The Significance of Logistics Performance to Industrial Modular Construction Project under the "Big Site" Scenario

by

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ABSTRACT

In the industrial modular construction, the fabrication shops, module assembly yards and construction field usually are adjacently located and viewed as the "site". The offshore sourcing of materials and prefabrication expands the site scope from local into global; hence, the site can be regarded as a "*big site*". Though this expansion does not fundamentally change the basic processes in industrial modularization projects, it presents more challenges in project planning. Previous research efforts either focused on the material delivery process or the module assembly process alone, while the integration of both for evaluating the impact of logistics performances upon modular construction planning has yet to be addressed. Thus, a special logistics simulation template is developed based on the *Simphony* platform to facilitate the simulation modeling of module fabrication, transportation, assembly, and installation processes. Three key performance indicators, named as *delivery efficiency*, *waiting-service ratio* and *occupancy rate* are adapted from port management literature in order to assess the material deliveries at different transit locations along the supply chain. A practical case study representing modular construction practice is presented. The final module field installation schedule is modified based on the simulation results as the logistics constraints, in addition to site resource constraints and module interconnection technological constraints.

PREFACE

This thesis is an original work by Jiongyang Liu. No part of this thesis has been previously published.

ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

1.1 Background

Industrial modular construction involves off-shore prefabrication, multi-mode transportation, and on-site installation of modules in the formation of the industrial engineering facilities. The "site" for a modular construction project includes fabrication shops, modular shops and construction fields, which are usually adjacently located in a local region (Taghaddos et al., 2014). However, the offshore sourcing of module fabricators makes that the scope of the site is no longer just within the local area but extends into the global domain. As per Figure 1-1, raw materials such as pipes and steels are first offshore prefabricated at the overseas fabrication shop. After that, the prefabricated materials are packed into containers in the fabrication shop to be transported to the port of loading (POL) and then shipped to the port of destination (POD) through ocean shipping. After arrival at POD, the container is further transported from POD to the module shop. In this case, there are multiple feasible routes for transferring the container from POD to Module Shop A or B. The selection of a particular shipment route is dependent on the container's specified destination and the transporters' availability. At the module shop, steel and pipe components in the container are assembled into modules by bolting, welding, and coupling connections. Then, the assembled module is transported to the construction site by trucks for field installation. On the site, the module is installed in accordance with preplanned field installation sequence (i.e., Module 1 installation precedes Module 2 installation). This complete global material supply chain can be regarded as an expanded site scope (from local to global), i.e., a "*big site*".

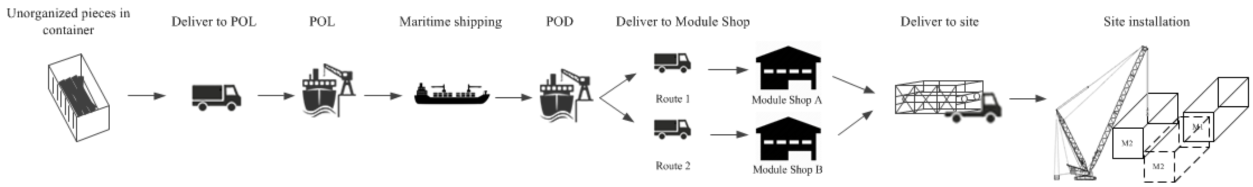


Figure 1-1: Typical supply chain of modular construction

Although the globalized material supply chain does not change basic processes for modular construction, which includes prefabrication, material delivery and handling, module consolidation, and site installation, this expansion indeed presents more challenges to project planning and scheduling. For instance, multiple resources constraints (e.g., limited number of transporters, assembly bays, etc.) during module fabrication and delivery process, decisions in selecting appropriate transportation modes and shipping routes, and uncertainties (e.g., bad weather, Customs delay) in terms of transportation time, all exert significant impacts on project management performances. Even though these problems were observed in previous research, it turns out to be more complex with much less controllability in a "*big site*" system. Insufficient logistic planning would potentially delay material arrival dates on module shop and site, and trigger the ripple effect of disrupting module assembly and field installation schedules. In addition, the nature of construction industry is time-driven that the delays in project schedule will also generate huge additional cost. In real practice, based on the interview with the industrial professionals, approximately 50% of the man-hours are wasted by the handling crews at the module shops for waiting the materials arrival. Both the direct cost (i.e., the labor cost and equipment cost per day) and indirect cost (i.e., overheads) are thus increased due to productivity loss, eventually causing the construction project to run over its budget.

Nevertheless, existing project planning tools are incapable to solve these problems. General commercial software such as Primavera P6, Microsoft Project is based on critical path method (CPM) (Taghaddos et al., 2014), which requires clear definitions of every dependency and precedence relationship between activities (i.e., all the activities on the CPM network are planned to be executed). In contrast, in real practice, the materials can be delivered using any feasible route between the origin and destination as shown in Figure 1-1. The materials are delivered through the selected route, while the activities in the unselected routes will not be executed. The CPM-based technique is thus not suitable for formulating the route schedule in consideration of transportation feasibility. The current industrial practice uses the spreadsheet to manually schedule the delivery via trial and error methods. Obviously, it is a tedious and error-prone exercise.

1.2 Research Objectives and Contributions

The primary objective of this study is to investigate the criticality of logistics service performance in an industrial modular construction project under the *big site* scenario. Furthermore, proper management of material deliveries can provide substantial benefits, encompassing the reduction of on-site traffic congestion, safety and labor productivity improvements by mitigating the idling time slot, etc. (Ballard and Hoare, 2015). As such, the material delivery performance at various transit locations along the supply chain requires quantitative evaluation. These objectives are achieved through the following four research tasks:

(1) A special logistics simulation template is developed as a supplement to the general template of *Simphony* platform in order to simulate the prefabrication process, material delivery process, module assembly process and site installation process.

(2) Three key performance indicators, namely, *delivery efficiency*, *waiting-service ratio* and *occupancy rate* are proposed based on the previous research in the port operation domain to assess the material delivery performance at different transit locations.

(3) A practical case study is given to investigate the effects of preceding logistics performance on the eventual field module installation schedule. The modified installation plan considers the logistics constraints (module ready on-site time), technological constraints (installation sequence between modules) and resource constraints (limited availability of cranes for lifting at field), integrally.

(4) Monte Carlo Simulation is employed to address the uncertainties problem (i.e., the probability of delays) during the material delivery in the practical case.

The main contribution of this study is for the first time the research introduces the concept of *big site* which integrates both processes in modular construction as a whole to investigate the logistics performance in relation to final field installation schedule. Although substantial research studies have been conducted, their focus was restricted to specific areas (e.g. the transportation stage, the module assembly stage, etc.) thus failed to couple both the delivery process and construction process integrally to assess the logistics performance. The definition of the problem was localized and less-structured in previous works. In this study, the material delivery stage is no longer isolated with the construction operational processes (i.e., module assembly, field installation), but integrated as an expanded site scope to study its influence. It integrates different less-structured and independent problems to become a structured problem with explicit logic, presenting a framework and guideline for simulation modeling and future analytical research. In addition, for evaluating the logistics performance, three key performance indicators are proposed based the research and practice in port operation domain. The proposed indicators can be extended to benchmark all types of construction projects' material delivery performance and particular performance yardsticks can be produced later when real data become available.

1.3 Thesis Organization

Overall, the thesis consists of five chapters, and a user's manual and sample code of the developed simulation template (in appendixes).

Chapter 1 introduces the research background, defines the *big site* problem to investigate the construction logistics performance, and outlines the main research objectives and contributions.

Chapter 2 first summarizes the features of construction logistics, particularly in the context of *big site*, in comparison with general logistics services in other industrial sectors. It also covers previous researches conducted in construction supply chain management, transportation management, and in modular construction and port operation management domain.

Chapter 3 presents the introduction of the developed logistics simulation template and three key performance indicators for assessing the material delivery in the applied context. An example case is also applied in order to verify and validate the proposed methodology.

Chapter 4 gives a practical case study to investigate the logistics performance in relation to final field installation schedule by employing the developed simulation template and indicators.

Chapter 5 concludes the entire research, addressing limitations in current research and making recommendations for future study.

CHAPTER 2: LITERATURE REVIEW

This chapter summarizes the characteristics of construction logistics, especially under the *big site* scenario. Previous researches conducted in regards to construction supply chain management, transportation management, modular construction and port operation management are also covered. Section 2.1 discusses the features of construction logistics in comparison with the general logistics services provided by other industrial sectors. Sections 2.2 to 2.5 review the existing studies in construction supply chain management, transportation management, and in modular construction and port operation management domain, respectively.

2.1 Features of Construction Logistics

The term of "logistics and supply chain" is widely accepted and used in industry and business world. The Council of Supply Chain Management Professionals (CSCMP, 2013) defines logistics as "the process of planning, implementing and controlling procedures for the efficient and effective transportation and storage of goods including services and related information from the *point of origin* to the *point of consumption* for the purpose of conforming to customer requirements and includes inbound, outbound, internal and external movements." This definition usually is confused with the concept of supply chain. Logistics is *part of* the supply chain that focuses on the *spatial movement* of the goods between locations. Whilst supply chain is defined as "the network of organizations that are involved through *upstream and downstream linkages*, in the different processes and activities that produce values in the form of products and services in the hands of *ultimate consumers* (Christopher, 1992)." It targets on the integration of processes/relationships among all the stakeholders (e.g., suppliers, intermediaries, customers), from the upstream (suppliers) to the downstream (customers), aimed to reduce waste and add value across the entire process (Morledge et al., 2009) in addition to the role of logistics.

Likewise, the construction supply chain consists of all construction business processes, from client's demand, front end planning, design and construction to ultimate operation, maintenance and decommission, with multiple stakeholders and organizations' engagement (e.g., clients, contractors and subcontractors, designer, etc.). It is a network between different stakeholders within a construction project (clients, contractors, suppliers and etc.) that works together in a concerted effort to manage the flow of information, materials, services, products and cash flow (Xue et al., 2007). Construction logistics belongs to the supply chain that targets on the timely manner in delivering construction materials to the needed locations to support the project execution. However, the characteristics of the construction industry are substantially different from other industrial sectors (e.g., manufacturing and retailing companies). There are many variances in the construction industry that would impact the logistics and supply chain services in the construction domain (Morledge et al., 2009; Azambuja and O'Brien, 2008). For instance, every construction project is unique that each one needs tailored material supply and delivery strategy (Grey, 1996). Each project is one-off and engages different suppliers, contractors and clients. Thus, the relationships between different stakeholders are adversarial as every party attempts to minimize the risks and maximize the revenues. By contrast, relationships in the manufacturing industry are long-term and collaborative; benefits are shared during the collaboration (Morledge et al., 2009; Azambuja and O'Brien, 2008). As such, the logistics service in the construction industry, particularly in the *big site* context, can be summarized with following features:

- **Specialization**

Compared with the standardized products in manufacturing industry, goods delivered for construction projects usually are oversized, irregular and heavy-weight (e.g., prefabricated construction modules, heavy equipment, etc.). Therefore, these cargoes need particular handling equipment and professionals to customize the handling plan during the delivery (Han, 2012). In addition, every construction project is unique and one-off. Differences such as locations, material characteristics and schedules between projects, require one-of-a-kind logistics plan to be tailored (Wang, 2008; Gray, 1996). Previous experience is difficult to be duplicated as each project has different cargoes, shipping routes, available handling equipment and client requirements.

- **High Risks**

As shown in Figure 1-1, the material delivery processes are complicated. Multiple transportation modes (i.e., roadway, railway, etc.) are combined and various alternative shipping routes are available for material transportation. Risks such as transportation delays, customs delay at the host country are commonplace in practice. In addition, the long lifecycle of a construction project also generates financial risks. A typical construction project spans years, leading to uncertain shipping cost due to the fluctuation of oil price (Han, 2012). However, these risks are hard to predict in advance due to the uniqueness of each project. In addition to that, handling the large-scale construction cargoes also gives rise to safety and occupational risks to the handling crews (CLG, 2005).

- **Time-driven**

Timely delivery of the construction materials to needed locations is critical to achieve smooth project execution. Any delay in connection with logistics would postpone the succeeding activities start time, and eventually extend the project duration (Han, 2012). In addition, some construction materials are also time-sensitive (e.g., concrete) that must be consumed within a certain time period. Nevertheless, unlike other industries, the just-in-time delivery in the construction domain is still difficult to achieve and may not be realistic in many cases (Franklin, 2015).

Overall, though the characteristics of logistics service in construction industry substantially differ from other industrial sectors, little attention has been given to study the construction logistics performance, especially under the *big site* scenario. Current industrial practice only recognizes the importance of materials' final arrival at site, how the materials are delivered and processed along the supply chain are largely overlooked (Sullivan et al., 2011; Vidalakis et al., 2011). In the following paragraphs, the author reviews the related research conducted in regards to construction supply chain management, transportation management and modular construction.

2.2 Construction supply chain management

Research conducted in construction supply chain management can be categorized into three streams. The first stream focuses on studying the material supply strategy in relation to field operations. It can be further sub-divided into (i) benchmarking material shipment for evaluating material delivery performance. For example, Anson (1998) and Lu (2004) et al. benchmarked the concrete supply performance in Hong Kong by observing the truck-mixers' arrival time at site. Another subdivision focuses on (ii) aligning material demand with material supply. Caron et al. (1998) assessed the amount of material should be available at site as the safety stock in consideration of the variability in material delivery date and site consumption. Said and EI-Rayes (2010) argued material supply decisions should be made in accordance with site layout settings. A construction logistics planning model was proposed for integrating and optimizing material supply and site layout for minimizing the total cost, including ordering, carrying, shortage and layout costs. Vidalakis et al. (2013) studied the varying demand of construction materials in relation to the performance of logistics services provided by material distribution companies. The simulation technique was employed to model the supply chain and the material delivery process. Criteria such as lead time and cost efficiency were used to evaluate whether the logistics service is executed in a timely and cost-effective fashion given the uncertain material demand.

The second stream targets at the interconnection between different stakeholders along the supply chain, from upstream to downstream, aimed at improving the supply chain performance. For instance, Pryke et al. (2009) recognized the concept of supply chain, with particular emphasis on the interrelations among the organizations, could change the adversarial relationship and fragmented nature in construction industry. Effective communication networks between both individuals and organizations are thus constructive to assemble the groups of stakeholders for strengthening the collaborations. The information, knowledge and experience are shared while risks are well-managed.

The last stream investigates the effect of transportation stage in relation to project performance (e.g., time and cost) in construction supply chain. Shakantu et al. (2003) discussed the hidden cost generated by transportation, which could contribute 10% to 20% of the total expenditure, should not be underestimated. In addition, late material arrival could delay succeeding activities' start time. Ahmadian et al. (2014, 2015) argued that material shipping delays could considerably interrupt construction execution progress. They investigated materials' physical characteristics (weight, size) and logistics variables (multiple transportation modes) in relation to the transportation duration. However, the role of logistics, particularly with respect to the resource availability and feasibility of various transportation modes and routes were absent in past studies.

2.3 Transportation management

In transportation management, researchers in the transportation area studied the shipping routes (path) optimization. Objectives such as identifying the optimal shipping paths, minimizing the transportation time and cost under different constraints are the most common. Methodologies are generally proposed to formulate shipment schedules with the shortest shipping distance and/or the fff shipping cost. Classic transportation problems, such as the shortest path problem, the Chinese postman problem, the travelling salesman problem, etc. are relevant to the transit route optimization (Bulbul et al. 2007). For instance, the shortest path problem was solved for identifying the shortest path between two locations on a road map. In general, various alternative paths are available to transit the material from one location to another. The route with the shortest transit path is selected. The Chinese postman problem is solved for formulating the shipment schedule so to call at all the planned locations on the map with the shortest walking distance. It was first proposed by the Chinese mathematician Kwan Mei-Go (1962) as a postman needs to visit all the planned locations at least once for distributing mails before returning to the post office. The travelling salesmen problem is intended for providing a route schedule for a salesman to visit all cities exactly once with the minimum travelling cost. Nevertheless, operational processes and resource constraints at the transit locations along the supply chain are often neglected in these researches. For instance, the module assembly process at the module shop, the materials handling at the port, the site installation sequence in accordance with construction technological constraints, etc. have not been addressed by transportation experts.

2.4 Modular Construction

In the industrial modular construction, previous researchers attempted to improve modularization engineering in the following perspectives. The first perspective is the proper selection and operation of cranes at site with the assistance provided by visualization and automation. Han et al. (2014) coupled 3D visualization with mathematical algorisms for mobile crane motion planning in industrial projects. The proposed methodology offered dynamic design changes (e.g., lifting sequence) and automated collision-free 3D visualization design of mobile cranes operations on various sites. Significant proportion of saving in lifting time and cost was observed. The second perspective is optimizing the construction operations in terms of scheduling and planning through simulation approach in industrial modular construction projects. Taghaddos et al. (2012) proposed a simulation-based methodology to schedule the module assembly sequence for multiple projects in consideration of limited resources and spaces in an assembly yard. The framework was capable of allocating skilled workers and assembly bays to execute a certain module assembly sequence in order to deliver projects before the planned deadlines. Wu and Lu (2014) used a simulation technique to evaluate the contractor's production capacity for module assembly. The contractor's production rate for assembling modules in its facility was estimated based on historical data, while the available capacity of the module yard facility was determined based on monthly production rate and module assembly time. Li et al. (2013) classified the risks in modular construction project as general risks, in-plant risks, and on-site risks. The general risks are those factors typically encountered on construction projects (e.g., design changes). The in-plant risks are associated with the off-site prefabrication of modules and panels. The on-site risks may impact the site installation process such as weather conditions. Fuzzy AHP method was applied for ranking the identified risk factors. The modular construction process was simulated in relation to the identified risks to estimate the time and cost. But the performance of the supply chain was not covered in previous researches for modularization. Material delivery performance evaluation at a module shop in the context of "*big site*" problem had not yet been investigated.

Proper management of material deliveries can provide substantial benefits in site control and assessing the logistics performance. For example, it can minimize the congestion at site and surroundings to avoid queuing at access, control the number of trucks at site for safety concerns and enhance the labor productivity by mitigating their idling time slot (Ballard and Hoare, 2015). Although some existing studies benchmarked performances for material supply on construction site, the transportation processes (i.e., multiple transportation modes, transportation feasibility, etc.) were ignored and the resulting benchmarks were restricted to assess the ready mixed concrete supply (Anson and Wang, 1998; Lu and Anson, 2004).

How to quantitatively evaluate material deliveries and also enable the foremen to quickly understand the implications on construction schedules without much effort is a critical question to be addressed. The answer must be straightforward and is capable of representing current material delivery performance. Thus, related literature in the port operation management domain is referenced.

2.5 Port Operation Management

Research endeavors in port management domain tried to shed light on the relationship between the number of port unloading bays and port handling efficiency (Weille and Jay, 1974; UNCTAD, 1985). Unloading bay at a port is referred to as *berth*, which is a place for handling the cargoes carried by the arriving ship, is the critical resource in port management. If the number of berths decreases, the utilization rate of the unloading bay would increase, while the waiting time of the arriving ship would increase. As a result, considerable waiting cost would incur (i.e., approximately $1,500 US dollars per day for a 10,000-tons ship). In contrast, overprovision of berths would substantially increase construction and maintenance costs on the port authority. Therefore, determining the optimum number of unloading bays by balancing against the demand of ships is paramount to port design. Queuing theory has been widely applied for optimizing berth number and port capacity (Edmond and Maggs, 1978). The theory models the arriving ships as customers while the port as the facility for providing unloading service. The ships' inter-arrival time and the port service time were modeled by fitting separate statistical distributions. Then, specific queue model was determined depending on the fitting results, and the optimum number of berths was derived from the model. The queuing theory was integrated with the simulation approach for modeling ships arrivals and port operations in order to determine the optimum port capacity (Ergin and Yalciner, 1991; Alattra et al., 2006). The queuing theory was also combined with artificial neural networks for predicting the demand of berths in relation to the future port operations service (Gokkus and Yildirim, 2015).

Researchers from port management recognized the port handling capacity and efficiency was significantly correlated to the unloading bays (berths) handling performance (UNCTAD, 1985; De Monie, 1987; Weille and Ray, 1974). The unloading bays are also common in construction projects for unloading the construction materials. However, measuring logistics performance in the modular construction domain has yet to be formalized with respect to the unloading bays at various transit locations along the supply chain. These studies conducted by the port industry inspired the author in finding a more effective quantitative approach to assess the material delivery under the *big site* scenario.

CHAPTER 3: METHODOLOGY

This chapter introduces the special logistics template developed in the *Simphony* platform and three Key Performance Indicators (KPIs) proposed for this study. Section 3.1 gives the instruction for the developed template. Section 3.2 introduces three proposed indicators, namely, waiting-service (*WS*) ratio, occupancy rate (*OR*), and delivery efficiency (*DE*) in assessing the performance of module logistics and supply chain in the context of *big site*. Section 3.3 gives an example case study in order to verify and validate the proposed methodology. Section 3.4 is the simulation results of studied case. Section 3.5 presents the discussion of the simulation results.

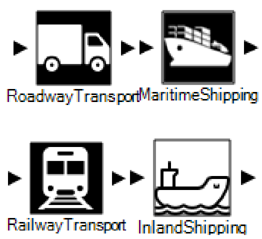
3.1 Special Logistics Simulation Template

In order to mimic both the transportation processes and operation processes (i.e., port handling, module assembly, etc.) at different transit locations, a special logistics simulation template is developed in *Simphony* platform. This special template is capable of interacting with the general simulation template provided by *Simphony* and the database to model the sub-assemblies off-shore prefabrication, material delivery, module assembly and site installation under multiple resources (e.g., transporters) and technological constraints. Two main types of elements, namely, "transportation" elements and "route selection" elements are developed for this purpose.

- *Transportation element*

The transportation elements are used to model various transportation modes for delivering materials to planned locations by using different types of transporters. Four major transportation modes, including roadway shipping, railway shipping, maritime/ocean shipping, and inland/waterway shipping are represented in four elements (Table 3-1). Note that due to the complexity of the real world, the procedures covered by the transportation elements are abstracted as 1) cargoes loading and unloading from the transporters, 2) the transit process and 3) the transporters' return process. Multiple demanded resources (e.g., transporters, storage, etc.) that involved in the transportation stage can be captured and/or released within the elements or interacted with other elements provided by the general template to comply with the reality.

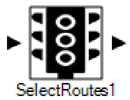
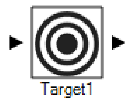
Table 3- 1: Four types of transportation elements developed in the template

Category	Modeling elements	Inputs	Explanations
Transportation elements		Loading duration	The duration for loading the containers to the transporter.
		Shipping duration	The duration for shipping the containers to planned location.
		Unloading duration	The duration for unloading the containers from the transporter.
		Return duration	The duration of the transporter returning to the origin location.
		Resource	The demanded resource that involved in the transportation stage (e.g., storage, unloading bays, etc.).

- *Route selection elements*

The "route selection" elements are developed to select feasible routes during material transshipment. The selection in reality is based on the assigned destination of the materials being shipped and the availability of the transporters at various transit locations. Users can input the number of the transporters on different paths and the selection elements will automatically allocate the simulation entities into the different paths based on the availability of transporters (Table 3-2). Interaction with the general template is only needed when the simulation entities have different predefined destinations. Note that if no transporters are currently available on all the shipping routes, the simulation entities will temporarily wait at the waiting file till the transporters return.

Table 3- 2: The route selection elements developed in the template

Category	Modeling elements	Inputs	Explanations
Route selection elements		Transporter resource	A collection of required transporter resources with respect to the feasible shipping routes.
		File	The waiting file for the simulation entity if no transporter resources are available.
		Resource Name	The name of the transporter resource on specific shipping route. The simulation entity will be transferred into targeted route if specific resource is available.

3.2 Key Performance Indicators

Overall, the material delivery processes can be generalized as per Figure 3-1. Materials are loaded to the transporter at the origin and then delivered to the destination. Upon arrival, the transporter queues for the available unloading bay. Once the unloading bay becomes available, the transporter unloads the materials at the unloading bay and returns to the origin. These basic procedures can be paralleled with the port handling operations. For instance, a ship is fully loaded at origin port and transits to destination port through ocean shipping. Before the arriving ship can call-on the terminal, it first has to wait for an available unloading bay (berth) at port entrance. Till all the carried cargoes are offloaded at quay, the ship departs from the port area. As stated in previous section, substantial amount of studies have been conducted in evaluating the delivery and port handling efficiency in the port industry. Based on the inspiration from these works, three key performance indicators (KPIs) named as *delivery efficiency* (*DE*), *waiting-service ratio* (*WS*), and *occupancy rate* (*OR*) are defined in order to assess the material delivery performance.

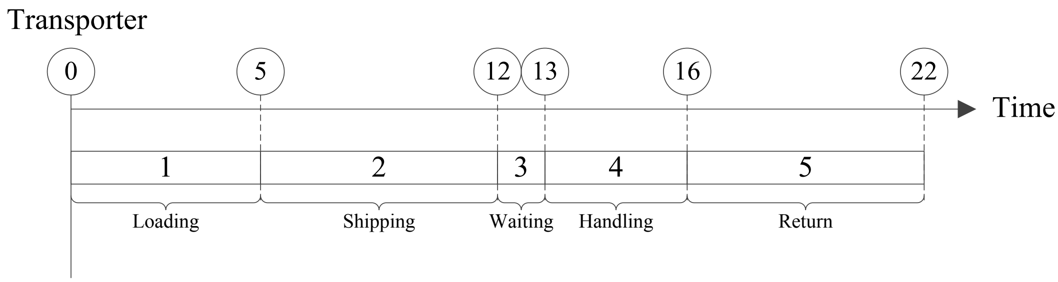


Figure 3- 1: Workflow of a transporter at an unloading bay

- *Delivery Efficiency*

The *DE* factor is used to evaluate delivery performance, which is calculated by dividing the ideal system production rate against the actual system production rate (Eq. 1). Note that the ideal and actual scenarios should be determined and modified in consistent with the real world situation. For example, the ideal scenario can be either non-delay or non-resource constrained scenario while the actual scenario is the complement. It can be varied project by project but must remain consistency under the same project system. A higher *DE* value indicates that the materials are delivered, assembled and installed within a shorter time period. Thus, the performance of material delivery is positively correlated with the value of *DE* factor.

$$DE = \frac{P_A}{P_I} \tag{1}$$

Where:
P_A = ideal system production rate
P_I = actual system production rate

- *Waiting-service Ratio*

The *WS* value indicates the ratio of the transporter's average waiting time against its average handling time (Eq. 2). It was originated from the port operation and management domain for evaluating the degree of ship waiting at port entrance before berthing as a measure of the level of service provided by the terminal (UNCTAD 1985). This indicator is adapted for assessing material delivery performance at various transit locations along the supply chain in construction. A lower *WS* value indicates shorter waiting time of the transporter at unloading bay. In contrast, it also implies the handling crews at the unloading bays are waiting for work, the idle time is thus increased. For instance, if the *WS* value equals to zero, implying the unloading operation can be started immediately when the transporter arrives at the delivery port. On the other side, it also means that the unloading bay and its handling crew stay idle much of the time, causing productivity loss.

$$WS = \frac{\overline{T}_w}{\overline{T}_h} \times 100\% \tag{2}$$

Where:
$\overline{T}_w$ =average waiting time per transporter
$\overline{T}_h$ = average handling time per transporter

- *Occupancy Rate*

The *OR* indicates the utilization rate of unloading bay which means the unloading bay's productivity during its service period (Eq. 3). The origin of this performance indicator also is related to how the port industry quantifies berths utilization in per year period as shown in Eq. 4. The numerator indicates the effective demand for service time, while the denominator represents the port capacity, both measured in terms of berth days of each year (De Weille and Jay, 1974). It is adapted and modified for evaluating utilization rates of unloading bays in connection with material delivery in this research. A higher *OR* value means a higher utilization rate of the unloading bay. But it also indicates a higher probability of transporter overprovision at the unloading bay. As a result, the waiting time of transporter increases.

$$OR = \frac{N_t \times \overline{T}_h}{N_{ub} \times T_s} \times 100\% \qquad (3)$$

Where:
N_t = number of transporter arrival during service time
N_{ub} =number of unloading bay
T_s =service time, time elapsed between the first transporter's arrival to last transporter's departure

$$\text{berth occupancy rate (\%)} = \frac{\text{number of ship arrivals during year} \times \text{average service time required per ship}}{\text{number of berths} \times 365} \times 100 \qquad (4)$$

Overall, the values of the WS and OR are interrelated. On one side, a higher OR value at the unloading bays indicates a higher utilization rate; on the other side, it also implies longer waiting times of the transporters at the entrance. Therefore, a trade-off between the WS and OR values can be observed in balancing transporter waiting percentage against the unloading bay utilization rate during the service period. For instance, as shown in Figure 3-2, Point A has the lowest value of WS indicates the shortest waiting of the transporter before handling. But the utilization rate of the unloading bay also is the lowest, which implies the unproductive time on handling crews and unloading bays. In comparison, Point C has the highest value of OR of the unloading bay but also the longest waiting time of the transporter at the entrance; which implies the transporter's time is wasted. Previous research in port operation domain provides the potential yardstick for benchmarking on those performance indicators: the WS ratio should range between 0.1 and 0.5 while the OR should not exceed 0.7 (the area within the red rectangle in Figure 3-2). (UNCTAD, 1985; 1987).

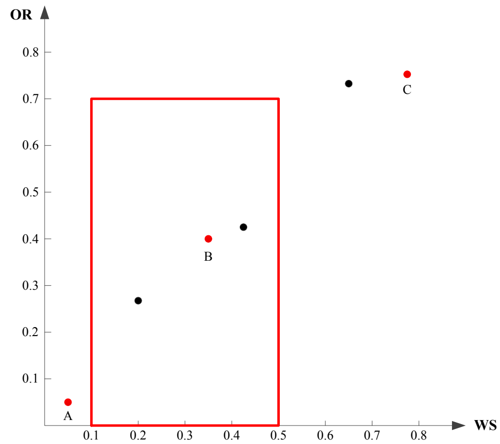


Figure 3- 2: The sample points for illustrating the usage of the proposed indicators

3.3 Verification and Validation

An example case study is given in order to verify and validate the logic of the developed simulation template and proposed indicators. Data and information for the example case are extracted and abstracted based on a modular construction project in Alberta, Canada. Transporters utilized in the example case are trucks, ships, and trains. Components for assembling 10 modules are prefabricated off-shore at the fabrication shop. There is a port of loading (POL) and a port of destination (POD) located on the material delivery route. These prefabricated components are shipped from POL to POD, and then transshipped to two module shops (Module Shops “A” and “B”) for assembly. After the module is assembled, the assembly is shipped from the module shop to the construction site for installation.

- Fabrication process

The prefabricated module materials are stored in separate containers after the prefabrication process. The materials for assembling one module are separately stored in four containers. Table 3-3 summarizes the attributes of the containers. Each individual container has a unique identifier, produced date (to be readily transported to POL), and feasible routes (represents the feasible routes for shipping the containers from POD to the assigned module shop or railway stations).

Table 3- 3: Attributes of the sea containers for storing the module materials (unit: day)

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Destination	A	B	B	B	A	A	B	A	B	B	B	B	B	B	A	A	B	B	A	B
Produced date	0	2	3	4	5	5	6	7	7	7	7	7	8	8	9	9	9	9	11	11
Feasible route	1	2/3	2/3	2/3	1	1	2/3	1	2/3	2/3	2/3	2/3	2/3	2/3	1	1	2/3	2/3	1	2/3
ID	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Destination	B	A	B	A	B	A	B	B	B	A	B	A	B	B	B	B	B	B	B	B
Produced date	11	12	12	13	13	15	15	15	15	16	16	17	17	18	19	19	19	19	20	21
Feasible route	2/3	1	2/3	1	2/3	1	2/3	2/3	2/3	1	2/3	1	2/3	2/3	2/3	2/3	2/3	2/3	2/3	2/3

Note: Route 1=From POD to Module Shop A; Route 2= From POD to Railway Station #1; Route 3=From POD to Railway Station #2.

- Shipment process

The shipment process is initialized when the materials are fabricated and stored in the container. The container is then loaded onto a truck for transferring from the fabrication shop to POL. Table 3-4 gives the carrying capacity and the availability limit of the transporters along the supply chain. Table 3-5 tabulates the transit duration of transporters between locations (i.e., load, ship, unload, and return). Note that the duration used in this paper denotes the most likely value (no distributions) in order to simplify the verification of the proposed methodology. At POL, the containers will be temporarily stored until all other containers arrive, assuming the capacity of storage yard is always sufficient. Then, every four containers are loaded to one ship for transporting the materials from POL to POD. Note that the arrival of the ships for other business at POD is also modeled to reflect the real port operation. The ships (for other business) occupy the berth for unloading the cargos at POD, which potentially delays the time of a module ship's call on the terminal. The inter-arrival time of ships (for other business) and its handling time at delivery port follow the negative exponential distributions (De Weille and Ray 1974) with the mean values equal to 0.35 days and 3 days, respectively. After the ship berths at POD, the containers are unloaded from the ship. The containers, which hold materials planned to be assembled at Module Shop A, are transshipped by trucks to Shop A directly. The remaining, which hold the materials planned to be assembled at Module Shop B, are first transshipped by train. Every two containers are loaded onto one train. Meanwhile, there are two feasible railways at POD for delivering the containers to either Rail Station #1 or Rail Station #2. The selection of the feasible route is dependent on the availability of the trains. Upon the arrival of the container at the rail station, it is transshipped to Module Shop B by trucks. At the module shop, the container is unloaded at the laydown yard (equivalent to unloading bay) and stored at the storage space of the module shop.

Table 3- 4: Carrying capacity and availability of the transporter

Transporter	Routes	Carrying capacity	Availability
Truck	Fabrication shop to POL	1 container per truck	5
Truck	POD to Module Shop A	1 container per truck	2
Train	POD to Rail Station #1	2 containers per train	2
Train	POD to Rail Station #2	2 containers per train	2
Truck	Module Shop A to Construction Site	1 module per truck	3
Truck	Module Shop B to Construction Site	1 module per truck	3

Table 3- 5: Transit duration in association with the shipping route and the transporter

Route	Transportation mode	Load duration	Ship duration	Unload duration	Return duration (of transporter)
Fabrication shop to POL	Roadway	0.1 day	1 days	0.1 day	1 day
POL to POD	Maritime	0.5 day	15 days	3 days	10 days
POD to Module Shop A	Roadway	0.1 day	2 days	0.1 day	2 days
POD to Rail Station #1	Railway	0.2 day	5 days	0.2 day	4 days
POD to Rail Station #2	Railway	0.2 day	5.2 days	0.2 day	4.2 days
Module Shop A to Site	Roadway	0.5 day	1 day	0.5 day	1 day
Rail Station #1 to Module Shop B	Roadway	0.1 day	1 day	0.1 day	1 day
Rail Station #2 to Module Shop B	Roadway	0.1 day	1 day	0.1 day	1 day
Module Shop B to Site	Roadway	0.5 day	1 day	0.5 day	1 day

- Module assembly process

At the module shop, the assembly process for assembling one particular module starts when the required materials shipped in four separate containers have all arrived and the assembly resources (i.e., the assembly bay, crane, and the assembly crew) are available. Table 3-6 shows the required containers and the duration for assembling particular modules. Table 3-7 depicts the availability limits of the assembly crew, the crane, the assembly bay, and the unloading bay. Table 3-8 lists the resource requirement for assembling per module.

Table 3- 6: Duration and required containers for assembling the modules

Module ID	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Required containers	1, 6, 15, 8	5, 26, 16, 22	24, 30, 19, 32	3, 9, 17, 11	13, 7, 10, 14	2, 4, 18, 12	27, 21, 39, 34	20, 28, 35, 40	23, 36, 33, 38	29, 26, 37, 31
Assembly duration (day)	5	3.5	4	3	2	3	5	4	4	5

Table 3- 7: Resource availability at module assembly yard

Module Shop	Crew	Crane	Assembly bay	Unloading bay
Module Shop A	4	1	1	2
Module Shop B	6	2	2	2

Table 3- 8: Resource requirement for assembling module

Module Shop	Crew	Crane	Assembly bay
Module Shop A	2	1	1
Module Shop B	3	1	1

- Field installation process

After the module is assembled, the module is delivered to the site by trucks for field installation. Note that the assembly bay cannot start next assembly work until the assembled module is loaded to the truck and assembly bay is empty. On site, the modules are installed in accordance with the planned installation sequence. Table 3-9 identifies the technological constraints for installing the 10 modules. It takes half a day to install one module on site.

Table 3- 9: Module installation sequence on site

Module	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Successor	M4	M7	M9	M5	M6	M2	M8	M3	M10	-

In order to demonstrate the usage of the proposed indicators, three “what-if” scenarios are postulated by changing the availability limits for (i) unloading bays at POD and (ii) number of transporters for transferring the containers from POL to POD and the modules from railway stations to Module Shop B (Table 3-10).

Table 3- 10: Resource limits for three “what-if” scenarios

Scenario	Number of berth at POD	Number of trucks at rail station	Number of ships at POL
Scenario 1	11	2	2
Scenario 2	7	4	3
Scenario 3	11	4	3

3.4 Simulation Results

Computer simulation is conducted by using of the *Simphony* platform in a single run with the most likely values as input. The simulation in this section is intended to represent the logic in the model and assess postulated “what-if” scenarios, rather than statistical analysis of outputs due to uncertain inputs. Impacts of uncertainties during the material delivery will be discussed in the next chapter. Figure 3-2 is the screen capture of the developed model.

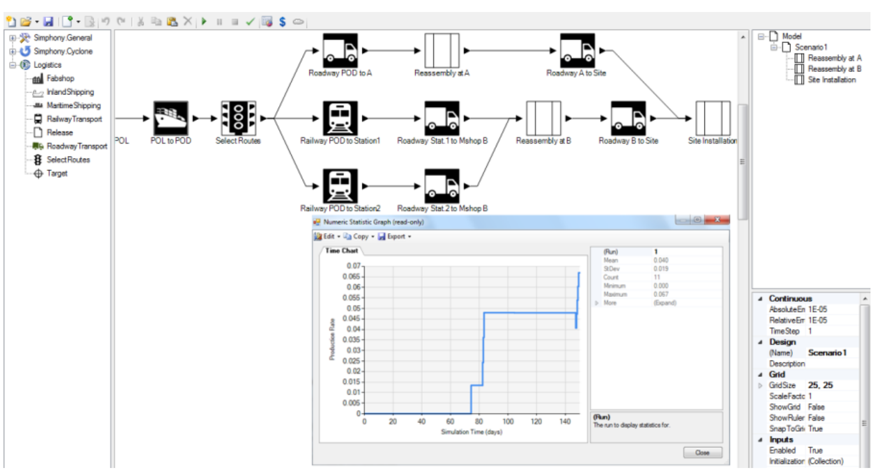


Figure 3- 3: Screen capture of the developed Simphony simulation model

Table 3-11 shows the simulated event list, which tracks the materials arrival times at particular locations (Scenario 1, Run #1). For instance, on Day 0, the materials for assembling Module 1 are ready for shipping at the fabrication shop and loaded into Container 1 for 0.1 day. On Day 1.2, Container 1 arrives at POL through roadway shipping from the fabrication shop. Container 1 is then stored at POL and waits for 4 days until the arrival of Containers 2, 3, and 4 (Containers 1, 2, 3, and 4 are batched in 1 ship). On Day 5.2, Container 4 is the last container arriving at POL. At POL, four containers are loaded to the ship for 0.5 day. On Day 5.7, the ship transports the containers from POL to POD for 15 days' maritime shipping. On Day 20.7, the ship arrives at POD. The containers are unloaded at POD for 3 days, including the custom clearance and inspection by the Custom officials. Then, the ship returns to POL for another 10 days. Meanwhile, the unloaded container is transshipped at POD with three feasible routes. The selection of the route depends on the planned destination of each container and the availability of the transporters. The destination of Container 1 is Module shop A such that it is transshipped by a truck from POD to Module Shop A. The destination of Containers 2, 3, and 4 is Module Shop B. Thus, they are transported by trains from the rail station to Module Shop B. Container 1 arrives at Module Shop A on Day 25.9 and unloaded for 0.1 day. Then, it is stored in the storage yard until Containers 6, 8, and 15 arrive. The assembly for Module 1 starts on Day 57.4 when last container (Container 15) arrives and finishes on Day 62.4. Then, Module 1 is loaded to a truck for 0.5 day, and moved from the module shop to the construction site for 1 day. On Day 64.4, Module 1 is unloaded from the truck at the field for another 0.5 day and is ready for final installation. On Day 64.9, the installation of Module 1 is completed. Note, the total project duration is defined as the time elapsed between first module material prefabricated at fabrication shop and last module installed on site. The total project duration in this scenario is 162.6 days.

Table 3- 11: Arrival times of materials at particular locations for Scenario 1, Run #1 (Unit: day)

Seacan ID	Module ID	Fab Shop	POL	POD	Railway Station 1	Railway Station 2	Module Shop A	Module Shop B	Ready on Site	Done
1	***M1***	***0***	***1.2***	***20.7***	-	-	***25.9***	-	***64.4***	***64.9***
2	*M6*	*2*	*3.2*	***20.7***	*29.1*	-	-	*30.3*	*93.4*	*95.9*
3	*M4*	*3*	*4.2*	***20.7***	*29.1*	-	-	*30.3*	*94.4*	*94.9*
4	*M6*	*4*	*5.2*	***20.7***	*32.1*	-	-	*33.3*	*93.4*	*95.9*
5	M2	5	6.2	23.7	-	-	28.9	-	118.5	119.0
6	***M1***	**5**	**6.2**	23.7	-	-	**28.9**	-	**64.4**	**64.9**
7	M5	6	7.2	23.7	32.1	-	-	33.3	68.0	95.4
8	***M1***	**7**	**8.2**	23.7	-	-	**29.0**	-	**64.4**	**64.9**
9	M4	7	8.2	49.2	57.6	-	-	58.8	94.4	94.9
10	M5	7.2	8.4	49.2	57.6	-	-	58.8	68.0	95.4
11	M4	7.2	8.4	49.2	57.6	-	-	61.0	94.4	94.9
12	M6	8.2	9.4	49.2	57.6	-	-	61.0	93.4	95.9
13	M5	9.2	10.4	52.2	-	60.8	-	62.0	68.0	95.4
14	M5	9.2	10.4	52.2	-	60.8	-	62.0	68.0	95.4
15	***M1***	9.4	10.6	52.2	-	-	**57.4**	-	**64.4**	**64.9**
16	M2	9.4	10.6	52.2	-	-	57.4	-	118.5	119.0
17	M4	10.4	11.6	78.8	87.2	-	-	88.4	94.4	94.9
18	M6	11.4	12.6	78.8	87.2	-	-	88.4	93.4	95.9
19	M3	11.4	12.6	78.8	-	-	84.0	-	123.0	161.6
20	M8	11.6	12.8	78.8	89.1	-	-	90.6	160.1	161.1
21	M7	11.6	12.8	80.7	89.1	-	-	90.6	160.1	160.6
22	M2	12.6	13.8	80.7	-	-	85.9	-	118.5	119.0
23	M9	13.6	14.8	80.7	115.7	-	-	116.9	155.6	162.6
24	M3	13.6	14.8	80.7	-	-	85.9	-	123.0	161.6
25	M10	13.8	15	107.3	115.7	-	-	116.9	155.6	162.6
26	M2	15	16.2	107.3	-	-	112.5	-	118.5	119.0
27	M7	15	16.2	107.3	115.7	-	-	119.1	160.1	160.6
28	M8	15.8	17	107.3	115.7	-	-	119.1	160.1	161.1
29	M10	15.8	17	110.3	-	118.9	-	120.1	154.6	162.1
30	M3	16	17.2	110.3	-	-	115.5	-	123.0	161.6
31	M10	17.2	18.4	110.3	-	118.9	-	120.1	155.6	162.6
32	M3	17.2	18.4	110.3	-	-	115.5	-	123.0	161.6
33	M9	18	19.2	135.8	144.2	-	-	145.4	154.6	162.1
34	M7	18	19.2	135.8	144.2	-	-	145.4	160.1	160.6
35	M8	19	20.2	135.8	144.2	-	-	147.6	160.1	161.1
36	M9	19.4	20.6	135.8	144.2	-	-	147.6	154.6	162.1
37	M10	19.4	20.6	138.8	-	147.4	-	148.6	155.6	162.6
38	M9	20.2	21.4	138.8	-	147.4	-	148.6	154.6	162.1
39	M7	20.2	21.4	138.8	-	147.4	-	150.8	160.1	160.6
40	M8	21.2	22.4	138.8	-	147.4	-	150.8	160.1	161.1

3.5 Discussions

The performances of the material supply chain for three scenarios are evaluated by use of the proposed indictors (Eqs. 1 to 3). Tables 3-12, 3-13 and 3-14 show the values of *DE*, *WS*, and *OR*.

In this case, the ideal scenario is assumed as the non-resource constrained (i.e., the transporters, unloading bays are always sufficient). From Table 3-12, the *DE* value in Scenario 3 (0.80) is the highest, indicating the best material delivery performance among all the scenarios. Scenario 3 has the maximum number of unloading bays at POD. Thus, the probability of the arriving ships congested at the port entrance waiting for available unloading bay is reduced. The waiting time of the arriving ships at POD is thus reduced. In addition, the number of transporters (i.e., trucks, ships) is also the greatest in Scenario 3. The more transporters are available, the more containers can be delivered simultaneously. As such, the delivery of the containers from POL to POD and from the railway station to the module shop can be completed in a shorter time period.

Table 3- 12: Delivery efficiency (DE) for three scenarios

Scenario	Delivery efficiency
Scenario 1	0.63
Scenario 2	0.51
Scenario 3	0.80

Table 3-13 shows the calculated *WS* ratio for the three scenarios. Note, the ratio divides the waiting time against the handling time. In Scenario 2, the *WS* ratio at POD is 589% which is much larger than the recommended range of *WS* ratio (i.e., from 10% to 50%). It implies that the ships waste a significant portion of time in waiting for available unloading bays before unloading the carried containers. The number of unloading bays at POD is insufficient.

In addition, the number of containers can be delivered in a certain time period is proportional to the quantity of the transporters. With the increment of the transporters arriving at unloading bay, the *WS* ratio also increases. For instance, in Scenario 3, the number of transporters for transferring the materials from the fabrication shop to the module shop is the greatest. However, the number of the unloading bays is finite. Thus, the probability of the unloading bays being congested with trucks increases. As a result, the waiting time of the transporters increases before unloading the containers. Furthermore, the components required for module assembly can be delivered to the module shop in a shorter time period if more transporters are available. Thus, the assembly work for more modules can be commenced at the same time. The *WS* ratios for both unloading bays and assembly bays at module shop are thus higher.

Table 3- 13: Waiting-service ratio (WS) for three scenarios

Scenario	POD	Module Shop A		Module Shop B	
		Unloading bay	Assembly bay	Unloading bay	Assembly bay
Scenario 1	35%	8%	4%	1%	21%
Scenario 2	589%	9%	5%	5%	35%
Scenario 3	37%	10%	11%	6%	38%

The *OR* is proposed to indicate the utilization rate of the unloading bay during its service period. The variances of *OR* values are negligible at POD as the unloading bays at the delivery port can be occupied by the ships for other business as well. In contrast, the changes of the OR values among the three scenarios are significant in regard to the unloading bays and assembly bays at the module shop which exclusively serve the current construction project. Table 3-14 shows that the *OR* value at module shops increases in accordance with the increment of unloading bays at POD and the transporters for material delivery. When the number of unloading bays at POD increases, less waiting time would occur to the arriving ships, leading to the earlier arrival time of the containers at the module shop. Likewise, the more transporters are available, the less time is required for transporting all the containers to the module shops. As a result, the service time (time elapsed between the first transporter arrival to the last transporter departure at unloading bay) at module shop is reduced accordingly; the *OR* value increases.

Table 3- 14: Occupancy rate (OR) for three scenarios

Scenario	POD	Module Shop A		Module Shop B	
		Unloading bay	Assembly bay	Unloading bay	Assembly bay
Scenario 1	2.6%	1.1%	14%	1.2%	11.9%
Scenario 2	2.7%	0.9%	12%	1.0%	10.4%
Scenario 3	3.0%	1.5%	17%	1.9%	15.6%

In short, attaining a high value on *DE* is the primary objective for improving system performance of the material supply chain. When the value of *DE* is similar (e.g., Scenario 1 and Scenario 3), a trade-off between the *WS* and *OR* is essential in order to balance the supply of unloading bays and the demand of transporters. An optimum scenario leads to the shortest waiting time of transporter and the least production loss at unloading bays simultaneously. Hence, Scenario 3 should be chosen in the current example. Moreover, based on the simulation results, insufficient unloading bays at the delivery port would significantly increase the waiting time of the arriving ships at the port entrance. This would further delay materials' arrival time at module shops and construction sites, eventually extending the total project duration of construction. In addition, the increment of transporters arriving at unloading bays per time also increases the *WS* ratio of transporters. Overprovision of the transporters would waste the transporters' time while an insufficient number of transporters increase the idle time of the unloading bays and its handling crews leading to system efficiency loss.

Overall, this example case is employed in order to verify the logic of this large simulation system and the proposed indicators. The most likely deterministic values as the shipping and handling duration are used in the simulation model. It simplifies the procedures for producing the simulation event list (Table 3-11) for verification purpose. In the next chapter, uncertainties during the material delivery are considered to investigate the influence of potential delays to modules' final field installation schedule. Monte Carlo Simulation is thus performed to account for these uncertainties.

CHAPTER 4: PRACTICAL CASE STUDY

In this chapter, a practical case study is given to evaluate the material logistics performance under the *big site* scenario by the proposed methodology. Section 4.1 gives the project background information. Section 4.2 is the developed simulation model. Section 4.3 presents the modified module field installation schedule.

4.1 Project Description

An industrial project is planning to install 30 modules at field, and off-shore prefabrication. Data used in the study were based on part of a real industrial modular construction project located in Alberta, Canada. The complete logistics network is shown in Figure 4-1. Various transit locations such as fabrication shops, POL, POD, module shops and site can be observed. Multiple feasible routes are available for module delivery.

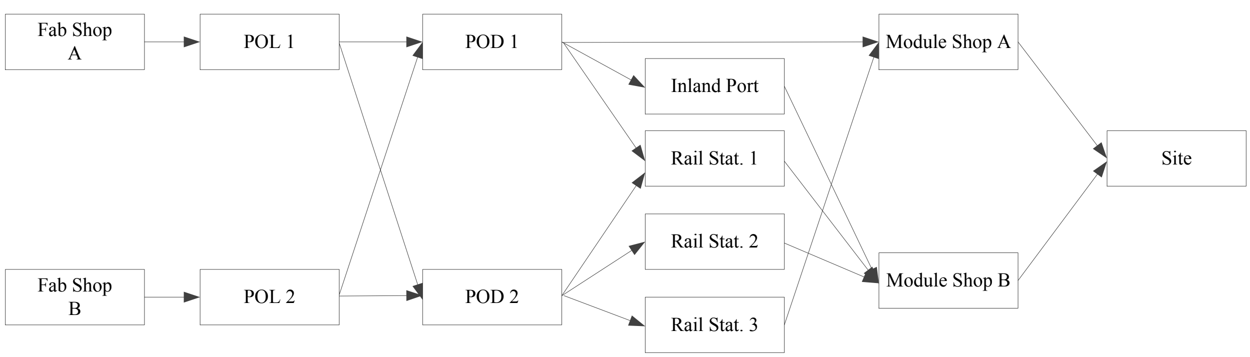


Figure 4 - 1: The logistics network of the studied case

4.1.1 Sub-assemblies prefabrication

Sub-assemblies such as pipes and steels are off-shore prefabricated at two fabrication shops located in China and Korea. Every piece is unique and assigned to the determined shipping destination either Module Shop A or Module Shop B for the assembly works. Every three pieces with the same assigned destination are packaged into one container (container's destination is consistent with the carried pieces), and then delivered to the module shop via multimodal transportation. Table 4-1 tabulates the attributes of each sub-assembly, including unique ID, produced date, predefined destination and assembling specification for particular modules (e.g., Module 1 is assembled by pieces ID 38, 39, etc.). The produced date is in accordance with the final installation schedule, i.e., pieces for the first installed modules will be prefabricated, delivered and assembled first as well.

Table 4- 1[a]: Attributes of the prefabricated sub-assemblies at fabrication shop A

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Destination	B	A	B	A	B	A	B	B	B	A	B	B	B	A	B	B	B	A	A	B
Produced date	12	30	16	9	18	5	24	21	27	27	25	20	27	18	16	19	9	7	22	23
Interconnection	M6	M24	M19	M5	M19	M13	M23	M21	M30	M24	M23	M21	M12	M9	M8	M19	M25	M4	M22	M23
ID	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Destination	B	A	A	B	A	A	A	A	A	A	A	A	A	A	A	B	B	A	A	B
Produced date	18	8	20	17	12	10	24	4	20	0	2	21	25	20	20	8	2	0	0	17
Interconnection	M19	M4	M10	M27	M17	M5	M22	M13	M10	M1	M13	M22	M22	M10	M10	M15	M2	M1	M1	M27
ID	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Destination	B	B	B	B	A	B	B	A	B	A	B	A	B	A	A	B	B	A	B	A
Produced date	15	7	17	8	21	16	21	1	18	5	27	4	6	1	8	12	9	10	16	1
Interconnection	M27	M15	M20	M15	M10	M27	M21	M1	M27	M14	M12	M13	M15	M1	M4	M6	M16	M17	M18	M1
ID	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Destination	B	A	B	B	B	A	B	B	B	A	B	A	A	B	A	B	A	B	A	B
Produced date	12	18	23	15	20	7	5	10	7	6	7	8	26	2	1	23	1	8	6	20
Interconnection	M6	M9	M11	M18	M28	M26	M3	M16	M15	M14	M16	M4	M24	M2	M1	M11	M1	M16	M14	M28
ID	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
Destination	B	B	B	B	B	B	B	A	A	B	B	B	B	B	B	B	A	B	B	A
Produced date	14	6	5	8	12	7	17	18	4	18	24	5	15	12	17	28	8	25	13	28
Interconnection	M7	M25	M3	M25	M6	M25	M28	M9	M14	M27	M11	M3	M18	M6	M20	M12	M26	M23	M6	M24
ID	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
Destination	B	B	B	A	A	B	B	A	A	B	A	A	B	B	B	A	A	B	B	A
Produced date	7	22	16	21	11	32	15	25	5	25	19	21	18	25	14	10	28	13	16	21
Interconnection	M15	M21	M8	M10	M17	M30	M18	M22	M14	M23	M9	M22	M20	M11	M7	M5	M29	M6	M27	M10
ID	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140
Destination	A	A	B	B	B	A	A	B	A	B	B	A	A	B	B	B	A	A	B	B
Produced date	19	23	14	15	25	5	4	8	22	30	15	26	28	20	27	14	9	4	16	14
Interconnection	M9	M10	M7	M18	M23	M14	M13	M15	M22	M30	M27	M24	M29	M21	M23	M18	M17	M13	M27	M7
ID	141	142	143	144	145	146	147	148	149	150										
Destination	B	B	B	B	B	B	B	B	B	B										
Produced date	14	14	30	31	9	32	15	2	8	6										
Interconnection	M7	M7	M30	M30	M25	M30	M7	M2	M25	M15										

Table 4 - 1b: Attributes of the prefabricated sub-assemblies at fabrication shop B

ID	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170
Destination	B	B	B	B	B	B	A	B	A	A	B	A	A	B	B	B	B	A	B	B
Produced date	2	13	25	22	17	16	5	17	24	10	3	8	27	6	17	7	15	7	19	19
Interconnection	M2	M18	M11	M21	M8	M20	M14	M8	M29	M5	M2	M4	M29	M3	M20	M25	M18	M26	M19	M28
ID	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190
Destination	B	B	B	B	A	A	A	A	A	A	A	B	A	B	B	A	A	A	B	B
Produced date	17	28	3	7	9	11	12	21	2	11	11	29	19	4	17	11	2	10	17	17
Interconnection	M8	M12	M2	M3	M4	M5	M17	M22	M13	M5	M5	M30	M9	M2	M8	M5	M1	M17	M8	M8
ID	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210
Destination	B	A	B	A	B	B	A	B	A	A	B	B	A	B	B	B	B	A	A	A
Produced date	13	9	20	9	20	28	25	28	25	10	15	29	4	13	16	17	29	25	28	9
Interconnection	M6	M26	M28	M17	M21	M30	M22	M12	M22	M17	M18	M12	M14	M6	M19	M28	M12	M29	M24	M4
ID	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230
Destination	A	B	B	B	A	B	B	B	B	B	A	A	B	B	A	B	B	B	B	B
Produced date	26	19	4	18	26	7	19	31	20	19	9	2	29	7	10	4	18	7	17	15
Interconnection	M29	M20	M2	M19	M24	M3	M20	M30	M21	M20	M4	M1	M12	M3	M17	M2	M20	M3	M28	M7
ID	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250
Destination	B	A	B	B	B	B	A	A	B	B	B	B	A	B	B	A	B	B	A	A
Produced date	6	1	25	16	7	14	19	9	26	7	17	9	10	9	26	9	26	23	9	25
Interconnection	M15	M13	M11	M7	M3	M18	M9	M26	M11	M16	M28	M16	M26	M25	M11	M4	M23	M23	M26	M29
ID	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270
Destination	B	B	B	B	B	B	B	B	B	B	B	A	B	B	B	A	A	A	A	B
Produced date	10	7	18	7	27	27	17	5	18	20	14	29	18	31	9	4	20	1	25	25
Interconnection	M16	M3	M28	M16	M11	M11	M19	M2	M28	M21	M6	M24	M8	M30	M25	M14	M9	M13	M29	M23
ID	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290
Destination	B	A	A	B	A	A	B	B	B	B	B	B	B	B	A	B	B	A	A	B
Produced date	29	11	11	7	4	23	18	18	17	8	7	7	16	29	0	21	18	12	23	18
Interconnection	M12	M26	M5	M15	M14	M29	M19	M8	M20	M16	M25	M16	M7	M12	M13	M21	M27	M17	M29	M19
ID	291	292	293	294	295	296	297	298	299	300										
Destination	A	A	A	A	A	A	A	A	A	A										
Produced date	10	27	20	8	20	23	30	8	11	23										
Interconnection	M5	M24	M9	M4	M9	M10	M24	M26	M26	M10										

4.1.2 Shipment Process

After every three pieces with the identical destination are fabricated, they are packed into a container and delivered to the POL for ocean shipping. The arrived containers are first temporarily stored at the port storage yard. Note that the storage capacity is assumed as always sufficient at all the transit locations to comply with the real world practice. Table 4-2 lists the carrying capacity and the availability limit of the transporters along the supply chain. Table 4-3 tabulates the transit duration of transporters between locations (i.e., load, ship, unload, and return). However, due to the long shipping distance and complexity of a global project, uncertainties such as weather changes potentially affect the transit duration. Table 4-4 lists the probabilities of delays and corresponding duration during the long journey. At each POL, there always are two feasible shipping routes and the selection is dependent on the availability of the ships. If no ships are currently available, the containers will keep staying at port storage and waiting for next shipment. Upon every five containers are loaded into the deck, the ocean shipping can commence. The ships transport the containers from POL to POD. Note that as mentioned in the example case study, *ships for other business* would continuously call on the POD and occupy limited berths, which potentially postpone the module's ship arrival time. Thus, *ships'* (for other business) inter-arrival time and handling time are assumed equal to 0.35 day and 3 days in the case study in order to reflect the real world port operations. After the module ships berth at POD, the containers are unloaded at the quay and then inspected by the Customs officials for fulfilling the import regulations. The further transshipment to the module shop is based on the assigned destination on each container as well as the availability of the transporters at POD. Specifically, at POD #1, containers with the destination "Module Shop A" are directly transhipped by trucks via roadway; otherwise, the remaining containers (i.e., destination is "Module Shop B") can either be transshipped by trains or barges depend on the availability of these transporters. Likewise, at POD #2, containers designated with destination as Module Shop A are transshipped by trains to Rail Station #2; the others are delivered to either Rail Station #1 or #3 based on the availability of trains. Eventually, all the containers will be transshipped to the assigned module shop for assembly by trucks again after reaching different transit locations (i.e., rail stations, inland port).

Table 4- 2: Carrying capacity and availability of the transporter

Transporter	Routes	Carrying capacity	Availability
Truck	Fabrication shop to POL	1 container per truck	10
Ship	POL to POD	5 containers per ship	3 per route
Truck	POD1 to Module Shop A	1 container per truck	5
Train	POD1 to Rail Station #1	4 containers per train	2
Barge	POD1 to Inland Port	4 containers per barge	1
Train	POD2 to Rail Station #1	4 containers per train	2
Train	POD2 to Rail Station #2	4 containers per train	2
Train	POD2 to Rail Station #3	4 containers per train	2
Truck	Rail Station #1 to Module Shop B	1 container per truck	5
Truck	Rail Station #2 to Module Shop A	1 container per truck	5
Truck	Rail Station #3 to Module Shop B	1 container per truck	5
Truck	Inland Port to Module Shop A	1 container per truck	5
Truck	Module Shop A to Construction Site	1 module per truck	5
Truck	Module Shop B to Construction Site	1 module per truck	5

Table 4- 3: Transit duration in association with the shipping route and the transporter (in day)

Route	Transportation mode	Load duration	Ship duration	Unload duration	Return duration (of transporter)
Fabrication shop to POL	Roadway	0.1 day	1 day	0.1 day	1 day
POL 1 to POD 1	Maritime	0.5 day	10 days	3 days	8 days
POL 1 to POD 2	Maritime	0.5 day	9 days	3 days	7 days
POL 2 to POD 1	Maritime	0.5 day	8 days	3 days	8 days
POL 2 to POD 2	Maritime	0.5 day	12 days	3 days	10 days
POD 1 to MShop A	Roadway	0.1 day	10 days	0.1 day	8 days
POD 1 to Rail Stat. 1	Railway	0.5 day	3 days	0.5 day	2 days
POD 1 to Inland Port	Waterway	0.5 day	5 days	0.5 day	3 days
POD 2 to Rail Stat. 1	Railway	0.5 day	4 days	0.5 day	3 days
POD 2 to Rail Stat. 2	Railway	0.5 day	4 days	0.5 day	3 days
POD 2 to Rail Stat. 3	Railway	0.5 day	5 days	0.5 day	4 days
Rail Stat. 2 to MShop A	Roadway	0.1 day	3 days	0.1 day	2 days
Rail Stat. 1 to MShop B	Roadway	0.1 day	4 days	0.1 day	3 days
Rail Stat. 3 to MShop B	Roadway	0.1 day	3 days	0.1 day	2 days
Inland Port to MShop B	Roadway	0.1 day	4 days	0.1 day	3 days
MShop A to Site	Roadway	0.5 day	1 day	0.5 day	1 day
MShop B to Site	Roadway	0.5 day	1 day	0.5 day	1 day

Table 4- 4: Probabilities of delay and related duration

Route	Transportation Mode	Delay Probability	Duration
POL 1 to POD 1	Maritime	0.2	Uniform (1, 3)
POL 1 to POD 2	Maritime	0.15	Uniform (1, 2)
POL 2 to POD 1	Maritime	0.2	Uniform (1, 3)
POL 2 to POD 2	Maritime	0.1	Uniform (1, 2)
POD 1 to MShop A	Roadway	0.1	Uniform (0.5, 1)
		0.25	Uniform (0.1, 0.5)
POD 1 to Rail Stat. 1	Railway	0.1	Uniform(0.2, 0.5)
POD 1 to Inland Port	Waterway	0.2	Uniform(0.1, 0.75)
POD 2 to Rail Stat. 1	Railway	0.15	Uniform(0.25, 0.75)
POD 2 to Rail Stat. 2	Railway	0.1	Uniform(0.2, 0.5)
POD 2 to Rail Stat. 3	Railway	0.1	Uniform(0.1, 0.5)

4.1.3 Module Assembly Process

At the module shop, the assembly process for assembling one particular module starts when the required materials stored have all arrived and the assembly resources (i.e., the assembly bay and the assembly crew) are available. In addition, approximately 5% materials are damaged upon arrival that a re-fabrication (10 days) is needed at the local fabrication shop. The assembly duration may vary from module to module due to the variance in terms of complexity. Table 4-5 gives the assembly duration for each module. In addition, a typical module yard usually simultaneously handles multiple projects; thus, limited assembly bays can be provided (Taghaddos et al., 2014). Table 4-6 depicts the availability limits of the assembly crew, the crane, the assembly bay, and the unloading bay. Table 4-7 lists the resource requirement for assembling per module.

Table 4- 5: Assembly duration of each module as module shops

Module ID	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
Assembly duration (day)	6	2	4	5	7	2	4	2	7	6	3	4	4	3	5
Module ID	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
Assembly duration (day)	3	4	3	5	3	4	3	3	2	4	6	4	3	2	2

Table 4- 6: Resource availability at module assembly yard

Module Shop	Crew	Assembly bay	Unloading bay
Module Shop A	15	3	2
Module Shop B	18	4	2

Table 4- 7: Resource-activity requirement for assembling per module

Module Shop	Crew	Assembly bay
Module Shop A	5	1
Module Shop B	4	1

4.1.4 Field Installation

After the module is assembled, the module is delivered to the site by trucks for field installation. At the field, the modules are installed in accordance with the planned installation sequence. Figure 4-2 plots the configuration of the final structure in the field interconnected by the assembled modules. The installation duration and technological constraints for each module are tabulated in Table 4-8. Two basic rules need to be followed in module installation. The first rule (Figure 4-3[a]) is that modules at elevation cannot be installed unless the module that provides physical support at the ground level has been installed. The second rule (Figure 4-3[b]) is applicable to modules that sit right next to one another: when modules on both sides are already installed while the one in the middle is not yet placed, it is difficult to maneuver the crane and to complete module lifting and placing (Hu, 2013).

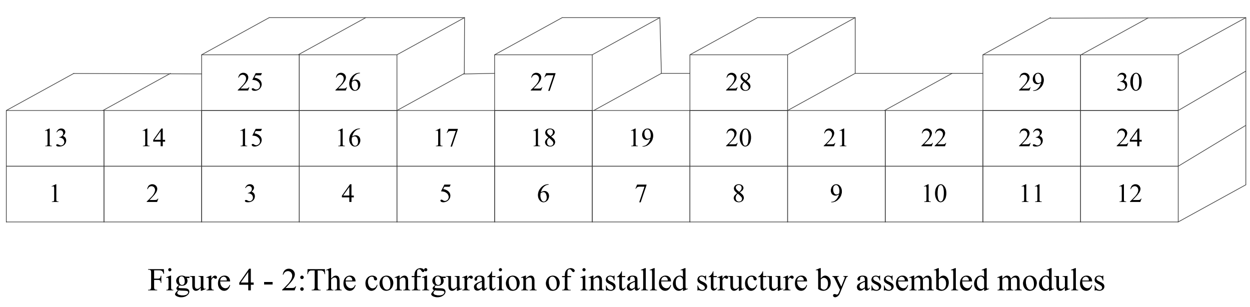


Figure 4 - 2:The configuration of installed structure by assembled modules

Table 4- 8: The installation time and technological constraints of module installation (day)

Module ID	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
Installation duration (day)	1.1	0.7	1.5	0.8	1.2	1.2	1.5	0.6	0.6	1.1	1.1	1.1	0.7	0.5	1.4
Vertical constraints	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	-	M14	M15	M16
Horizontal constraints	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	-	-	M25
Module ID	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
Installation duration (day)	0.5	0.6	1.1	1	1.5	0.7	0.8	1.3	1.1	1.3	0.6	1.4	0.5	1.1	1.1
Vertical constraints	M17	M18	M19	M20	M21	M22	M23	M24	-	M26	-	-	-	M30	-
Horizontal constraints	-	M27	-	M28	-	-	-	-	-	-	-	-	-	M29	M30

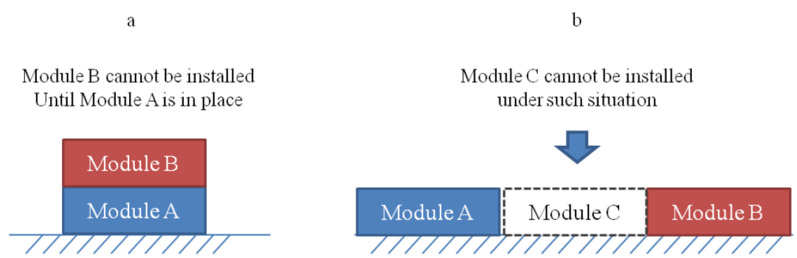


Figure 4 - 3: Installation constraints of modules (Hu, 2013)

4.2 Simulation Model

The simulation model is developed by the special logistics template with the interaction of the general template in the *Simphony* platform for mimicking material delivery and handling processes at each transit location. Figure 4-4 is the screenshot of the developed simulation model in Simphony.

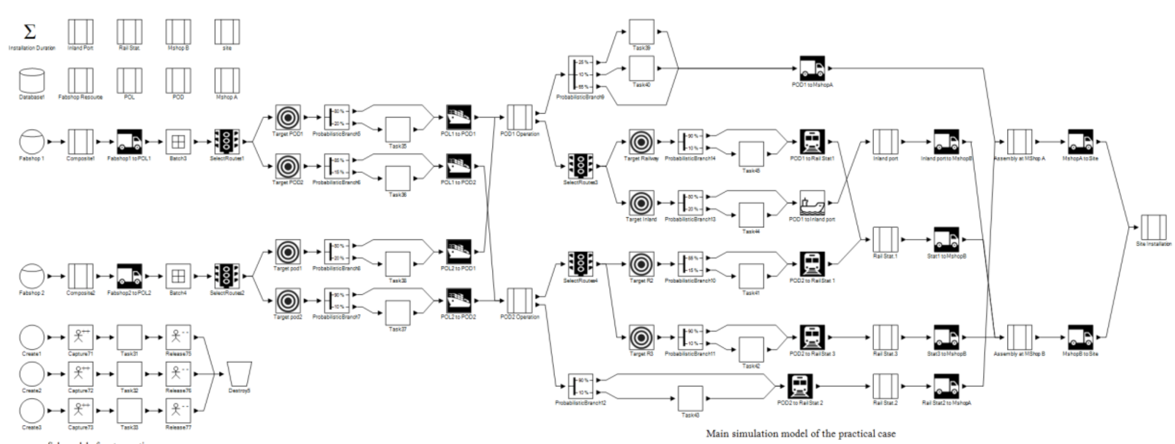


Figure 4 - 4: Screenshot of the developed simulation model

4.3 Logistics Performance Evaluation

In order to minimize the effects caused by the uncertainties during the delivery and at the POD, Monte Carlo Simulation is performed (100 runs). The delivery performance at each transit location is evaluated by the three proposed indicators as tabulated from Table 4-9 to Table 4-11. Note that the ideal scenario in the practical case is the non-delay material delivery whilst the actual scenario is the scenario considering the probabilities of delays in Table 4-4. The delivery efficiency factor is calculated as ration of the non-delay (ideal) system production rate against the delayed (actual) system production rate.

Table 4- 9: Delivery efficiency of the practical case

Scenario	Production Rate
Ideal	0.215
Actual	0.201
Delivery Efficiency	**0.93**

The *DE* factor is proposed to assess the overall material delivery performance, which is positively correlated to its value. As shown in Table 4-9, the impact of uncertainties during the material delivery is insignificant to the overall delivery performance: a relatively high *DE* value (0.93) is achieved. It implies the potential delays that occur in the entire module shipment process are not substantial in terms of interrupting the project schedule.

Table 4- 10: Waiting-service ratio of the practical case

Scenario	POD1	POD2	Module Shop A		Module Shop B	
			Unloading bay	Assembly bay	Unloading bay	Assembly bay
Ideal	29.7%	22.7%	20.0%	6.0%	5.0%	6.3%
Actual	35.9%	24.0%	15.0%	4.5%	5.0%	4.2%

Table 4-10 lists the *WS* ratio of the transporters and modules at different transit locations in both non-delay (ideal) and delayed (actual) scenarios for assessing the waiting percentage before handling. At PODs, the ratio is increased due to the port is handling the *ships for other businesses* simultaneously. Potential delays in the ocean shipping postpone the arrival time of the project-relevant ships at POD. Late arrival increases the queue length of those ships at port entrance; thus, the *WS* ratio increases. In contrast, the unloading bays and assembly bays at module shops exclusively serve the current project. Material delivery delays reduce the number of transporters arriving at one time that the probability of transporters congested at unloading bays thus decreases. Likewise, materials' late arrival also delays the module assembly start date, reducing the number of assembly tasks that can commence each time. As a result, the *WS* ratio of the assembly bay also decreases. In addition, the values of *WS* ratio at module shops are lower than the commonly recommended yardstick (0.1~0.5) as stated in the methodology section, indicating the handling crews and bays are idling and waiting for work and hence production loss is experienced due to the current logistics plan.

Table 4- 11: Occupancy rate of the practical case

Scenario	Module Shop A		Module Shop B	
	Unloading bay	Assembly bay	Unloading bay	Assembly bay
Ideal	7%	51%	6%	37.40%
Actual	6%	48.30%	5%	35.68%

The *OR* is proposed to indicate the utilization rate of the bays during its service period. Table 4-11 shows the occupancy rate of the assembly bays and unloading bays at respective module shops. Delays during the delivery stage interrupt the materials' arrival. As such, the service times both at unloading bays and assembly bays are prolonged, leading to decrease on the bays' utilization rate. Note that the unloading bays (berths) at the port can be continuously occupied by the *ships for other business* as well, the variance between two scenarios is negligible. So, they are not listed in the table.

4.4 Site Installation Schedule Modification

The uncertainties during the material delivery vary the arrival times of different modules to be consolidated into the final structure at site, which is impacted by the preceding logistics service performance in delivering the prefabricated materials. Hence, the arrival times of these components determine the start times of module assembly and site installation activities. As such, the module ready on site (MROS) time should be considered in the site installation planning in accordance with the technological installation sequence constraints.

For instance, four Modules A, B, C, and D are planned to be installed with an installation time equal to 1, 2, 1 and 2 days, respectively. General scheduling methodology such as CPM only considers the dependencies between activities as shown in Figure 4-5[a] (the critical path is highlighted in red). However, the varying arrival days of the modules make this schedule unrealistic. It is impacted by the preceding logistics service performance in delivering the prefabricated materials to module shop. Assuming the MROS times of four modules are at Day 0, 0, 3 and 7. As such, Module B cannot be installed until Module A has been installed due to the interconnection technological constraints, though it is initially available on Day 0. In contrast, Module C's MROS times Day 3, indicating the actual early start (ES) time of installing Module C should not come earlier than Day 3. Therefore, the ES time for installing a particular module in field is to take the larger value between the MROS time and the predecessor's installation completion time (Eq.4). The calculation of early finish (EF), late start (LS), and late finish (LF) follows the general CPM rules (forward and backward).

$$ES_j = \max(AT_j, EF_i) \tag{5}$$

ES_j = the early start time of installing Module j

AT_j = the module ready on site (MROS) time of Module j

EF_i = the early finish time of installing the predecessor Module i (technological constraint)

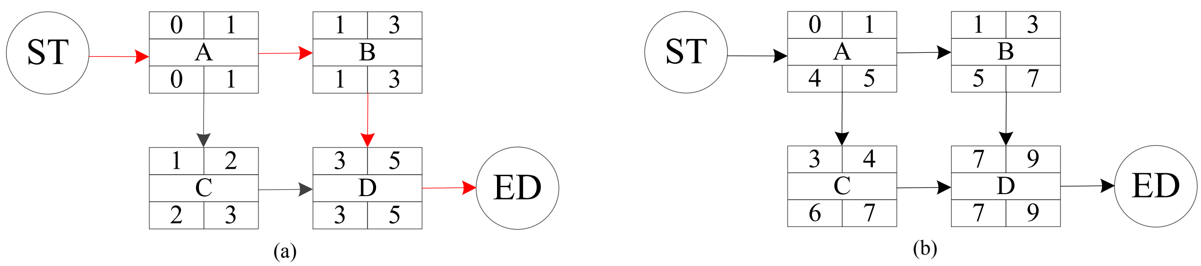


Figure 4 - 5:The AON diagram of the site installation schedule sample

Based on the proposed equation, a modified AON diagram is plotted as per Figure 4-5[b]. With the considerations of MROS time, the total floats for installing Module A, B and C are correspondingly increased, which gives more freedom in planning their installation. Compared with the modified diagram, the general method (Figure 4-5[a]) fails to impose the logistics constraints (material available time) into the AON network (material could be unavailable at scheduled time point that interrupts activity's start time). This limitation also is observed in current commercial software such as Primavera P6 applied for the crew (labor/equipment) centric project scheduling. Although manually adding constraints to each activity is a possible solution, it is a tedious and time-consuming exercise. In addition, the critical activity normally is recognized as the activities with zero total float (they must be executed right on scheduled start and finish times without any delay). However, with the considerations of MROS time, the original critical activities' total floats could no longer equal to zero as shown in Figure 4-5[b]. As a result, the critical path does not exist in the modified network while the activity with fewer floats at each branch can be regarded as it is *more critical* than the others. For example, the installation of Module C is more critical than Module B because it has less tolerance (3 days) in terms of delaying its execution. The total installation time is thus increased from 5 days to 9 days.

Table 4-12 tabulates the most likely MROS time (i.e., the average value from 100 simulation runs) of the practical case through Monte Carlo Simulation. Detailed results (with the considerations of MROS time and technological constraints) for each installation activity are listed in Table 4-13. The overall installation duration for 30 modules equals to 48.5 days based on 100 simulation runs, which requires triple time durations than the original CPM schedule (15.5 days).

Table 4- 12: The most likely MROS time of assembled modules from 100 runs (days)

Module ID	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
MROS	41.5	42.7	48.7	55.8	61.1	57.0	61.8	67.0	76.3	78.7	84.1	85.7	44.2	44.3	54.1
Module ID	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
MROS	53.0	62.0	61.3	73.9	76.1	82.0	79.8	84.9	87.8	54.0	56.6	73.0	77.3	86.0	85.2

Table 4- 13: The results of site installation activities with the consideration of MROS (days)

Activity	Duration	Early Start	Early Finish	Late Start	Late Finish	Total Float
1	1.1	41.5	42.6	75.1	76.2	33.6
2	0.7	42.7	43.4	76.2	76.9	33.5
3	1.5	48.7	50.2	76.9	78.4	28.2
4	0.8	55.8	56.6	78.4	79.2	22.6
5	1.2	61.1	62.3	79.2	80.4	18.1
6	1.2	62.3	63.5	80.4	81.6	18.1
7	1.5	63.5	65	81.6	83.1	18.1
8	0.6	67	67.6	83.1	83.7	16.1
9	0.6	76.3	76.9	83.7	84.3	7.4
10	1.1	78.7	79.8	84.3	85.4	5.6
11	1.1	84.1	85.2	85.4	86.5	1.3
12	1.1	85.7	86.8	86.7	87.8	1.0
13	0.7	44.2	44.9	78.6	79.3	34.4
14	0.5	44.9	45.4	79.3	79.8	34.4
15	1.4	54.1	55.5	79.8	81.2	25.7
16	0.5	56.6	57.1	81.3	81.8	24.7
17	0.6	62.3	62.9	81.8	82.4	19.5
18	1.1	63.5	64.6	82.4	83.5	18.9
19	1	73.9	74.9	83.5	84.5	9.6
20	1.5	76.1	77.6	84.5	86	8.4
21	0.7	82	82.7	85	85.7	3.0
22	0.8	82.7	83.5	85.7	86.5	3.0
23	1.3	85.2	86.5	86.5	87.8	1.3
24	1.1	87.8	88.9	87.8	88.9	0.0
25	1.3	55.5	56.8	84	85.3	28.5
26	0.6	57.1	57.7	85.3	85.9	28.2
27	1.4	73	74.4	85.9	87.3	12.9
28	0.5	77.3	77.8	87.3	87.8	10.0
29	1.1	86.5	87.6	87.8	88.9	1.3
30	1.1	88.9	90	88.9	90	0.0

Nevertheless, only two heavy cranes are available for lifting the modules into the assigned positions at field and each module installation requires both cranes' cooperation. Limited availability of cranes generates a resource constraint in scheduling module site installation plan. Therefore, aligning limited crane resources with the MROS time and technological requirements is needed to modify the installation plan. Figure 4-6 draws the Gantt chart of module site installation plan with the consideration of both MROS times and site resource constraint. The shadowed areas in the figure indicate the delay effect on planned start time of each module as shown in Table 4-13 without the considerations of limited cranes at field. Due to the limited availability of the cranes at site, 13 out of 30 modules' site installations have to be postponed (e.g., Module 4, Module 16, etc.). The total installation duration also is slightly increased by 0.9 day.

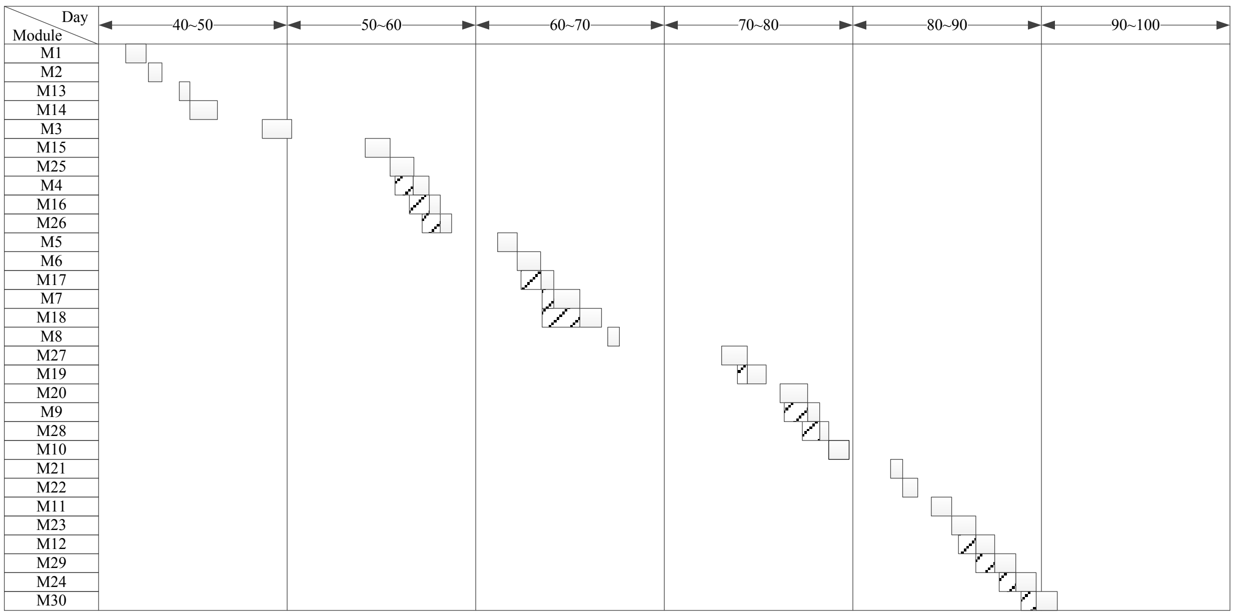


Figure 4 - 6: The Gantt chart of module site installation with the consideration of MROS time and site resource constraint

CHAPTER 5: CONCLUSION

This chapter summarizes all the work conducted in this research. Section 5.1 presents the conclusion of the thesis. Section 5.2 outlines the limitations in the current study and gives some recommendations for future study.

5.1 Conclusion

Generally, in the industrial modular construction, the fabrication shops, modular shops and construction fields are adjacently located in a local region, which can be integrally viewed as the "site". Nevertheless, because of the advances in transportation methods and a shortage of skilled labors in some parts of the world (O'Brien et al., 2008), the practice of outsourcing construction materials and assemblies, and then transshipping them to the local area through multiple transportation modes for final installation, is observed in today's construction industry. Hence, the scope of the site is no longer restricted to the local area; it extends into a global perspective. But this extension does not fundamentally change the basic processes engaged in a project, including the assemblies' prefabrication, material delivery, module assembly and field installation.

Though substantial studies have been conducted previously, the integration of both the material delivery process and construction operation processes (e.g., module assembly, site installation, etc.) at various transit locations, aimed to evaluate the logistics service performance, is absent in the literature. This present study defines a "*big site*" problem in industrial modular construction, which turns various localized and less-structured problems in past works into a structured problem in a logical fashion. In addition, in order to support the research study, a special logistics simulation template is developed in the *Simphony* platform to model material delivery, module fabrication and assembly and the site installation processes. Three key performance indicators named as *delivery efficiency* (DE), *waiting-service ratio* (WS), and *occupancy rate* (OR) are proposed to evaluate the material supply performances in regard to construction planning. The *DE* is proposed to assess the material delivery performance. A Higher value of *DE* indicates the materials are delivered, assembled and installed within a shorter time period. The *WS* is proposed to represent the waiting percentage of the transporter at the unloading bay, while the *OR* represents the utilization rate of the unloading bays during the service time period. These performance indicators originate from the port operation and management domain, which have been adapted to cater for the needs of the present research. Recommended benchmark values for each indicator are currently available to port industry only. When real world data become available in construction domain, these system performance indicators can be established for construction projects in order to evaluate and benchmark construction logistics services.

A practical case study is given to investigate the effects of the material delivery performance in relation to final field module installation in industrial modularization projects. Due to the uncertainties during the transportation process, the module arrival times at field are varied that delay the planned schedule. Monte Carlo Simulation is thus applied to produce the most likely module ready on site (MROS) time. The simulation results are considered as the logistics constraints, coupling with the field resource constraints and installation technological constraints to generate a more realistic schedule for planning the modules field installation.

5.2 Limitations and Future Research

Due to the absence of real data from the construction industry, the recommended benchmarks for assessing the material delivery performance are referenced from the previous studies conducted in the port management area. The recommended ranges and values probably are not suitable in evaluating construction logistics performance. In addition, the current version of the developed template simplifies the real world operations with extensive interactions with the general template offered by *Simphony*, which is not user-friendly to the beginners.

For future research, the simulation template needs further embellishments to make it work independently. New elements can be added, such as port element to model the Customs clearance and inspections, in order to produce more accurate simulation results.

Moreover, later when the real-world data are available, the yardsticks for assessing the construction logistics can be produced in all types of construction projects. In addition, the given practical case study considers the logistical constraints, resource constraints and technological constraints to modify the module installation schedule. These constraints can be mathematically generalized and structured at the conceptual level to revise the current scheduling practice, and eventually assist the project planner to produce a more accurate and realistic project schedule.

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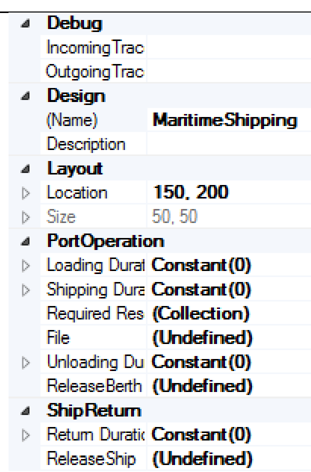
Appendix I: User Manual of the Template

Maritime Shipping Element

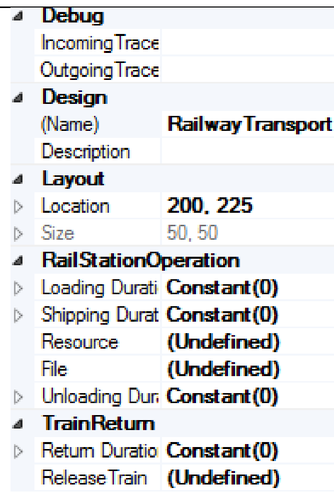
This element, as its name indicates, mimics the mode of transport of shipping project cargoes across the oceans to different ports via vessels as well as the basic port operation works (e.g., loading and unloading cargoes at the terminals, requesting berths and/or storage yard , ship return and release, etc.). Since detailed operation works in real port operation is highly sophisticated while the modeling element is just to abstract the reality, thus, tasks like custom clearance, documentation and inspection, etc. are not included in order to simplify the cargoes handling procedures.

<table>
<tr><td>Element Symbol</td><td>
</td></tr>
<tr><td>Properties</td><td>
</td></tr>
<tr><td>Input Parameters</td><td>Port Operation Function
Loading Duration: the amount of time in order to load cargoes to the vessels.
Shipping Duration: the amount of time to transfer cargoes to the destination port across the oceans.
Required Resource: needed resource before starting the offloading tasks at the destination port like the berth, storage space, etc.
File: defines the waiting file for the entities.</td></tr>
</table>

	Unloading Duration: the amount of time to offload the cargoes at the port. The entity would be transferred out for next task after this function. *Release Berth*: after the cargoes have been offloaded, the vessel would leave the port and the berth would firstly be freed. **Ship Return Function** *Return Duration*: the amount of time that vessel return from destination port to original. *Release Ship*: Release the vessel after return.

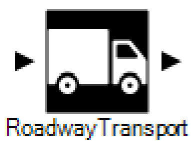
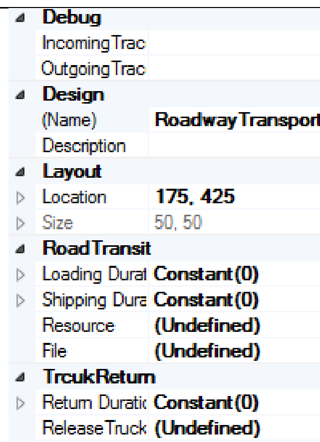
Railway Shipping Element

The Railway Shipping element simulates the transferring process via rails for large loads of cargoes going long distance by train. The railway shipping usually is interacting with other mode of transport as part of the intermodalism network in nowadays logistics service. This element also includes basic cargoes handling works at the rail stations like loading and storage.

Element Symbol	
Properties	
Input Parameters	**Rai Station Operation Function** *Loading Duration*: the amount of time in order to load cargoes to the trains. *Shipping Duration*: the amount of time to transfer cargoes to the destination station via rails. *Required Resource*: needed resource before starting the offloading tasks at the destination station like storage space. *File*: defines the waiting file for the entities. *Unloading Duration*: the amount of time to offload the cargoes at the station. The entity would be transferred out for next task after this function. **Train Return Function** *Return Duration*: the amount of time that train return from destination station to original. *Release Train*: Release the train after return

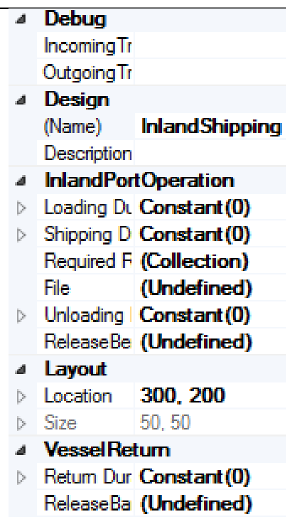
Roadway Shipping Element

This element depicts an indispensable mode of transport for almost all the shipments, both for domestically and internationally services. Owing to the roadway shipping can achieve the door-to-door performance; it is most widely utilized by the carrier to fulfill/finalize the logistics objective via roads, superhighways, bridges, etc. by trucks.

<table>
<tr><td>Element Symbol</td><td>
</td></tr>
<tr><td>Properties</td><td>
</td></tr>
<tr><td>Input Parameters</td><td>Road Transit Function
Loading Duration: the amount of time in order to load cargoes to the trucks.
Shipping Duration: the amount of time to transfer cargoes to the destination via roads.
Required Resource: needed resource before starting the offloading tasks at the destination like storage space.
File: defines the waiting file for the entities.
Truck Return Function
Return Duration: the amount of time that truck return from destination to original.
Release Train: Release the truck after return</td></tr>
</table>

Inland Shipping Element

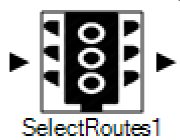
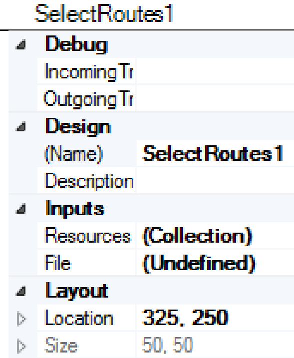
The inland shipping element refers to the water transport that operates within lakes, rivers and canals, as contrasted to maritime shipping on open oceans. The ships (barges) and related service are very different from maritime shipping and can easily be constrained by the limits of geography, however, the basic operations at port as well as to the cargoes handling are still similar.

Element Symbol	
Properties	
Input Parameters	**Inland Port Operation Function** *Loading Duration*: the amount of time in order to load cargoes to the barges. *Shipping Duration*: the amount of time to transfer cargoes to the destination port across the rivers, lakes, etc. *Required Resource*: needed resource before starting the offloading tasks at the destination port like the berth, storage space, etc. *File*: defines the waiting file for the entities. *Unloading Duration*: the amount of time to offload the cargoes at the port. The entity would be transferred out for next task after this function. *Release Berth*: after the cargoes have been offloaded, the barges would leave the port and the berth would firstly be freed. **Vessel Return Function**

	Return Duration: the amount of time that barge return from destination port to original. *Release Ship*: Release the barge after return

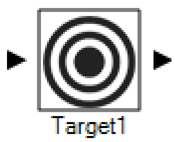
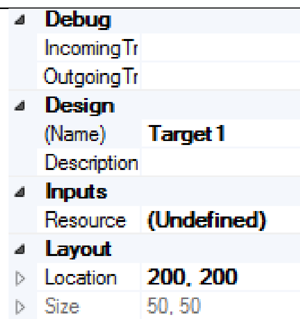
Select Route Element

This element is applied for automatically selecting which route the cargoes can be further transported depends on the availability of the transporter resources (i.e. trucks, trains, etc.). The user can select as many types of transporter resources as they required in the collection editor and determine once it available, which target element it should link to (this element must connect with the target element). Once the (batch) module entity transfer into this element, it will release all the resources it original contains (e.g., the storage resource) and then looping through all the transporter resources and once it available it will capture that resource and transfer into the right target element, otherwise it will wait at the waiting file till the transporter resource becomes available.

<table>
<tr><td>Element Symbol</td><td>
</td></tr>
<tr><td>Properties</td><td>
</td></tr>
<tr><td>Input Parameters</td><td>Operation Function
Resources: A collection editor that the user can input as many transporter resource options as desired.
File: the waiting file that if the resource is not available, the entity will wait in it. For emphasis, all the transporter resource must share the same waiting file.</td></tr>
</table>

Target Element

Target element must connect with the select routes element and it determine which transporter resource is utilized for a specific route. Within the select route element, the user can specify each target transporter resource as well as the number of servers per (batch) entity requires. If the resource is available, it will transfer into the target element; otherwise the simulation entity will stay at the waiting file in the selection element.

Element Symbol	
Properties	
Input Parameters	**Operation Function** *Resources Name*: the name of the target resource.

Appendix II: Sample Code of the Template

Roadway Element:

```
namespace Logistics
{
    using System;
    using System.Collections.Generic;
    using System.ComponentModel;
    using System.Drawing;
    using System.Drawing.Design;
    using System.Xml;
    using Simphony;
    using Simphony.ComponentModel;
    using Simphony.Mathematics;
    using Simphony.Modeling;
    using Simphony.Simulation;

  [Image("truck")]
  [Description("Construction materials shipping through roads and highways.")]
  public class RoadwayTransport : FlowElement<GeneralEntity>
  {
      private Simphony.Simulation.MultipleResourceRequirement multipleResourceRequirement;

      public RoadwayTransport()
      {
          this.LoadingDuration = new Constant(0);
          this.ShippingDuration = new Constant(0);
          this.UnloadingDuration = new Constant(0);
          this.ReturnDuration = new Constant(0);
          this.RequiredResources = new List<SimpleResource>();
          this.LoadingTime = new NumericStatistic("LoadingTime",
NumericStatisticInterpretation.Duration);
          this.ShippingTime = new NumericStatistic("ShippingTime",
NumericStatisticInterpretation.Duration);
          this.UnloadingTime = new NumericStatistic("Unloading Time",
NumericStatisticInterpretation.Duration);
          this.AddStatistic(this.LoadingTime);
          this.AddStatistic(this.ShippingTime);
          this.AddStatistic(this.UnloadingTime);
      }

      public override void  Paint(Graphics graphics, RectangleF bounds)
     {
        graphics.DrawImage(Properties.Resources.roadway, bounds);
           base.Paint(graphics, bounds);
     }

      [Category("TruckStatistics")]
      [Description("A statistic describing the loading time.")]
      [DisplayName("Loading Time")]
      public NumericStatistic LoadingTime { get; private set; }

      [Category("TruckStatistics")]
```

```
        [Description("A statistic describing the unloading time.")]
        [DisplayName("Unloading Time")]
        public NumericStatistic UnloadingTime { get; private set; }

        [Category("TruckStatistics")]
        [Description("A statistic describing the shipping time.")]
        [DisplayName("Shipping Time")]
        public NumericStatistic ShippingTime { get; private set; }

        [Category("RoadTransit")]
        [DisplayIndex(1)]
        [Description("The time it takes to load the prefabbed modules from POD to trains in
days.")]
        [DisplayName("Loading Duration")]
        public Distribution LoadingDuration { get; set; }

        [Category("RoadTransit")]
        [DisplayIndex(2)]
        [Description("The shipping duration from POD to Rail Station in days.")]
        [DisplayName("Shipping Duration")]
        public Distribution ShippingDuration { get; set; }

        [Category("RoadTransit")]
        [DisplayName("Required Resources")]
        [DisplayIndex(3)]
        [Editor(typeof(CollectionEditor<SimpleResource>), typeof(UITypeEditor))]
        [TypeConverter(typeof(CollectionConverter))]
        public IList<SimpleResource> RequiredResources { get; set; }

        private Simphony.Simulation.WaitingFile file;
        [Category("RoadTransit")]
        [DisplayName("File")]
        [DisplayIndex(4)]
        [TypeConverter(typeof(ElementListConverter<Simphony.General.File>))]
        public string File { get; set; }

        [Category("RoadTransit")]
        [DisplayIndex(5)]
        [DisplayName("Unloading Duration")]
        public Distribution UnloadingDuration { get; set; }


        // Trucks Return Function
        [Category("TrcukReturn")]
        [DisplayIndex(1)]
        [Description("The Return duration of trains from rail station to POD in days.")]
        [DisplayName("Return Duration")]
        public Distribution ReturnDuration { get; set; }

        private Simphony.Simulation.Resource truck;
        [Category("TrcukReturn")]
        [DisplayName("ReleaseTruck")]
        [DisplayIndex(2)]
        [TypeConverter(typeof(ElementListConverter<Simphony.General.Resource>))]
        public string ReleaseTruck { get; set; }

        public override void ReadXml(XmlReader reader)
```

```
        {
            this.ReleaseTruck = reader.GetAttributeAs<string>("ReleaseTruck", null);
            this.File = reader.GetAttributeAs<string>("File", null);
            base.ReadXml(reader);
            this.LoadingDuration =
reader.ReadComplexElementAs<Distribution>("LoadingDuration");
            this.ShippingDuration =
reader.ReadComplexElementAs<Distribution>("ShippingDuration");
            reader.ReadComplexCollection("RequiredResources", "Resource",
this.RequiredResources);
            this.UnloadingDuration =
reader.ReadComplexElementAs<Distribution>("UnloadingDuration");
            this.ReturnDuration =
reader.ReadComplexElementAs<Distribution>("ReturnDuration");
        }

        public override void WriteXml(XmlWriter writer)
        {
            writer.WriteAttribute("ReleaseTruck", this.ReleaseTruck);
            writer.WriteAttribute("File", this.File);
            base.WriteXml(writer);
            writer.WriteComplexElement("LoadingDuration", this.LoadingDuration);
            writer.WriteComplexElement("ShippingDuration", this.ShippingDuration);
            writer.WriteComplexCollection("RequiredResources", "Resource",
this.RequiredResources);
            writer.WriteComplexElement("UnloadingDuration", this.UnloadingDuration);
            writer.WriteComplexElement("ReturnDuration", this.ReturnDuration);
        }

        protected override void CheckIntegrity(IList<CheckIssue> errors)
        {
            base.CheckIntegrity(errors);
            Simphony.General.Resource temptruck;
            if (!this.Scenario.TryGetElement<Simphony.General.Resource>(this.ReleaseTruck,
out temptruck))
            {
                errors.AddError(this, "Selected truck is not existed ");
            }
        }

        protected override void TransferIn(GeneralEntity entity, InputPoint point)
        {
            entity.LX[0] = this.Engine.TimeNow;
            var interval = this.LoadingDuration.Sample();
            var timespan = TimeSpan.FromDays(interval);
            this.Engine.ScheduleEvent(entity, this.Shipping, timespan);

        }

        private void Shipping(GeneralEntity entity)
        {
            this.Engine.CollectStatistic(this.LoadingTime, this.Engine.TimeNow -
entity.LX[0]);

            entity.LX[0] = this.Engine.TimeNow;
            var interval = this.ShippingDuration.Sample();
            var timespan = TimeSpan.FromDays(interval);
```

```
            this.Engine.ScheduleEvent(entity, this.RequestUnloadingResources, timespan);
        }

        private void RequestUnloadingResources(GeneralEntity entity)
        {
            this.Engine.CollectStatistic(this.ShippingTime, this.Engine.TimeNow -
entity.LX[0]);
            this.Engine.RequestResource(entity, this.multipleResourceRequirement,
this.PerformUnloadingTasks, this.file);
        }

        private void PerformUnloadingTasks(GeneralEntity entity)
        {
            entity.LX[0] = this.Engine.TimeNow;
            var interval = this.UnloadingDuration.Sample();
            var timespan = TimeSpan.FromDays(interval);
            this.Engine.ScheduleEvent(entity, this.TruckReturn, timespan);
        }

        private void TruckReturn(GeneralEntity entity)
        {
            this.Engine.CollectStatistic(this.UnloadingTime, this.Engine.TimeNow -
entity.LX[0]);
                    var releaseEntity = new GeneralEntity();
                    releaseEntity.LO[0] = entity;
            var timespan = TimeSpan.FromDays(this.ReturnDuration.Sample());
            this.Engine.ScheduleEvent(releaseEntity, this.ReleaseTruckAfterReturn,
timespan);
            this.OutputPoint.TransferOut(entity);
        }

        private void ReleaseTruckAfterReturn(GeneralEntity releaseEntity)
        {
                var entity = (GeneralEntity)releaseEntity.LO[0];
            this.Engine.ReleaseResource(entity, this.truck, 1);
        }

        protected override void InitializeScenario()
        {
            base.InitializeScenario();
            this.multipleResourceRequirement = new
Simphony.Simulation.MultipleResourceRequirement();
            for (int i = 0; i < this.RequiredResources.Count; ++i)
            {
                Simphony.General.Resource myResourceModelingElement =
this.Scenario.GetElement<Simphony.General.Resource>(this.RequiredResources[i].ResourceNam
e);

this.multipleResourceRequirement.Add(myResourceModelingElement.InnerResource,
this.RequiredResources[i].Servers);

            }
            this.multipleResourceRequirement.Action = RequirementActionType.All;

            this.file =
this.Scenario.GetElement<Simphony.General.File>(this.File).InnerFile;
```

```
            this.truck =
this.Scenario.GetElement<Simphony.General.Resource>(this.ReleaseTruck).InnerResource;
            }

    }
}
```

Route Selection Element

```
namespace Logistics
{
    using System;
    using System.Collections.Generic;
    using System.ComponentModel;
    using System.Diagnostics;
    using System.Drawing;
    using System.Drawing.Design;
    using System.Linq;
    using System.Xml;
    using Simphony;
    using Simphony.ComponentModel;
    using Simphony.General;
    using Simphony.Mathematics;
    using Simphony.Modeling;
    using Simphony.Simulation;


    [Image("TrafficLight")]
    [Description("Select the transitting mode depends on the availability of the
resource")]
    public class SelectRoutes: FlowElement<GeneralEntity>
    {
        private Simphony.Simulation.MultipleResourceRequirement
multipleResourceRequirement;
              private List<Simphony.General.Resource> resourceElements;

        public SelectRoutes()
        {
            this.RequiredResources = new List<ComplexResource>();
        }

        public override void Paint(Graphics graphics, RectangleF bounds)
        {
            graphics.DrawImage(Properties.Resources.TrafficIcon, bounds);
            base.Paint(graphics, bounds);
        }

        [InputsCategory]
        [DisplayName("Resources & Targets")]
        [DisplayIndex(3)]
        [Editor(typeof(CollectionEditor<ComplexResource>), typeof(UITypeEditor))]
        [TypeConverter(typeof(CollectionConverter))]
```

```
        public IList<ComplexResource> RequiredResources { get; set; }

        private Simphony.Simulation.WaitingFile file;
        [InputsCategory]
        [DisplayName("File")]
        [DisplayIndex(4)]
        [TypeConverter(typeof(ElementListConverter<Simphony.General.File>))]
        public string File { get; set; }

        public override void ReadXml(XmlReader reader)
        {
            this.File = reader.GetAttributeAs<string>("File", null);
            base.ReadXml(reader);
            reader.ReadComplexCollection("RequiredResources", "Resource",
this.RequiredResources);
        }

        public override void WriteXml(XmlWriter writer)
        {
            writer.WriteAttribute("File", this.File);
            base.WriteXml(writer);
            writer.WriteComplexCollection("RequiredResources", "Resource",
this.RequiredResources);
        }

        protected override void TransferIn(GeneralEntity entity, InputPoint point)
        {
            var batchEntity = entity as BatchEntity<GeneralEntity>;


            if (batchEntity != null)
            {
                this.Engine.RequestResource(batchEntity,  this.multipleResourceRequirement,
this.CheckAvailabilityofResource, this.file);
                foreach (var childEntity in batchEntity.BatchOfEntities)
                {
                    foreach (var myElement in this.resourceElements)
                    {

                            var quantity =
myElement.InnerResource.ServersOwnedByEntity(childEntity);

                            if (quantity > 0)
                            {
                                this.Engine.ReleaseResource(childEntity,
myElement.InnerResource, quantity);
                            }
                         }
                }

                     //     this.Engine.RequestResource(batchEntity,
this.multipleResourceRequirement, this.CheckAvailabilityofResource, this.file);
            }

            else
            {
```

```
                this.Engine.RequestResource(entity, this.multipleResourceRequirement,
this.CheckAvailabilityofResource, this.file);
                foreach (var myElement in this.resourceElements)
                {
                    if (myElement.InnerResource.Name != "truck" &&
myElement.InnerResource.Name != "ship" && myElement.InnerResource.Name != "train" &&
myElement.InnerResource.Name != "barge")
                    {

                        var quantity =
myElement.InnerResource.ServersOwnedByEntity(entity);

                        if (quantity > 0)
                        {
                            this.Engine.ReleaseResource(entity, myElement.InnerResource,
quantity);
                        }
                    }

                }

            }
        }

        private void CheckAvailabilityofResource(GeneralEntity entity)
        {
            //Declare a variable for the name of the resource modelling element
            var ResourceModellingElementName =string.Empty;

            //Get the name of the new resource that has been granted
            foreach(Simphony.Simulation.ResourceQuantityPair myResourceQuantityPair in
entity.NewResources)
            {
                foreach (var myElement in this.resourceElements)
                {
                    if(myResourceQuantityPair.Resource == myElement.InnerResource)
                    {
                        ResourceModellingElementName = myElement.Name;
                        break;
                    }
                }
            }


            //Search for the target element that has a resource name that matches the one
that we just got from the above code
            foreach (Simphony.Modeling.ElementBase myElement in this.Scenario.Children)
            {
                if(myElement is Target)
                {
                    if (((Target)myElement).ResourceName == ResourceModellingElementName)
                    {
                        //Transfer the entity into this target element
                        ((Target)myElement).InputPoint.TransferIn(entity);
                        break;
                    }
                }
```

```
            }
        }


        protected override void InitializeScenario()
        {
            base.InitializeScenario();
                     this.resourceElements =
this.Scenario.Descendants.OfType<Simphony.General.Resource>().ToList();

            this.multipleResourceRequirement = new
Simphony.Simulation.MultipleResourceRequirement();
            for (int i = 0; i < this.RequiredResources.Count; ++i)
            {
                Simphony.General.Resource myResourceModelingElement =
this.Scenario.GetElement<Simphony.General.Resource>(this.RequiredResources[i].ResourceNam
e);

this.multipleResourceRequirement.Add(myResourceModelingElement.InnerResource,
this.RequiredResources[i].Servers);
            }
            this.multipleResourceRequirement.Action = RequirementActionType.Any;

            this.file =
this.Scenario.GetElement<Simphony.General.File>(this.File).InnerFile;
        }


    }
}
```

Target Element

```
namespace Logistics
{
    using System.ComponentModel;
    using System.Drawing;
    using System.Xml;
    using System.Xml.Schema;
    using System.Xml.Serialization;
    using Simphony;
    using Simphony.ComponentModel;
    using Simphony.Modeling;
    using Simphony.Simulation;
    using System;

    [Image("target")]
   [Description("Check the availability of the mode of transport for shipping")]
   public class Target : FlowElement<GeneralEntity>, IXmlSerializable
    {

       public override void Paint(Graphics graphics, RectangleF bounds)
       {
```

```
    graphics.DrawImage(Properties.Resources.LTarget, bounds);
    base.Paint(graphics, bounds);
}

[InputsCategory]
[DisplayIndex(1)]
[DisplayName("Resource")]
[TypeConverter(typeof(ElementListConverter<Simphony.General.Resource>))]
public string ResourceName { get; set; }

public override void ReadXml(XmlReader reader)
{
    this.ResourceName = reader.GetAttributeAs<string>("ResourceName", null);
    base.ReadXml(reader);
}

public override void WriteXml(XmlWriter writer)
{
    writer.WriteAttribute("ResourceName", this.ResourceName);
    base.WriteXml(writer);
}

public XmlSchema GetSchema()
{
    // Always return null from GetSchema()
    return null;
}
```