Integrated Approaches to Design for Manufacture and Assembly: A Case Study of Huoshenshan Hospital to Combat COVID-19 in Wuhan, China

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Abstract

Rapid deployment of modular hospital facilities has become an essential action in the COVID-19 response. Design for Manufacture and Assembly (DfMA) has played a significant role with governments commissioning emergency hospital projects. Due to the conflict between some DfMA strategies/guidelines, their integration requires further thorough investigation. This study aims to explore the integrated approaches to DfMA. A three-step method, including a focus group, eighteen designer interviews, and archival study, formed the basis and validation of the case. Finally, the study identified 31 DfMA measures, revealed three organisational (concurrence, integration and collaboration) and five design attributes that correspond with integration strategies for DfMA. Critical to the integrated approaches to DfMA is breaking the "mirroring trap". This study contributes to the theory development of DfMA in terms of systems integration. Future practitioners can take the example by the case to adapt the project organisational structure to the building production.

Keywords: design for manufacture and assembly, DfMA, healthcare, prefabrication,

1. Introduction

According to the World health statistics 2019, more than half of the world's 7.3 billion people cannot access the essential health services they need. In response, a United Nations goal aims to improve health-related sustainable development and achieve universal health coverage by 2030. Healthcare buildings will play a critical role (Mills *et al.*, 2015), although the shortage of healthcare capacity and inefficiency in healthcare building delivery remains a significant challenge (Gray *et al.*, 2014; Iskandar *et al.*, 2019; Wright *et al.*, 2019). The outbreak of the COVID-19 pandemic has intensified the global consensus on these challenges. Some countries are trying to expand the healthcare capacity in a short period and smooth the virus's expansion speed through rapid healthcare construction projects (Cai *et al.*, 2020; S. Chen *et al.*, 2020; Feng *et al.*, 2020; Zhou *et al.*, 2020). Off-site construction techniques and Design for Manufacture and Assembly (DfMA) play a significant role and support the preparedness for future pandemics.

Although different modern construction technologies (e.g. component prefabrication, and volumetric solutions) have been applied in current practice, many studies have a technical focus on the construction phase rather than design (Ali *et al.*, 2008; Arashpour, 2019; Melhado, 1998). This is surprising given the significant impact of design and particularly in the complex healthcare setting where DfMA strategies have rarely been explored in academia. DfMA was introduced from the manufacturing industry(Arashpour, 2019; Gao *et al.*, 2020), but significant adaptation is needed to address complex healthcare construction projects. Although some studies have explored DfMA in the construction industry, there is a considerable need to understand their use within the context of healthcare hospital manufacture.

DfMA must integrate stakeholders to achieve integrated design (Arashpour, 2019; Gao *et al.*, 2020; Yuan *et al.*, 2018). It should not be seen as a collection of design guidelines alone. Many studies have emphasized the importance of a multidisciplinary team in DfMA (Ashley, 1995; Gao *et al.*, 2020; Omigbodun, 2001). Within the context of complex healthcare environments, the design have to involve a broad range of speciality sub-consultants, sub-contractors and a large number of owner-representatives in early project phases (Cama, 2009; Guenther & Vittori, 2008; Lavy & Fernández-Solis, 2010). These broad and highly integrated teams are needed to address improvements in patient outcomes (Codinhoto *et al.*, 2009; McCullough, 2010), and overcome or build compromises between functional conflicts (Adebayo *et al.*, 2006; Guenther & Vittori, 2008).

This study aims to explore the strategies and capabilities applied to establish an integrated approach to DfMA. It deciphers the efforts and actions to rapidly build the 1000-bed emergency Huoshenshan hospital in 10 days. There are three research questions accordingly:

1. To explore the attributes of DfMA guidelines/strategies;

2. To describe the interdisciplinary design team integration in DfMA;

3. To identify the methods applied to integrate DfMA.

The rest of this article consists of four parts. The first is an overview of healthcare construction and the development of DfMA. Secondly, research methods, including data collection, data analysis and the selected frontier DfMA case, are described. Next, the thematic data analytical processes and research results are presented. Finally, the implications of the research are discussed and summarized. This research can help healthcare construction practitioners to implement and integrate DfMA better. By introducing Wuhan's experience and efforts to cope with COVID-19 through rapid healthcare construction, this research will be an important basis for sharing international best practice in DfMA and building a new rapid hospital manufacture approach.

2. Literature review

The urgent need for healthcare services has accelerated the development of healthcare infrastructure worldwide. In 2019, the total value of healthcare construction underway worldwide was $ 400 billion (Ellis, 2019). But many industry reports criticized the inefficiency or even failure of healthcare-sector projects (Gray *et al.*, 2014; Iskandar *et al.*, 2019; Wright *et al.*, 2019). The outbreak of the COVID-19 pandemic has exacerbated capacity shortages and a crisis in healthcare facilities. Modern Methods of Construction (MMC) are regarded as an advanced pathway to accelerate capabilities and revolutionize traditional healthcare delivery (Adebayo *et al.*, 2006). Many governments are expanding their emergency healthcare capacity through the use of off-site and modular construction techniques. However, customisation, user-centric integrated design and innovation remain challenging (Lahtinen *et al.*, 2020).

Several studies have detailed the application of DfMA construction policy, strategies and practices, although many are adaptations of manufacturing-oriented DfMA (Tan *et al.*, 2020a). These strategies and guidelines have not had academic validation in the context of healthcare building projects. Others have described the technical implementation of DfMA. Few studies, however, focus on the design strategies of the whole building project. Single building components/parts relatively have received more attention, although infrequently in complex healthcare settings. And there is no research to comprehensively investigate DfMA application for modern healthcare building manufacture, nor evaluate the delivery effect (e.g. efficiencies and increased quality).

Systems integration refers to combining multiple individual sub-systems or sub-components into one all-encompassing system that allows the sub-systems to function together (Brady et al., 2005; Grady, 1994; Whyte et al., 2020). The integration of various functional and operationally interconnected components raises challenges. And the relationship between DfMA and systems integration has not been fully explored. The indiscriminate usage of DfMA guidelines will not contribute to the achievement of building systems integration. Besides, current DfMA research has little considered the interactions between people, process and technology, namely the management issues around design. DfMA should respond to the integration challenges for complex building systems. Although many studies have highlighted the importance of integrating modular principles in design and the necessity for collaboration, coordination, and early involvement of contractors and suppliers, facilitating these advantages for the implementation of DfMA through organisational adaption and innovation is rarely discussed. Also, the design management of DfMA in different organisation context was ignored.

The relationship between organisational structure and product structures (i.e. the "mirroring" hypothesis) has been discussed for the past decade. It predicts that organisational ties within a project, firm, or group of firms (e.g., communication, collocation, employment) will correspond to the technical dependencies in work being performed (Colfer & Baldwin, 2016). Modular organisational forms in which loosely coupled organisational units specialize in distinct knowledge domains are more likely to design modular products (Sorkun & Furlan, 2017). However, the Architectural, Engineering and Construction (AEC) industry has fallen into a “mirroring trap” (Colfer & Baldwin, 2016), hindering systems integration and project success. “Mirroring trap” means professional knowledge is deeply rooted in the personal behaviour of professional companies and their employees (Hall *et al.*, 2020), which traps project design and execution into the prevailing standard system architecture and resists attempts for system-level innovation (Katila *et al.*, 2018; Taylor & Levitt, 2007). Many recent studies have explored the company's strategic actions to achieve systems innovation and how integration strategies can make individual projects eliminate the "mirroring trap". To further advance the previous construction-oriented DfMA studies (Gao *et al.*, 2020; Gbadamosi *et al.*, 2019; Tan *et al.*, 2020a; Tan *et al.*, 2020b; Yuan *et al.*, 2018), this paper goes beyond design guidelines and evaluation systems to design-related management issues by using a qualitative case study. Integrated approaches were studied to expand the previous discussion about DfMA.

3. Methodology and Methods

3.1 Research Setting and Design

Many studies have studied and highlighted the emergency hospital in Wuhan for COVID-19 (Cai *et al.*, 2020; L.-K. Chen *et al.*, 2021; Luo *et al.*, 2020; Wang *et al.*, 2021). Huoshenshan Hospital provides an example of a rapidly deployed healthcare facility to increase capacity to cope with increased hospitalisations of COVID-19 patients in Wuhan, China. This megaproject is the first emergency hospital built worldwide since the outbreak of COVID-19 and well-known for its rapid design and construction. It is a unique opportunity to explore DfMA due to the high uncertainty, limited time, complex functionality and rapid capability of the hospital design. There were more than 100 stakeholders in the project. On January 23, 2020, the Wuhan Government decided to build the Huoshenshan Hospital with 33,940 square meters and 1,000 beds. After ten days, Wuhan Huoshenshan Hospital was completed on February 2, 2020.

General Institute of Architectural Design and Research Co., Ltd. (CITIC) and China Construction Third Engineering Bureau Co. Ltd. were involved as the main actors in the design and construction. They worked closely with local sub-contractors, government departments and suppliers to coordinate and integrate building systems. The CITIC's team acted as a design unit responsible for negotiating and making design and technological decisions with limited time and available resources. Similarly, the Chinese government's last time had combated SARS outbreak by a modular healthcare project in Beijing, namely Xiaotangshan Hospital, in 2003. Designers saw in the Huoshenshan an opportunity to rapidly industrialise their design results for a modular hospital. For CITIC, Huoshenshan meant consolidating all its design disciplines in a single complex building system. The project used DfMA for its rapid construction. All participants devoted themselves to complete the design and construction quicker than the proposed target time, even during the Chinese Spring Festival. The first ward building was completed in only 16 hours and rapidly handed over for beneficial occupation.

To understand the role and capabilities of DfMA for the rapid delivery of systems integrated healthcare projects, this study conducted an inductive, interpretive, qualitative enquiry (Eisenhardt *et al.*, 2016; Gioia *et al.*, 2013) through a single case study for its superiority of critically questioning, verifying and extending old theoretical relationships (Eisenhardt & Graebner, 2007; Flyvbjerg, 2006; Yin, 2017). This research approach allowed a specific and contextual implementation of DfMA, which promoted understanding of the principles and philosophies beyond guidelines.

3.2 Data Collection

This study adopted semi-structured interviews for its advantages in combining both the structured and unstructured interview styles and offering opportunities to explore specific topics spontaneously (Galletta, 2013). The semi-structured interview is almost equated with the main method of collecting qualitative data for case research because of its flexibility (Easton, 2010). This research approach avails an opportunity to interpret the meaning of experience as lived by participants to gain fresh perspectives (Creswell, 2007). The sample was selected using two inclusion criteria: 1) participants must be involved in the design process of the Huoshenshan Hospital project; 2) participants must be designers. The total designer population was 60 participants from the CITIC. Secondly, a sample size of around 15-22 in-depth interviews was considered. Leaders and directors of five disciplines were all interviewed as they controlled the main information flow for their specialisations. All junior designers reported their progress to their corresponding directors and leaders, and were also included to achieve saturation. Also, the sample size is considered by checking previous American Society of Civil Engineers (ASCE) single case studies. For example, Martinez *et al.* (2020) collected semi-structured interviews from 2 safety managers. Talebi *et al.* (2021) conducted 16 semi-structured interviews for a single case.

The purposive sampling strategy combined critical case sampling and stratified sampling to specify categories of person to be included in the sample. Hereafter, a written invitation coupled with a schematic presentation of questions (shown in Table 1), explaining the purpose of the semi-structured interview, were sent to the participants before telephone interviews. The authors contacted 90% of the Huoshenshan Hospital designer population members, and the junior designers not engaged throughout the design were not contacted. Table 2 shows the 18 interviews undertaken. All interviews lasted between 30 and 60 min and were recorded with the permissions of the interviewees. As shown in Figure 1, semi-structured interviews were combined with multiple other data sources, including one focus group, public news, reports, and interviews, and published books and documents. This mixed-method supported data validation and triangulation. In the first period, various resources were reviewed to understand the basic information about the project case and the design institute. CNKI was used to download all Huoshenshan-related Chinese reports, news and technical analyses. These documents provided essential knowledge and understanding about the project. Two authors then organised a focus group discussion with the CITIC for their traditional practices about Building Information Modeling (BIM) and DfMA, which provided a context to understand the uniqueness of Huoshenshan Hospital. Five directors and one researcher from the CITIC, and one associate professor in construction management from the local university joined in the focus group discussion. Besides, one of the authors has been working in the CITIC for more than ten years as a design director and provided rich information about the project, design team, and CITIC. In the last period, newly uploaded documents about Huoshenshan were reviewed from CNKI, and an official book about the detailed technical information of Huoshenshan was used to validate the interviews. The research content was finally checked and discussed with the designers to form the triangulated validation.

[Table 1 near here]

[Table 2 near here]

[Figure 1 near here]

3.3 Data Analysis

Content-driven thematic analysis was used to obtain meaning from the interview data (Morse, 1994) using Atlas-ti qualitative data analysis tool. The analytical technique follows a general phenomenological approach where data was evaluated to identify significant statements and sentences that provide an understanding of how participants experienced the phenomenon (Creswell & Poth, 2016). This analytical technique is also known as horizonalisation (Leech & Onwuegbuzie, 2008; Moustakas, 1994), which is followed by the careful development of clusters of meaning. Others have applied such methods to identify design and innovation strategies (Ajayi *et al.*, 2017; Tang, 2020). The method has six phases: 1) familiarising with data; 2) generating initial codes; 3) searching for themes; 4) reviewing themes; 5) defining and naming themes; and 6) producing the report (Braun & Clarke, 2006).

In line with the procedure for thematic analysis, the coding scheme and final categorization of identified factors were based on dominant themes that emerged from the interview scripts. The data-driven (inductive) coding process was adopted and manually implemented (Saldaña, 2021). The coding scheme enhanced the identification of key design attributes, strategies, as well as the broad categories of measures for integrating DfMA. Word cruncher facility of Atlas-ti was used to facilitate initial data familiarization to carry out a data-driven thematic analysis. Data coding was done using three categories of labelling. In addition to the identified comment from transcribed data, the three elements are code/super codes, discussion and measures. Based on initial word crunching, codes were used to search through each of the 18 transcripts of semi-structured interviews. The discussion represents the semi-structured interviews from which a comment was made, while measures are the summed-up statements and strategies derived from each comment. Table 3 demonstrates how the strategies were derived from thematic analysis.

Based on this process, 31 measures for DfMA were established. All these results were validated and triangulated by reviewing the related book/documentation for Huoshenshan Hospital.

[Table 3 near here]

4. Findings

This section presents the aggregated results to document a set of DfMA strategies from 18 semi-structured interviews. As shown in Table 4, the identified outcomes were classified and grouped by the coding method mentioned in Table 3. There are eight main categories: modularity, adaptability, flexibility, simplification, standardisation, integration, collaboration, and concurrent engineering.

[Table 3 near here]

4.1 Attributes of DfMA strategies

Although there are some case studies about DfMA, the attributes behind the strategies/guidelines have not been systematically discussed. DfMA strategies/guidelines may change on different projects (Tan *et al.*, 2020a). For example, the reported healthcare case does not entirely follow the general DfMA guidelines. Summarizing DfMA's strategies/guidelines simply from case studies may not make the results externally valid and generalised. Therefore, this research tried to explore the design attributes behind DfMA-related strategies/guidelines. Five attributes are observed. The first-level codes include flexibility, adaptability, modularity, simplification and standardisation. All of these attributes have been mentioned in previous DfMA studies. And these attributes are not limited to healthcare but all general projects. The difference is the implementation degree. For example, residential projects have a high degree of standardization, while complex megaprojects need relatively higher degree of adaptability and flexibility. There are also conflicts between these attributes. For example, standardization and flexibility have interrelationship/trade-off in design. Thus, the critical question is how DfMA integrates these attributes and what benefits of building systems integration can be achieved. This section described these five attributes separately.

Simplification represents the functionalism of the project. In this reported case, design to a strict set of building requirements was the priority. These requirements looked to maximize the capability to respond to the COVID-19 rather than other aesthetics, cultural or architectural attributes. For example, as mentioned by many interviewees, the primary goal was to meet the bed requirements under the epidemic prevention situation. Inventory-based design is one of the most significant actions to achieve simplification. Due to the limited construction time, the building was designed based on what the contractor and suppliers had in the inventory to simplify and reduce the manufacturing process instead of following the traditional DfMA path. In addition, many functional and design requirements have been simplified as the building was specified as a temporary building.

Modularity saves the design and construction time. Especially for complex projects like hospitals, there are numerous sub-technical systems and corresponding knowledge and suppliers. Modularity was used to solve these challenges. In this project, the modular wards, as physical modularity, were assembled by redesign and retrofit the mobile houses initially used for construction workers' living. And some buildings equipment, such as electrical, also adopted modularity to reduce on-site installation and deployment. Besides physical modularity for the built products, the concept of modularity was also implemented at the organisation level.

Adaptability reflects the construction resilience and ability to respond to on-site uncertainty through early design. It meant the design could cope with the actual situation of the site without changing. Compared with conventional extensive on-site wet construction of the on-site assembly process, prefabrication required more accurate design and control. Due to the construction speed and material inventory, there were challenges for on-site craftsmanship. Many adaptability-related measures, such as design functions/equipment adapting to weather change, were undertaken in this project.

Flexibility is a coordination mechanism that allows design changes to cope with the actual construction situation. Flexibility and adaptability represent construction resilience. The difference between these two concepts is whether the design is changed to cope with the real situation. The project demonstrates the value of flexibility in several different ways. For example, hand-drawn design on site was used to deal with emergencies, and multiple connectors with different sizes were used to solve accuracy problems.

Standardisation has been recognized as an effective strategy for the construction sector. However, it is also challenging to accomplish (Choi *et al.*, 2020b; Shrestha *et al.*, 2020). The critical challenge is to balance the trade-off between standardisation and flexibility, as the former can undermine construction resilience. Similar requirements of many building and functional components of the hospital provided an opportunity for design standardisation.

4.2 An organisational approach to integrated DfMA

Integrated approaches to design have been proved as a promoter for the success of manufacturing products (Ettlie, 1997; Vajna *et al.*, 2014). But integration approaches to DfMA have not yet been fully explored, as various challenges of integrated design remain in the construction industry (Owen *et al.*, 2010). While integrated design processes have been proposed (Moe, 2008; Reed & Gordon, 2000; Sanvido & Norton, 1994), how attributes of DfMA are integrated and understood has received little attention. Integration cannot be achieved without corresponding management strategies of DfMA in terms of project organisation. Through the data analysis, three project organisation strategies were identified by three first-level codes, including collabotation, concurrent engineering, and integration.

Collaborative and coordinative planning generally describes a mode of professions working closely together (i.e. collaborating) in the design process and project delivery. In this case, a close collaboration has many concrete manifestations. For example, a 24-hour shift schedule, high-density information exchange, daily meeting and decision-making were all adopted. It is worth noting that advanced design and communication technologies, such as BIM software, were not used in the design stage. Collaboration was achieved through very conventional methods, including Telephone and WeChat group communication, screenshots/pictures sharing, and SketchUp/AutoCAD drawings. The reported case is highly consistent with the arguments proposed by (Erdogan *et al.*, 2008), namely the factors related to change, implementation, human and organisational support collaboration environment. At the same time, the designers all have rich work experience and long-term cooperation. The CITIC and main contractor also are all local companies with long-term cooperative relations, which contributes to quickly establishing the collaboration between each other to promote the project. As shown in Figure 2, the transformation from loose coupling to close coupling of collaboration changed the building system integration in the reported case. In this way, building systems were integrated even in a linear process.

[Figure 2 near here]

Concurrent design and construction involve simultaneously completing design and construction stages. Thus, buildings are assembled in less time while lowering cost. It is an effective strategy adopted in the investigated project. Extensive communication and collaboration between disciplines and stakeholders were promoted and involved in daily decision making. There were many pieces of evidence in this project about concurrent design and construction. For example, from the moment the design started, construction began on the site. In addition, the on-site designers conducted on-site design based on actual construction situations. Besides, the contractor was involved in the early decision-making with design institutes, the government, and healthcare operators.

Integration generally describes fragmented organisations subsumed into a single organisational framework. Integration requires collaboration as a precondition, but collaboration does not require integration. Firstly, (1) Members of multi-enterprise teams penetrate each other to work together. All disciplines of the CITIC had corresponding designers from contractors to work together. Vice versa, all disciplines of the contractor had corresponding on-site designers from the CITIC. This hybrid structure promoted integration between temporary organisations. Secondly, (2) Members of multi-disciplines teams penetrated each other to work together. The healthcare building is one of the most complex public buildings, and building systems for infectious disease also increase complexity. The project involves many technical disciplines, far exceeding the needs of ordinary buildings. Extensive communication, penetration and integration between multi-disciplines teams were critical to this project.

5. Discussions

Internationally, COVID-19 caused fundamental changes and a highly dynamic environment. Uncertainty, complexity and the fast pace of change illustrated that a stable solution was no longer desirable (Assaad & El-adaway, 2021; Fortner, 2020). The fundamental role of hospitals has been challenged by the COVID19 pandemic. As was seen during the initial stages of the pandemic, there were significant efforts made to adapt and reconfigure at speed. A modular hospital with standards for design, manufacture and assembly might support healthcare preparedness and resilience, but only if designers think about the integration. In the Huoshenshan Hospital, it would be impossible to rely on the traditional stick-built construction method within ten days. The pandemic is an accelerator for the use of prefabrication, modular construction, and the concepts of DfMA (Assaad & El-adaway, 2021; Wang *et al.*, 2021).

For the AEC industry, project organisational structure is usually multi-organisational and formed by contractual relationships (Turner & Simister, 2001). It is concerned with establishing a temporary governance framework (Turner & Müller, 2003). A valuable assumption under this theory is that the building, as a one-off product (Katila *et al.*, 2018), tends to "mirror" its organisational structures in which they are developed. As the highest level of prefabrication, modular building assembly is more similar to the product assembly process than traditional on-site construction. This highly integrated building type poses challenges to the organisation of design and construction firms. Many firms have not adapted their organisational structure to modular products, which has limited their innovation and capability. Without adjustments in the organisational structure, the designed process and the products will fall into the "mirroring trap" (Hall *et al.*, 2020). There is a need for a more strategic modular solution to transform project organisation for better building design.

The reported case strongly supported this assumption. As a modular healthcare building (i.e. one-off modular product), Huoshenshan Hospital was affected by its modular organisation. The reported case broke the "mirroring trap" by adapting the temporary organisation to the one-off modular product. The radical innovation in the organisation adaptation transformed the conventional DfMA path and integrated DfMA attributes. The sub-organisations were fully and effectively authorised internally to follow the building system rules and control requirements. This facilitated the independent operation of the organisation's sub-system modules at all levels and formed a flexible organisational structure, which contributed to the realization of concurrent design for manufacture and assembly.

The reported case provided a real scenario for investigating the in-relationship between DfMA countermeasures. The challenges are manifold, including (1) risks and uncertainties brought by more resource investment at the early stage; and (2) different interests and trust issues of stakeholders in the organisation network. Due to the rapid spread of the COVID-19, the budget for Huoshenshan Hospital was not an obstacle - the government made an evident commitment regardless of cost. The design and construction firms were all state-owned enterprises, which meant that economic and market forces were less likely to impact construction activities. Political incentives from the government encouraged close collaboration and coordination between different project stakeholders. The common desire to help Wuhan urges all parties to unite and cooperate. All stakeholders shared the same goal and worked together. All employee wore masks to work in the office and on the construction site and used online meetings to communicate in real-time. The concept of DfMA was successfully implemented based on these foundations. Hereafter, organisational integration occurred because the "mirror" breaking process became possible.

In the reported case, DfMA attributes were integrated by adapting the modular organisation to the technical structure of the modular building. The coupling between the modular organisation and the modular building provides a coordination mechanism to integrate DfMA. Designers made design trade-offs together, and multi-disciplines were integrated. As a characteristic of modularity (Langlois, 2002), information hiding provided a foundation for concurrent design and construction. It divided knowledge and work interfaces to make independent work possible in a very complex system.

Various studies have explored design strategies to improve quality defects (Woo & O'Connor, 2021), standardisation design (Choi *et al.*, 2020a), participation and coordination (Jang *et al.*, 2019), modularisation (Choi *et al.*, 2020b). This research contributes to the existing literature and knowledge base about DfMA guidelines/strategies by exploring its integration and implementation. Firstly, this research revealed the common attributes behind various DfMA guidelines/strategies. In addition, the conflict and relative nature of DfMA attributes are recognised. This research highlights the importance of integrating DfMA attributes more than just implementing all DfMA guidelines/strategies individually. Secondly, this proposes an integrated approach to DfMA by bridging the theory of DfMA and systems integration. This research found that the integration cannot be achieved without corresponding management strategies of DfMA in terms of project organisation. Thirdly, this study adds to the knowledge base of DfMA research from an organisational lens, and tries to facilitate integrated approaches through a lens of "mirror hypothesis". The correlations between organisational structure and product structure of the modular building are explored for the implementation of DfMA. Under the coupling of modular organisations and modular buildings, multi-disciplines can be systematically integrated. The breaking process of the "mirroring trap" raises opportunities and also potential challenges to the design and construction firms.

This case study provides insights for medical planners, healthcare architects, and healthcare project or corporate managers. Some studies have explored various aspects of emergency hospitals for COVID-19 in Wuhan, such as organisational citizenship behaviour (Wang *et al.*, 2021), standardisation, BIM (L.-K. Chen *et al.*, 2021) and POP modelling (Luo *et al.*, 2020). However, there is no research that focuses on design and design management. This paper goes beyond the previous academic discussion around DfMA guidelines/strategies to explore the integration organisations, incentives and mechanisms behind them. This research might support designers/managers in their decision making about diffusing DfMA guidelines/strategies. Firstly, this paper summarised five attributes of DfMA strategies and guidelines. The results could provide practitioners with a benchmark to evaluate the implementation of DfMA, especially for the performance of DfMA guidelines and strategies. Secondly, the integrated approaches identified in this study could be used to integrate the attributes of DfMA guidelines and strategies and tackle the conflicts among the achievement of attributes. Thirdly, critical to the integrated approaches to DfMA is breaking the "mirroring trap". DfMA could be facilitated by using the concept of modularity for the project organisation. Future practitioners can borrow the idea from the investigated case to adjust their project organisational structure to adapt to the building they will produce.

7. Conclusion

DfMA is widely regarded as an essential way to transform the AEC industry. However, the specific measures to implement DfMA guidelines/strategies proposed by the academic community and the integration of these measures are still unclear. The integration of complex building systems has not been fully explored. Therefore, this study adopted a single case study method to explore how DfMA attributes were achieved and integrated for building systems integration. The research suggests that DfMA's guidelines/strategies integration relies on the systematic integration of the five attributes. Breaking the "mirroring trap" by realising collaborative, concurrent engineering and integrated organisational structure innovation can better help realise this DfMA integration to influence the integration of complex building systems through DfMA effectively. Specifically, this research studied the first emergency building action to combat COVID-19 (i.e. Huoshenshan Hospital) and proved that (1) "mirror" organisational structure to technical structure could help the integration of DfMA attributes; (2) the systems integration of complex building relies more on integrated DfMA rather than using one or some of DfMA guidelines; and (3) integrated DfMA process also can feedback the strengthening of the organisational adaptation ("mirror") process. Specifically, this research found that although many studies emphasise the use of technology to promote communication between all parties involved in the building process, adopting advanced design and information technology is not a necessary approach for the adaptation (i.e. "mirror") and integration process. This research does not intend to deny the impacts of advanced technologies. It aims to investigate the essence of these transformation processes in a conventional construction environment, which can help us better use these advanced technologies to accelerate transformation. The reported case did not use advanced technologies (i.e. BIM software, design configurator, etc.) during the design stage but achieved systems integration, which provides an excellent opportunity for the investigation. The findings have contributed to the theoretical development of DfMA in the AEC industry.

This study has implications for modular hospitals as well as other complex buildings. At the theoretical level, the study advocates a transfer of research interest from DfMA guidelines/strategies to integrated DfMA. The exploration of delivery methods, procurement models, organisation innovation and technology promotion can create an ecosystem for the integration of DfMA. Using some DfMA guidelines/strategies alone may not improve manufacturability and assemblability at a whole life-cycle level. Still, the trade-off and the integration among all DfMA attributes are the most significant. And the latter largely depends on the ecosystem of the project organisation, including its innovation, adaptability, resilience. At the practical level, this research identified several design and management strategies to improve manufacturability and assemblability for complex buildings, especially for modular hospitals. By introducing Wuhan's experience, this research can enlighten relevant practitioners by using design strategies to achieve rapid healthcare construction capabilities. This case uses qualitative data to conduct a single case study, and other studies can use quantitative data to widen the breadth of its findings and determine its generalizability. In addition, the design and construction period studied in this case is relatively short. Future research may focus on organising and adapting to changes in different project phases in a long-term megaproject to integrate DfMA and promote the building systems integration.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, Tan Tan (tan.tan.17@ucl.ac.uk), upon reasonable request.

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Figure Captions

Fig. 1. Data collection process

Fig. 2. Collaboration between multiple disciplines

Table Captions

Table. 1. Interview questions

No.	Questions
1	Could you describe the project, including your role and responsibilities?
2	Could you describe the required outcomes, especially about manufacturability and assemblability?
3	Could you describe the strategies to improve DfMA. How were these strategies integrated?
4	Who was involved in the design stage? What should design and construction team integration look like? Were there any specific digital techniques that made it possible (e.g. BIM)?
5	Could you describe the design evaluation approaches used in this project?
6	Could you describe the decision-making process of design? Who was involved in the decision-making?
7	Could you describe challenges to DfMA? Were there any digital advancements to the application of DFMA?
8	Are there any lessons that you would take on to the next project?
9	Are there any important experience or opinions about the project that you want to add?

Table. 2. Sample of interviewees

No.	Specialization	Role	Working years
1	Architectural design	Leader	> 16

2		Designing principal	> 16
3		On-site designer	11-15
4		Designer	6-10
5	Structural engineering	Leader	> 16
6			> 16
7		Designing principal	> 16
8	Water supply and drainage	Leader	> 16
9		Designing principal	> 16
10		Designer	11-15
11			11-15
12			6-10
13	HVAC	Leader	> 16
14		Designing principal	> 16
15		Designer	11-15
16	Electrical engineering	Leader	> 16
17		Designing principal	> 16
18		Designer	> 16

Table. 3. Examples of coding data segments

Code/super codes	Interviews	Comments (from the data, highlighted by the code)	Measures (established from the comment)

Standardization	S1	"I designed a standardized ward that can be replicated everywhere. In the future, when we encounter a similar emergency project, these reserved wards can be used immediately for this assembly-type project."	Use standard modules
Collaboration	S2	"Four parties, including The CITIC, the healthcare operator, the main contractor and the government, participated in the decision-making and collaborated closely for the whole process."	Collaborative decision-making to avoid changes
Integration	S3	"Designers from the main contractor worked in the CITIC for better communication. Each design disciplines from CITIC allocated 1-2 designers to work on-site with the contractor."	All disciplines have designers from the main contractor

Table. 4. Attributes of DfMA and its management strategies

Aggregate dimensions	Code/super codes	Second Code
Design attributes	Modularity	Architectural design follows building modulus
		Building is formed by container modules
		Employ modular equipment

	Adaptability	Design functions/equipment adapting to weather change
	Flexibility	Use multiple connectors with different sizes
		Hand-drawn design on site to deal with emergencies
	Simplification	Installation adopts simplified procedures and methods
		Reduce the adjustment of the construction site
		Consider material supply and construction schedule issues
		Simplify the design of site foundation
		Design based on available construction materials
		Simplify design standards
		Simplify construction technique process and craft
		Assembly container modules off-site, install container modules on-site
		Follow temporary building standards
	Standardisation	Use standard modules
		Use standard interface
Design management attributes	Integration	All disciplines have designers from the main contractor
		All disciplines have on-site designers
		Purchase team work with designers directly
	Collaboration	All majors reserve interfaces for other majors
		Work in two shifts
		Online instant communication
		Collaborative construction process
		Collaborative decision-making to avoid changes

		Daily meeting and decision-making
	Concurrent Engineering	Concurrent design and construction
		Concurrent design, proofread and review
		Concurrent construction, inspection, acceptance
		Simultaneous construction in sub-regions
		Partial construction can be carried out when the partial design was completed