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Research Article

A DES simulation aided construction planning of modular integrated construction: A Hong Kong Case Study

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Abstract

Many countries face ongoing pressures from limited land resources and housing shortages, which has driven planners to seek more efficient construction methods to meet the growing demand for high-density and sustainable housing. Given that, Modular Integrated Construction (MiC) has emerged as an innovative solution that transforms conventional fragmented on-site construction into integrated off-site production and on-site assembly of prefabricated modules. Previous research on MiC has explored various aspects, such as schedule optimization, transportation arrangements, and site management strategies. However, most studies have overlooked the uncertainty associated with off-site resource planning and activity durations. Meanwhile, there is still a lack of a decision support system for MiC that can comprehensively evaluate project performance. Therefore, this study develops a Discrete Event Simulation (DES) model to simulate the MiC construction process while considering uncertainty, aiming to optimize comprehensive performance, including cost, duration, and carbon emissions. After incorporating activity durations and available resources, this study continuously adjusts off-site and on-site resource planning to determine the optimal resource configurations and identify the factors that most significantly impact performance. The DES model is applied to a case study in Hong Kong after validation. The results show that MiC performance is more sensitive to off-site resources, like trucks, cranes, and wrapping crews. Furthermore, the weight of key performance indicators also significantly affects resource planning. The proposed DES model provides practical support for MiC construction, enabling managers to make better decisions under multiple objectives and complex constraints, thereby optimizing project resource planning and overall performance.

Keywords: Modular Integrated Construction (MiC), Discrete Event Simulation (DES), Resource planning, Carbon emission, Performance evaluation

Highlights

- Off-site resource allocation is critical for efficient MiC construction.
- The weight of key performance indicators significantly affects resource planning.
- Simply increasing the number of resources does not necessarily improve overall performance.

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1 Introduction

Hong Kong is a typical high-density metropolis with 7.5 million people residing in only 24% of the total land area of 1,115 km2 (LD, 2023), which has long faced land resource limitations and housing shortages. Additionally, the dilemma between the ageing workforce and the increasing construction projects has led to a shortfall of over 40,000 skilled and semi-skilled workers in Hong Kong (CIC, 2023). Given that, Modular Integrated Construction (MiC), which transforms fragmented on-site construction into integrated production and assembly of prefabricated modules, has emerged as an innovative solution due to its shorter construction duration (Wen et al., 2024), saved manpower and resources (Mao et al., 2013), and enhanced productivity (Shahpari et al., 2020). Since 2017, the Hong Kong government has promoted MiC and prioritized its application in the delivery of public rental housing units (Legislative Council, 2023). It is estimated that more than 80 MiC projects are currently underway (CIC, 2024), with a minimum of 154,000 MiC public housing units in the next decade (HB, 2023).

Despite the growing adoption of MiC in practice, its implementation is facing several challenges. One of the top challenges is transportation restrictions (Zhang et al., 2021). Unlike traditional construction, MiC involves additional processes, such as transporting modules from an off-site factory to the construction site (Zhang et al., 2024). Three common transportation-related challenges include the dimensional constraints of modules (Thai et al., 2020), extra packaging and protection of the modules (Jellen Anthony & Memari Ali, 2018), and high transportation costs (Kamali & Hewage, 2016). However, due to the limited land area and manufacturing technology in Hong Kong, prefabricated modules are not manufactured locally but are transported from mainland China (Wuni & Shen, 2020), increasing more challenges to MiC implementation, such as longer transportation distance, more complex transportation planning, and more accompanying uncertainties (Hussein et al., 2023; Zhang et al., 2021). Another challenge is installation-related. MiC modules installation or assembly is also an additional process compared to traditional construction, where restrictions of site layout are identified as an obstacle to MiC application due to the limited onsite area available for construction (Pan & Hon, 2020).

To address these construction-related challenges, several attempts have been made over the past few years, such as optimizing dispatching times (Hsu et al., 2020), loaded positions (Zhu et al., 2021), transportation modes (Hussein et al., 2023), and on-site management concepts (Goh & Goh, 2019). Most of these studies, however, have overlooked the allocation of off-site resources and the uncertainty of activity durations, which may lead to changes and delays in MiC transportation and installation schedules. In addition, a decision support system for the MiC construction process that comprehensively considers construction duration, costs, and carbon emissions is still lacking. Therefore, this study is designed to simulate the construction process of MiC with considerations of uncertainties using a Discrete Event Simulation (DES) modelling approach by simulating the model resources and discrete steps from module wrapping in the off-site factory to module installation on-site. Meanwhile, simulation experiments under different scenarios are conducted to identify the near-optimal solution regarding construction duration, costs, and carbon emissions.

2 Literature review

2.1 DES application in MiC

As a popular method in construction process simulation, DES has been proven useful for evaluating and redesigning construction projects (Larsson et al., 2016). The essence of DES is to split the real system into a series of related activities according to the logical order of things and allocate corresponding time and resources to the activities, in which each planned activity module can read the resources necessary and predecessor activities from the linked database and consume the materials required for the activity to provide information for subsequent activities (Al-Bataineh et al., 2013). Such an operating mechanism enables it to realize interactive simulation between resources and activities and can handle the complexity and uncertainty inherent in construction operations. Therefore, DES-based optimization of production performance and design layout has been increasingly recognized (Moghadam et al., 2014). For example, Goh and Goh (2019) enhanced a DES-based model with lean principles for MiC projects, resulting in a 17.91% increase in resource utilization, a 398% boost in labour productivity, and an 81.27% reduction in project cycle time compared to the basic model. In another study, Rashid et al. (2020) combined a DES model with genetic algorithms to optimize worker numbers and construction time in a modular factory, demonstrating a 15% reduction in construction time without changing the workforce size. In addition to the performance study, some details related to MiC construction have gradually attracted researchers' attention, who hope to improve the accuracy of simulation results and restore the authenticity of simulation as much as possible by considering the influence of external factors (Liu et al., 2019). Therefore, applying it to different construction scenarios to evaluate resource allocation strategies can effectively help MiC stakeholders make comprehensive and scientific decisions.

2.2 Performance evaluation measures

MiC has emerged as an effective alternative to traditional on-site construction and has been widely adopted in many regions, such as Europe, North America, and Japan (Annan, 2014). According to Song et al. (2005), MiC offers a significant means of improving construction project performance when conditions permit. Some common indicators, such as cost and duration, are used as key performance indicators. Han et al. (2012) substantiated the utility of simulation in enabling project managers to comprehend the ramifications of process fluctuations. This insight equips project managers with the ability to pre-emptively simulate such variations, thereby facilitating process enhancements, time savings, rework reduction, and cost efficiencies. Besides, Kim et al. (2010) proposed a multi-agent-based simulation to evaluate the traffic flow and construction equipment at construction sites and explore how it influences site efficiency and productivity. Their findings revealed that simulation is a valuable tool for assessing equipment efficiency and anticipated durations, aiding decision-makers in choosing alternative methods to ensure projects are completed on time within set deadlines. In addition to construction duration and costs, some researchers have evaluated the carbon emissions of MiC. Quale et al. (2012), for example, quantified the carbon emissions of a 186-square-meter MiC compared to a traditional building during the construction phase, finding that the average carbon emissions of the MiC were approximately 6 tons less than those of a traditional one of the same size. Similarly, Paya-Marin et al. (2013) assessed energy use in two modular schools with different materials and systems. The eco-designed building, featuring daylight control and low-emissivity windows, achieved nearly a 48% reduction in carbon emissions, demonstrating superior energy savings. Furthermore, in a quantitative study by González and Echaveguren (2020), they used DES to improve the sustainability of road construction, thereby reducing carbon emissions and determining the optimal number of trucks and loaders for environmentally sustainable and timely project completion. Taken together, these studies mainly focus on comparing or optimizing single performance indicators rather than developing a comprehensive evaluation structure. Therefore, it is imperative to establish a comprehensive evaluation system for new construction technologies like MiC, assessing project performance from construction duration, costs, and carbon emissions.

3 Methodology

Based on the research gaps identified in previous studies, this study selects a real-world case study in Hong Kong. During this study, the collected case data are used to develop a DES model using AnyLogic simulation software. Subsequently, the model is validated, and scenario simulations are conducted to analyze the impact of different resource combinations on MiC performance. The MiC construction process necessitates the provision of adequate logistics, equipment, and human resources. In general, the MiC transportation process involves MiC modules loading, transportation, and unloading; thus, off-site resources such as cranes, trucks, wrapping crews, workers, and drivers are primarily considered. Furthermore, the MiC installation process includes MiC modules tying, lifting, horizontal moving, descending, untying, and connecting modules, with tower cranes, crane operators, typing crews, alignment crews, connection crews, and inspectors being the main on-site resources involved. Therefore, the MiC construction process can be further detailed into nine steps: (1) module wrapping at the MiC factory; (2) truck maneuver; (3) module loading on the truck; (4) transportation from factory to onsite; (5) module unwrapping; (6) tying module to crane; (7) lifting module; (8) moving module; (9) descending module; (10) aligning and untying module from crane; (11) connecting module; and (12) module inspection, as shown in Figure 1.

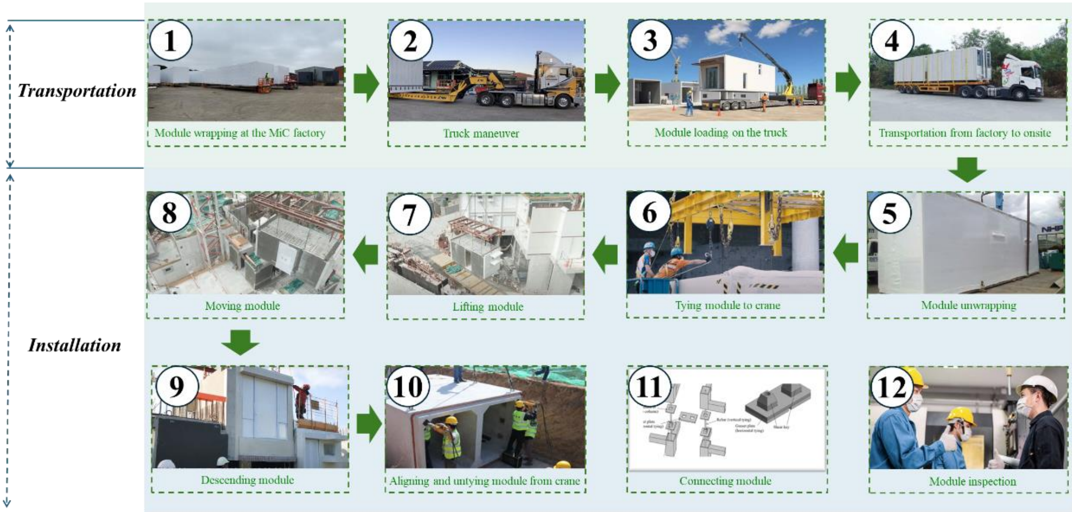

Figure 1. The construction process of MiC.

4 Case study

4.1 Case selection

The “Married Quarters for the Fire Services Department at Pak Shing Kok” MiC completed by Feb 2021 in Hong Kong is selected as the case project, considering that: (1) it is the common type and represents the state-of-the-art modular building in Hong Kong, and (2) there is available information (CIC MiC, 2024; Zhang et al., 2024) for this study. This project is the first public project adopting MiC in Hong Kong (CIC MiC, 2024). As presented in Figure 2, it is a concrete modular residential building that comprises 16-17 stories with module designs. This five-block building has a construction floor area (CFA) of 47,000 m^2, of which the MiC CFA is 32,000 m^2. Meanwhile, it is constructed by stacking 3,800 concrete modules, divided into 7 different types, whose construction cycle for MiC is 5 days per typical floor.

Description items	Specifications
Location	Hong Kong
Function	Staff quarters (residential)
Module type	Concrete
MiC stories	16-17
No. of MiC modules	3,800
No. of blocks	5
Construction period	2018.08–2021.02
Design service life	50 years
CFA (m^2)	47,000
MiC CFA (m^2)	32,000
Construction cycle of typical MiC floor	5 days

Figure 2. The view and main features of the case building.

4.2 Data collection

As discussed in the preceding section, the present study considers construction duration, costs, and carbon emissions as key measures to evaluate the performance of the simulation results under different scenarios. Therefore, the collected data is mainly categorized into three types: the duration of each activity, the cost of workers and equipment, and the corresponding carbon emission factors. Table 1 lists the duration of each task from module wrapping at the off-site factory to module connection on-site. The triangular distribution is applied to randomize the duration of each task with the consideration of uncertainties. These data are taken from Moghadam et al. (2012) and Hussein et al. (2023), with slight adjustments for the studied case building.

Table 1. Duration of construction activities.

Task	Duration (minutes)
Wrapping/Unwrapping	TRIA (6,8,10)
Tying	TRIA (8,10,12)
Truck Maneuver in factory	TRIA (2,3,4)
Loading on truck	TRIA (4,6,8)
Inspection in factory	TRIA (4,5,7)
Transport from factory to onsite	TRIA (55,60,70)
Lifting inspection	TRIA (5,7,9)
Lifting module	TRIA (2,3,4)
Moving module	TRIA (1.5,2,2.5)
Descending module	TRIA (1,2,3)
Aligning module	TRIA (15,20,25)
Untying	TRIA (1,2,3)
Connecting module	TRIA (25,30,35)
Fire and waterproof	TRIA (10,12,15)

To simplify the cost calculation, some resources have been condensed, like packing four wrapping crew members as a single wrapping crew and combining the crane and its operator as a single resource due to their similar cycles. Table 2 provides the cost of resources used both off-site and on-site, which are extracted from the Census and Statistics Department of the Government of the HKSAR. Besides, the carbon emission factors of various resources are mainly obtained from SimaPro software and published literature (Wen et al., 2024). As discussed in the preceding section, some resources are aggregated into a single category, and corresponding emission factors are computed and summarized in Table 2.

Table 2. Cost and carbon emission factors of allocated resources.

	Resource	Cost (HKD per hour)	Carbon emission factor (kg CO_{2e} per hour)
Off-site	Wrapping crew (4 members)	551.20	9.88
	Factory workers (4 members)	551.20	9.88
	Crane (1 crane and 1 operator)	1136.70	29.26
	Factory inspector	300.10	2.47
	Truck (1 truck and 1 driver)	253.40	174.12
On-site	Tying crew (4 members)	507.98	9.88
	Tower crane (1 crane and 1 operator)	1136.70	47.58
	Onsite inspector	300.10	2.47
	Alignment crew (4 members)	412.72	9.88
	Connection crew (4 members)	809.20	9.88

4.3 Simulation modelling

After clarifying the specific steps in the MiC transportation and installation processes and collecting essential data for the case project, a DES model is developed using AnyLogic software. As shown in Figure 3, the DES-based simulation model for MiC construction consists of various blocks interconnected by links. Figure 4 presents the layout of the entire simulation model, which consists of four parts: the upper left displays the DES model for MiC construction; the lower left lists main parameters related to task duration, cost, and carbon emission factors; the upper right shows the resources required for MiC construction, including a resource pool for allocation and release, along with a resource utilization chart; the lower right illustrates the cumulative probability distribution of module and equipment cycles, calculated using “Time Measure End” and “Time Measure End” blocks.

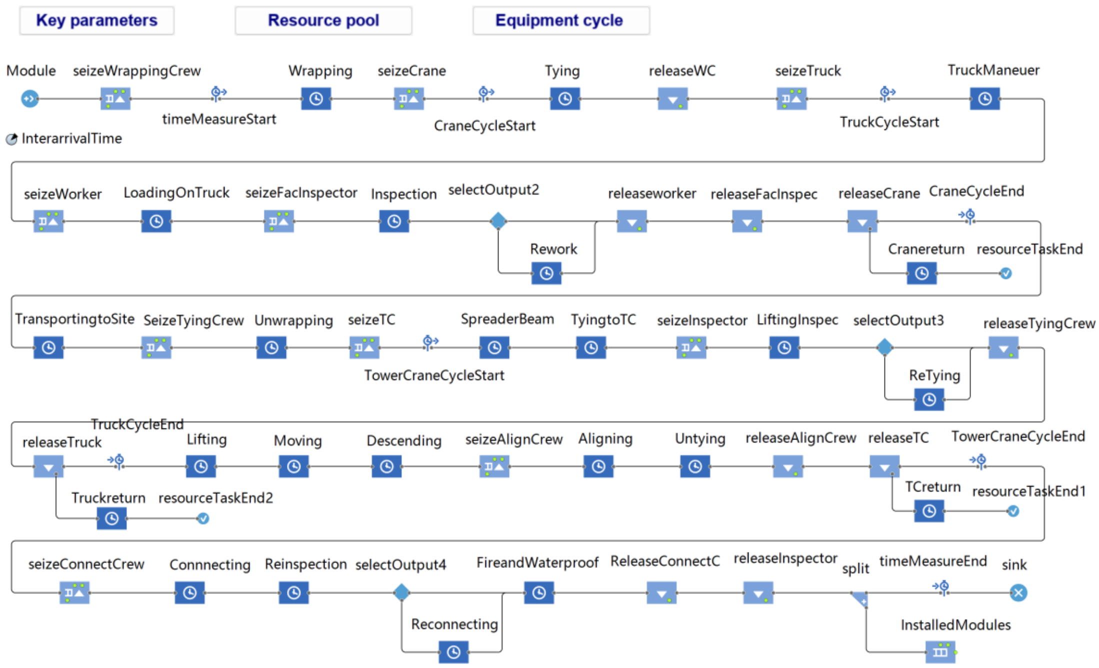

Figure 3. The DES model.

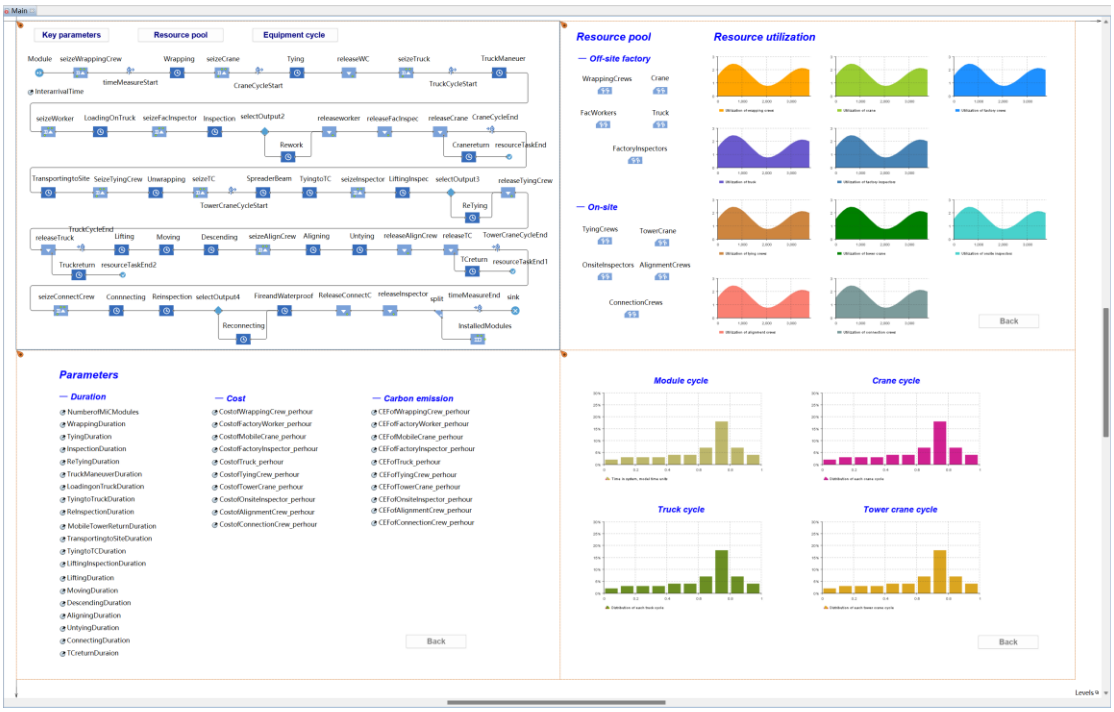

Figure 4. The layout of simulation model.

4.4 Key performance measures

In this project, total duration, total direct cost, and total carbon emissions are selected as the three key indicators for evaluating the performance of different simulation scenarios. The total duration equals the total time required to transport 3800 modules of the case project from the off-site factory and install them on-site. It can be calculated based on the simulation time, as detailed in Equation (1).

$$TD = \frac{ST}{WH} \tag{1}$$

Where TD is the total duration (Unit: day); ST denotes the output simulation time of DES model (Unit:

hour); and WH represents the number of working hours per day, typically set at 8. The total direct costs of the resources can be calculated using Equation (2).

$$TC = (\sum N \times E + \sum M \times C) \times ST \quad (2)$$

Where TC is the total costs (Unit: HKD); N represents the total number of a given equipment (i.e., crane, truck, and tower crane); E denotes the hourly cost of the equipment (Unit: HKD); M represents the total number of a given crew; C denotes the hourly cost of the equipment (Unit: HKD); and ST is the output simulation time of DES model (Unit: hour). Unlike crews, who generate carbon emissions regardless of whether working or idle, equipment consumes energy and emits carbon only during operation. Therefore, the total carbon emissions of resource consumption can be estimated by Equation (3).

$$TCE = \sum H \times CEF_e + \sum M \times CEF_C \times ST \quad (3)$$

Where TCE is the total carbon emissions (Unit: kg CO_{2e}); H denotes the total operation time of a give equipment (Unit: hour); CEF_e and CEF_c represent the carbon emission factors for equipment and crew, respectively, indicating the carbon emissions per hour (Unit: kg CO_{2e}).

4.5 Scenario setting

To obtain a near-optimal configuration of different resources with a shorter duration, lower costs, and less carbon emissions, various simulation scenarios are designed: one serves as the baseline scenario where all numbers of resources are set to one, while the remaining are experimental scenarios. It should be noted that the resource allocations in the experimental scenarios are not predetermined; instead, they are adjusted and designed based on the results of preceding scenarios. Specifically, if the utilization rate of trucks is close to 100%, while that of other resources is significantly lower in the first scenario, the number of trucks will be increased in the second scenario, and the simulation will run again. This iterative process of adjusting resources continues to explore different simulation scenarios.

5 Results and discussion

5.1 Baseline scenario analysis

The simulation results of the baseline scenario are shown in Table 3. When the number of each resource is set to 1, the utilization rate of the off-site resources, such as wrapping crew, cranes, and trucks, reaches 99%. However, the utilization rates of factory workers and inspectors are only 10% and 5%, respectively. In comparison, the utilization rate of on-site resources is relatively low, especially for the tying crew, tower crane, alignment crew, and connection crew, whose utilization rates are 31%, 54%, 23%, and 47%, respectively. The model performance obtained based on the simulation results is shown in Table 3, from which the comprehensive time cost is 890.72 days, the total investment cost is about HK$42 million, and the total carbon emissions are about 1.9 million kg CO2e. The baseline scenario will serve as the basis for comparison of subsequent scenarios. By continuously optimizing resource allocation, we strive to reduce duration, costs, and carbon emissions.

Table 3. Simulation results of different scenarios.

		S1	S2	S3	S4	S5	S6	S7	S8
Off-site resources (Number/ Utilization %)	Wrapping crew	1 (99%)	1 (99%)	1 (99%)	**2 (99%)**	**2 (99%)**	**2 (98%)**	**2 (98%)**	**2 (97%)**
	Crane	1 (99%)	1 (99%)	**2 (99%)**	**2 (99%)**	**2 (99%)**	**2 (99%)**	**2 (99%)**	**2 (99%)**
	Factory workers	1 (10%)	1 (12%)	1 (12%)	1 (12%)	1 (12%)	1 (37%)	1 (99%)	1 (97%)

	Truck	1 (99%)	**2 (99%)**	**2 (99%)**	**2 (99%)**	**2 (99%)**	**2 (99%)**	**3 (99%)**	**3 (99%)**
	Factory inspector	1 (5%)	1 (6%)	1 (6%)	1 (6%)	1 (6%)	1 (28%)	1 (89%)	1 (87%)
On-site resources (Number/ Utilization %)	Tying crew	1 (31%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)	1 (55%)	1 (56%)	1 (67%)
	Tower crane	1 (54%)	1 (99%)	1 (99%)	1 (99%)	**2 (63%)**	**2 (48%)**	**2 (48%)**	1 (97%)
	Onsite inspector	1 (84%)	1 (99%)	1 (99%)	1 (99%)	1 (99%)	**2 (78%)**	**2 (78%)**	**2 (78%)**
	Alignment crew	1 (23%)	1 (28%)	1 (28%)	1 (28%)	1 (28%)	1 (43%)	1 (43%)	1 (43%)
	Connection crew	1 (47%)	1 (55%)	1 (55%)	1 (55%)	1 (55%)	1 (85%)	1 (85%)	1 (85%)
Key performance measures	Total duration (Hours/Days)	7125.77 / 890.72	5997.40 / 749.68	5996.96 / 749.62	5997.09 / 749.64	6001.73 / 750.22	3917.11 / 489.64	3905.24 / 488.16	**3902.22 / 487.78**
	Total direct cost (HKD)	42,464,601.16	37,260,046.98	44,074,057.82	47,380,609.25	54,239,434.53	36,575,622.91	37,454,375.79	**32,989,758.10**
	Total carbon emissions (kg CO_{2e})	1,997,624.24	2,851,913.42	3,026,811.84	3,086,126.50	3,166,194.43	**2,011,818.03**	2,682,356.03	2,676,871.75

5.2 Comparison of different scenarios

According to Table 3, the utilization rates of the wrapping crew, crane, and truck in scenario 1 all reached 99%, which means that these three resources may be too small and affect project performance. Therefore, a truck is added in scenario 2. The results show that this scenario significantly improves the utilization rate of tying crew, tower crane, and onsite inspectors to 99%, but does not have much impact on the utilization rate of other resources. From the main performance evaluation indicators, it can be observed that scenario 2 can shorten the total duration from 890 days to 750 days, about 15.7%. Meanwhile, the cost is reduced by 12.3% compared with scenario 1, while the total carbon emissions increase by 42.8%.

Based on scenario 2, scenario 3 continues to add an off-site crane, which causes the cost and total carbon emissions of scenario 3 to increase by 18.3% and 6.1%, respectively, compared with scenario 2. Compared with Scenario 3, Scenario 4 adds a wrapping crew. This change does not optimize resource utilization and total carbon emissions but increases total costs. Overall, in the process of gradually increasing off-site resources in scenarios 3 and 4, the resource utilization rate of on-site resources has been greatly improved, especially the resources of tying crew, tower cranes, and on-site inspectors. However, from the perspective of key performance indicators, the changes in scenarios 3 and 4 did not bring about a significant improvement in project performance. Therefore, subsequent scenarios will consider adding resources to on-site resources to improve project performance and optimize the utilization of each resource. Scenario 5 adds a tower crane based on scenario 4, which reduces the utilization rate of the tower crane in the on-site stage from 99% to 63%, and the utilization rate of other resources remains unchanged. This scenario does not reduce the total time but leads to an increase in total cost and total carbon emissions. Scenario 6 chooses to add an on-site inspector based on scenario 5. This scenario significantly optimizes the total duration, reducing the total number of days to 490 days, while keeping the total cost and total carbon emissions lower than the previous scenario.

Scenario 7 adds a truck to scenario 6, resulting in a significant increase in resource utilization in the off-site stage to 99%, except for the factory inspector. The project performance in this scenario is very close to Scenario 6, but the total carbon emissions increased by 33.4%. Compared with scenario 7, scenario 8 reduces one tower crane. This change significantly increases the utilization rate of the tower crane to 97%. At the same time, the utilization rate of the tying crew increases by 11%. Although this scenario performs similarly to scenario 7 in terms of total duration and total carbon emissions, the total cost is reduced by 11.9%. In summary, scenarios 2, 3, and 4 add some resources in the off-site stage, resulting in a significant increase in resource utilization in the on-site stage, while the project performance indicators only reduce the project duration to about 750 days. On the contrary, scenarios 5 to 8 add some resources in the on-site phase, reducing resource utilization in the on-site phase and significantly reducing the project duration, total cost, and carbon emissions.

5.3 Comprehensive performance evaluation

This section combines duration, cost, and carbon emissions into a comprehensive indicator to evaluate the overall performance of the project. First, the data is normalized, then the weight of each item is defined as 33.3% equally, and finally they are added together. The smaller the result, the better the overall performance. As shown in Table 4, the results of scenarios 6, 7, and 8 are 0.06, 0.27, and 0.19, respectively, indicating that these three scenarios have good comprehensive performance in duration, cost, and carbon emissions.

Table 4. Comprehensive performance evaluation of different scenarios.

	S1	S2	S3	S4	S5	S6	S7	S8
Duration	0.33	0.22	0.22	0.22	0.22	0.00	0.00	0.00
Cost	0.15	0.07	0.17	0.23	0.33	0.06	0.07	0.00
Carbon	0.00	0.24	0.29	0.31	0.33	0.00	0.20	0.19
Sum	0.48	0.53	0.68	0.75	0.88	0.06	0.27	0.19

6 Conclusions

MiC is a disruptively innovative construction technique that enhances productivity, shortens duration, and improves construction sustainability. It has been increasingly adopted in Hong Kong to address housing demand and approach carbon neutrality. However, compared to conventional construction, MiC presents additional challenges related to module transportation and installation. To address these challenges, this project simulated the MiC construction process and conducted scenario experiments using a DES model to identify near-optimal resource configurations that achieve shorter durations, lower costs, and fewer carbon emissions.

The simulation results indicated that the model is more sensitive to variations in off-site resources than on-site resources. Interestingly, using two off-site cranes, two wrapping crews, three trucks, and two on-site inspectors achieves the shortest duration and lowest cost (Scenario 8). However, reducing the number of trucks to two and increasing the number of on-site tower cranes to two (Scenario 6) results in lower carbon emissions, despite a slight increase in duration and cost. Therefore, it is essential to balance these three key performance indicators. When equal weights of 1/3 are assigned to duration, total costs, and total carbon emissions after normalization, Scenario 6 demonstrates the best overall performance, followed by Scenario 8 and Scenario 7. Surprisingly, Scenario 5 performs the worst, even falling below the baseline scenario, which suggests that increasing resources does not necessarily lead to improved overall performance, highlighting the importance of reasonable resource configuration in MiC construction.

This project simulated the MiC construction process and optimized the configuration of off-site and on-site resources, outlining the significance of off-site resource allocation, which has attracted little attention in previous studies. The proposed simulation model can serve as a useful tool for assisting in the planning of MiC construction projects. The simulation results will enable construction practitioners to understand how variations in resources affect project duration, costs, and carbon emissions. Nevertheless, there are some limitations. First, the developed model might be simple, as actual processes are far more complex than the established DES simulation model. Therefore, this simulation model can be expanded and improved with additional activities and resources. Second, some dynamic factors, such as weather conditions, traffic congestion, and worker absenteeism, have not been considered, which may affect the progress of MiC construction. Thus, a simulation study on optimizing MiC construction planning with dynamic considerations is expected.

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Data Availability Statement

Some or all of the data and models that support this study's findings are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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