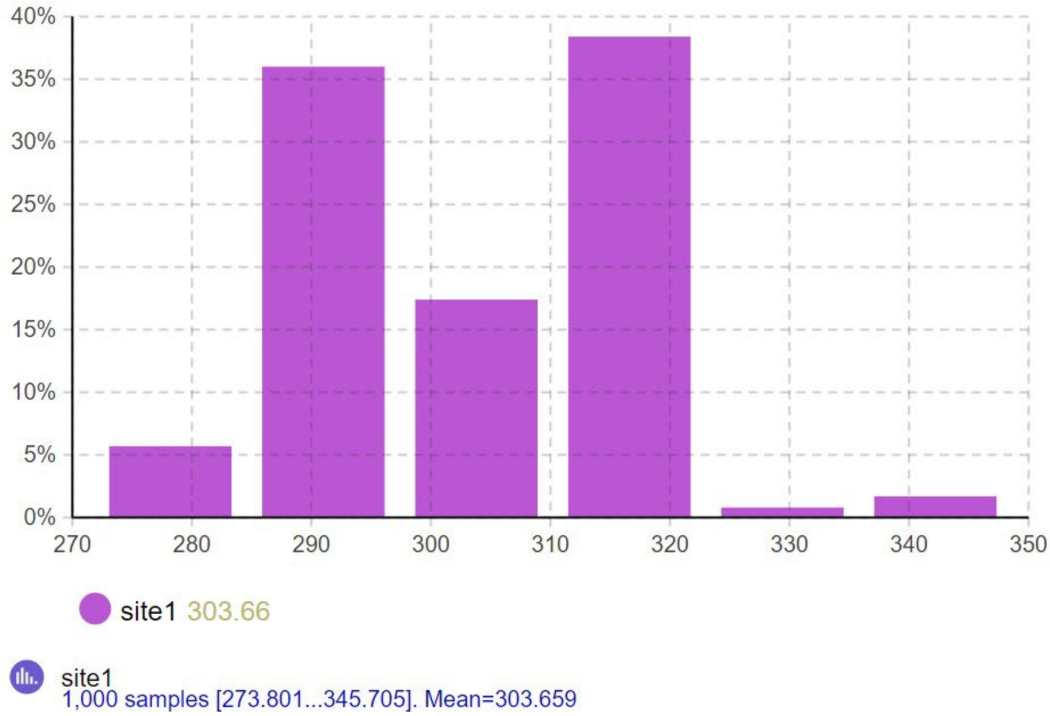

Figure [38]: project makespan result example

Regarding time, three types of idle times are recorded: suborder idle time, truck idle time, and trailer idle time. The result mean is listed in Table [10]. The table shows that PLS has much less suborder waiting time, less trailer waiting time, and a bit more truck waiting time. The trailer idle time happens when the trailer waits for truck connection at the factory or on sites or when it queues for panel unloading at the site. The truck idle time happens when the truck is waiting for trailer connection at the factory or on sites. For effective idle time calculation, the time after all panels have arrived is not calculated. Due to the different nature of the two types of resources, truck idle time is less problematic because the truck can always be utilized for any new tasks in their idle state. Trailer idle time, however, cannot be utilized for new tasks until it is empty at the factory. In this sense, the pull planning better utilizes the resources because it presents less trailer idle time. Suborder idle time consists of the time waiting at the factory storage area for trailers and trucks and the time waiting on site for installation. However, most cases show that for PSS, all orders arrive before the 10-day capping waiting time ends. This time before installation also counts for suborder waiting time. Even though this time is not preferred, the time does not reflect the level of workflow coordination. Therefore, this time is deducted from the PSS suborder waiting time for better comparison with PLS. Suborder idle time shows the level of continuation of the entire process. Therefore, PLS has shown a much shorter suborder idle time, which means it has a smoother progression.

Table [10]: resource and suborder idle time: mean

idle time unit: hr	**truck**	**trailer**	**suborder**
pull	376.78	4794.54	3014.43
push	300.97	9077.00	15293.21

The completion progress mean is shown in Table [11]. Four time points are recorded: floor capping finish, lifting start point, all panel arrival on site, and project finish. Pull Planning finish time are set to a same time and planned backward, therefore not all projects start at the 0^{th} hour. To better understand the progress, each project makespan under both approaches is shown in Figure [39]. For PSS, all projects are finished at hour 385.87, while PLS ends at hour 337.40. The pull approach has the better result for all project completion; moreover, the pull approach results in an overall shorter project makespan than the push approach. In PSS, most sites have all panels arrived before lifting starts (Table [11]), leading to an excessive number of suborders piling up on site during the ten days capping, so after the period, installation can operate continuously. The site storage, however, ideally should be reduced to the minimum because a long waiting time on site would put panels subject to weather damage.

Table [11]: project progress comparison, one of the simulation results

Unit: hr	**capping finish**		**lifting start**		**all panel arrival**		**project finish**	
	push	**pull**	**push**	**pull**	**push**	**pull**	**push**	**pull**
A	82.65	75.29	322.65	315.31	174.77	339.71	362.07	337.40
B	70.73	75.16	310.73	317.21	154.47	340.37	321.09	337.40
C	62.3	21.60	302.3	264.03	314.04	339.67	385.87	337.40
D	54.22	94.56	294.22	336.09	102.14	340.17	312.90	337.40
E	46.13	76.77	286.13	317.21	91.59	340.22	295.81	337.40
F	35.27	74.53	275.27	317.21	80.22	340.52	294.28	337.40
G	31.25	76.89	271.25	317.21	75.99	340.08	303.42	337.40
H	13.90	68.93	253.90	311.53	105.04	340.54	310.18	337.40
I	9.87	67.81	249.87	310.18	93.63	340.20	312.70	337.40
J	6.38	67.03	246.38	310.03	85.10	339.68	315.20	337.40

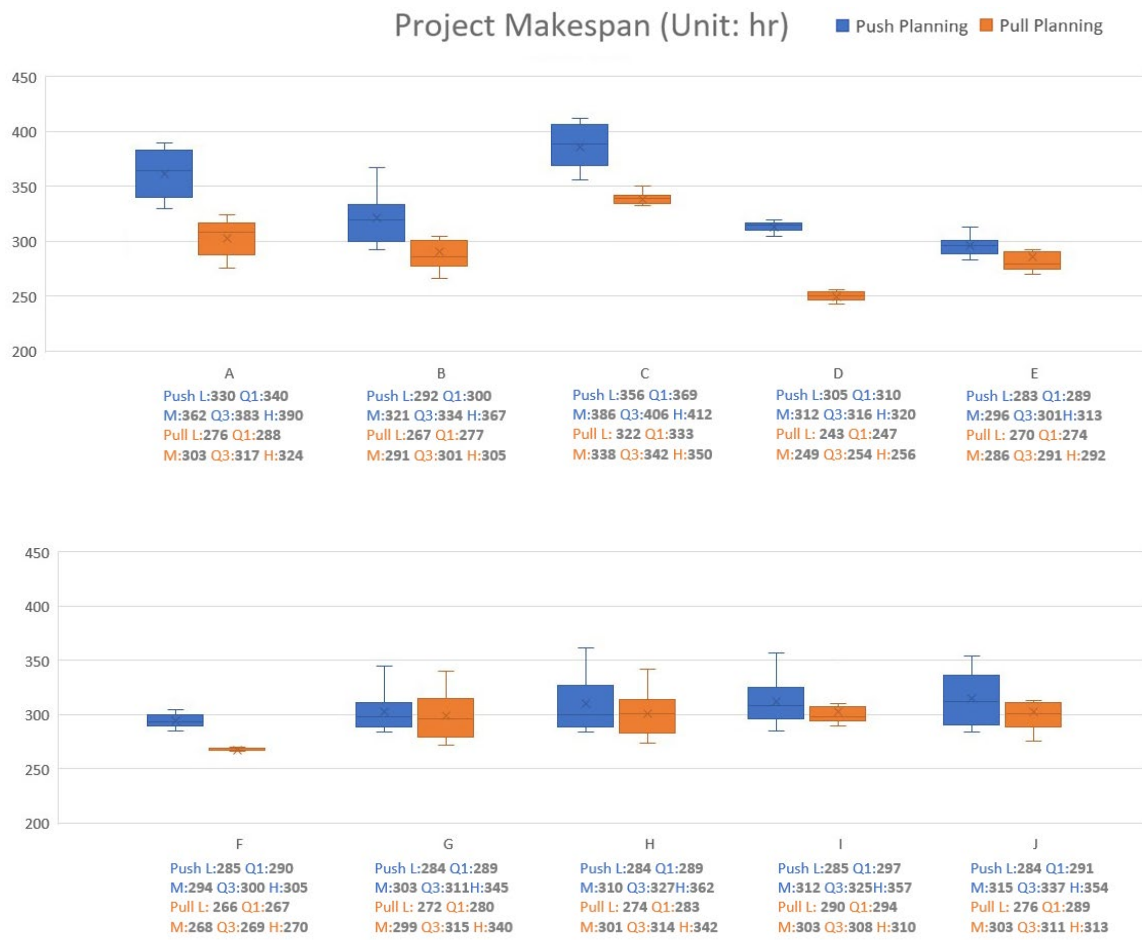

Figure [39]: project makespan boxplot chart

Dynamic factory storage under both planning methods is shown in Figure [40] and Figure [41]. All storage line charts' horizontal axis represents time in minutes, the vertical axis in wallsqf, floorsqf and 10 workerhr. Both inventories have not reached the maximum inventory level, but the condition is different. For PLS, the limit has already been reached, however, because the condition for a suborder to enter the storage area is the sum of current inventory and this suborder panel amount cannot exceed the storage limit. Therefore, mostly the limit number would not be reached. The flatline close to the storage limitation (for example, the section of cyan flatline close to 6000) indicates the storage constraint is delaying subsequent suborder entrance. In PSS, the storage limit has never been reached. The pull method, however, has demonstrated a larger factory inventory for longer time. This results from the modeling algorithm that in PSS, the factory is the "active" entity that keeps sending out panels, while in PLS factory is the "passive" entity that keeps receiving panels. Both systems use vehicle resources (truck and trailer) at their maximum.

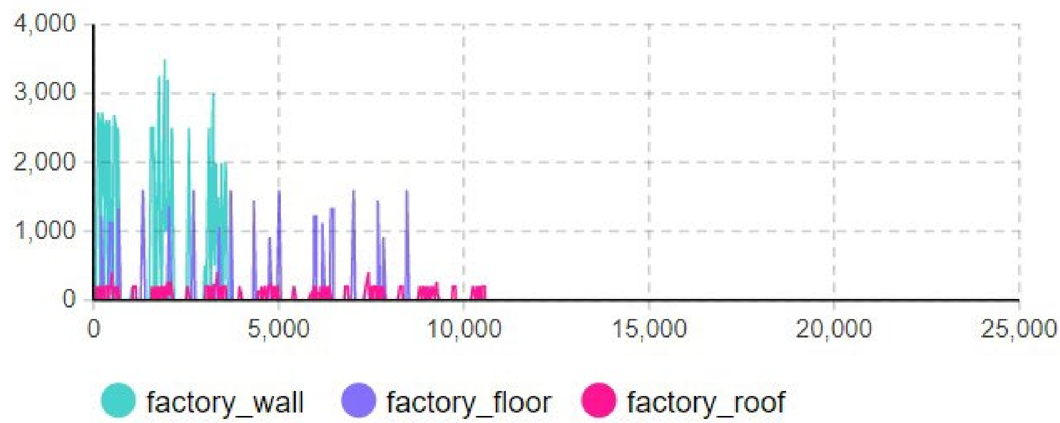

Figure [40]: push planning factory storage. The y axis unit are floor sq.ft for floor, wall sq. ft for wall, and 10 workerhr for roof. The x axis is in unit minute.

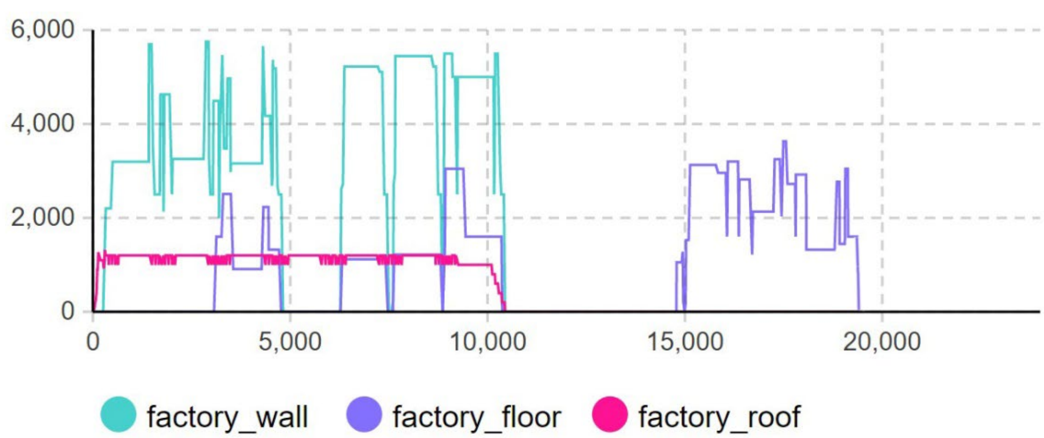

Figure [41]: pull planning factory storage. The y axis unit are floor sq.ft for floor, wall sq. ft for wall, and 10 workerhr for roof. The x axis is in unit minute.

In contrast, PLS has a close peak site inventory level with PSS but for much less duration. (Figure [42] and Figure [43]). The pull method charts record the inventory level backward, so the charts in Figure [43] should also read backward. The charts in Figure [43] should flip horizontally for comparison. Roof panel storage is scaled ten times for clearer visualization in all charts. Both simulation site inventory implies the constriction phases and the job environment. For example, the peak inventory level for both simulations is the total project panel amount. The charts also indicate that floor panels for two-story buildings are done in two batches: capping and lifting, while for bungalows, floor panels are installed in one batch (D, E, F, G, H). Additionally, floor inventory is always cleared first, then the wall, and finally, the roof, which implies the site installation sequence. The ten days interval between capping and lifting is shown in both simulations: for two-story single-family houses, the period is where after the capping floor inventory (first batch of the floor) had dropped to 0 and before lifting floor inventory (the second batch of the floor) started to drop; for bungalows, the period is where after the capping floor inventory (first batch of the floor) had dropped to 0 and before lifting wall inventory (the second batch of the floor) started to drop.

The simulation charts also imply the different planning approaches. Even though the orders are generated in the installation order, most cases in PSS have wall panels arriving before capping happens because the wall line produces faster than the floor line. During the 10-day waiting after floor capping, PSS factory continuously produce panels and transport them to the site, resulting in a high inventory level during the site waiting time between capping and lifting. PLS, however, would push the vehicle request for panels at the factory to a later time during this interval so the site can start lifting right after the interval. The peak inventory level for both planning approaches equals the total panel amount. This results from the fact that any of the three types of panels of almost all projects can be moved from the factory to the site within five trips. For PSS, this inevitably results in all panel arrival before lifting. In PLS, site is the active entity continuously "deconstructs" houses. Due to vehicle resource shortage and site parking limitations, site inventory inevitably goes up waiting for trailers and trucks. Both methods have a continuous site installation flow. However, PSS achieves this by pushing all the panels through as early as possible, leading to excessive panels waiting on sites for a long time. Moreover, the push method maximized factory productivity, while the pull method still reserves some productivity for project insertion.

The inventory charts also indicate resource configuration optimization possibilities. For example, in PLS, the charts show that even though roof panels are the last panels for installation, the transportation of this type of panels happens the earliest. This means the system is short of roof trailers. Similarly, among the three trailer types, the floor is comparatively enough in this configuration.

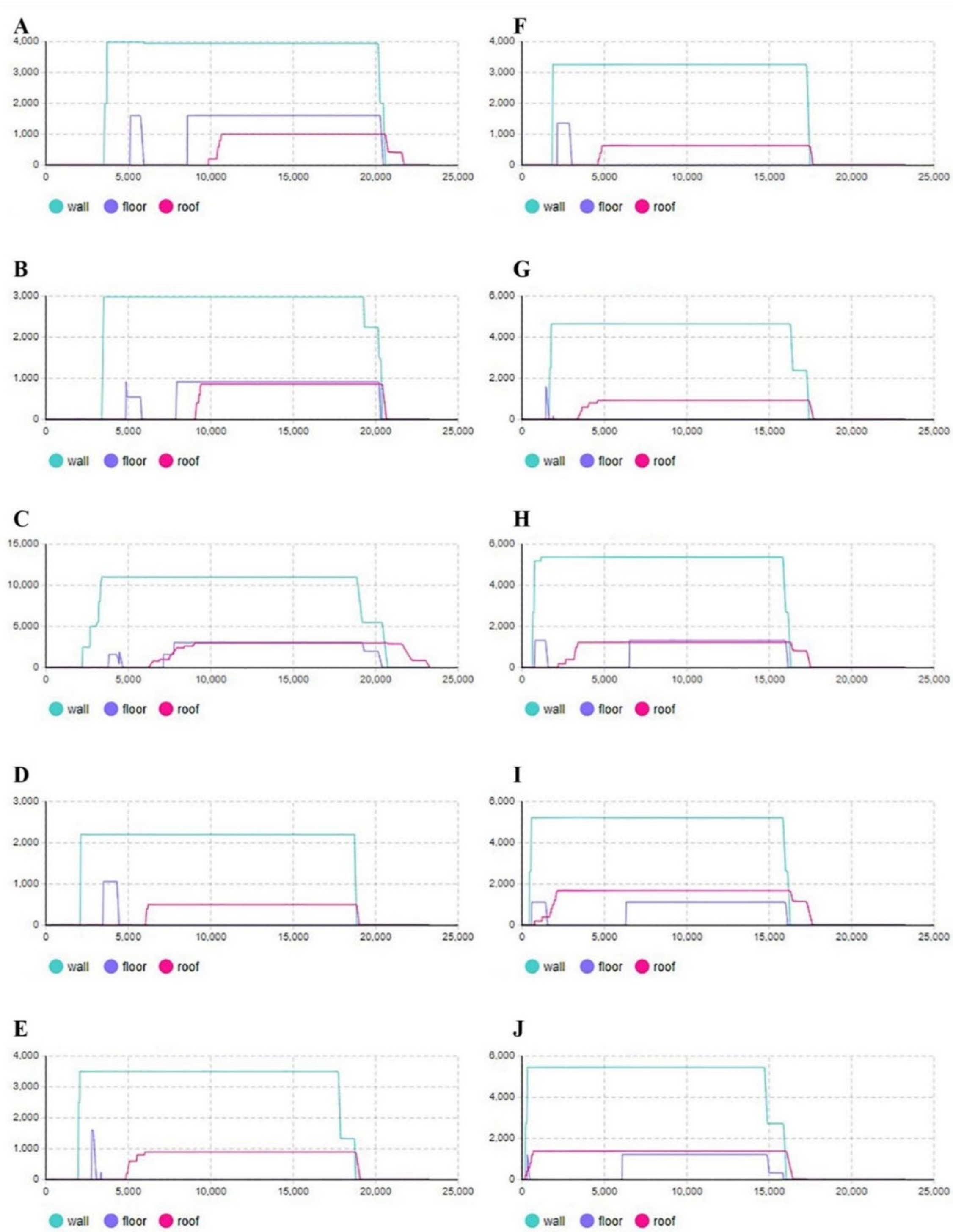

Figure [42]: push planning site inventory level

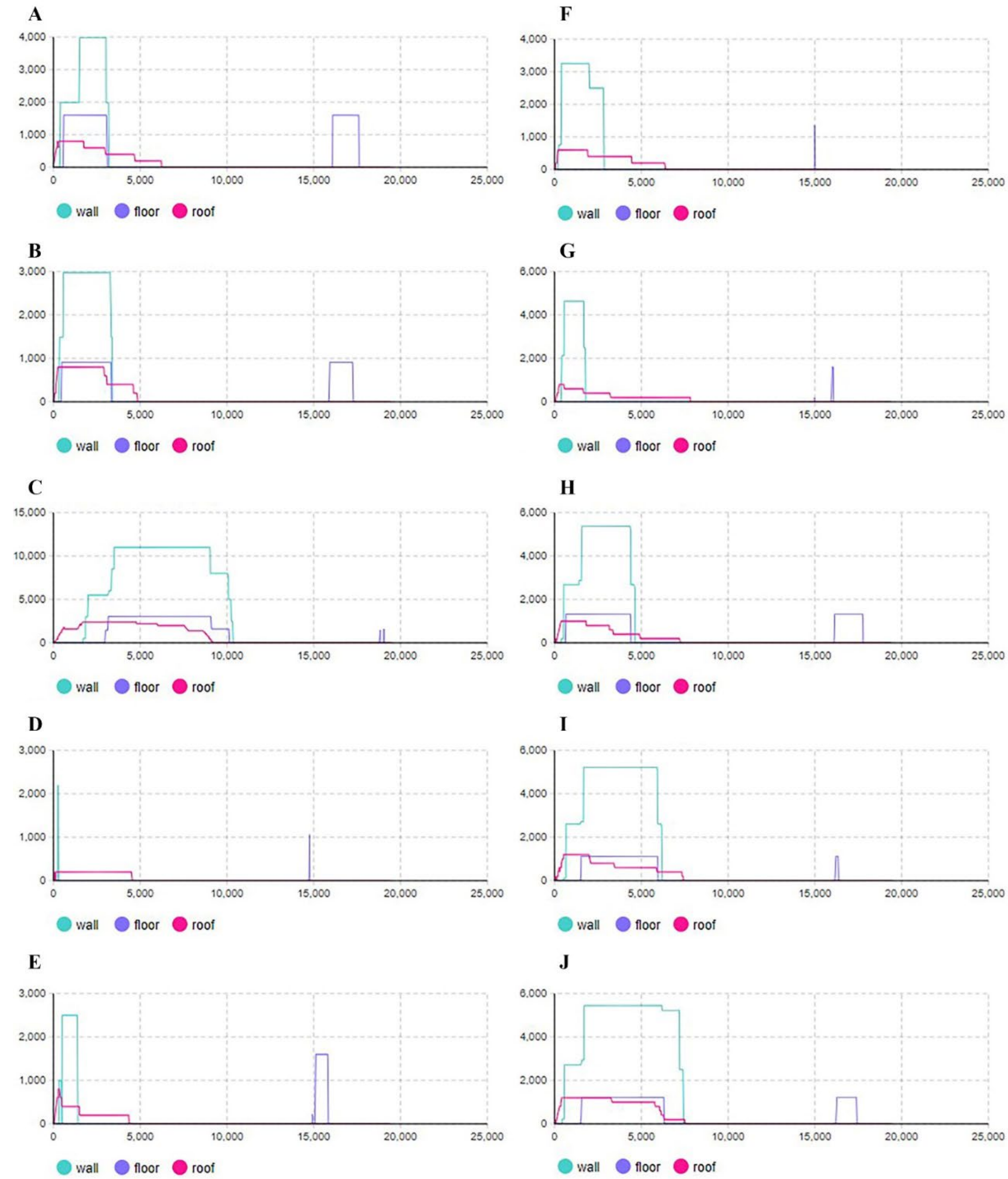

Figure [43]: pull planning inventory level

5.3 Result Discussion

Three criteria for scheduling method evaluation are analyzed in the previous section: (1) resource idle time, (2) project makespan and progress, and (3) inventory level for sites and the factory. The result not only evaluates the two scheduling approaches but also reveals the problem and schedule details. The results for the three criteria are discussed as follows:

(1) Pull Planning approach has demonstrated an 80.2% reduction in panel waiting time, a 25.2% increase in truck idle time, and a 47.2% reduction in trailer idle time. Resource idle time indicates resource usage efficiency, while suborder idle time indicates the level of coordination. The result also indicates the different causes of trailer and truck idle time. Trailer idle time is calculated when the trailer waits for truck connection at the factory or on sites, or when it queues for panel unloading at the site. The truck idle time happens when the truck is waiting for trailer connection at the factory or on sites. Therefore, decreased trailer idle time is the cause of the increased truck idle time. They both indicate less trailer waiting time on sites and at the factory in PLS. As mentioned in the previous section, truck idle time is less problematic because trucks can always take on new tasks at this state, and suborder idle time indicates the level of process continuation. Therefore, Pull Planning offers higher efficiency and better coordination. There are mainly two causes for idle time: (1) resource shortage. For example, the tightest resource is truck. There are only two trucks, which inevitably results in trailer and order waiting time. (2) system constraints, such as production speed,

installation speed, site parking limit, etc. For example, if the site parking space is filled, even though the next batch is loaded and there are trucks available at the factory, the trailer would not connect to a truck.

(2) Pull Planning has demonstrated steadier progress and an overall shorter project makespan (Table [11] and Figure [36]). The major problem shown in Table [11] is that in PSS, almost all panels arrived on site way before any lifting started. By doing so, the planning method assures a continuous installation flow for lifting. However, in the real world, panels cannot stay on site for a long time because of weather damage. This means the push method can result in even longer makespan and idle time in the real application. Additionally, pull planning can ensure Just-in-Time project delivery by setting up the due date first. It also allows project managers to identify the jobs that cannot be completed even start processing immediately. In this case, the project delivery date needs to be adjusted.

(3) Pull Planning has demonstrated a more preferred inventory level. PSS has all the panels arriving as early as possible, resulting in an excessive number of panels piling up on sites after capping and before lifting. Thus, PSS has a smaller factory inventory by pushing all the inventory overflow to sites. In contrast, PLS results in a larger factory inventory and much smaller site inventory by offering just-in-time site panel delivery. Between the two locations, panels are preferred to be stored in the factory than on site because site conditions can cause more damage to panels than the factory.

In conclusion, Pull Planning not only generates better schedule than Push Planning in terms of resource usage, project makespan and inventory, but offers more control to the schedule as well. When trying to achieve Just-in-Time (JIT) project delivery, the dispatch logistics is too complicated for the push method to make accurate estimation, resulting in delay, larger inventory, and increased cost. Pull Planning, however, suits naturally to the objectives. Additionally, by starting from the project delivery date, Pull Planning reserves earlier dates for more urgent jobs, if any.

Current panelized construction multi-project scheduling is an in-between half measure between the push planning and pull planning. In reality, the scheduling is a negotiation and conflict between project manager's decisions and system execution. Human decisions often intuitively reflect Pull Planning philosophy while the system executes in Push Planning approach. For example, while the processes seem to have used Push Planning, projects are not likely to start right away. Instead, project manager would try to achieve the Just-in-Time (JIT) delivery by manually estimating the project makespan. Project managers would give tentative completion dates and start dates based on this estimation. After the project initiation, however, the factory and sites follow Push Planning to execute factory and site activities. During execution, the complexity of dispatch logistics often makes delivery time hard to schedule, resulting in delays and frequent changes. Another example of this wrestling between decision and execution is that if panels on site had piled up, project managers would decide to stop producing panels for this site to avoid excessive panel inventory. However, this is done ad hoc, leading to constant coordination changes. This research offers a tool to start using Pull Planning at the very beginning to assist decision-making and streamline executions.

6. Conclusions and Recommendations

This research compares Push Planning and Pull Planning scheduling approach using integrated simulation models that combine DES and ABM modeling method to improve workflow coordination by generating optimized schedules for both the factory and sites. In order to achieve this goal, the research first identifies the integrated off-site panelized construction workflow by interviewing the industry partner to understand the real operations, including factory production, fleet dispatch, and site installation. The workflow is used to establish the problem statement and flowcharts. Following the flowcharts, two simulation models using Pull Planning and Push Planning approaches are developed using a combined modeling method of DES and ABM. The simulation models use real case data for result comparison. The result reveals that approximately 48 hours earlier completion of projects for PLS, and trailer idle time was reduced by 47.2%. Meanwhile, PLS reduced site inventory to a level that was just enough to ensure continuous installation.

In current practice, managers make panelized construction schedules manually based on resource availability, site progress, and factory working schedule. The ad hoc decisions result in project delays and excessive resource idle time. The lack of sound decision-making tools has become the main obstacle for the off-site construction industry to achieve benefits over traditional stick-built construction. This research lays the foundation for an integrated Pull Planning approach spanning factory production, transportation management, and site installation. The research contributions include (1) integration of the factory fabrication, transportation management, and site installation processes for a more coordinated workflow; (2) introduction of a combined simulation modeling method of DES and ABM to more accurately represent off-site construction entities such as trailer, truck, factory, and site; (3) proposal of a Pull Planning approach in off-site construction multi-project scheduling and prove the feasibility and benefit of this planning approach. This research could serve as a framework for factory production and site installation studies. There are many research problems regarding production lines and installation procedures, respectively. These studies could use this framework to coordinate the findings within a larger scope of the integrated off-site construction procedures and planning approach. Although the research is in the domain of panelized construction, the scheduling approach could be applied in other off-site construction settings, such as modular construction.

Future research efforts need to be made to address the following problems:

(1) The research compares Push and Pull Planning approaches using DES and ABM modeling methods. For comparison purposes, some data input is simplified. However, the simulation model could be improved and further implemented by incorporating more realistic travel time, production speed, and installation speed. In this research, these data are estimated according to empirical experience. For more accurate estimation, operation data collection is required. For example, installation speed needs to consider factors such as the type of project and panel, site complexity, worker condition, and weather impact.

(2) More project types should be considered. This research generalizes the housing types by stories: one-story bungalows and two-story single-family houses. In the real world, different housing types, such as single-family housing (attached or detached

garage), condos, townhomes, duplexes, and bungalows, each have their own archetype model with customization options and different production line processes.

(3) The Pull Planning method could be expanded to other types of off-site constructions, such as modular construction. The transportation management may follow different trailer settings and constraints, such as site parking space. However, the flow is similar to panelized construction. However, further research should be done to address modular-construction-specific problems, such as the transportation and production of larger volume three-dimensional modules.

(4) While Pull Planning has shown better performance over the Push Planning approach, a planning approach can be further optimized using a heuristic technique. For example, each site's waiting time after floor capping can be utilized for other sites' operations. All job due dates are set to the same time for this research, resulting in situations when multiple sites wait simultaneously. This problem can be addressed by introducing different due dates based on managers' planning experience.

References

Abourizk, S., Halpin, D., Mohamed, Y., and Hermann, U. 2011. Research in modeling and simulation for improving construction engineering operations. Journal of Construction Engineering and Management, **137**(10): 843–852. doi:10.1061/(ASCE)CO.1943-7862.0000288.

Ahn, S.J., Han, S., Altaf, M.S., and Al-Hussein, M. 2022. Integrating off-site and on-site panelized construction schedules using fleet dispatching. Automation in Construction, **137**: 104201. doi:10.1016/j.autcon.2022.104201.

Altaf, M.S., Bouferguene, A., Liu, H., Al-Hussein, M., and Yu, H. 2018. Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. Automation in Construction, **85**: 369–383. doi:10.1016/j.autcon.2017.09.009.

Alvanchi, A., Azimi, R., Lee, S., AbouRizk, S.M., and Zubick, P. 2012. Off-Site Construction Planning Using Discrete Event Simulation. Journal of Architectural Engineering, **18**(2): 114–122. American Society of Civil Engineers. doi:10.1061/(ASCE)AE.1943-5568.0000055.

Arashpour, M., Wakefield, R., Abbasi, B., Lee, E.W.M., and Minas, J. 2016. Off-site construction optimization: Sequencing multiple job classes with time constraints. Automation in Construction, **71**: 262–270. doi:10.1016/j.autcon.2016.08.001.

Arashpour, M., Wakefield, R., Blismas, N., and Minas, J. 2015. Optimization of process integration and multi-skilled resource utilization in off-site construction. Automation in Construction, **50**: 72–80. doi:10.1016/j.autcon.2014.12.002.

Ballard, H.G. 2000. The last planner system of production control. d_ph, University of Birmingham.

Boyd, N., Khalfan, M.M.A., and Maqsood, T. 2013. Off-site construction of apartment buildings. Journal of Architectural Engineering, **19**(1): 51–57. doi:10.1061/(ASCE)AE.1943-5568.0000091.

Brioso, X. 2015. Teaching Lean Construction: Pontifical Catholic University of Peru Training Course in Lean Project & Construction Management. Procedia Engineering, **123**: 85–93. doi:10.1016/j.proeng.2015.10.062.

Chan, W.-H., and Lu, M. 2008. Materials Handling System Simulation in Precast Viaduct Construction: Modeling, Analysis, and Implementation. Journal of Construction Engineering and Management, **134**(4): 300–310. American Society of Civil Engineers. doi:10.1061/(ASCE)0733-9364(2008)134:4(300).

Chan, W.K.V., Son, Y.-J., and Macal, C.M. 2010. Agent-based simulation tutorial - simulation of emergent behavior and differences between agent-based simulation and discrete-event simulation. *In* Proceedings of the 2010 Winter Simulation Conference. pp. 135–150.

Changali, S., Mohammad, A., and Van Nieuwland, M. 2015. The construction productivity imperative. *In* McKinsey Quarterly.

Dai, F., and Lu, M. 2013. Three-Dimensional Modeling of Site Elements by Analytically Processing Image Data Contained in Site Photos. Journal of Construction

Engineering and Management, **139**(7): 881–894. American Society of Civil Engineers. doi:10.1061/(ASCE)CO.1943-7862.0000655.
Dubiel, B., and Tsimhoni, O. 2005. Integrating agent based modeling into a discrete event simulation. *In* Proceedings of the Winter Simulation Conference, 2005. p. 9 pp.-.
Gao, S., Jin, R., and Lu, W. 2020. Design for manufacture and assembly in construction: a review. Building Research and Information, **48**(5): 538–550. doi:10.1080/09613218.2019.1660608.
Gbadamosi, A., Mahamadu, A., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C. 2019. Offsite construction : Developing a BIM-Based optimizer for assembly. Journal of Cleaner Production, **215**: 1180–1190. Elsevier Ltd. doi:10.1016/j.jclepro.2019.01.113.
Gerth, R., Boqvist, A., Bjelkemyr, M., and Lindberg, B. 2013. Design for construction: Utilizing production experiences in development. Construction Management and Economics, **31**(2): 135–150. doi:10.1080/01446193.2012.756142.
Ghosh, S., Reyes, M., Perrenoud, A., and Coetzee, M. 2017. Increasing the Productivity of a Construction Project Using Collaborative Pull Planning. : 825–836. American Society of Civil Engineers. doi:10.1061/9780784480502.069.
Gibb, A.G.F. 1999. Off-site Fabrication: Prefabrication, Pre-assembly and Modularisation. John Wiley & Sons, New York.
Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D. 2015. New offsite production and business models in construction: priorities for the future research agenda. Architectural Engineering and Design Management, **11**(3): 163–184. Taylor & Francis. doi:10.1080/17452007.2014.891501.
Groover, M.P. 2010. Fundamentals of Modern Manufacturing: Materials, Processes, and Systems. John Wiley & Sons.
Hamdan, S., Barkokebas, B., Manrique, J., and Al-Hussein, M. 2015. A BIM-Based Simulation Model for Inventory Management in Panelized Construction.
Hussein, M., Eltoukhy, A.E.E., Karam, A., Shaban, I.A., and Zayed, T. 2021. Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction. Journal of Cleaner Production, **310**: 127503. doi:10.1016/j.jclepro.2021.127503.
Innella, F., Arashpour, M., and Bai, Y. 2019. Lean Methodologies and Techniques for Modular Construction: Chronological and Critical Review. Journal of Construction Engineering and Management, **145**(12): 04019076. American Society of Civil Engineers. doi:10.1061/(ASCE)CO.1943-7862.0001712.
Killian, J., Abdallah, M., and Clevenger, C. 2020. Industry Feedback on Implementing Pull Planning in the Construction Industry. : 515–524. American Society of Civil Engineers. doi:10.1061/9780784482889.054.
Kong, L., Li, H., Luo, H., Ding, L., and Zhang, X. 2018. Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction. Journal of Cleaner Production, **193**: 684–701. doi:10.1016/j.jclepro.2018.05.037.
LEU, S.-S., and HWANG, S.-T. 2001. A Ga-Based Model for Maximizing Precast Plant Production Under Resource Constraints. Engineering Optimization, **33**(5): 619–642. Taylor & Francis. doi:10.1080/03052150108940936.

Liu, Z., Zhang, Y., and Li, M. 2014. Integrated scheduling of ready-mixed concrete production and delivery. Automation in Construction, **48**: 31–43. doi:10.1016/j.autcon.2014.08.004.

Lu, W., and Olofsson, T. 2014. Building information modeling and discrete event simulation: Towards an integrated framework. Automation in Construction, **44**: 73–83. doi:10.1016/j.autcon.2014.04.001.

Ng, M.S., and Hall, D. 2019. Toward Lean Management for Digital Fabrication: a Review of the Shared Practices of Lean, DfMA and dfab. pp. 725–736.

Salama, T., Moselhi, O., and Al-Hussein, M. 2018. Modular Industry Characteristics and Barriers to its Increased Market Share. Modular and Offsite Construction (MOC) Summit Proceedings,. doi:10.29173/mocs34.

Salari, S.A.-S., Mahmoudi, H., Aghsami, A., Jolai, F., Jolai, S., and Yazdani, M. 2022. Off-Site Construction Three-Echelon Supply Chain Management with Stochastic Constraints: A Modelling Approach. Buildings, **12**(2): 119. Multidisciplinary Digital Publishing Institute. doi:10.3390/buildings12020119.

Shewchuk, J.P., and Guo, C. 2012. Panel Stacking, Panel Sequencing, and Stack Locating in Residential Construction: Lean Approach. Journal of Construction Engineering and Management, **138**(9): 1006–1016. American Society of Civil Engineers. doi:10.1061/(ASCE)CO.1943-7862.0000520.

Shewchuk, J.P., Nussbaum, M.A., Kim, S., and Sarkar, S. 2017. Simulation Modeling and Ergonomic Assessment of Complex Multiworker Physical Processes. IEEE Transactions on Human-Machine Systems, **47**(6): 777–788. doi:10.1109/THMS.2016.2628771.

Siebers, P.O., Macal, C.M., Garnett, J., Buxton, D., and Pidd, M. 2010. Discrete-event simulation is dead, long live agent-based simulation! Journal of Simulation, **4**(3): 204–210. doi:10.1057/jos.2010.14.

Sivaraman, A., and Varghese, K. 2016. Pull Planning System to Coordinate the Engineering Procurement and Construction on Process Plant Projects. : 1720–1730. American Society of Civil Engineers. doi:10.1061/9780784479827.172.

Slack, N. 2015. Push and Pull Planning and Control. *In* Wiley Encyclopedia of Management. John Wiley & Sons, Ltd. pp. 1–1.

Tam, V.W.Y., Fung, I.W.H., Sing, M.C.P., and Ogunlana, S.O. 2015. Best practice of prefabrication implementation in the Hong Kong public and private sectors. Journal of Cleaner Production, **109**: 216–231. doi:10.1016/j.jclepro.2014.09.045.

US Census Bureau, M.C.D. (n.d.). US Census Bureau New Residential Construction. Available from https://www.census.gov/construction/nrc/index.html. [accessed 4 October 2022].

Wang, J., Li, Z., and Tam, V.W.Y. 2015. Identifying best design strategies for construction waste minimization. Journal of Cleaner Production, **92**: 237–247. doi:10.1016/j.jclepro.2014.12.076.

Wang, Z., and Hu, H. 2017. Improved Precast Production–Scheduling Model Considering the Whole Supply Chain. Journal of Computing in Civil Engineering, **31**(4): 04017013. American Society of Civil Engineers. doi:10.1061/(ASCE)CP.1943-5487.0000667.

Wang, Z., Hu, H., Gong, J., Ma, X., and Xiong, W. 2019. Precast supply chain management in off-site construction: A critical literature review. Journal of Cleaner Production, **232**: 1204–1217. doi:10.1016/j.jclepro.2019.05.229.

Wang, Z., Zhang, Q., Yang, B., Wu, T., Lei, K., Zhang, B., and Fang, T. 2021. Vision-Based Framework for Automatic Progress Monitoring of Precast Walls by Using Surveillance Videos during the Construction Phase. Journal of Computing in Civil Engineering, **35**(1): 04020056. American Society of Civil Engineers. doi:10.1061/(ASCE)CP.1943-5487.0000933.

Yi, W., Wang, S., and Zhang, A. 2020. Optimal transportation planning for prefabricated products in construction. Computer-Aided Civil and Infrastructure Engineering, **35**(4): 342–353. doi:10.1111/mice.12504.

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