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MODULAR CONSTRUCTION SYSTEM SIMULATION INCORPORATING OFF-SHORE FABRICATION AND MULTI-MODE TRANSPORTATION

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ABSTRACT

The global material supply chain for modular construction, consisting of assemblies prefabrication, material delivery and handling, module assembly, and site installation, can be regarded as a "*Big Site*" problem. With a combination of various transportation modes (i.e., trucks, ships, and rails), insufficient logistic planning on the capacity and time availability of unloading bays and transportation resources potentially delays material arrival dates on an industrial construction site and field installation schedules. Previous related research in construction engineering and project management domain largely focused on matching material supply with site demand without emphasis on logistics and supply chain management. A special purpose simulation template is developed based on the *Simphony* platform to facilitate the simulation modeling of module fabrication, transportation, assembly, and installation processes. System performance indicators are adapted from port management literature in order to assess different scenarios of modular construction planning. A case study representing modular construction practice is presented.

1 INTRODUCTION

Modular construction involves off-shore prefabrication, multi-mode transportation, and on-site installation of modules in the formation of the industrial engineering facilities. Generally, fabrication shops, modular shops and construction fields are adjacently located in a local region, which can be integrally viewed as the "*site*". However, the practice of globally sourcing materials, off-shore fabrication and then transshipment to local module shops for assembly and eventually installed in field, is observed in current industrial projects. Thus, the scope of the *site* is no longer just within the local area; it extends into the global domain. As per Figure 1, raw materials such as pipe and steel are prefabricated at the fabrication shop offshore. The prefabricated materials are loosely packed in a sea container bounded for a particular module shop for assembly operations. The container is delivered from the fabrication shop to the port of loading (POL) by trucks. Then, it is transferred from POL to the port of destination (POD) by ship. The container is further transported from POD to the module shop. In this case, there are two 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 truck's availability. At the module shop, steel and pipe components in the container are assembled into modules by bolting, welding, and coupling connections. Then, the module is transported to the construction site by truck for field installation. On site, the module is installed in accordance with preplanned field installation sequence (i.e., Module 1 installation precedes Module 2 installation). In short, this global material supply chain for modular construction, consisting of assemblies prefabrication, material delivery and handling, module assembly, and site installation, can be regarded as a "*Big Site*" problem. With a combination of various transportation modes (i.e., trucks, ships, and rails), insufficient logistic planning on the capacity and time availability of unloading bays and transportation resources potentially delays material arrival dates on an industrial construction site, thus triggering the ripple effect of disrupting module assembly and field installation schedules.

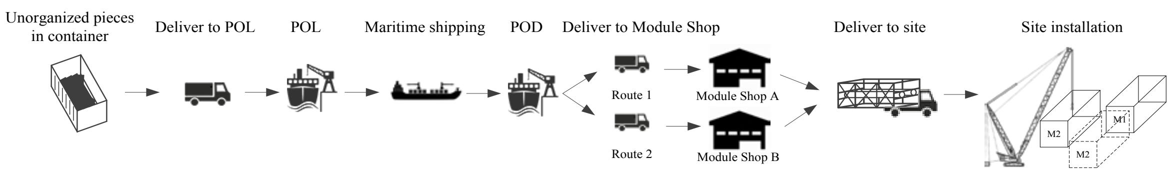


Figure 1: Supply chain of modular construction.

Figure 2 shows the generalized workflow of a transporter at an unloading bay. 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. Until the unloading bay becomes available, the transporter unloads the materials at the unloading bay and returns to the origin (i.e. the fabrication shop).

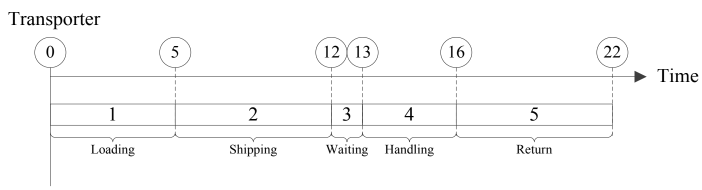


Figure 2: Workflow of a transporter at an unloading bay.

Researchers in port management domains realized that the limited unloading bays at port would significantly constrain port handling capacity and efficiency (UNCTAD 1985; De Monie 1987; De Weille and Ray 1974). Commercial software such as Primavera P6 applies CPM-based methodology, which requires the definition of precedence relationships between activities. All activities on the network are planned to be executed. In contrast, the materials can be delivered using any feasible route from the origin and destination points as shown in Figure 1. When materials are delivered through the selected route, other activities in unselected routes would not be executed. Thus, the CPM-based technique is not suitable for formulating the route schedules in consideration of the transportation feasibility.

The intricate relationship between (i) the capacities of unloading bays at various locations throughout the supply chain and (ii) the material arrival dates for module shop assembly and on-site module installation has yet to be thoroughly investigated in construction planning. In addition, logistics performance measures in modular construction have yet to be formalized with respect to the capacities of unloading bays at various locations along the supply chain. In this research study, a special purpose simulation template is developed based on the *Simphony* simulation platform to facilitate the problem definition and simulate relevant processes of the *big site*.. Three quantitative performance indicators, namely, *waiting-service ratio*, *occupancy rate*, and *delivery efficiency*, are defined in order to effectively characterize logistics performances in the *big site* system. In the following sections, literature review is first given to discuss the state-of-the-art in logistics and supply chain management from the perspectives of transportation management, port management, and construction management. Then, the simulation platform is introduced and relevant performance indicators are proposed. A case study based on the current industry practice is given for demonstration. Conclusions are drawn at the end.

2 LITERATURE REVIEW

In transportation management, shipping routes throughout the supply chain are planned to transport materials between locations. Methodologies are generally proposed to formulate shipment schedules with the shortest shipping distance and the lowest shipping cost. The classic transportation problems are relevant to transit route optimization (Bulbul, Ulusoy, and Sen 2007). Nevertheless, operational processes and resource constraints at the transit locations are commonly neglected in formulating the schedules. For instance, the container handling process at port is ignored, along with the availability of unloading bay and the port handling efficiency.

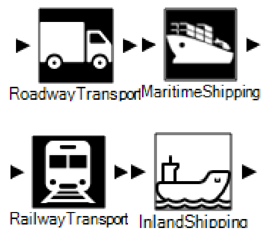
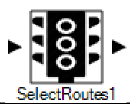
Research endeavors in port management domain attempted to shed light on the relationship between the quantity of port unloading bays and port handling efficiency during the container transhipment process (De Weille and Jay 1974; UNCTAD 1985). *Unloading bay* at a port is referred to as berth, which is the critical resource in port management for handling the containers delivered by the arriving ship. 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 of the port. Simulation approach was integrated with queuing theory for modeling ships arrivals and port operations in order to determine the optimum berth number and port capacity (Ergin and Yalciner 1991; Edmond and Maggs 1978). The theory modeled the arriving ships as customers while the port as the facility for providing unloading service. However, critical factors relevant to modular construction including the routes of shipping materials and the number of unloading bays at various locations throughout the material supply chain were not considered.

In modular construction, previous researchers in the construction management domain focused on improving the scheduling of assembly tasks at a module yard. Taghaddos et al. (2012) proposed a simulation-based methodology to schedule module assembly sequences in consideration of limited resources and space in an assembly yard. The framework is capable to allocate skilled workers and assembly bays to execute a certain module assembly sequence in order to deliver multiple projects before the planned deadlines. Li et al. (2013) classified general risks, in-plant risks, and on-site risks in modular construction. 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. The modular construction process was simulated to evaluate the identified risks. Wu and Lu (2014) used a simulation technique to assess the contractor's production capacity for module assembly. The contractor's production rate for assembling modules in its facility was estimated based on available historical data, while the production capacity of the module yard facility was determined based on monthly production rate and module assembly time.

3 METHODOLOGY

A special purpose template has been developed based on the *Simphony* simulation platform. The modeling elements are designed for representing the material supply chain, categorized into the "transportation" element and "route selection" element (Table 1). The transportation element is used to model various transportation modes for delivering module components to planned locations by using different types of *transporter*. Four major transportation modes, namely, the "roadway", "railway", "maritime", and "inland" elements, are created. The "route selection" element is developed to select feasible routes during material transshipment. In general, selecting the route is based on the assigned destination of the materials being shipped and the availability of the transporters at transit locations (for instance, by applying the first-in-first-out heuristic rule.) The module assembly process and the site installation process are modelled by utilizing the typical "task" element provided in *Simphony* (AbouRizk and Mohamed 2000).

Table 1: Summary of developed simulation elements.

Category	Modeling elements	Inputs	Explanations
Transportation		Loading duration	The duration for loading the containers to the transporter.
		Shipping duration	The duration for shipping the containers to planned location.
		Resource	The demanded resource before starting the unloading tasks (e.g., storage resource, unloading bay resource).
		Unloading duration	The duration for unloading the containers from the transporter.
		Return duration	The duration of the transporter returning to the origin location.
Route selection		Transporter resource	A collection of required transporter resources with respect to the feasible shipping routes.

Three system performance indicators, named as *delivery efficiency* (*DE*), *waiting-service ratio* (*WS*), and *occupancy rate* (*OR*) are defined as per Eqs. (1), (2), and (3), respectively. The *DE* factor is used to evaluate delivery performance, which is calculated by dividing the system production rate subject to the limited availability of resources (i.e., transporters, unloading bays, etc.) against the system production rate when the availability constraint of resources is removed (Eq. 1). 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 = system production rate with the limited availability of resources; P_I = system production rate with unlimited availability of resources

The *WS* value indicates the ratio of the transporter's average waiting time against its average handling time (Eq. 2). It was proposed in the port operation and management domain for evaluating the degree of ship waiting at port entrance before berthing (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. Note, the idle time of the unloading bay along with its handling crew would be increased. For instance, if the *WS* value equals to zero, implying that the unloading operation can be started immediately when the transporter arrives the delivery port. On the other side, it also implies that the unloading bay and its handling crews 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

The *OR* indicates the utilization rate of unloading bay when the bay is occupied by the transporters during its service period (Eq. 3). The origin of this performance indicator also is related to how the port industry quantifies berths utilization in a year period (De Weille and Jay 1974). It is adapted for evaluating utilization rates of unloading bays in connection with material delivery in this research. A high *OR* value means a higher utilization rate of the unloading bay, which enhances the unloading bay's productivity as well. But it also indicates a higher probability of transporter overprovision at the unloading bay. The waiting time of transporter increases.

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

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 the last transporter's departure

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. 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. (UNCTAD 1985; 1987). In the near future, when real data become available, the benchmark for assessing the construction logistics service can also be produced. Although previous studies benchmarked performances for material supply on construction site, the transportation processes was largely overlooked and the resulting benchmarks were restricted to ready mixed concrete supply with single unloading bay (Anson and Wang 1998; Lu and Anson 2004). In addition, the *WS* and *OR* are also applicable to assess the assembly bay performance at the module shop. Take the *OR* as example: N_t is the number of modules that need to be assembled; $\overline{T}_h$ is the average assembling time per module; N_{ub} is the number of the assembly bays; T_s is the service time (i.e., time elapsed between the first module starts assembly and the last module assembled). Such logistics performance benchmarks also can be produced for the modular shop in terms of best utilizing assembly bays, particularly during the busy season.

4 CASE STUDY

A case study is used to investigate the influence of the availability of unloading bays at delivery ports upon material delivery performance at the construction site based on the developed logistics simulation template. Data for the case study were based on a modular construction project in Alberta, Canada. Components for assembling 10 modules are prefabricated at the off-shore fabrication shop.

4.1 Fabrication Process

The prefabricated *module materials* for assembling one module are separately stored in four sea containers. Table 2 summarises the *attributes* of the containers. Each individual container has a unique identifier, ready-to-ship 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 2: Attributes of the sea containers for storing the module materials (unit: day).

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

4.2 Shipment Process

The shipment process is initialized when the materials are fabricated and stored in the container. The container is then loaded to a truck for transferring from the fabrication shop to POL. Table 3 gives the carrying capacity and the availability limit of the transporters along the supply chain. Table 4 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 a module ship's call on the terminal on time. 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 day 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 to 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 transhipped to Module Shop B by truck. 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: 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 4: 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

4.3 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 5 shows the required containers and the duration for assembling particular modules. Table 6 depicts the availability limits of the assembly crew, the crane, the assembly bay, and the unloading bay. Table 7 lists the resource requirement for assembling per module.

Table 5: 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, 25, 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 6: 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 7: Resource requirement for assembling module.

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

4.4 Field Installation Process

After the module is assembled, the module is delivered to the site by truck for field installation. On site, the modules are installed in accordance with the planned installation sequence. Table 8 identifies the technological constraints for installing the 10 modules. It takes half a day to install one module on site.

Table 8: 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	-

4.5 Operation Simulation

Computer simulation is conducted by use of the *Simphony* platform in a single run using the most likely values as input. It is reemphasized the simulation is only intended to represent the logic in the model and assess postulated “what-if” scenarios, instead of statistical analysis of outputs due to uncertain inputs. In this research study, 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 9).

Table 9: 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

Table 10 shows the simulated event list, which tracks the materials arrival times at particular locations (Scenario 1, Run #1). 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 for this scenario is 147.6 days.

Table 10: 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***	-	***64.9***	***65.4***
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**	-	**64.9**	**65.4**
7	M5	6	7.2	23.7	32.1	-	-	33.3	68.0	95.4
8	***M1***	**7**	**8.2**	23.7	-	-	**29.0**	-	**64.9**	**65.4**
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**	-	**64.9**	**65.4**
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	M2	13.8	15	107.3	115.7	-	-	116.9	118.5	119.0
26	M10	15	16.2	107.3	-	-	112.5	-	155.6	162.6
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

4.6 Performance Evaluation

The performances of the material supply chain for three scenarios are evaluated by use of the proposed indictors (Eqs. 1 to 3). Tables 10, 11, and 12 show the values of *DE*, *WS*, and *OR*. In Table 11, 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 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 highest 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 11: Delivery efficiency (*DE*) for three scenarios.

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

Table 12 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 thus 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 highest. 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 12: 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 is negligible at POD as the unloading bays at 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 13 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 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 13: 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 shortest waiting time of transporter and least production loss at unloading bays simultaneously. Hence, Scenario 3 should be chosen in the current example.

5 CONCLUSION

The present study applies a simulation approach to define the "big site" problem in industrial modular construction. A special simulation template is developed in the *Simphony* platform to model material delivery, module fabrication and assembly and the site installation processes. Three quantitative 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. These performance indicators originate from the port operation and management domain, which have been adapted to cater for present research needs. 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 case study based on Alberta's oil sands modular construction is given to demonstrate the simulation-based methodology. Based on the simulation results, insufficient unloading bays at delivery port would significantly increase the waiting time of the arriving ships at port entrance. This would further delay materials' arrival time at module shop and construction site, eventually extending the total project duration of construction. In addition, the increment of transporters arrive at unloading bays per time also increases the *WS* ratio of transporter. 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. In order to verify the logic of this large simulation system, the authors used most likely deterministic values as the shipping and handling duration in the simulation model. It simplifies the procedures for producing the simulation event list (Table 10) in order to verify and validate the proposed methodology. In the near future, when real-world data are available, the constant duration can be changed into distribution at the input modeling stage to enable Monte Carlo simulation processes. In addition, as *ships for other business* continuously call on the POD and occupy limited unloading bays at port, the berthing time of module-specific ships at POD becomes uncertain. Monte Carlo simulation can be employed to account for this uncertainty.

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