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Evaluating Modular Healthcare Facilities for COVID-19 Emergency Response—A Case of Hong Kong

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Abstract: In response to the COVID-19 pandemic, modular construction has been adopted for rapidly delivering healthcare facilities, but few have systematically explored the impacts of the pandemic and the contributions of modular construction. This paper aims to evaluate modular construction for delivering healthcare facilities in response to COVID-19, through the exploration of the challenges, strategies, and performance of using modular construction for emergency healthcare building project delivery. The study was conducted using 12 real-life healthcare building projects in Hong Kong with both within- and cross-case analyses. The results of the within-case study reveal critical challenges such as tight program but limited resources available and the corresponding strategies such as implementation of smart technologies. The results of the cross-case analysis indicate 106% improved time efficiency and 203% enhanced cost efficiency of using modular construction compared with conventional practices. Based on the multi-case studies, the paper develops an innovative framework which illustrates the roles of stakeholders, goals, engineering challenges, and management principles of using modular construction. Practically, the paper should assist both policymakers and industry stakeholders in addressing the critical challenges of delivering healthcare facilities under COVID-19 in an efficient and collaborative manner. Theoretically, it should set an exemplar of linking the building construction industry with emergency management and healthcare service systems to facilitate efficient response to pandemics.

Keywords: COVID-19; emergency response; healthcare facility; modular integrated construction; modular building

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1. Introduction

The fast spread of the COVID-19 pandemic has disrupted healthcare systems globally and has imposed great challenges on the construction industry [1,2]. Nevertheless, the pandemic may also accelerate the process of innovation adoption to address urgent social needs under the COVID-19 pandemic. Various strategies and innovations have been proposed to ensure the capacities of healthcare facilities during and after disasters, e.g., optimization of public hospital resources under calamitous situations [3], application of preparedness control measures such as communication and information management and training [4], and design of safe spaces for residential housing [5].

With the adoption of prefabricated construction, various emergency healthcare facilities have been rapidly delivered worldwide. For example, the Leishenshan hospital in China was delivered in only two weeks using prefabricated steel structures [6]; and an isolation hospital in Korea was built in 23 days using steel-framed modules manufactured in China [7]. The adoption of prefabricated systems (e.g., precast and modular construction) can speed up the project delivery process to provide isolation and curing places in the shortest time possible, and it can also mitigate the risks of cross infection during construction due to the minimized on-site labor [8].

Although these facilities were built in an ever-fast manner, the adoption of the modular approach was significantly challenging to the construction industry under the COVID-19 pandemic. On the one hand, modular construction normally involves intensive and complex module prefabrication [9]. On the other hand, the pandemic raises some new challenges such as uncertain cross-border logistics [10]. Nevertheless, most previous studies focused simply on the impact of the pandemic such as Prasad and Bhat [11], but they ignored how the industry responds to the pandemic. In addition, the modular approach has been widely explored in residential buildings [12], but with few investigations of its applications in emergency healthcare projects.

To comprehensively understand the impact of COVID-19 on the construction industry and to appreciate the contributions of modular construction to addressing the pandemic, this paper aims to evaluate the performance of modular construction-enabled healthcare facility delivery in response to COVID-19. The evaluation was conducted by systematically identifying the challenges, exploring the strategies, and measuring the time and cost efficiency of using modular construction for healthcare building project delivery. Multiple case studies were conducted by engaging 12 real-life building projects in Hong Kong, including modular quarantine camps and hospitals.

Following this introduction, the paper reviews the features of modular construction and the principles of emergency building project delivery, and develops a conceptual framework of modular construction for addressing COVID-19. The paper then elaborates on the methods of data collection and analyses, followed by the presentation of the identified challenges and strategies and the measured performance. Based on the results, the paper develops and discusses a systematic framework of efficient response to COVID-19 through modular construction. Finally, the paper draws its conclusions.

2. Literature Review

2.1. Features of Modular Construction

Modular construction represents the highest level of prefabricated construction technologies and was defined by Pan et al. [13] as an innovative approach to transforming fragmented site-based construction into integrated value-driven production and assembly. Modular construction is an instance of the application of modularity theory in the construction industry, which emphasizes product modularization and standardization and aims for productivity enhancement [14]. Globally, the modular approach has been widely adopted in building projects, e.g., modular integrated construction (MiC) in Hong Kong [15]. Compared with conventional construction, modular construction changes the project delivery process mainly in two aspects: spatially, volumetric modules are prefabricated in the factory, and then installed on site; temporally, prefabrication is carried out concurrently with the on-site installation [16]. The tempo-spatial transformation with modularization improves the construction performance of building projects. Both concrete and steel modular systems were demonstrated with multi-faceted benefits, e.g., faster construction, better product quality, improved environmental friendliness, reduced health and safety risks, and an improved industry image [17–19]. Nevertheless, different modularization schemes may have different construction performance. For example, highly modularized buildings with more work fabricated in factory can reduce the on-site labor consumption and increase the speed of superstructure construction [15].

The multi-faceted benefits demonstrate high potential of modular construction in response to COVID-19 by fast delivering healthcare facilities. Nevertheless, various constraints exist in prefabricated construction supply chain especially following a large-scale disaster, for example, the shortage of skilled workers [20], challenging just-in-time delivery of modules [9,21], the unsecured construction material procurement and delivery [22], and the complicated prediction of supply and demand [23]. To address the challenges along the construction supply chain, an innovative approach was designed to facilitate the procurement planning of construction materials following a large-scale disaster [24], and a dynamic model of prefabricated construction supply was developed to address the statistic constraints considering the multiple factories [22].

As the supply chain of modular construction is not as mature as that of conventional prefabrication, it is even more challenging for delivering emergency modular healthcare projects due to the tight program and limited resources. Therefore, it is critical to explore the challenges to, and identify the strategies for adopting modular construction in addressing the COVID-19 pandemic.

2.2. Emergency Project Delivery and Management

To explore the challenges and strategies of using modular construction for COVID-19, it is necessary to first examine the concept, principles and process of emergency project delivery and management. Emergency management is to apply science, technology, planning, and management to deal with extreme events that can cause extensive property damage and disrupt community life [25]. It addresses how humans and institutions interact and cope with hazards through a cycle with four major activities, i.e., mitigation, preparedness, response, and recovery [26,27]: mitigation includes actions taken to prevent or reduce the impact and consequences of disasters; preparedness involves planning and training activities for events that cannot be mitigated; response includes activities designed to address the immediate and short-term effects of an emergency or disaster; and recovery refers to long-term activities designed to return all systems to normal status. "Build Back Better" principles are normally introduced as an ideal reconstruction/recovery process to improve community's resilience following a disaster event, e.g., improved building codes and land-use plans [28]. This study focused on the emergency response, i.e., how modular construction contributes to the efficient response to the outbreak of COVID-19 through fast delivery of healthcare facilities.

Many researchers have examined the principles of emergency response and management. For example, Waugh Jr and Streib [26] and Bae et al. [29] elaborated on the importance of leadership and collaboration. Chen et al. [30] presented a set of design principles, e.g., resource monitoring and group decision-making. Cowick and Cowick [31] argued the effectiveness of using new technologies such as online coordination tools.

For emergency project delivery, Capolongo et al. [32] proposed some strategies such as strategic site selection, flexibility and user-centeredness. To accelerate the process of emergency project delivery, Schexnayder and Anderson [33] and Wang and Shi [34] summarized various techniques, e.g., working overtime, providing additional labor and equipment, and adopting innovative construction methods. To address the shortage of resources during an emergency, Chen et al. [35] suggested to develop logistics management and resource-sharing networks across local, national, and international levels. In addition, the importance of establishing an emergency response team with close collaboration was highlighted by McWilliams [36] and Gransberg [37].

However, the existing emergency response frameworks only specify the generic organizational roles and actions which cannot directly apply to the delivery of modular emergency healthcare facilities, e.g., that the HKSAR Government is committed to providing responses to emergency situations that threaten life, property and public security [38] and to convert suitable holiday camps into quarantine camps for COVID-19 [39]. In addition, the emergency project delivery strategies in the literature did not consider the features of modular construction and the waves of COVID-19. Therefore, this research was designed to also develop an innovative emergency response framework in the context of fast delivery of modular healthcare facilities in response to the COVID-19 pandemic.

2.3. Conceptual Framework of Modular Construction-Enabled Response to COVID-19

SWOT analysis is a strategic planning and management technique used to identify the internal strengths and weaknesses and the external opportunities and threats for a specific situation [40]. To guide the exploration of the challenges and strategies of modular construction-enabled response to the COVID-19, a conceptual framework (Figure 1) was developed based on a critical SWOT analysis. Modular construction has significant advantages over conventional construction such as improved speed of construction (strength) [17], and thus can address the urgent social needs on healthcare facilities (opportunity). Nevertheless, the modular construction itself is facing challenges such as cross-border logistics (weakness) [9], and the construction industry encountered new issues during the COVID-19 pandemic such as shortage of material supply (threat).

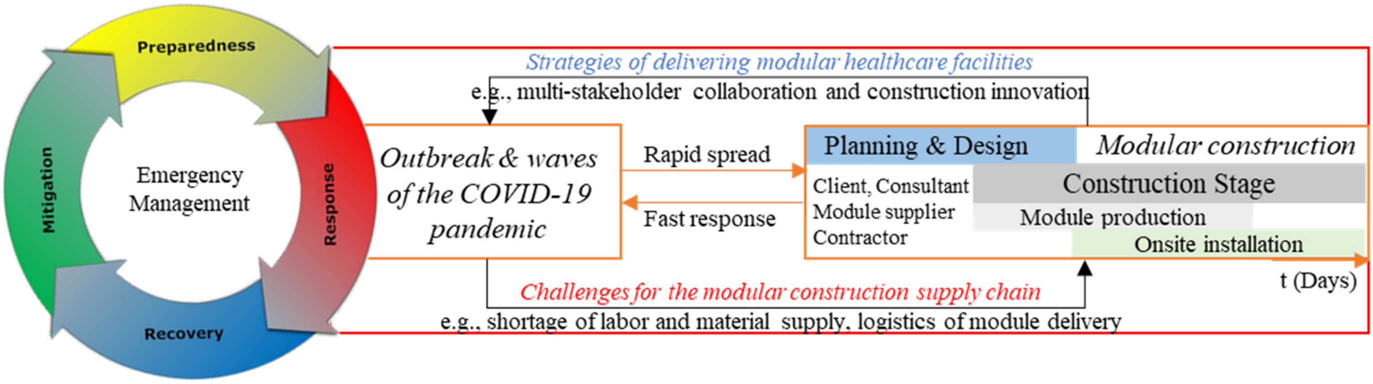

Figure 1. Conceptual framework of modular construction-enabled response to COVID-19.

Correspondingly, the framework integrates the potential challenges facing the construction industry during COVID-19 (e.g., shortage of material supply), the basic principles of emergency response (e.g., multi-stakeholder collaboration), and the process of modular project delivery (e.g., parallel module production and on-site installation). It illustrates the mutual impacts between modular construction and COVID-19: modular construction mitigates the impact of COVID-19 by rapidly delivering healthcare projects; COVID-19 greatly affects the modular construction supply chain. It also indicates the focus of this study, i.e., 'Response' of the four-stage cycle of emergency management [24]. Guided by the conceptual framework, the study has systematically identified both common and project-specific challenges, explored the corresponding strategies for better adoption of modular construction under the pandemic, measured how efficient the modular approach is in response to the pandemic, and finally proposed the framework of how modular construction addresses the COVID-19 pandemic.

3. Research Methodology

3.1. Overall Research Design

This research has adopted a multi-case study strategy using 12 case projects, and was carried out following the process shown in Figure 2. To start, a comprehensive literature review was conducted, and a conceptual framework was developed. Guided by the conceptual framework, a within-case study using 5 cases was conducted to identify and validate the challenges and strategies of using modular construction for addressing COVID-19; in parallel, a cross-case study using 12 cases was conducted to measure the performance of modular construction for healthcare project delivery. Based on the multi-case studies, the performance (e.g., time and cost efficiency) of modular healthcare facilities was evaluated, and the framework of modular construction-enabled efficient response to COVID-19 was developed.

The case studies were conducted in Hong Kong to demonstrate how an administrative region and its construction community have responded to COVID-19. The 12 case projects (referred to as Projects A-L) were selected by adopting the purposive sampling strategy, considering that (1) Hong Kong has established the supply chain of modular construction; (2) all projects were emergency healthcare facilities; (3) all major modular healthcare projects in Hong Kong were selected; (4) the projects covered conventional construction for benchmarking.

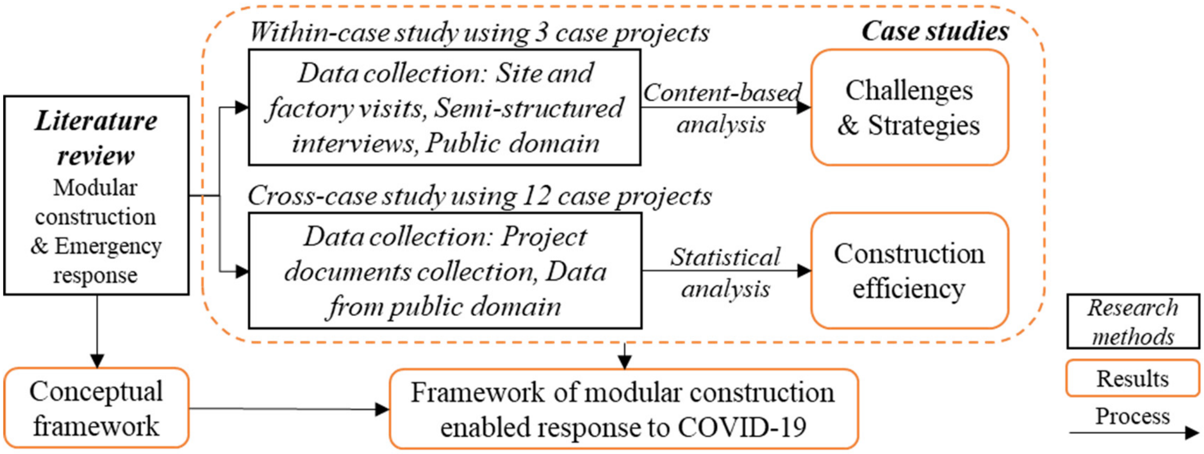

Figure 2. Overview of the research process with methods adopted and results derived.

The selected case projects included 10 quarantine camps (i.e., Projects A-I using modular construction, Project J using in-situ construction) and 2 hospitals (i.e., Project K using modular construction, Project L using in-situ construction). Project J was a scenario that was designed by the authors according to the expert interviews with the construction practitioners. To ensure the consistency of analysis, all projects adopted design-and-build contracts. All quarantine camps selected were completed in 2020. The basic project information is provided in Table 1. Projects A, B, C, H, and K were selected for the within-case study, while all 12 projects were used for the cross-case study. The timeline of project delivery and waves of COVID-19 are illustrated in Figure 3.

Table 1. Information of the selected case projects.

Cases	A	B	C	D	E	F	G	H	I	*J*	K	*L*
MR (%)	>95 (A–I)									*N/A*	>70	*N/A*
CFA (m2)	2052	5980	2000	3470	3000	13,158	13,125	15,938	15,938	*16,000*	44,000	*21,600*
No. of beds	118	234	120	198	110	700	700	850	850	*850*	816	*108*
Supplier Experience	CN 3–5	CN 3–5	CN >10	SG 3–5	HK 1–3	CN 3–5	HK 3–5	CN >10	CN 3–5	*N/A*	CN 3–5	*N/A*
Year of completion	2020 (A–I)									*2020*	2021	*2007*
Duration (days)	26	62	66	84	68	73	87	88	87	*300 (↑)*	~120	*~930 (↑)*
Cost (HK$M)	15	29.5	29.8	28	193.7	433	418	605.5	663	*663*	N/A	*964*

Notes: (1) 'Cost': contract sum; (2) MR (modularization rate) = modularized floor area/CFA; (3) Projects (J and L) in *italic*: in-situ construction method; (4) CN: China; HK: Hong Kong; SG: Singapore; (5) Experience: years in modular construction; (6) "↑": longer time consumed.

From Figure 3, it can be seen that all quarantine camps using modular construction were delivered within 3 months, and the design and construction of the modular hospital were completed within 4 months from the 4th quarter of 2020 to the 1st quarter of 2021. To accommodate the people who needed isolation (e.g., visitors from overseas), there was an urgency to deliver quarantine camps (e.g., Projects A to F) with sufficient beds as soon as possible since the outbreak of the pandemic. To address the future waves of the pandemic, it was also critical to build more isolation facilities for the locally confirmed cases, e.g., Projects G to I. In addition, to release the pressure of both the public and private hospital systems, a temporary hospital (Project K) was delivered between the peak of the 3rd and 4th waves, which provided both isolation and curing facilities. The rapid delivery of these facilities facilitated a timely response to the 4 waves of the pandemic in 2020.

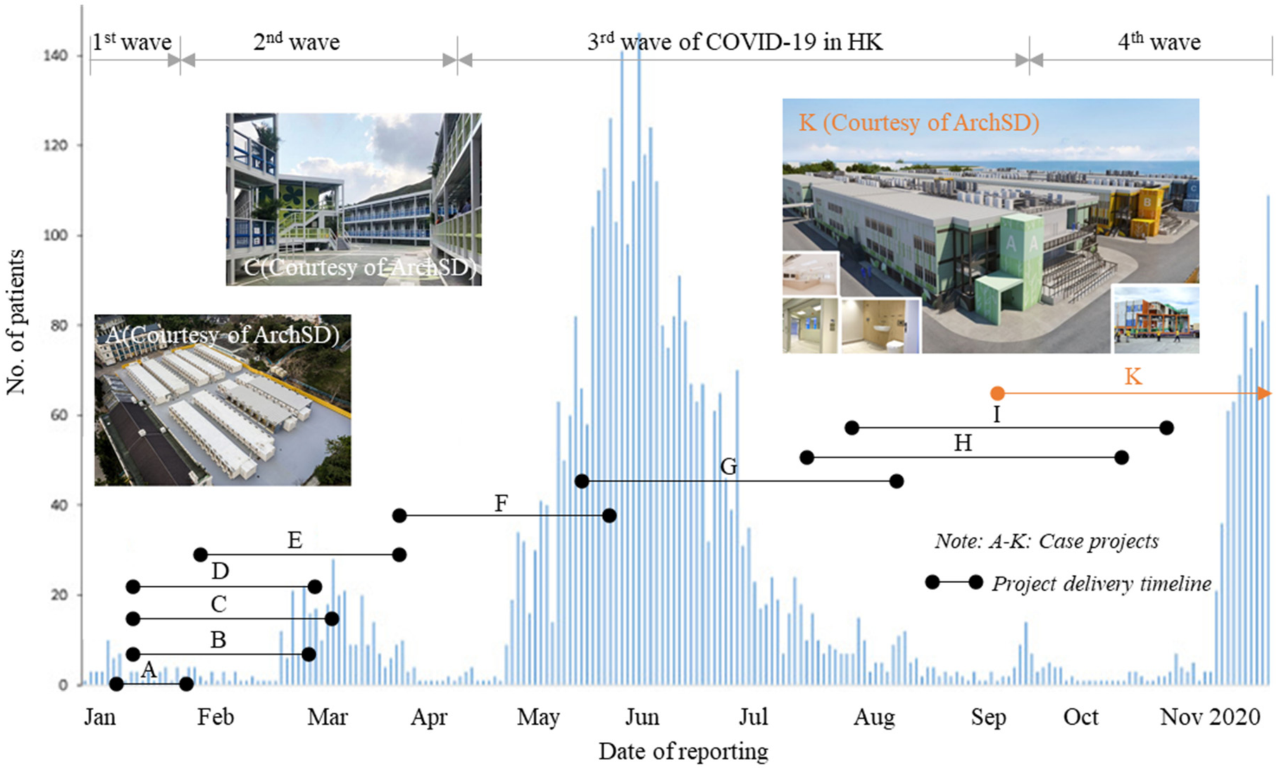

Figure 3. Timeline of project delivery and waves of COVID-19 in Hong Kong.

3.2. Methods of Within-Case Study

Considering the data availability, 5 case projects were used in the within-case study, i.e., Projects A, B and K for identification of the challenges and strategies, and Projects C and H for validation. Projects A, B, C and H were the typical quarantine camps in Hong Kong, and Project K was the only modular hospital that performed as an infection control center in response to COVID-19. To comprehensively identify the challenges and strategies and enhance the data validity, data were collected and verified through the triangulation of evidence sources [41]: site and factory visits, semi-structured interviews, and data from the public domain. Specifically, site and factory visits to Projects A, B and K were conducted to better understand the processes of site construction and factory production. Semi-structured interviews with project stakeholders were carried out to identify and validate the critical challenges and strategies. Information of the interviewees is summarized in Table 2.

Table 2. Information of the interviewees in the within-case study.

Interviews	Projects A, B and K	Projects C and H
Interviewees	Project Director (Client), Project Manager and Site Engineer (Main Contractor), Project Manager (Module Supplier)	Project Director (Client), General Manager and Project Manager (Main Contractor)

Informed by the conceptual framework (Figure 1), content-based analysis was adopted to summarize the challenges and the corresponding strategies. Explicitly, the identified challenges and strategies were categorized according to the major phases of project delivery (i.e., planning, design, and construction), and were classified as common ones that apply to all case projects and specific ones that only appeared in some of the projects.

3.3. Methods of Cross-Case Study

The cross-case study was conducted using 12 case projects with both quantitative and qualitative analyses (Figure 4). First, an *Excel* table was used to quantitatively measure the construction efficiency, followed by a comparative analysis using a scatter plot. Construction project efficiency is normally measured using time- and cost-efficiency [42]. The following equations were used: (1) Time efficiency (m^2/day) = CFA/Duration of project delivery; and (2) Cost efficiency (m^2/$) = CFA/Cost of project development. The 'CFA' refers to the total construction floor area and was extracted from architectural drawings; 'Duration of project delivery' covers project design and construction and was extracted from the master program; and 'Cost of project development' is the contract sum approved by a client and was collected from public domain. Second, qualitative evaluation was conducted to comprehensively reflect the performance of modular construction in response to COVID-19. To enable like-to-like comparison, only projects of the same type were compared with each other, e.g., modular quarantine camp vs. conventional quarantine camp. The information was mainly collected from the project teams (e.g., design and construction documents) and public domain (e.g., government website and reports of public seminars), and analyzed under the three pillars of sustainability: economy, environment, and society.

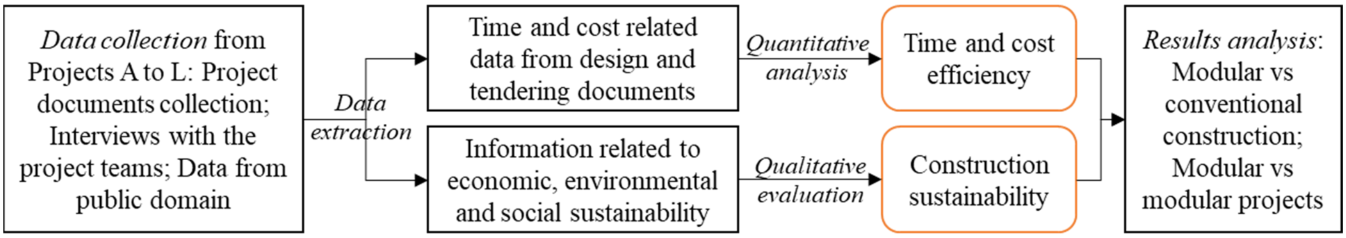

Figure 4. Research process of the cross-case study.

4. Results of Within-Case Study

Guided by the conceptual framework of modular construction-enabled response to the COVID-19 pandemic, the critical challenges and corresponding strategies were identified based on the within-case studies using Projects A, B and K, and supplemented and validated with Projects C and H. The results of the identified challenges and strategies are summarized in Table 3.

Table 3. Challenges and strategies of delivering modular healthcare facilities for COVID-19.

Process	Identified Challenges	Corresponding Strategies
Planning	Multi-faceted communication and coordination Tight program for planning	To enhance inter-government and cross-department collaboration To enable wide-industry partnership and early contractor involvement
Design	Multi-faceted communication and coordination Tight program for design Strict regulatory compliance Challenging modularization of hospital	To enable wide-industry partnership and early contractor involvement To follow the principle of Less is More To adopt professional and modularized design To design for production and transportation
Construction	Multi-faceted communication and coordination (between site and factory) Tight program but limited resources available (for both site and factory) High pressure on COVID-19 prevention (for both site and factory) Challenging logistics Project-specific site constraints	To enhance government-industry collaboration To count construction by hours and organize resources efficiently (for both site and factory) To take comprehensive infectious control measures To implement smart technologies To conduct systematic construction and production planning To take specific monitoring and control

Notes: Italic: project-specific challenges and strategies.

4.1. Identified Challenges

4.1.1. Multi-Faceted Communication and Coordination

Project clients and main contractors of all case projects were coordinating with multiple stakeholders to ensure efficient project delivery. For example, over 20 stakeholders were involved in Projects A and B, and over 26 in Project K. The multiple stakeholders included but were not limited to regulatory and works departments for design approval, sub-contractors for on-site activities, module suppliers for off-site logistics, and non-local governmental departments for factory production and cross-border transportation. It was also important but challenging for coordination between the site and factory teams, as fewer face-to-face meetings can be arranged due to the quarantine requirement. The efficiency of multi-faceted coordination determined the project success under COVID-19.

4.1.2. Strict Regulatory Compliance

It was challenging for the project teams to prepare statutory submissions in such a short time, e.g., approval-in-principal, detailed design approval, and shop drawings. These works determined the intensive coordination with relevant regulatory departments. In addition, the quarantine camps were designed not only for temporary purposes but also with life-cycle considerations, e.g., re-used for transitional housing. Although Project K was a temporary infectious control center, it was designed as a permanent hospital. The project teams had to prepare a feasible but efficient scheme to fulfill all regulatory requirements.

4.1.3. Tight Program but Limited Resources Available

The project teams were expected to complete their projects the soonest to address the urgent social needs. For Projects A and B, a one-month target was set to complete the design and construction. For Project K, design and construction were expected to be completed within 4 months to reach a permanent hospital standard, which was quite challenging for the industry even without COVID-19. However, there were limited resources available, e.g., challenging raw material procurement due to the restrictions at customs under the pandemic. The module suppliers were facing great challenges to deliver a large number of modules in such a short time, as most of the suppliers had insufficient experience on modular construction at that time.

4.1.4. High Pressure on COVID-19 Prevention

Facing the fast spread of the virus the construction teams were under high pressure on COVID-19 prevention and control. The increasing number of confirmed cases resulted in high risks of construction in a confined site. It was even more challenging to avoid such infections in a modular construction project with multiple transportation of modules from overseas. For example, in Project K over 300 management staff and workers were working and eating on site during the outbreak of the 4th wave of COVID-19 in Hong Kong.

4.1.5. Challenging Cross-Border Logistics

Logistics for module transportation from overseas was challenging in Projects A, B and K, as the border was under strict control and even closed in some countries under the COVID-19 pandemic. According to the interviews with Projects C and H, these challenges did exist in other healthcare projects. For example, Project C engaged a Malaysia module supplier, but the border was closed at the time of construction. They had to take additional efforts to negotiate with the Malaysian government for special arrangements.

4.1.6. Project-Specific Challenges

Apart from the common challenges above, the interviewees also mentioned some critical but project-specific challenges. For example, the modularized design for Project K (temporal hospital) is much more challenging than that for Projects A and B (quarantine camps), as it involved more types of modules (e.g., that for negative pressure ward) and many over-sized modules to satisfy hospital requirement (e.g., modules with the overhead ventilation system).

The modules had to be designed at 3.8 m in height, and thus the vehicle together with the modules approached the height limit of transportation (4.6 m) in Hong Kong.

In addition, various site constraints existed in some projects. For example, the site of Projects A and B was transformed from a football court on a mountain, and thus more time was needed for site formation, and it was challenging to ensure water and electricity supply. The site of Project K was close to the airport with strict height limits and also to an MTR line with requirements on noise and vibration control. Interviewees of Projects C and H also indicated the project-specific site constraints due to the urgent transformation of temporary lands for healthcare facilities.

4.2. Corresponding Strategies

4.2.1. Cross-Department Collaboration and Wide-Industry Partnership

To address the challenges of multi-faceted coordination, cross-department collaboration and wide-industry partnership were taken as a primary strategy. In Projects A and B, the strategic planning was mainly executed at two levels (Figure 5): (1) cross-department collaboration coordinated by a works department of the HKSAR Government with 16 supportive government agencies and regulatory departments; and (2) wide-industry partnership led by the main contractor with over 40 sub-contractors and 20 material suppliers involved. One more strategy in Project K was the inter-government collaboration between Shenzhen Municipal Government and HKSAR Government to facilitate efficient planning.

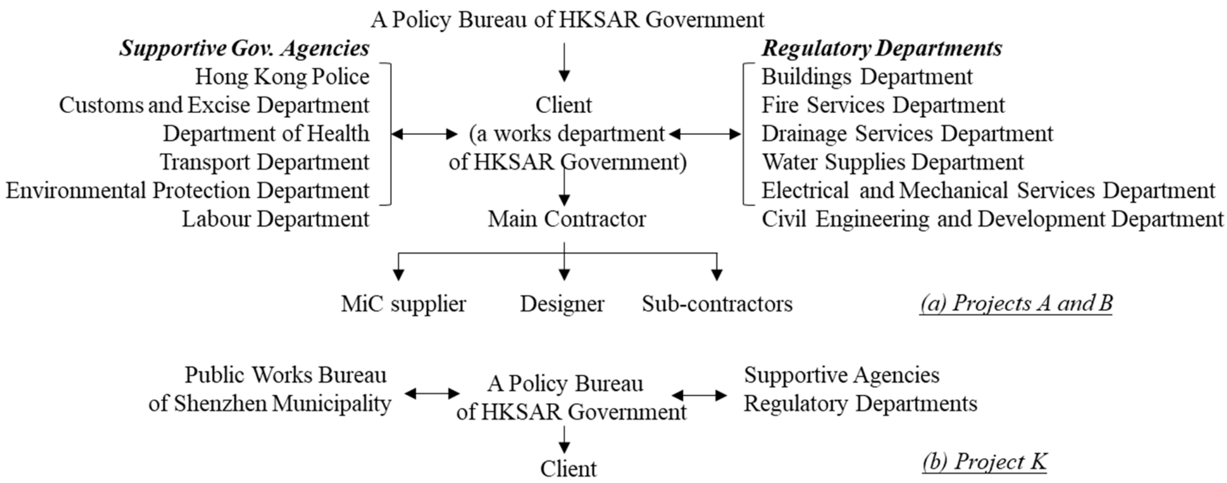

Figure 5. Inter-government and cross-department collaboration.

The cross-department collaboration assisted the project teams in fluent regulatory approvals thus facilitating fastest completion of design works. In addition, the clients of Projects A and B teamed up with the Transport Department and the Customs to make sure that the modules could be transported from the factory in Mainland China to Hong Kong within 4 h. The wide-industry partnership helped to address the problems of limited resources available, which made intensive construction realized within a shortest period possible.

4.2.2. Comprehensive Infectious Control

The design of modules in Projects A and B incorporated 12 infectious disease control criteria, mainly including clean and dirty zones for layout and unit arrangement, opposite orientation design of toilet units, use of anti-bacteria and easy-to-clean materials, natural ventilation for toilet, W-trap discharge pipe, double pipes system to eliminate the possible spread of virus and germs, and drainage system connections outside the units.

During construction, the project teams proposed infection control plans with various measures taken such as access monitoring, uniform arrangement of accommodations, and regular site training. Specific traffic control was taken for blocking the virus spread during cross-border transportation, e.g., transportation at night in Projects A and B.

4.2.3. Professional and Modularized Design

To deliver the project as fast as possible, 'less is more' was adopted as the design principle in Project A, which denoted to fulfill all functional requirements with minimized resources. After proposing 25 design schemes, an optimized design with repetitive units was selected. The optimized design was selected with the considerations as below: (1) it fulfilled the quarantine purposes, e.g., separation of clean and dirty zones; (2) it provided as many rooms and beds as possible; and (3) it involved the least materials that need to be procured from overseas. The project team streamlined all rooms into three types of modules. In Project K, extended modularized components were adopted to enable the fastest delivery of a high-quality hospital, e.g., modularized negative-pressure wards and building services modules.

4.2.4. Works Counting by Hours and Systematic Planning

To cater for the urgent social needs, all case projects adopted a 24-h working arrangement both on sites and in factories, with the principle of counting by hours. To ensure construction efficiency in such a tight program, systematic planning was conducted by the project teams both on site and in the factory. For example, the schedule and timeline of module delivery and installation were designed by minutes in Projects A and B. Modules were transported during nighttime and were installed successively from midnight to the early morning. The 'counting by hours' working arrangement made it possible for timely and fast project delivery (Figure 6), e.g., Project A was completed in 600 h and Project K in 120 days providing over 800 beds.

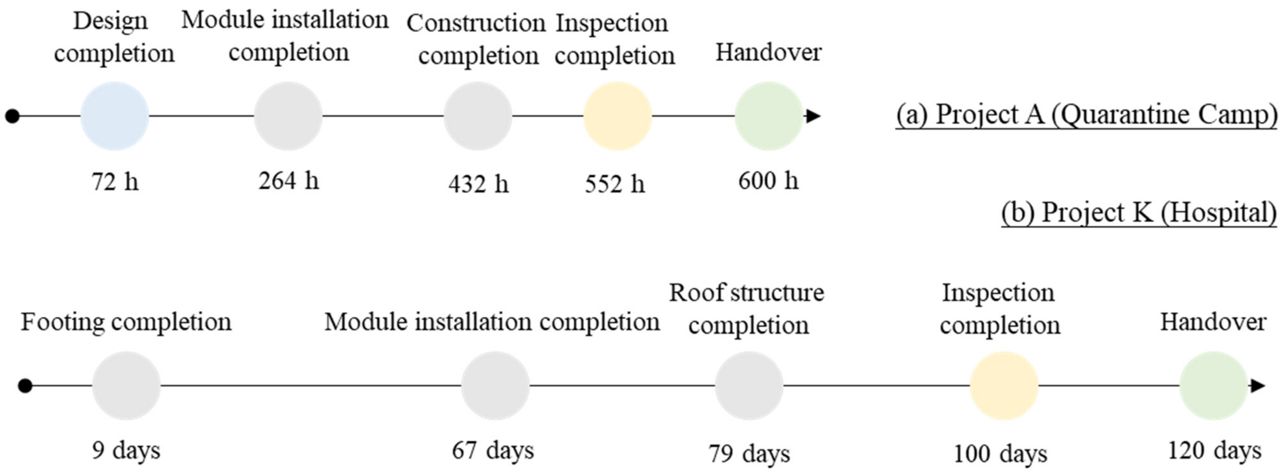

Figure 6. Timeline of project delivery.

4.2.5. Adoption of Smart Technologies

To address the challenging logistics and site constraints, the project teams adopted various smart technologies. For example, a cloud-based web portal was developed in collaboration with an academic research center for achieving real-time logistics monitoring in Projects A and B, which ensured the smoothness of the 24-h construction arrangement. In Project K, an AR-based building services checking system was developed by the main contractor, which allowed the construction team to easily do collision checking on site as hospitals normally involve complicated overhead ventilation pipes. Furthermore, an online quality checking platform was adopted in Project K to facilitate remote coordination between factory production and the project supervision team.

4.2.6. Project-Specific Strategies

To address the project-specific challenges, the project teams adopted corresponding strategies. For example, in Project K, vehicles with the super-low trailer were used, and transportation was arranged at night for the oversized modules. In Project H, the site was divided into several zones to facilitate efficient resource mobilization.

5. Results of Cross-Case Study

5.1. Measured Construction Efficiency

Cross-case studies on Projects A to L were conducted to evaluate the effectiveness and efficiency of emergency healthcare project delivery using modular construction. The time- and cost-efficiency were quantitatively measured and shown in Figure 7, and several interesting findings were identified from the measured results.

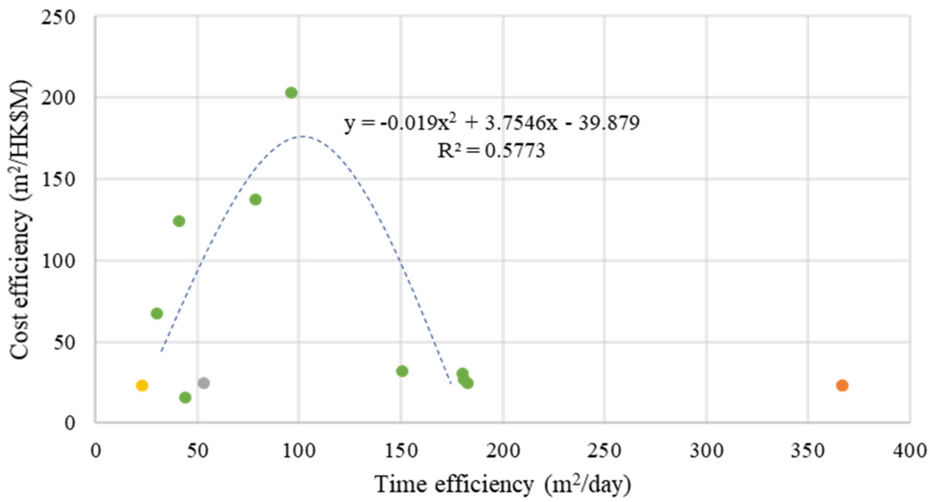

Figure 7. Measured time-efficiency and cost-efficiency. Notes: green dots—Projects A to I (modular QCs); yellow dot—Project J (conventional QC); orange dot—Project K (modular hospital); grey dot—Project L (conventional hospital).

The time and cost-efficiency of modular quarantine camps varied from each other, which was due to different project complexities (e.g., scales), teams, and site constraints. Nevertheless, compared with conventional construction (i.e., 53.3 m^2/day and 24.1 m^2/HK $million of Project J), modular construction (i.e., 109.6 m^2/day and 73.1 m^2/HK$million on average) increased the time and cost-efficiency by 106% and 203%, respectively.

In addition, the mathematical expression generated from the statistical analysis is a quadratic function, where there is an optimal point (i.e., optimized time and cost efficiency for modular quarantine camps). From Project A to E (CFA: 2000 m^2–6000 m^2), cost efficiency increased with the increase of time efficiency; while from Project F to I (CFA: 13,000 m^2–16,000 m^2), cost efficiency decreased with the increase of time efficiency. It was mainly due to that the complexity of the project (e.g., CFA to be built) affects the efficiency of project delivery. Therefore, each project should be designed with an appropriate scale (e.g., moderate CFA) to best mobilize the resources for achieving maximized efficiency. Nevertheless, the results were derived assuming that all projects were delivered in the same level of urgency.

Regarding the delivery of hospitals, the time efficiency was greatly enhanced by using modular approach (Project K: 366.7 m^2/day) versus conventional construction (Project L: 23.2 m^2/day). According to the interviews with the project teams, the cost efficiency of using modular construction should be around 20% higher than using conventional construction. The results suggest that with proper planning and design modular construction can greatly enhance the time- and cost-efficiency of various healthcare facilities under pandemics.

5.2. Qualitative Performance Analyses

Qualitative performance was analyzed in terms of not only economic performance but also environmental and social aspects. Economically, modular construction was proved efficient by speeding up the construction process but without cost increase, which echoes the quantitative measurement. In particular, modular construction greatly improved construction productivity and reduced delivery uncertainties, which addressed the challenges under the COVID-19 pandemic such as insufficient labor.

Environmentally, modular construction enhanced sustainability by reducing construction waste and pollution. For example, the waste generated from Project A was decreased significantly by using steel-framed modules; and noise generated in Project K was largely reduced with the mass adoption of prefabricated components. The reduced waste and pollution facilitated sustainable delivery of healthcare facilities under COVID-19.

Socially, modular construction addressed urgent social needs by delivering healthcare facilities in an ever-fast manner. In addition, the modular healthcare facilities could be easily disassembled after the pandemic and re-located for other purposes such as transitional housing, which could further address the severe housing shortage and unaffordability. In terms of lifespan, as interviewed with the case project teams, all these healthcare facilities comply with the design standard of permanent structures and should also have the same service life as that using conventional construction.

From the analysis above, modular construction can not only facilitate an efficient and sustainable response to COVID-19, but also help with the improvement of community recovery process through risk reduction of the built environment and effective integration of stakeholders along the construction supply chain to build back better.

6. Discussion

Derived from the results of the case studies and the evaluation, a systematic framework of modular construction-enabled response to COVID-19 was developed to facilitate efficient delivery of healthcare facilities. As is shown in Figure 8, the framework is process- and stakeholder-integrated, and involves the principles of stakeholder collaboration, professional and modularized design, early involvement of contractors, and the adoption of smart technologies.

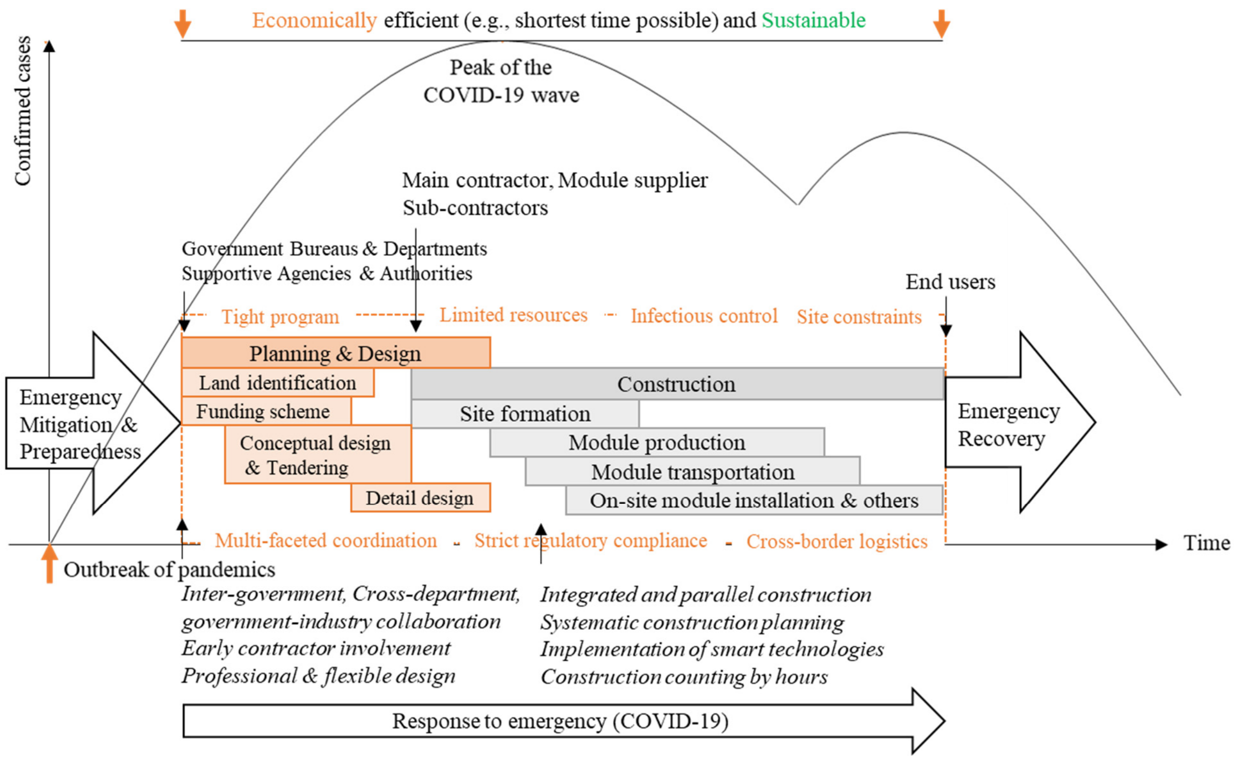

Figure 8. Framework of modular construction-enabled efficient response to COVID-19.

6.1. Major Principles of Modular Construction-Enabled Response to COVID-19

Collaboration mainly resides in the aspects of inter-government, cross-department, and government-industry collaboration. The three aspects echo the suggestions by Chen et al. [35] that joint effort should be made among public and private sectors across local, national, and international boundaries. The fast delivery of modular quarantine camps indicated the importance of cross-department and government-industry collaboration, e.g., to streamline the statutory submission and approval process. The importance of inter-government collaboration was reflected in Project K that the HKSAR Government teamed up with Shenzhen Government to rapidly set up the modular hospital delivery strategies. Multi-stakeholder collaboration and coordination is extremely important for modular construction compared with conventional practices [43]. For example, the guaranteed inter-government coordination in Project C ensured smooth cross-border logistics of module transportation. Government-industry collaboration is also necessary for emergency project delivery to facilitate efficient resource mobilization (e.g., water and electricity supply) considering the compressed time frame, which was fully reflected in Project B.

Professional and modularized design facilitates quality and fast delivery of emergency healthcare facilities. First, healthcare facilities for COVID-19 should be designed considering the infectious control criteria such as clean and dirty zones [8]. Second, the modularized design enables parallel factory and on-site construction, which accelerates the project delivery process and addressed the critical pandemic impacts such as labor scarcity identified by Rani et al. [44]. By incorporating the critical features of modular construction and healthcare facilities, these principles should outperform the existing design and construction strategies for conventional building projects, e.g., cost-effective design for commercial buildings [45], and should enhance the existing emergency design strategies proposed by Chen et al. [30] and Capolongo et al. [32].

The main contractor and module supplier should be involved in the early stage to design for manufacture and assembly, which was also suggested by Tan et al. [46]. The project team can then fix the design as early as possible and avoid late changes which are not allowed under COVID-19. The efficiency of early involvement of construction teams was proved in all case projects. For example, the design of Project A was completed within 72 h with contributions from the main contractor. In addition, the early contributions by the contractors and module suppliers in modular construction can reduce the late design changes which always occur in conventional building construction, and thus can minimize the time and cost uncertainties of project delivery.

As the activities of emergency construction are normally counted by hours, the use of smart technologies can help ensure construction efficiency, for example, a digital monitoring platform in Project A for coordinating off-site and on-site logistics [8] and a quality information management system for improving the efficiency of quality management process of module manufacturers [47]. Chen et al. [35] also suggested using smart technologies for emergency response, e.g., accurate time control with the assistance of sensor networks and GIS communication platforms. Apart from the enhancement of construction efficiency, the adoption of smart technologies in emergency healthcare project can also reduce the infection risks such as using tracking bracelets in Project B, and facilitate efficient design such as using a cloud-based synchronous collaboration platform in Project K.

6.2. Efficiency and Innovation of Modular Construction-Enabled Response to COVID-19

The results of the cross-case study indicated that the delivery of healthcare facilities using modular construction can enhance the cost-efficiency, which is inconsistent with Mao et al. [48] and Jang et al. [49] that prefabricated and modular construction was more expensive than conventional construction. Most importantly, the duration of building an emergency quarantine camp using conventional construction may take over a year, but only a few months by using modular approach. Nevertheless, to maximize both time- and cost-efficiency a large piece of land is suggested to be divided into a few for procurement, e.g., the development at Penny's Bay site was divided into Projects E to I. The framework was demonstrated efficient and effective in delivering community isolation facilities for addressing the 5th wave of the pandemic in Hong Kong, that 20,400 beds were delivered in 32 days to isolate the thousands of virus-infected cases [50].

Compared with the existing emergency response frameworks, e.g., that were developed by WHO [51] and FHB [39], the framework of modular construction-enabled response to COVID-19 is problem-driven (i.e., for pandemics), goal-oriented (i.e., economically efficient, socially and environmentally sustainable), stakeholder-integrated (i.e., governmental and industry stakeholders), and principle-explicit (i.e., principles concerning project planning, design and construction). By integrating modular construction into the emergency response process, the framework provides an exemplar for government-industry collaboration. Nevertheless, the effectiveness of the proposed framework and the time and cost efficiency of using modular construction can be further verified using more emergency healthcare building projects.

7. Conclusions

This paper has systematically evaluated the performance of modular construction for healthcare facility delivery in response to COVID-19. The evaluation was conducted based on the examination of the challenges to, strategies for, and efficiency of using modular construction for delivering emergency healthcare facilities. Multi-case studies were conducted using 12 real-life projects.

Within-case study revealed multi-faceted challenges to and corresponding strategies for the rapid delivery of modular healthcare facilities. The major ones are: (1) government-industry collaboration for addressing the limited resources available; (2) early contractor involvement and construction counting by hours for overcoming the tight program; (3) professional design for releasing the high pressure on COVID-19 prevention; and (4) inter-government collaboration and smart technologies for smooth cross-border logistics.

Cross-case analysis showed that modular construction can enable fast, cost-efficient and sustainable delivery of emergency healthcare facilities: (1) greatly improved economic efficiency, e.g., 106% improved time efficiency and 203% enhanced cost efficiency of the modular quarantine camps measured; and (2) enhanced environmental and social sustainability, e.g., reduced waste of materials.

Based on the multi-case analyses, a novel framework was developed to facilitate efficient delivery of modular healthcare facilities to address the issue of ‘emergency response’ in the circle of emergency/disaster management. Compared with the existing frameworks of emergency management (e.g., by WHO and Asian Disaster Reduction Center), it is innovative in three aspects. First, it integrates the multi-stakeholders along both the supply chain of modular construction (e.g., module supplier) and organizations for emergency response (e.g., Hospital Authority). Second, it involves a series of new principles such as inter-government collaboration to facilitate efficient logistics for module transportation. Third, it sets the goals of modular construction-driven emergency response, i.e., not only improved efficiency but also enhanced sustainability.

Practically, the identified challenges and strategies should assist both government and industry stakeholders in fighting COVID-19 by efficient delivery of modular healthcare facilities in a collaborative manner. Specifically, a joint working group could be formed with the involvement of building regulators, clients, contractors, and module suppliers to collaboratively deliver the healthcare projects as fast as possible. Theoretically, the developed framework should enhance the four-stage emergency management cycle by integrating modular construction into the stage of emergency response.

Although the study was conducted within the Hong Kong context, the paper should enlighten the emergency responses in other regions with established supply chains of modular construction. By exploring the contributions of the modular approach to addressing COVID-19, the paper should set an exemplar for linking the building construction industry with urban emergency management systems.

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