Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction

Zhikang Bao[1], Vikrom Laovisutthichai[2,*], Tan Tan[3], Qiong Wang[4], and Weisheng Lu[5]

1. Ph.D. Candidate, Department of Real Estate and Construction, Faculty of Architecture, University of Hong Kong, Pokfulam, Hong Kong. E-mail address: u3004700@hku.hk;
2. Ph.D. Candidate, Department of Real Estate and Construction, Faculty of Architecture, University of Hong Kong, Pokfulam, Hong Kong. E-mail address: vikrom@connect.hku.hk;
3. Ph.D. Candidate, The Bartlett School of Construction & Project Management, University College London, London, UK. E-mail address: tan.tan.17@ucl.ac.uk;
4. Professor, Department of Interior Design, School of Architecture, Soochow University, Suzhou, China. E-mail address: wangqiongdesign@vip.163.com;
5. Professor, Department of Real Estate and Construction, Faculty of Architecture, University of Hong Kong, Pokfulam, Hong Kong. E-mail address: wilsonlu@hku.hk.

* Corresponding author

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Abstract

Interior design and construction (IDC) is a sophisticated and often prolonged process that delivers a building to occupation. Traditional practice is rather unproductive, involving the work of several different trades crowded in situ and delivered sequentially one after another. To enhance productivity in IDC, offsite practice is receiving increasing attention as a process innovation along with Design for Manufacture and Assembly (DfMA), an emerging concept in the industry. This paper aims to investigate offsite IDC practice and develop a set of DfMA enablers for better achieving this building process. It undertakes a literature review, case study, and 18 semi-structured interviews. To support the offsite IDC and its production line, standardized procedure, automated machinery, and supply chain, 10 DfMA enablers are adopted, such as early collaboration, design standardization and simplification, and light material selection. These findings indicate a paradigm shift not only in interior design methodology but also in IDC professional practice process. This research enriches the literature on DfMA and IDC, in particular their synergy, and offers a new model for interior designers and offsite IDC practitioners.

Keywords: Design for Manufacture and Assembly; Enablers; Interior design and construction; Offsite construction.

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Introduction

In the building industry, an 'interior' refers to the internal space of a building structure or microscale human-made environment (Ching & Binggeli, 2018; Harwood, 1991). Design of an interior is a challenging undertaking because it has an immediate effect on the wellness, physical and mental health, and productivity of its users (Evans, 2003; Ulrich, 1991). Designers must consider an array of factors, including regulations, mood and tone, decorative styles, spatial planning, construction, materials, indoor environment, and sustainability (Friedmann & Savage, 2020). Likewise, interior construction is notoriously complicated and time-consuming. Before a building can be occupied, the work of several trades must be completed, such as flooring, partitioning, finishing, heating, ventilation, air conditioning (HVAC), and mechanical, electrical, and plumbing (MEP) installation. Traditional practice depends heavily on in situ construction, which is labour intensive and often done without a standardized working procedure (Jaillon & Poon, 2008). Among all aspects of project delivery, including foundation and superstructure erection, interior design and construction (IDC) is usually the most onerous, causing project delays, errors and reworks, workforce safety risks, poor constructability, and loss of productivity (Friedmann & Savage, 2020).

Inspired by the project management techniques of crashing and fast tracking (Ballesteros-Perez et al., 2019) and prefabrication construction (Gibb, 1999), the nascent area of offsite IDC (which may also be referred to as prefabricated IDC) is receiving increasing attention, particularly in repetitive high-rise building projects. While the superstructure is under erection, IDC can be performed in an offsite place (e.g., a factory) in parallel. The interior elements such as flooring, partitioning, finishing, and HVAC are designed in modules and prefabricated. Offsite IDC moves many construction activities from a site to a manufacturing line, providing a factory-like working environment and enabling mass production in the industry. It also significantly reduces wet trades and potential crowding of labour onsite. For these reasons, many industry practitioners and scholars consider offsite IDC to be an important process innovation in building project delivery (DEVB, 2018). It also presents significant opportunities and challenges for Design for Manufacture and Assembly (DfMA).

DfMA is 'both a philosophy and a methodology whereby products are designed in a way that is as amenable as possible for downstream manufacturing and assembly' (Gao et al., 2020). Originated from the manufacturing industry, DfMA has been applied to many sectors, such as automotive (Suresh et al., 2016), aerospace (Rajamani & Punna, 2020), and consumer products (Boothroyd, 1994). Recently, some architectural, engineering, and construction (AEC) organizations have begun to adopt this emerging design thinking to unlock value for clients. DfMA, sometimes regarded as a 'buddy system' of prefabricated construction, offers a new way to meet the demand for mass, efficient, and high-quality production (Tan et al., 2020). Various studies have explored DfMA enablers in the AEC industry. Here, a design enabler is a tool, technique, or strategy that assists designers at various phases of the design cycle and can

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be as simple as a requirements checklist or as complex as a customized computer-based analysis tool (Kayyar, 2007). In the AEC industry, DfMA enablers include transformation and development of the industry (Gao et al., 2020), understanding of project conditions and construction process (Tan et al., 2020), digitalization (Yuan et al., 2018), government legislation and incentives (Gao et al., 2018), and design optimization (Gerth et al., 2013).

However, most DfMA enablers, instructions, and frameworks are based on architectural design and construction, with little consideration, if any, of IDC. Differences in the design and assembly phases of architectural and interior design mean that construction-oriented DfMA enablers are not necessarily applicable to interior design scenarios. The DfMA enablers from offsite IDC practice remain unexplored. Moreover, the investigation of modern offsite construction has been mainly undertaken by the architecture and civil engineering communities. There is almost no research on prefabricated design and construction for indoor environments (Schneiderman, 2011).

To fulfil this gap and maximize the value of this innovative building process, this study aims to investigate offsite IDC practice and develop a set of DfMA enablers. It adopted qualitative approaches involving a real-life case study, 18 semi-structured interviews and a site visit.

Interior design and construction

Interior design and construction (IDC) is a creative and coordinated methodology used to design and construct interior and microscale environments that improve quality of life, productivity, health, safety, and welfare (Ching & Binggeli, 2018; Harwood, 1991). It primarily emphasizes various details, such as space planning, furniture arrangement, interior surface treatments, fixtures, colour and tone, finishing materials, lighting, electrical and communication system, graphics, and signage. Compared to architectural design and construction, IDC is perceived to be more 'feminine', 'artistic', and 'detailed' (Havenhand, 2004). It is often a subsystem of projects that takes place after architectural design and building construction (Havenhand, 2004). This unique profession requires special qualifications and has its own set of principles, knowledge, criteria, standards, and organizations. It also has a massive impact on or is impacted by the activities such as material processing, production, assembly, occupancy, renovation, and demolition (FIDER, 1988; Harwood, 1991).

Recently, the influence of offsite construction technology has begun to be seen in IDC. While traditional methods heavily rely on onsite activities such as wet processing and cutting materials to fit available space, offsite IDC transfers a portion of in situ works to a factory-like environment to allow mass production (Jaillon & Poon, 2008). It can be considered an innovative construction practice, involving pre-assembly of components in a manufacturing line and then transportation of these components to the site where the structure is located (DEVB, 2018; Gibb, 2001). This shift instigates many advantages to the industry, including an

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escalation in construction productivity and safety (Jaillon & Poon, 2008). However, the achievement of offsite IDC requires strong support and change in the traditional IDC professional practice. The interior design process holds a prodigious opportunity to support this construction technology from the early stage of a building life cycle, but the implementation of DfMA in interior design first needs to be reinterpreted and contextualized. Thus, exploration of DfMA enablers for IDC is a pressing need.

DfMA in construction

DfMA was introduced in the manufacturing industry under the umbrella of Design for Excellence (DfX), where 'X' or 'Excellence' can be substituted by many terms to mitigate various challenges (Kuo et al., 2001), e.g., Design for Environment (DfE), Design for Safety (DfS), and Design for Construction Waste Minimization (DfCWM) (Laovisutthichai et al., 2020). This doctrine has been reinterpreted and adopted by the automotive (Suresh et al., 2016) and aerospace industries (Rajamani & Punna, 2020), among others. In the AEC industry, DfMA can be defined as: (1) a design process and principles for approaches to structural or component manufacturing and assembly; (2) a design evaluation system for manufacturability and assemblability; and (3) a design philosophy embracing prefabricated construction technologies (Gao et al., 2020). To promote DfMA in the AEC industry, numerous DfMA enablers have been investigated and proposed. After searching databases and scrutinizing the collected findings, we have compiled a list of 10 DfMA enablers for architectural design, shown in Table 1 with explanations.

Table 1. DfMA enablers for architectural design from the literature

These DfMA enablers help remedy discontinuity and fragmentation in the AEC industry by breaking 'the wall' between designer and manufacturer (Boothroyd, 1994). Other advantages include savings in time and costs, process simplification, labour force safety, and improvements in constructability. However, it can be seen from Table 1 that these lessons are mainly derived from the architectural and structural design cases. DfMA enablers for IDC, including finishing, MEP, and HVAC design and construction, are rarely investigated.

Research methods

The study adopts a series of qualitative research approaches, combining interviews and a site visit organized as single case study. A case study allows researchers to focus on a particular issue, feature or unit of analysis to comprehend complex real-life activities (Crowe et al., 2011; Noor, 2008). It is often jointly used with other qualitative methods to enhance robustness (Yin, 2017; Bao et al., 2019). In this study, by examining the case of one of the largest IDC companies in China, we aim to develop a set of DfMA enablers that are of immediate use and potential referential value to interior designers and other interested parties.

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Case description

The case study firm has undertaken a series of IDC projects and built a reputation around the globe. It is the IDC provider for almost all well-known hotel management groups. For a greener and smarter IDC industry, in recent years, the firm has pioneered the promotion of prefabricated IDC. The firm has developed a relatively mature system for prefabricated IDC, which has been implemented in several real-life projects. Given its prominence in the offsite IDC business both in China and overseas, we expect to derive sufficient insights from our case study of this firm.

Interviews

To garner insights into DfMA for prefabricated IDC, the authors conducted a series of semi-structured interviews with stakeholders in the case study firm. A semi-structured interview is a qualitative research method where interviewees are usually asked a series of predetermined, but open-ended questions (Given, 2008). It is particularly useful where the opinions and perceptions of interviewees on complex issues are sought (McIntosh and Morse, 2015), and is thus considered a suitable method for teasing out insights on DfMA for prefabricated IDC. In total, 18 semi-structured interviews were conducted over a two-month period. Basic profiles of the interviewees are shown in Table 2. Selection of interviewees was based on two criteria. One was the experience in IDC and practical involvement in at least one phase of prefabricated IDC. For a rounded picture, the other was a sufficient diversity of interviewee backgrounds to cover different phases of IDC. All semi-structured interviews were conducted face-to-face to allow for an intuitive approach and the opportunity to elicit more in-depth information. Since the goal of data saturation was accomplished, they were considered satisfactory for this study.

Table 2. Basic profiles of interviewees

Interviews were conducted in two rounds. During the first round, the questions were more open-ended. In the second round, with reference to the 10 DfMA enablers identified by the authors (see Table 1), interviewees were asked whether they had adopted any strategies in their design process. If yes, they were asked to describe each strategy and operation in detail. To minimize bias in interviewees' opinions, the authors used objective questions to elicit factual responses rather than subjective personal opinions. Given the potential for DfMA enablers beyond those previously identified by us, flexibility was provided for interviewees to discuss additional DfMA strategies used in their practice, if any. Each interview lasted between 1 and 1.5 hours and was audio-recorded with interviewees' informed consent. All recordings were transcribed, and labelled by interviewee name. During transcription, the authors contacted some interviewees again through telephone to verify and clarify vague information. After 18 transcription documents were produced, DfMA enablers for interior design mentioned by the majority, i.e., two-thirds of interviewees, were noted. At least two authors were involved in the conduct of interviews and interpretation of the transcribed documents to ensure transparency and minimize bias in the results. Further, all authors could access the transcripts and comment and revise the data analyses, an approach similar to enhancing inter-rater reliability.

Site visit

The site visit was undertaken to deepen our understanding of how DfMA enablers are executed and reflected in real-life prefabricated projects and inform our interpretation of the interview results. Sample prefabricated interior projects that the case study firm showcases to customers were viewed, mainly to observe differences between the appearances of prefabricated IDC projects (see Figure 1) and conventional IDC projects. The site visit took about two hours, and the project manager accompanied the authors and elaborated on how these prefabricated IDC projects are conducted using different construction technologies.

Figure 1. Building interiors completed using offsite IDC

Results

The case study and interview results, based on the criterion of interviewee mention frequency, support the formation of DfMA enablers for offsite IDC (see Table 3).

Table 3. A summary of DfMA enablers for offsite interior design and construction

Collaborative design with early engagement with architect

The emergence of offsite interior construction suggests that interior design should be involved at a very early stage to better synchronize with the architectural design. At a very early stage, architects are strongly suggested to consider many offsite IDC factors such as the standard dimensions of prefabricated interior modules. Interviewee 11 explained:

> *The width and depth of a room are encouraged to better fit into the dimensions (best in an integral multiple) of some most commonly adopted modules in the interior design.*

However, due to lack of understanding of prefabrication technology, some stakeholders decide to adopt prefabricated IDC after the main civil structure has been finished. In such cases, matching the interior space and the pre-defined modules is more challenging. Additional work, such as cutting the existing modules to fit into the dimensions, has to be conducted onsite, leading to considerable material wastage. Interviewee 2 reflected that:

> *If prefabricated bathrooms are adopted, then the level, slope, waterproof, and space for the drainage system should be integrated, requiring depth for sloping of at least 300 mm.*

Without early engagement of interior designer, manufacturer, and contractor, prefabricated IDC project delivery is hugely problematic. For instance, some clients adopt hollow bricks for wall construction to save costs. These walls are unsuitable for a prefabricated interior because they cannot provide enough support for the bolts that need to be embedded to install wallboards. Moreover, some stakeholders reduce floor-to-floor height to maximize saleable area, but

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prefabricated interior projects require additional ceiling space. Interviewee 5 suggested that:

> *If we could have an early engagement, we would suggest leaving some holes or space for locating equipment at the same level as the floor beams or slabs without sacrificing storey height.*

Modular design

Modular design is unanimously a DfMA enabler for prefabricated IDC. Usually, the interior designer keeps some of the most commonly adopted modules of different systems in mind. For example, the case study firm has a long-term cooperation with some suppliers, who provide a list of modules that they can produce efficiently and economically in advance. The interior designers will then select modules from that list. Usually, types of prefabricated IDC modules are rather limited due to equipment and technology constraints. For prefabricated construction, types of modules are much more diversified and customized given their development over five decades and relatively mature equipment and technology (Marchesi and Matt, 2017). Interviewee 8 said that:

> *There may be only three most commonly used types of modules for the floor system, e.g., 300 mm×300 mm, 400 mm×400mm and 500 mm×500mm. The interior design will select one of the three to match the room's dimension and minimize material wastage.*

There are some exceptions for module selection. Sometimes, the existing modules cannot match the dimensions of a room. If the project is on a large scale, interior designers will negotiate with manufacturers to see whether they can customize particular modules for the project. However, it is not easy for manufacturers to produce customized modules. Interviewee 12 explained that:

> *The manufacturer has to make new moulds and adjust the equipment to produce customized modules, which is extremely costly. As such, only if the project is large enough in scale will the manufacturer agree to produce customized modules.*

Connection detail design

Connection detail design is a critical factor affecting the quality and performance of prefabricated projects. As prefabricated IDC is still in its infancy, great efforts have been devoted to exploring connection detail design, for example, through cross-sectoral learning. Interviewee 10 reflected that:

> *Due to the lack of relevant experience, our company has employed some experts from the automotive industry to see whether the connection detail design from a relatively mature industry can be applied to offsite IDC.*

The case study firm has developed various technologies for connection detail design in prefabricated IDC project systems (see Figure 2). The floor system consists of three layers: levelling stents, GRC (glass fibre reinforced concrete) basal plate, and surface plate, e.g., ceramic tile or wood parquet. Usually, one GRC basal plate is supported by four levelling stents

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at the bottom and covered by one surface plate at the top. This three-layer structure in the floor system applies interlocking connection design between elements. Onsite workers just need to level the four stents to keep them in the same plane horizontally and connect different elements manually, without the need to use large amounts of emulsion varnish. For the wall system, three types of connection detail design have been developed: skirting line connection, stitch connection, and tight connection in response to block-brick based wall, hollow-brick based wall, and shear wall, respectively. The wallboard is connected with a light gauge steel joist by a physical connector. The connection detail design of the integrated ceiling system is the most complicated. Interviewee 5 said that:

> *We adopted a kind of end cap in 'L' shape to connect the elements of the gypsum board integrated ceiling system. However, some customers feel it affects the aesthetics as the connection would lead to an inevitable gap between elements. Therefore, we have developed a new connection to overcome this drawback.*

Figure 2. Connection detail design and construction of floor, wall, and ceiling systems

Design simplification

Design simplification involves various techniques. First, the design philosophy at the case study firm is to pursue simple and flat design, which means the elements will be kept in very basic geometry, and some unique geometries are forbidden (see Figure 3). For example, the use of arch elements is minimized as manufacturers still have difficulty designing the connection details and producing this structure. Design simplification contributes to the simplification of production, logistics, and assembly process. This design technique also reflects the objective of offsite construction to achieve mass production (Monizza et al., 2018).

Figure 3. Design using basic geometry in real-life projects

The simplification of connection detail types and designs is also critical for improving the efficiency of onsite assembly, as fewer connection types mean less dependence on the skills of onsite workers. The case study firm aspires to the simplicity of IKEA furniture and LEGO assembly, such that non-professionals could quickly assemble their products. Interviewee 14 explained that:

> *Initially, we have eight types of connection, three for the wall system, two for the floor system, two for the integrated bathroom system and one for the integrated ceiling system. Now, we have unified the types of connection design for the wall and integrated ceiling system into one.*

Design should also support interior component integration and offsite production processes. Designers have endeavoured to shift most of the workload from onsite to offsite to achieve the objective that all elements are independent product. Accessories, e.g., intelligent switches,

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should be integrated offsite, so their onsite assembly by workers does not demand too much expertise. One compelling example of construction technology simplification by the case study firm is in wallpapering work. Interviewee 5 explained that:

> *Traditionally, we need at least seven steps to conduct the wallpapering work. Now, we just need two steps onsite, installing the light gauge steel joist and attaching the surface plate with a physical connector. Most work can be conducted offsite, e.g., attaching a PVC (Polyvinyl Chloride) membrane on its surface.*

It is also recommended to reduce the number of elements to a minimum, a form of DfMA thinking that has been seen in Tesla (Synnes and Welo, 2016). For example, for spaces 1.20 m in length, modules 600 mm in length is preferred over 300 mm as then the manufacturer only needs to produce two modules, and onsite workers will need to assemble the two modules at a time. Interviewee 10 said that:

> *If we find a 200 mm gap when using the module of 600 mm, we would consider whether a single module of 800 mm could be adopted instead of dividing into two modules.*

Finally, a consistent modules' numbering process throughout design, manufacturing, and assembly has been well established in the case study firm. It facilitates the manufacturer and onsite workers to quickly comprehend and execute the design, minimizing human error or misunderstanding and simplifying the working procedure. Interviewee 11 explained that:

> *We will envision the construction sequence of the onsite workers. During this process, from design to construction, we would consecutively number the modules. Afterwards, the manufacturer will produce these modules in the same order. Finally, the onsite workers will also assemble these modules accordingly.*

Design standardization

Design standardization is a crucial DfMA enabler for prefabricated IDC. Presently, residential unit designs vary from one to another depending on project conditions, laws and regulations, and users' requirements. This variation is not convenient for interior prefabrication and design standardization. To encourage interior DfMA and offsite IDC, the concept of house type standardization should be embedded throughout a broader range of stakeholders. For example, if a house is 93 m^2 or 120 m^2, its layout and dimensions should be standardized even across developers. Interviewee 10 said that:

> *Now, we are working towards this objective by collaborating with some leading stakeholders in China, such as Evergrande and Vanke, to standardize the house types.*

The dimensions of elements made of different materials should also be standardized and coordinated across manufacturers. For example, many standard material dimensions, e.g., calcium silicate plate or bamboo wood fibreboard, are 200 mm or its multiple in length. The other manufacturers should also produce elements with lengths of 200 mm, 400 mm, 600 mm,

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and so on. By establishing such a standard, manufacturers could keep modules inventory without considering the market much, further facilitating manufacturing and assembly efficiency. Interviewee 4 added that:

> *We are now collaborating with China Building Decoration Association to establish such a standard.*

The case study firm has also standardized the procurement process. For example, the procurement process for the elements in the floor system, wall system and integrated bathroom system have all been standardized. The process is applicable to almost all prefabricated interior projects and allows both manufacturers and onsite workers to quickly comprehend the interior design. Apparently, the achievement of such a standardization technique requires coordination from all stakeholders in the IDC supply chain.

Element shape, weight, and dimension concerns

When designing the shape, weight, and dimensions of a prefabricated interior element, various limitations should be considered, including transportation method, vehicle, lift and stairs, room entrance, and ease of handling and assembly. For example, dimensions should not exceed those of vehicles, lift, or stairs (see Figure 4). In main structure construction, tower crane are used to deliver heavy materials, but interior construction materials are usually delivered via service lift, thus limiting the dimensions of elements significantly. Sometimes the lift is unavailable, so the elements have to be handled manually and manoeuvrable, without damage, around corners between flights of stairs. The dimensions of integrated sanitary ware, consisting of three elements (chassis, wall, and top) are a particular challenge. Interviewee 15 explained that:

> *The chassis is usually in a size of 2 m×2 m, but many times the construction of the main structure has been finished when we conduct the interior, and the entrance of the bathroom is just 2 m×1.2 m. Given that, we need to consider dividing the whole element into two pieces and assemble them onsite.*

Figure 4. Component shape, weight, and dimension concerns

Regarding element weight, handling equipment should be considered during interior design. If a handling bracket is used, how many elements should be bundled into one package without overloading should be calculated. The same applies if the elements are to be carried manually, to avoid overburdening onsite workers. Interviewee 9 provided the example that:

> *In terms of the calcium silicate integrated plate, three such plates should be bundled so that the total weight, e.g., 50 kg, is suitable to be taken by two onsite workers.*

Material-lightened design

Material-lightened design enables prefabricated elements to be manufactured and assembled efficiently and safely. The case study firm has developed a new type of lightweight concrete

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for use in their projects, reducing weight by one third. It also always coordinates with its manufacturers to condense elements to as small a depth as possible without jeopardizing material performance and durability. This strategy benefits all stakeholders as the thinner the elements, the larger space available for other purposes. Interviewee 8 added that:

> *Based on our exploration, we are now able to use some elements in an extreme depth. For example, we use a ceramic plate with a depth of 6 mm (see Figure 5) or a calcium silicate plate with a depth of 5 mm.*

Figure 5. Ceramic plate with a depth of 6 mm in real-life projects

However, adopting a material-lightened design strategy can be difficult. Use of an alternative lightweight material or condensing to an extreme depth must also be allied to other factors. For example, in the integrated ceiling system, fire resistance rate matters, while water and corrosion resistance are the key for the wall system. In the floor system, a 500 mm×500 mm basal plate, should bear loading of at least 2 tons.

Interviewee 13 added that:

> *Even if the material properties can fulfil all the requirements, the cost is another decisive factor.*

Technology-rationalized design

The rational adoption of some digital technologies to aid the offsite IDC process is an important DfMA enabler. Presently, BIM technologies have been widely applied to many prefabricated projects. The case study firm adopts two BIM routes in their interior design. First, it uses Revit, a BIM software developed by Autodesk, to facilitate coordination as its use is universal among AEC industry stakeholders. Using the models built by Revit, the firm can simulate the practical construction process to detect any errors, such as overlapping pipelines, and correct them. Afterwards, it extracts a detailed working plan from Revit and sends it to the project manager for precise installation onsite.

However, it is time-consuming and costly to train professionals in the use of Revit, further exacerbated by the fact that existing software is not easily adaptable to prefabricated IDC. Hence, the case study firm has developed its own BIM software for prefabricated IDC, called ‘Fun Plus’ (see Figure 6). The firm inputs all the modules in different dimensions and materials, connection types, construction technologies and even price. During the BIM process, the designers just need to select the proper modules and construction technologies, without having to adjust some parameters as they do in Revit. Interviewee 17 explained that:

> *Afterwards, we can quickly extract the Bill of Quantities (BOQ) of all the materials and send it to the manufacturers for immediate procurement. This practice can enhance working efficiency.*

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Figure 6. BIM process with 'Fun Plus' in a real-life projects

Knowledge and information management

As the development of prefabricated interiors is still in its early stage, proper knowledge and information sharing and management are essential for successful project delivery. In practice, very few practitioners have a good understanding of construction technologies. In every project, the case study firm has a three-level technology training process, including technical training of the project manager by the decoration technology designer, onsite worker group leaders by the project manager and onsite workers by their group leaders. Interviewee 13 added that:

> *Our designers will visit the sites regularly to gain the workers' opinions on whether the design and current technologies are convenient and straightforward enough and what we can do in the interior design process for further improvement. This is a kind of bidirectional knowledge and information sharing process.*

The case study firm also regularly arranges demonstration meetings for knowledge and information sharing among interior designers, technology designers, BIM designers, project managers, and other professionals. Interior design is sometimes more focused on aesthetics, but the execution of their design relies more on technology designers. In such meetings, stakeholders learn from each other about a wide range of criteria from different perspectives.

Materials selection and combination

The selection and combination of materials for offsite IDC projects is even stricter than in traditional projects. Environmental friendliness and geographical difference are two critical material selection criteria. In terms of environmental friendliness, for traditional IDC, a 3- to 6-month transitional period is typically required to let some harmful gases, e.g., formaldehyde and benzene, fully emit from materials before the occupancy stage. Environmentally friendly materials and a dry installation process for prefabricated IDC shorten this transitional period, and users can move in immediately. This poses higher requirements to the materials. Interviewee 8 said that:

> *We only ever spent 12 days completing the prefabricated IDC for a residential unit with an area of 97 m^2.*

The case study requires that all materials used in a prefabricated interior fulfil E0-class environmental standards, which stipulate a formaldehyde content of no more than 0.5 mg/L, the highest standard internationally. Moreover, to increase the reuse and recycling rate, all modules are detachable and decomposable. Wide adoption of virgin materials, such as timber and stone, in traditional IDC has caused severe ecological damage, so virgin materials are not suggested in the prefabricated interior projects. Interviewee 5 said that:

> *We try to select some artificial composite materials, e.g., rigid vinyl plank (see Figure 7), a new developed composite material to replace the traditional wood floor. We also use an imitation marble plate to replace the original marble for the wall.*

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Figure 7. Some artificial composite materials in real-life projects

Regarding geographical difference, the selected material properties should align with the temperature, humidity, and corrosivity of the geographical location in which they are to be used. For example, bamboo wood fibreboard is not recommended for use in extremely cold places, as it will become brittle and cracked, but is preferred in places with very high humidity, as it has a good water absorption abilities. In coastal regions, either galvanized or plastic screws can be a wise choice for better corrosion resistance. Before using a new material, its geographical feasibility and compatibility to prefabrication must therefore be tested.

Discussion

The arrival of offsite IDC brings both opportunities and challenges to the AEC industry. It transforms traditional artistic interior design, and site-intensive and time-consuming in-situ construction, making it more manageable and systematic through the adoption of innovative offsite construction technology (Friedmann & Savage, 2020; Jaillon & Poon, 2008). This empirical investigation reveals that offsite IDC relies on a well-integrated supply chain, standardized production procedures in a factory-like environment, advanced planning and scheduling of building components logistics, dry installation processes, and advanced machinery involvement. These characteristics challenge conventional professional practice, architectural and interior design methods, stakeholders' roles and responsibilities, and organizational structure. Also, since prefinished interior components must be considered from the beginning to improve offsite constructability, offsite IDC changes the position of the interior design team from follower of architectural and engineering design (Havenhand, 2004) to collaborator in the collaborative design process from the beginning.

To facilitate this process, DfMA encourages the interior design methods of, for example, early coordination for a well-prepared construction, design simplification and standardization for facilitating the production process, exploring design opportunities without neglecting criteria from the transportation stage, and selecting standard components from a supply chain instead of crafting or customizing for a specific area. These can be regarded as assistive tools or time-saving standards for practitioners to prepare an interior design scheme and deliver the best practice. Although many interior DfMA enablers, at first glance, are similar to those proposed in the previous literature (Tan et al., 2020), their details, interpretations, and utilizations are not identical. Rather, they mainly focus on the internal or microscale environment, including space arrangement and functions, surface materials, interior modules and elements, and dimensions, to ease offsite production, component and module transportation, and assembly flows.

Comparing DfMA enablers for offsite IDC with conventional practice, it becomes apparent that its realization will confront various challenges. First, as offsite IDC needs earlier decision-

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making from upstream design, involved stakeholders must overcome the chronic fragmentation in the AEC industry. Second, successful implementation of DfMA and offsite IDC relies not only on designers but integration of the whole supply chain, including proprietors, developers, and manufacturers. For instance, integrated and standardized interior modules can be achieved only if many manufacturers in the supply chain are coordinated to produce standardized materials, and then only if designers include these materials in a design. Finally, there exists a stereotypical perception that the products of offsite technology lack aesthetic value, are too standardized to satisfy customized demands, and are inferior in quality due to lightened materials (Steinhardt & Manley, 2016). To counter this, IDC stakeholders should devote more efforts to developing offsite IDC and improving end-users' confidence. Overall, a healthy ecosystem involving various stakeholders in the IDC supply chain must be established to unlock the promise of offsite IDC and DfMA.

This study has limitations in four areas. Firstly, the reliability and replicability of a single case study are inevitably a concern (Yin, 2009; Flyvbjerg, 2006; Yang et al., 2021; Zhao et al., 2020), although we selected one of the largest IDC companies in China as a case study, and it indeed provided many insights. Secondly, as offsite IDC emerged only recently, even a sizeable company like the one studied here has acquired its insights mainly from residential projects. To what extent the DfMA enablers can be applied to other types of offsite IDC projects is unclear. Thirdly, this study is mainly qualitative in nature. A subjective intention of the authors may be imposed on interpretation of the data collected, leading to possible bias in the interpreted results, despite measures taken (e.g., group discussions, multi-round revisions) to minimize it. Fourthly, the results are mainly based on the interpretations of the 18 interviewees. Due to difficulties of accessibility and liaison, results are not validated through focus group discussion or interviews with IDC practitioners and scholars outside the case study firm. This likely affects the validity and generalizability of the results in a wider context.

Conclusion

Offsite IDC is an innovation in the AEC industry that can revitalize site-intensive conventional construction by the establishment of a supply chain, the machinery involved in the production, well-planned transportation, and standardized dry assembly method. From the initiation stage of a building's life cycle, DfMA has great potential to assist in the design of interior components and in facilitating their offsite production and assembly. This study identifies 10 DfMA enablers for offsite IDC: (1) collaborative design, (2) modular design, (3) connection detail design, (4) simplification, (5) standardization, (6) material-lightened design, (7) shape, weight and dimensions of elements, (8) knowledge and information management, (9) technology-rationalized design, and (10) material selection and combination. Interior designers must collaborate from the start, integrate with the supply chain, consider offsite construction processes, and select and compose standard components and materials. These findings highlight the changes in both interior design methodology and construction stakeholders' roles and

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responsibilities. They also expand understanding of DfMA and offsite technology from architecture to interior in the AEC industry.

The advantages of offsite IDC suggest it will increase in popularity while the use of DfMA for this purpose will gradually extend to various building types. However, full benefits of this innovative design and construction method will only be enjoyed by the AEC industry when the supply chain is well established and coordinated and the market is prosperous enough. Thus, more developers, designers, manufacturers, couriers, contractors, and vendors are encouraged to coordinate and step into this value chain. The 10 DfMA enablers for offsite IDC identified here are just some examples. Future research is recommended to explore the innovativeness of offsite IDC and interior DfMA enablers in other settings and building types, such as healthcare and hospital facilities and from other construction stakeholders' perspectives. The trend of integrating home appliances and automation with interior components in offsite IDC should also be investigated.

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