Digital-enabled Design for Manufacture and Assembly (DfMA) in Offsite Construction: A Modularity Perspective for the Product and Process Integration

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Abstract

This study aims to use modularity to impact various facets of Design for Manufacture and Assembly (DfMA) and explore the relationship between product modularity, process modularity, and DfMA within the context of Offsite Construction (OSC). The study fills this

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gap through an exploratory single case study by identifying perceptual measures of these three concepts. The study shows the alignment between multi-dimensionality of modularity, such as product modularity and process modularity, enhances the capability of DfMA. From a modularity perspective, the reconfiguration of abstraction, information hiding, and interface is an essential strategy to change the traditional design process. This reconfiguration is to adapt to the new scenarios brought by OSC and digital fabrication technologies and the new design tasks associated with these scenarios. This study has theoretical implications for the modular approach to DfMA and practical implications for those who expect digital fabrication techniques in offsite construction.

Keywords: Product modularity; Process modularity; Design for manufacture and assembly; Design innovation; Modular construction

Introduction

Offsite Construction (OSC) refers to the process of manufacturing and pre-assembling elements or components of a construction project at a location different from the installation location. Usually, it includes planning, design, manufacturing, and assembly in purpose-built factories (Goodier and Gibb, 2007). The meaning of OSC sometimes appears in the literature through some interchangeable terms, such as 'prefabrication', 'industrialised construction', 'offsite manufacture', 'manufactured construction', 'Modular Integrated Construction (MiC)' and 'Modern Methods of Construction (MMC)'. These concepts all favour repetitive components with a factory-based environment for the construction products and create a vision with capabilities in production safety, economies of scale, and sustainability. However, many implementation barriers of OSC hinder the transformation of the Architectural, Engineering and Construction (AEC) industry, such as inappropriate design processes, high initial set-up costs, immature techniques, and lack of skilled labourers (Arif et al., 2012, Pan and Sidwell, 2011, Mao et al., 2015, Gan et al., 2018).

Digital fabrication techniques, such as robotics, are transforming traditional design processes and building products in OSC. Meanwhile, Design for Manufacture and Assembly (DfMA) has the potential to empower digital fabrication techniques and accelerate OSC implementation (Lu et al., 2021, Gao et al., 2019). DfMA has gained attention globally due to government promotion policies (Langston and Zhang, 2021, Tan et al., 2020). The primary purpose of DfMA is to assist designers in increasing productivity by integrating downstream knowledge into the design stage (Kuo et al., 2001, Tan et al., 2020). Compared with design approaches focusing mainly on aesthetics and functions, DfMA considers buildability, sustainability, and usability. DfMA aims to systematically integrate these objectives without compromising aesthetics and functions to ensure the maximum value of sustainable projects by introducing both methods and mindsets from the manufacturing industry (Yuan et al., 2018, Arashpour, 2019). DfMA breaks sector boundaries and poses severe challenges to interdisciplinary and interdepartmental collaborative innovation (Lu et al., 2021, Gao et al., 2019). Many studies emphasise the significance of a multidisciplinary team in DfMA (Ashley, 1995, Omigbodun, 2001, Gao et al., 2020). With interdisciplinary teams and heterogeneous software/hardware systems, the integrated design process between multidisciplinary teams is regarded as a significant prerequisite for efficient and effective collaboration (Shen et al., 2010). The shift towards utilising OSC increases the integration challenges between multidisciplinary teams and requires further transformative design workflows. However, how to adapt DfMA processes for OSC productions is still in its infant stage. Understanding the relationship between design processes and products would be valuable for filling this research gap.

This study aims to explore the relationship between product modularity, process modularity, and DfMA within the context of OSC. The main research question is: whether and how do the alignment of product modularity and process modularity enhance the capability of DfMA? Data were collected through a longitudinal action research case study. The remainder of the paper is organised as follows. Section 2 reviews product modularity and process modularity. Section 3 describes the methodology. Section 4 presents three major themes identified in the study, namely 1) embarking on digital-enabled DfMA; 2) product modularity in OSC; and 3) modularity in the design process. The discussion is shown in section 5. And finally, section 6 reports the conclusions.

Theoretical Background

Modularity

Modularity, as a complexity-reduction strategy (Baldwin et al., 2000), has the potential to empower OSC techniques and impact various facets of DfMA. Baldwin and Clark (2006) indicated three purposes of modularisation in design: 1) to make complexity manageable; 2) to enable parallel work; and 3) to accommodate future uncertainty. In addition, modularity emphasises the interdependence within and independence across modules. Baldwin et al. (2000) captured the essence of modularity from three ideas: 1) abstraction; 2) information hiding; and 3) interface. The *abstraction* means to hide the elements' complexity (Baldwin et al., 2000). *Abstraction* is usually used as a complexity mastering strategy by keeping essential features of an object without including background or inessential detail (Graham, 1994). Parnas (1972) introduced *information hiding* to devise modular structures in software design. This term is also applied to complex systems (Baldwin et al., 2000). *Information hiding* refers to the fact that all information about a module (including data and functionality) is encapsulated and hidden from other modules unless specifically declared public (Graham, 1994). The *interface* is a shared linkage between components (e.g. people, information) for open interchanges and a rule to control the flow of information (Voss and Hsuan, 2009). In essence, the *interface* as part of the public information set is a pre-established way to resolve potential conflicts between the interactive parts of the design.

The modularity research in the AEC industry shows mainly two directions. From a technical perspective, modularity usually refers to modular construction and focuses on physical building component-based integration to modules. From a social-technical standpoint, there are emerging concepts, including modular projects (Flyvbjerg, 2021, Gil et al., 2005), modular supply chains (Doran and Giannakis, 2011), and modular design processes (da Rocha and El Ghoz, 2019).

Product modularity

Product modularity as a sub-concept of modularity corresponds to 'modularity-in-design'. Product modularity is a product design strategy using standardised and interchangeable components to configure various products (Schilling, 2000). As a multi-faceted concept, there is little consensus on the definition of product modularity (Gershenson et al., 2003). Campagnolo and Camuffo (2010) classified definitions into three main categories. Firstly, from a functional perspective, product modularity considers the degree of modularity of product architectures. A product architecture can be defined by 1) the arrangement of functional elements, 2) the mapping from functional elements to physical components, and 3) the specification of the interfaces between interacting physical components (Ulrich, 1995). The differences between "modular" product architecture and "integrated" product architecture can be identified through these three aspects. From a technical-oriented perspective, the rationale indicates the existence of an 'optimal' degree of product modularity. In addition, various objectives of modularisation lead to a more complex definition of product modularity (Gershenson et al., 1999, Ishii, 1998). For example, the objectives could be designed for time-to-market, manufacture, assembly, logistics and disassembly. Thus, they have different modularisation methods and measures. In design for manufacture, the measure is to reduce the recycling time of the manufacturing process. In design for assembly, reducing assembling operations is the main measure.

There is a strong relationship between the objectives, definition of modules, modularization method and measures. It is difficult to establish a one-for-all definition fitting each life-cycle phase. Therefore, a clear goal is essential for defining product modularity and ways of modularisation (Campagnolo and Camuffo, 2010). Other research tries to adopt a mixed perspective for developing a modularization methodology by combining functional and life-cycle perspectives. In the AEC industry, a few have investigated the concept of product modularity (da Rocha and El Ghoz, 2019, Chauhan et al., 2022, Da Rocha and Koskela, 2020, Eriksson et al., 2021). However, these studies all adopted a single-level perspective of modularity without considering other perspectives. In other words, few strategies of product modularity are generated based on the relationships among the multi-dimensionality of modularity.

Process modularity

Process modularity, corresponding to 'modularity-in-production', mainly used for planning purposes, describes the degree to which a process can be decomposed into modules for parallel execution (Parraguez et al., 2019). Specifically, process modularity is to standardise manufacturing sub-processes to be resequenced easily or open inter-change for new modules' "plug-and-play" (Tu et al., 2004). Hence, there are few strong ties between process modules (i.e. sub-processes), which facilitates rapid decoupling and resequencing of processes (Fine et al., 2005). Feitzinger and Lee (1997) proposed three principles for process modularity, including 1) process standardisation, 2) process resequencing, and 3) process postponement. Firstly, process standardisation is the decomposition of a process into standard sub-processes. Then, process standardisation produces standard basic units and customises sub-processes of the base units shared by products. Secondly, process resequencing stands for reordering sub-processes to achieve the occurrence of standard sub-processes firstly and the occurrence of customization sub-processes lastly. Thirdly, process postponement means postponing customisation sub-processes until a customer order is received or placing those sub-processes in distribution centres for maximum flexibility. In addition, there are two process dimensions (i.e. time and space) for defining the coupling between modules. Highly integral process architectures can be integrated with time and space at the same time. It is also possible to integrate process architectures in either time or space (Voordijk et al., 2006).

In the AEC industry, there are rarely existing studies about process modularity. As most studies related to process modularity are from the manufacturing industry, the uniqueness of the AEC industry may make some attributes, relationships, or effects of process modularity not work in architectural practices. In addition, buildings, as a one-off product manufactured by a temporary organization, may increase or decrease the importance of certain principles of process modularity, as the scale effects of cross-project/product may be difficult to be achieved in many cases. Thus, more evidence is required to test the concept and theory of process modularity.

The alignment of product and process modularity

Research about the relationship between product modularity and process modularity accounts for most studies related to the relationships of multi-dimensionality of modularity. However, different views exist regarding these relationships. Some studies argue that there is a strong relationship between product modularity and process modularity (Kusiak, 2002). For example, some studies state that product modularity positively impacts process modularity in a best-fitting model. In contrast, product modularity and process modularity tend to be specified as independent exogenous constructs in poorly fitting models (Jacobs et al., 2011). The alignment of product and process modularity has advantages in developing and managing various postponement solutions in product manufacturing (Forza et al., 2008). Nevertheless, the impact of product modularity on process modularity raises a concern to an essential question firstly proposed by Hayes (1979): must there be an alignment of structure and infrastructure to improve performance? A few studies tried to explain the relationships between the multi-dimensionality of modularity in the AEC industry. For example, Tan et al. (2021) explored the relationship between product structure and organizational structure at a project level. Hall et al. (2020) investigated this relationship at a firm level. However, in the AEC industry, little existing research explores the relationship between product and process modularity (Viana et al., 2017).

Understanding the relationship between multi-dimensionality of modularity can contribute to the achievement of modularity as a whole. The lack of relevant research makes the current focus more on the design and implementation of modularity at a single level, such as product modularity. However, these implementations of product modularity cannot be separated from the context (i.e. process and supply chain) and the support of the context. Implementing the single-level modularity strategy proposed in research, such as some of the guidelines in the construction-oriented DfMA, may not work. By adopting the modularity theory as an analytic lens, this study expects to add knowledge to the development of DfMA and the relationship between the multi-dimensionality of modularity in the AEC industry.

Methodology

Data collection and analysis

This paper uses modularity as an analytical lens to study various facets of DfMA within the context of OSC and explore the relationship between three concepts, namely product modularity, process modularity, and DfMA. The study fills this gap through an action research case study by identifying perceptual measures of these three concepts. Action research aims to build and test the theory by solving an immediate practical problem in a real setting (Azhar et al., 2010, Smith and Rebolledo, 2018, Stringer and Aragón, 2020). Three authors participated in the project's design and worked with wider off-campus partners by an engaged scholarship approach. This approach is defined as a participative form of research for obtaining the advice and perspectives of key stakeholders to understand a complex social problem and calls (social science) researchers to action on how we think about and conduct research (Van de Ven, 2007).

The data collection and analysis workflow are shown in Figure 1. As shown in Table 1, the data includes: formal, transcribed, semi-structured interviews; design documents; daily construction diary; informal meetings and notes; observations; and feedback on reports. Analysis proceeded in stages. This research adopted the three-step framework proposed by Forman and Damschroder (2007) to approach qualitative content analysis, including 1) data immersion; 2) data reduction; and 3) data interpretation. Systematic coding of observational data supported the development of categories and subcategories. With the addition of interview data, design documents and construction diaries, case reports were developed using an inductive, iterative thematic process. After completing the case report, the feedback session further corroborated the thematic, practice-specific analysis.

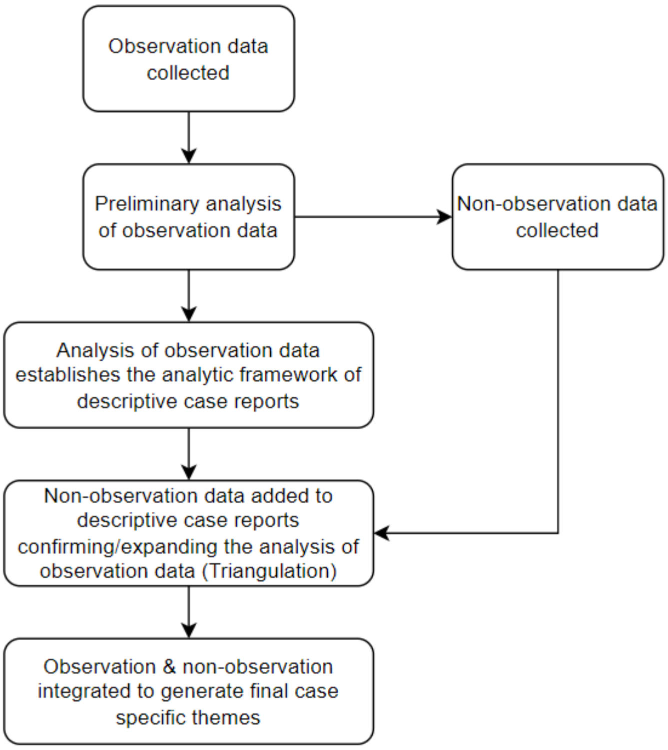


Figure 1: Data collection and analysis workflow

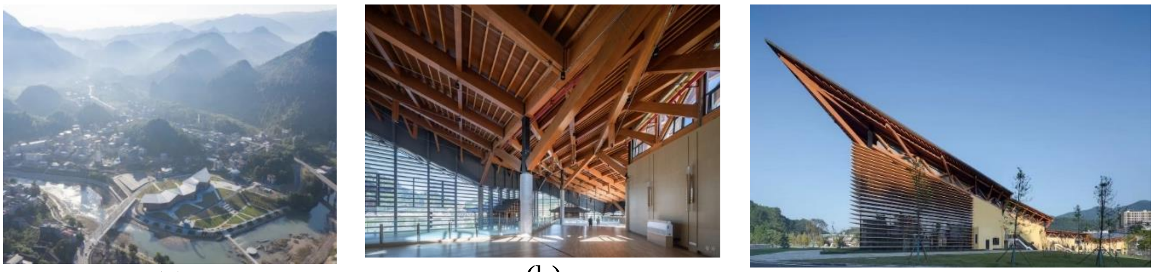
Table 1: Data types collected

Item	**Type**	**Amount**	**Description, sampling etc.**
1	Interviews	One recorded interview and two informal interviews	Interviewees include the design director from the sub-contractor and the architect lead from the design firm
2	Design documents	100%	Including design drawings, diagrams, and so on
3	Meeting and notes	23 times	Including all meetings between architect lead with other stakeholders over a period of 3 months
4	Construction diary	Three months	Daily diary reported by the main contractor

5	Construction site visit	Seven days in 3 months	Visit of construction site around twice every month
6	Manufacturing factory visit	1 day	Visit of the production line for prefabricated timber structure

Case setting

In the case study, the case selection is generally intended to both find a case that is a representative sample and which has variations on the dimensions of theoretical interest (Seawright and Gerring, 2008). A typical and influential case contributes to the theory interpretation and test. In addition, there is a preference for cases with researchers' in-depth local knowledge and position to "soak and poke". Thus, the inclusion criteria include 1) easy data access; 2) rich dataset; 3) award-wining project; 4) adoption of digital fabrication techniques; 5) adoption of offsite manufacture and on-site assembly, and 6) high construction difficulty. An OSC project adopting digital robotic fabrication is finally identified. The spread and adoption of robotics in the AEC industry are very slow, and practical cases in projects are limited (Kim et al., 2015). Novel robotic fabrication applications are typically explored through empirical studies and demonstrator projects (Wagner et al., 2020). Robotic applications from actual large-scale OSC projects can provide valuable experience in examining robotic fabrication development. As shown in Figure 2, the case is a museum construction project with 40 000 m^2 gross floor area for the Tujia minority in Enshi, Hubei province, China. It is the largest prefabricated timber structure building in China. The design was from December 2017 to December 2018, and the construction was from February 2019 to July 2021. The major stakeholders are shown in Table 2. More information can be found on the project introduction website (https://www.archiposition.com/items/20210915050527). This case well suits the selection criteria. Firstly, the project is an award-winning project with many prizes. It has been exhibited in Biennale Architettura 2021, Venezia. Secondly, a Non-uniform rational B-spline (NURBS) modelling approach and virtual programming plug-in interfaces were used in the split design of the timber structure. The robotic arm directly read the 3D models from Rhinoceros 3D, which significantly improved manufacturing productivity. By avoiding the conversion from 3 dimensions models to 2 dimensions drawings, this machine-level collaboration reduced human errors and improved the efficiency of integrated design. Thirdly, the three authors lead the design and possess all relevant design data and most of the construction data, which provides an opportunity for an action research case study.



(a) (b) (c)

Figure 2: Offsite manufacturing and on-site assembly

Table 2: Project major stakeholders

Type	**Sub-type**	**Name**
Contractor	Main Contractor	Hubei Industrial Construction Group Co., Ltd. (HICC)；Woodtech.ai
	Sub-Contractor (Timber structure)	Wuhan LingLang Wooden Architecture and Engineering Co., Ltd.
Designer	Scheme design	Huazhong University of Science and Technology Architectural Planning and Design Institute Co., Ltd.
	Construction drawing design	Wuhan Hechuang Construction Engineering Design Co., Ltd.
	Interior design	Hubei Institute of Fine Arts

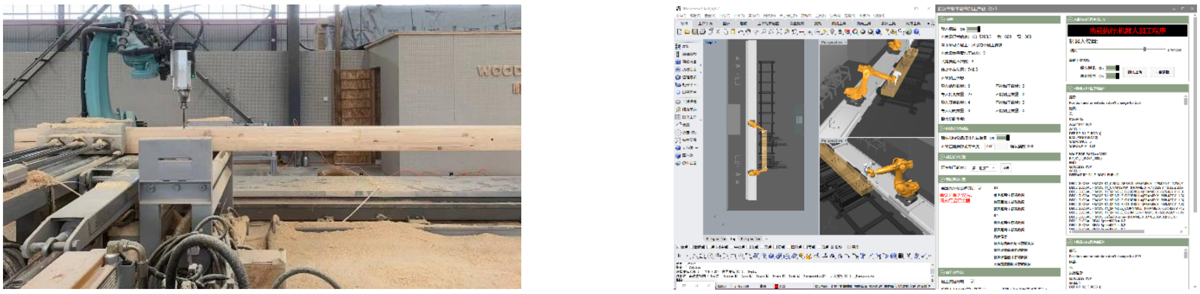
	Timber structure design	Wuhan LingLang Wooden Architecture and Engineering Co., Ltd.
	Landscape design	Zhongchuang Huanya Architectural Landscape Design Co., Ltd.
Client		Hubei Xuan'en Tourism Investment Co., Ltd.

Findings and lessons learned

The examination evaluates the relationship between product modularity, process modularity and DfMA. Then, the three most significant actions were observed and validated through multiple data sources during the action research case: 1) embarking on digital-enabled DfMA; 2) product modularity in OSC; and 3) modularity in the design process. The study tried to summarise the practices regarding these three aspects and analyse their relationships.

Embarking on digital-enabled DfMA

Given the massive workload of timber processing, robotic fabrication was adopted in this project to enable DfMA. As shown in Figure 3, NURBS parametric modelling (i.e., Rhinoceros 3D) is the software base for digital fabrication. The manufacturer of robotic arms collaborated with the subcontractor to develop a timber structure processing plug-in to realise robotic fabrication. The real-time operation of the physical robot arm can be mirrored and generated in the virtual 3D software to simulate all the modular component processing and manufacturing processes. Customised software development and maintenance services improved the robot arm's ability to adapt to the needs of the project. Robotic fabrication and Building Information Modeling (BIM) technologies have greatly improved design quality, production efficiency and reduced labour demands. Automated production tools drive the exchange upgrade of design information at the corresponding stage. However, from the perspective of the entire project, the traditional exchange method by using CAD-based file transfer and WeChat-based chatting group is still a habitual tradition for existing project organisations and what practitioners think is a more efficient way to fit the project. Besides, from the perspective of the overall project, construction automation is only a small part. The final product of the building is currently not manufactured in the factory, and there is still a long way to go before the final building is fully dependent on automation. The application of robotic arms also brings many challenges. Processing equipment has limitations on its capabilities, such as component size, processing tool size and shape, and processing direction. These attributes put forward new requirements for designers, requiring close communication between designers and manufacturers to understand the material characteristics and the ability of processing and manufacturing characteristics to realise DfMA.



(a) Physical manufacturing (b) Digital representation of the physical object

Figure 3: Robotic fabrication

Product modularity in OSC

The nature of OSC as a component-based construction requests the adoption of modularity in design (i.e. product modularity) for effective assembly. As shown in Figure 4, the strategy of the modularisation process can be classified into 1) abstraction, 2) information hiding and 3) standardised interface. The split design of the design scheme was the process of considering the reconfiguration of design elements. Various elements were categorised into modules based on their interdependence (i.e. abstraction). All timber modules were standardised within the project rather than across multiple projects. As shown in Figure 5, colours represent different cross-sectional dimensions of various components of the timber structure. By standardising the modular components required within the project, the timber that needs to be transported and processed has been reduced, which is in line with the interest of designers and manufacturing subcontractors to reduce costs. The following manufacture and assembly of these modules were considered as a whole without the need to understand and interact with the elements in the modules (i.e. information hiding), as robotic arms fabricated all these timber components automatically. In addition to abstraction and information hiding, the strategy of the standardised interface is widely adopted in this case. Figure 6 shows the distribution of steel connectors (i.e. standardised interface). The connector is a physical interface between different prefabricated components, representing the modularity of products. It can be observed the "bus modularity" (see Figure 7) is widely used in the project as a standardisation strategy for interfaces.

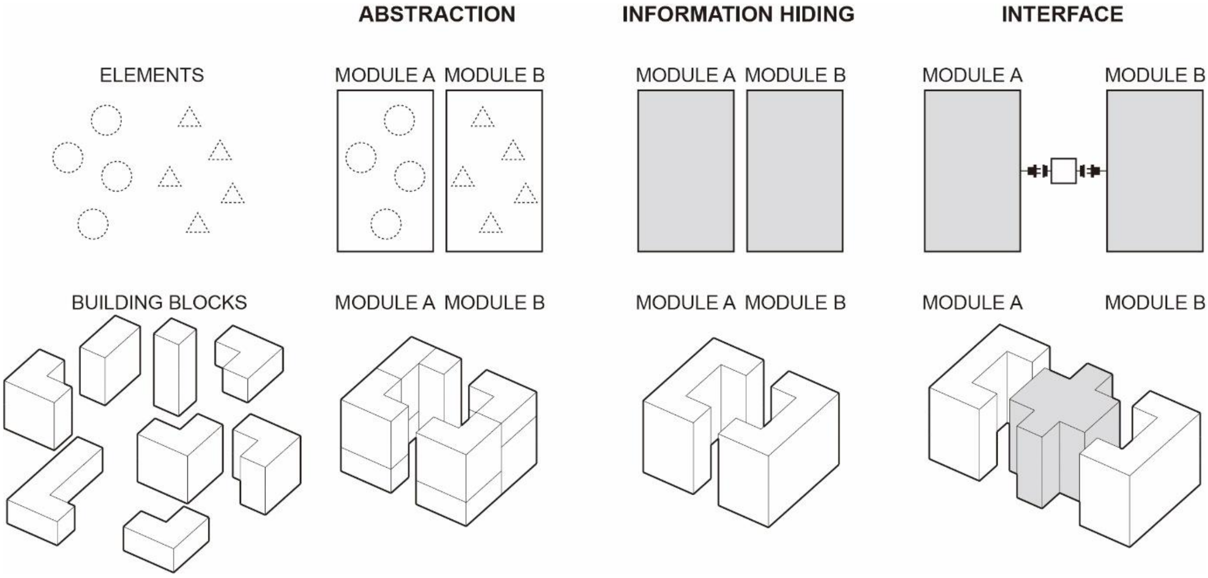


Figure 4: Abstraction, information hiding and interface

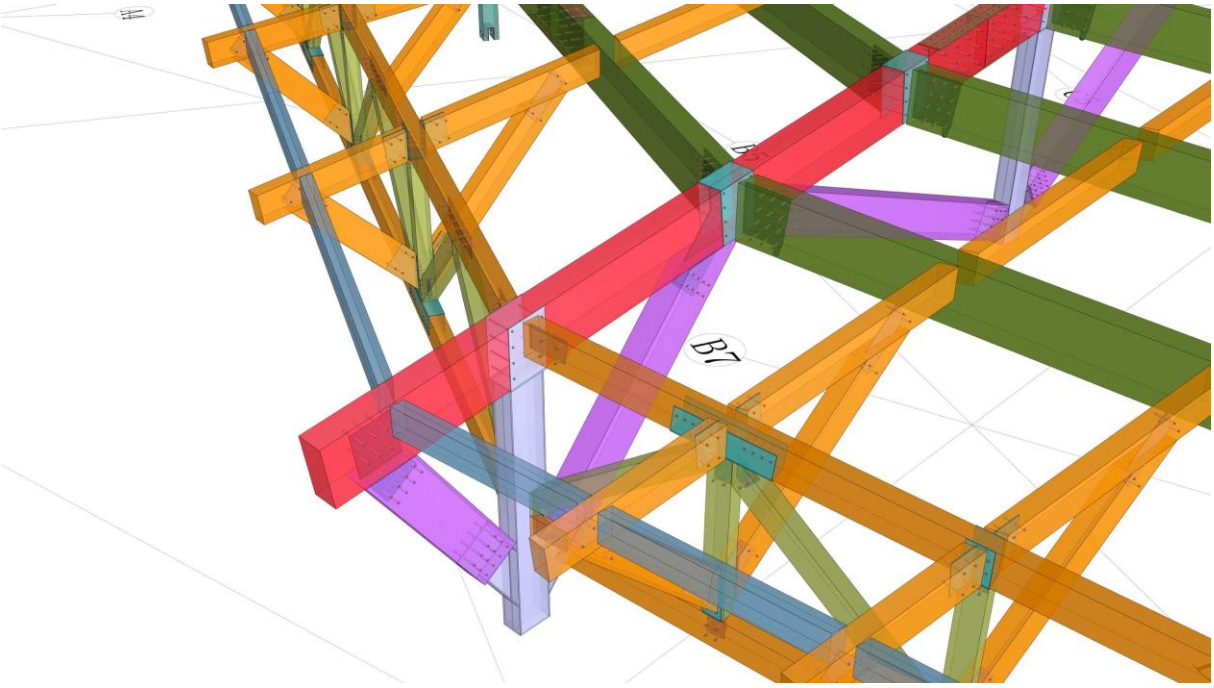


Figure 5: Component-based standardisation within the project

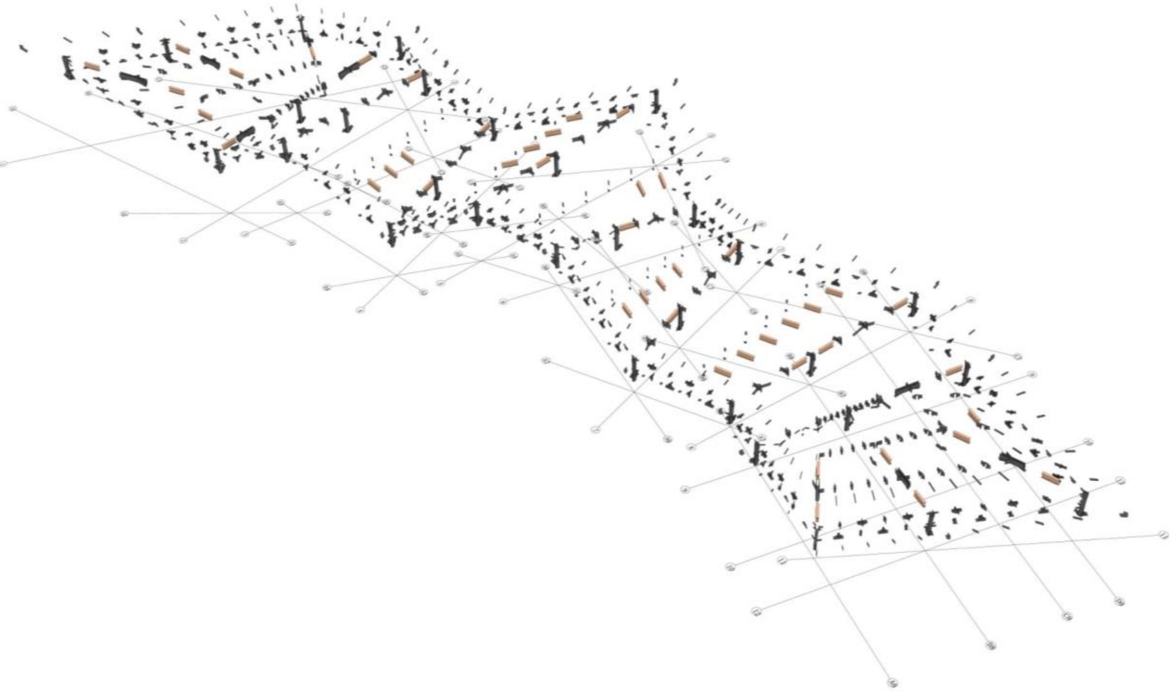


Figure 6: Distribution of steel connectors

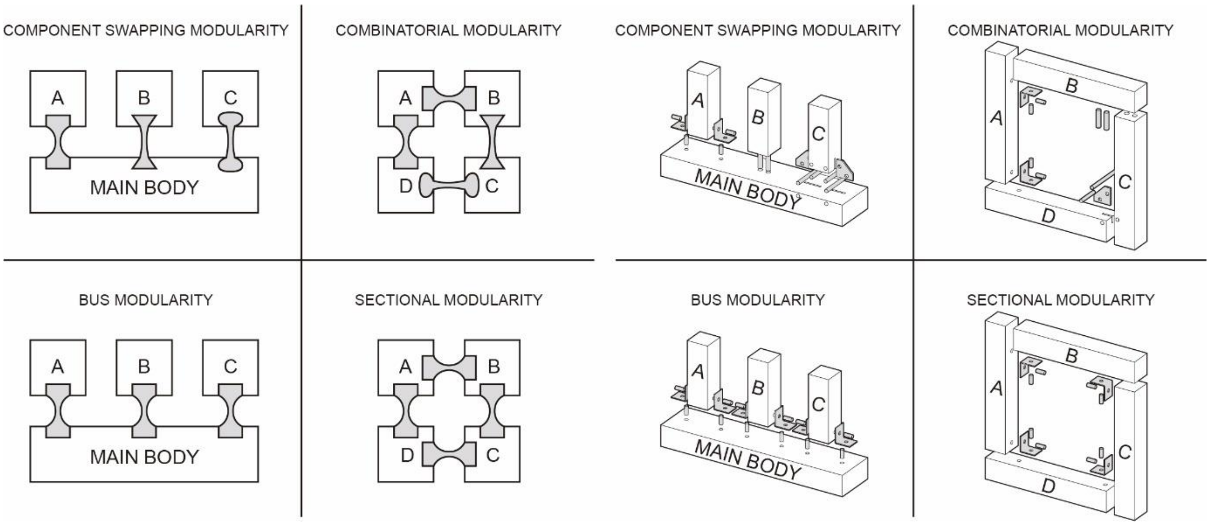


Figure 7: Typology of modularity

Modularity in the design process

This project adopted a hybrid construction method involving a prefabricated timber roof and an on-site cast wall and foundation, significantly impacting the traditional design process. It is a widespread practice in OSC to use both cast-in-situ parts and offsite manufactured components together. The project maintained a balance between standardisation and flexibility and achieved ideal cost and building performance. The biggest construction challenge of this project comes from the combination of the prefabricated timber roof and the concrete foundation. It is the first time in China to adopt prefabricated timber structure roofs on such a large scale. The design team transformed the traditional design process to adapt to the particular building systems.

The three strategies, namely abstraction, information hiding, and standardised interface, can also be used to analyse the modularity in the design process. Figure 8 shows the network of the multidisciplinary team for implementing the DfMA-oriented design in this project. The directions of the arrows indicate the information flow. The socio-technical perspective regards the architecture of the design process as a network of interdependent activities executed by people over time (Parraguez et al., 2019). The design process is highly affected by the network of the multidisciplinary team (i.e. a temporary organisation). In this case, the integration and DfMA relied on the collaboration between the three parties' architects and the main contractor's project manager. The principal architect from the design firm took a major role in design changes, design optimisations and DfMA process integration. Abstract is the reallocation of various design activities based on their characteristics in the new scenario. Information hiding in the design process represents the reconfiguration of design activities, and some activities might be hidden rather than visible to others. In this way, the complexity of design activities is decomposed. For example, engineers and manufacturers and their design activities were "hidden" and not directly involved in the cross-organisation communication but led by the architect of their firms. The interface in the design process represents the rules of interaction and how different groups' design activities interact. As shown in Figure 9, the interface between two modules is changed based on the reconfiguration of the two groups' design activities. With the change of boundaries (i.e. dashed boxes), the interface between two groups changed from one connection to two connections, which is activated by the move of "C". And the left side grouping way is relatively more modular than the right side.

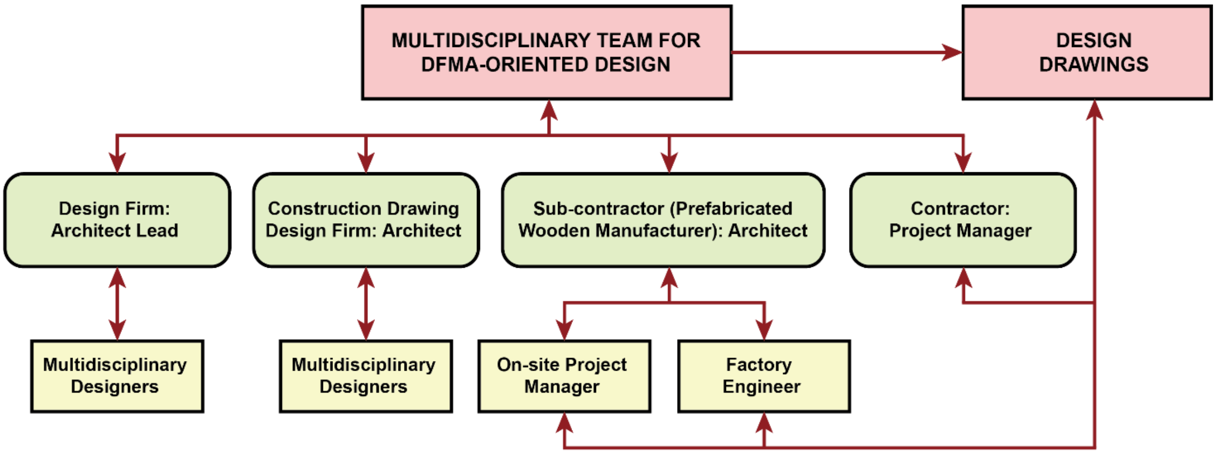


Figure 8: Multidisciplinary team for implementing the DfMA-oriented design in this project

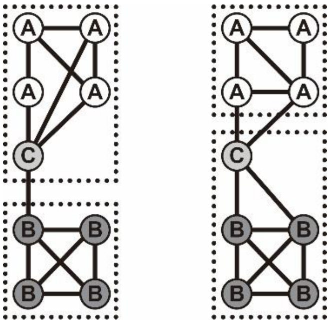
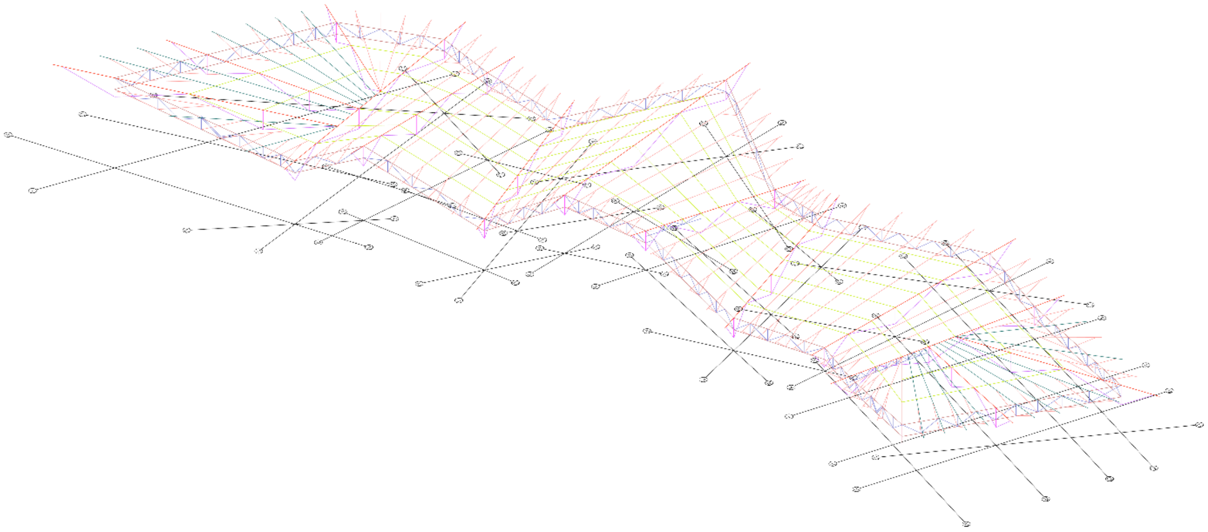
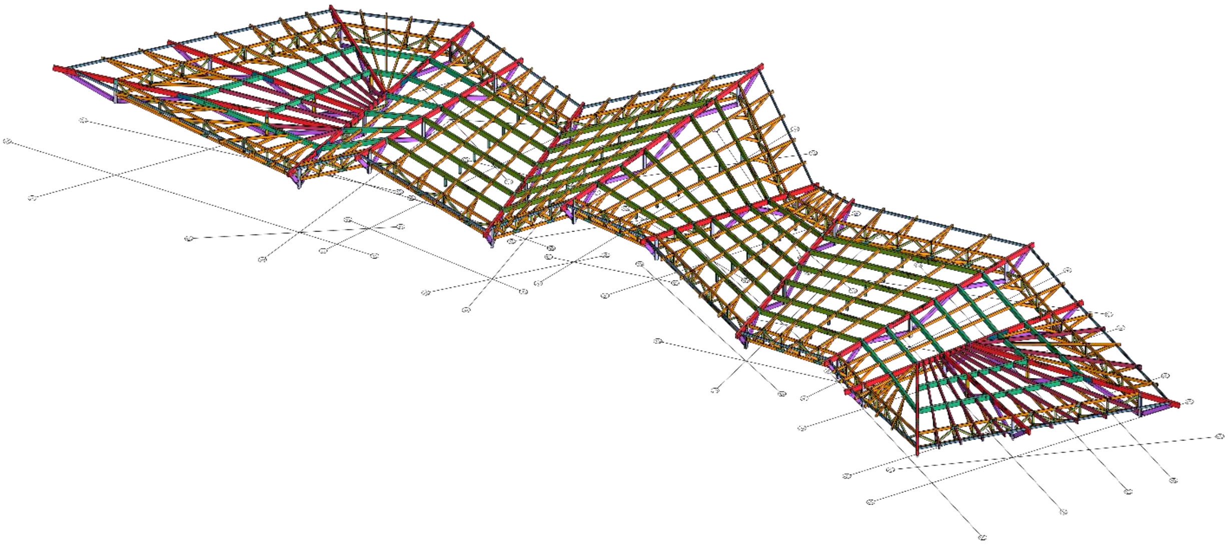


Figure 9: Reconfiguration of key design activities

In this case, design firms prefer not to share all information or 3D models with other stakeholders if contracts do not require them to do so. Figure 10 is a typical practice of abstraction and information hiding. In this project, the architect from the design firm and the architect from the sub-contractor of timber structure took more structural engineering responsibilities to ensure the form appearance of prefabricated systems. For example, the single-line model is usually a design task conducted by civil engineers. In this case, architects took the role of this design task and confirmed with civil engineers the section dimension size. Because civil engineers were not responsible for the appearance forms and the aesthetics of the structural system, the architects allocated these tasks to themselves to keep design quality and make the OSC efficiently. The change of design tasks is a reconfiguration of the design process. Relatively simpler information documents (i.e. single-line model) were exchanged as an interface for different design tasks between architects and civil engineers, representing the modularity in the design process.



(a) Single-line model



(b) Model with section dimension size

Figure 10: Information hiding in single-line model

Discussion

How the digital fabrication of OSC changes the design process?

The case result shows that digital fabrication of OSC changes the traditional design process through the reconfiguration of abstraction, information hiding and interface. The transformation from cast-in-situ concrete structures to hybrid OSC represents a modularisation process for the physical product components. The case supports previous studies about robotic power regarding manufacturing efficiency (Bock, 2015, Carra et al., 2018), reinforces the need to transform the traditional design and production approaches in robotic fabrication (Gharbia et al., 2020), and further previous robot-oriented design (ROD) studies in terms of co-adaptation of construction products, processes, organisation and management, and automated or robotic technology (Bock, 2015). Product modularity contributes to the requirement generation of co-adaptation of various parts in ROD and facilitates the design transformation to modularity in the process. And the adoption of robotic fabrication which is the technique for modularity in production has an incentive to transform co-adaption towards modularity in the process. Specifically, digital fabrication reconfigures the allocation of design tasks, as the conventional structure of roles and organisations cannot deal with new knowledge and information requirements brought by emerging technologies. If the traditional assignment of tasks continues, subcontractors' and designers' design quality and production profits will decrease, leading these stakeholders to make changes. Information hiding plays a primary role in the modularity process to reduce risks and adapt to the needs of new knowledge. Traditionally, the single-line model is a design task completed by civil engineers. Taking the case as an example, the architect took the duty to generate a single-line model. In this way, the architect team involving architects from both the design firm and timber structure sub-contractor can better control the structural forms and utilise the capabilities of robotic fabrication. In this way of information hiding, knowledge about aesthetics is hidden for civil engineers, and knowledge about mechanics is hidden for architects. The single-line model acted as an interface between two design task clusters, namely the architect and civil engineer tasks. Although many studies advocate the significance of information exchange and bringing various stakeholders' information to the design stage (Chen et al., 2015), they neglect the information redundancy and intellectual property protection issues. The constant flow of various aspects of information will make it difficult for designers to make correct judgments and choices. The co-adaption cannot ignore these inherent issues within the stakeholders. Rather than *more is better*, streamlined and concise information is more conducive to ROD decisions and multi-team collaboration. Modularity therefore contributes to the co-adaptation of construction products, processes, organisation and management, and automated or robotic technology. And robotic fabrication changes traditional design process through information hiding and tasks reconfiguration.

There are also some limitations in the analysis and results regarding this research question. The study took a single case analysis and identified its DfMA process, which differs from previous studies. In other cases, they have specific DfMA processes determined by their project organisation and construction methods. The case study cannot be used to describe or explain the generation and results of various design process transformations specifically but can only focus on the drive mechanism and approaches for the transformation. Future research can conduct multiple case studies to identify typical DfMA processes for robotic fabrication and explain their generation, similarities, and differences.

How does modularity enhance the capability of DfMA?

Although robotic fabrication increased manufacturing productivity, the modularisation of physical building components in OSC (i.e. product modularity) did not prevent the project delay. Many studies have pointed out the empowering ability of OSC techniques to improve construction speed and efficiency (Jiang et al., 2018, Abanda et al., 2017), but observations in the case do not fully support these advantages. The results do not indicate the disadvantages of modularity in physical products. It implies that the process and organisation structure accustomed to the conventional on-site construction does not match the OSC activities. Also, an organisation accustomed to OSC may encounter obstacles during conventional on-site construction, representing the mismatch between the organisations and the construction methods. It further implicates that modularity in robotic fabrication does not necessarily lead to improving DfMA capabilities. The project requires a co-adaptation process in DfMA, and modularity theory may help with the process.

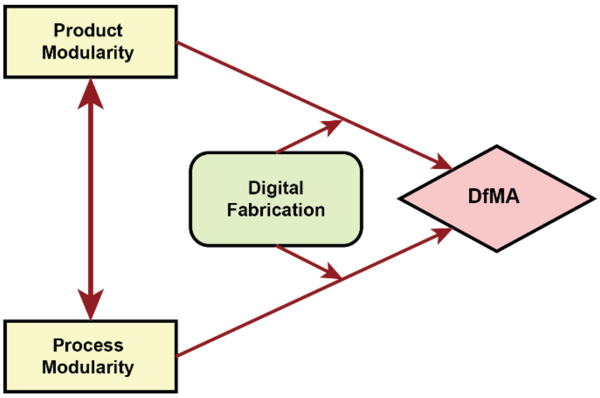


Figure 11: Relationship between product modularity, process modularity and DfMA

The case attempts to analyse the realisation of DfMA by adjusting the design task clusters from the perspective of technology adoption (i.e., robotic fabrication). The use of emerging technologies necessitates changes in design tasks and processes (Bock, 2015, Gharbia et al., 2020). The architects of each team, such as the design team and subcontractor team, will take more responsibility to realise the modular task group clustering caused by this information hiding. The results implicate that applying modular thinking to the project level may contribute to the implementation of DfMA. The study further challenges the previous definition of modular construction, namely physical and standardised component combination (Bertram et al., 2019, Lawson et al., 2014, Innella et al., 2019, Alwisy et al., 2012), by transforming to a definition focusing more on the integration of various modularity aspects in the construction. Modularity not only includes physical components but also includes modularity in the design process, building systems, space functions, organisational structure, and supply chain. As shown in Figure 11, the realisation of DfMA may not be successful by basing on the realisation of a single aspect of modularity, whereas more significant is the matching of different aspects of modularity. For example, the mirror hypothesis in modularity theory is related to this perspective, that is, the study of the matching relationship between technical structural and organisational structural (Colfer and Baldwin, 2016). In architectural practices, these different types of modularity have strong independence. For example, the building project may adopt modular physical components when the design process or organisation maintain non-modularity. Vice versa, it is also possible that the building has modularity in the design process with cast-in-situ construction. The project's success may not depend on either the high degree of single modularity or modularity in all aspects, but the matching between these modularity aspects matters. For practical implications, future architectural projects can adopt above three mentioned essences of modularity, namely abstraction, information hiding, and interface, to reconfigure both building components and design processes to achieve complexity reduction of design (Baldwin et al., 2000), design option value (MacCormack et al., 2007), intellectual property protection of design (Baldwin and Henkel, 2015), and so on.

The limitation of the single case study is that it is hard to generate a strong correlation or causal relationship between various modularity aspects in construction. Some theories explore the relationship between modularity aspects, such as the mirroring hypothesis which predicts the relationship between organisation level and product level. Some studies have been conducted to explore the relationships in other industries, but not the AEC industry. Future research can try to fill these gaps and choose multiple cases with design process shifts to observe the modularity in DfMA. The clarification of these relationships is conducive to the realisation of modularity in projects and DfMA.

Conclusion

Construction methods, such as OSC, are increasingly applied in the AEC industry and challenge conventional design processes. DfMA, as an emerging design approach, is expected to harness digital fabrication's capability to deal with OSC challenges. Modularity, as a complexity-reduction theory, can serve as a lens and tool for analysing, enabling and adding value to DfMA. The study addressed the research question through a longitudinal action research case study. The study shows that the alignment between multi-dimensionality of modularity, such as product modularity and process modularity, enhances the capability of DfMA. From a modularity perspective, the reconfiguration of abstraction, information hiding, and interface is an essential strategy to transform traditional design processes. This reconfiguration aims to adapt to the new scenarios brought by OSC, digital fabrication technologies and new design tasks associated with these scenarios. Using abstraction, information hiding, and standardised interface, these three strategies of modularity theory can reduce the design complexity in OSC. Both for modularity-in-design (i.e. product modularity) and modularity-in-production (i.e. process modularity), the modularisation processes exist threats and challenges. The alignment of strategies in these two dimensions could reduce complexity not only in their own systems (i.e. physical product systems and virtual design activity network systems) but also in the complexity between these two systems.

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Data Availability Statement

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

References

ABANDA, F., TAH, J. & CHEUNG, F. 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering,* 14**,** 89-102.

ALWISY, A., AL-HUSSEIN, M. & AL-JIBOURI, S. 2012. BIM approach for automated drafting and design for modular construction manufacturing. *Computing in civil engineering (2012).*

ARASHPOUR, M. 2019. Design for manufacture and assembly in offsite construction and relationship with concurrent engineering. *In:* JACK S. GOULDING, F. P. R. (ed.) *Offsite Production Manufacturing for Innovative Construction: People, Process Technology*.

ARIF, M., GOULDING, J. & RAHIMIAN, F. P. 2012. Promoting off-site construction: Future challenges and opportunities. *Journal of Architectural Engineering,* 18**,** 75-78.

ASHLEY, S. 1995. Cutting costs and time with DFMA. *Mechanical Engineering,* 117**,** 74-77.

AZHAR, S., AHMAD, I. & SEIN, M. K. 2010. Action research as a proactive research method for construction engineering and management. *Journal of Construction Engineering and Management,* 136**,** 87-98.

BALDWIN, C. Y. & CLARK, K. B. 2006. Modularity in the design of complex engineering systems. *Complex engineered systems.* Springer.

BALDWIN, C. Y., CLARK, K. B. & CLARK, K. B. 2000. *Design rules: The power of modularity,* MIT press.

BALDWIN, C. Y. & HENKEL, J. 2015. Modularity and intellectual property protection. *Strategic management journal,* 36**,** 1637-1655.

BERTRAM, N., FUCHS, S., MISCHKE, J., PALTER, R., STRUBE, G. & WOETZEL, J. 2019. Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure***,** 1-34.

BOCK, T. 2015. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction,* 59**,** 113-121.

CAMPAGNOLO, D. & CAMUFFO, A. 2010. The concept of modularity in management studies: a literature review. *International journal of management reviews,* 12**,** 259-283.

CARRA, G., ARGIOLAS, A., BELLISSIMA, A., NICCOLINI, M. & RAGAGLIA, M. Robotics in the construction industry: state of the art and future opportunities. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, 2018. IAARC Publications, 1-8.

CHAUHAN, K., PELTOKORPI, A., LAVIKKA, R. & SEPPÄNEN, O. 2022. The Monetary and Non-Monetary Impacts of Prefabrication on Construction: The Effects of Product Modularity. *Buildings,* 12**,** 459.

CHEN, K., LU, W., PENG, Y., ROWLINSON, S. & HUANG, G. Q. 2015. Bridging BIM and building: From a literature review to an integrated conceptual framework. *International journal of project management*, 33**,** 1405-1416.

COLFER, L. J. & BALDWIN, C. Y. 2016. The mirroring hypothesis: theory, evidence, and exceptions. *Industrial and Corporate Change,* 25**,** 709-738.

DA ROCHA, C. G. & EL GHOZ, H. B. 2019. A model for implementing product modularity in buildings design. *Engineering, Construction and Architectural Management*.

DA ROCHA, C. G. & KOSKELA, L. Why is product modularity underdeveloped in construction? Annual Conference of the International Group for Lean Construction, 2020. International Group for Lean Construction.

DORAN, D. & GIANNAKIS, M. 2011. An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal*.

ERIKSSON, H., SANDBERG, M., JANSSON, G. & LESSING, J. 2021. Exploring Product Modularity in Residential Building Areas. *Buildings,* 11**,** 281.

FEITZINGER, E. & LEE, H. L. 1997. Mass customization at Hewlett-Packard: the power of postponement. *Harvard business review,* 75**,** 116-123.

FINE, C. H., GOLANY, B. & NASERALDIN, H. 2005. Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach. *Journal of Operations management,* 23**,** 389-403.

FLYVBJERG, B. 2021. Make Megaprojects More Modular. *Harvard Business Review*.

FORMAN, J. & DAMSCHRODER, L. 2007. Qualitative content analysis. *Empirical methods for bioethics: A primer.* Emerald Group Publishing Limited.

FORZA, C., SALVADOR, F. & TRENTIN, A. 2008. Form postponement effects on operational performance: a typological theory. *International Journal of Operations & Production Management*.

GAN, X., CHANG, R. & WEN, T. 2018. Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis. *Journal of Cleaner Production,* 201**,** 735-747.

GAO, S., JIN, R. & LU, W. 2020. Design for manufacture and assembly in construction: a review. *Building research & information,* 48**,** 538-550.

GAO, S., JIN, R., LU, W. J. B. R. & INFORMATION 2019. Design for manufacture and assembly in construction: a review. *Building Research & Information***,** 1-13.

GERSHENSON, J. K., PRASAD, G. & ZHANG, Y. 2003. Product modularity: definitions and benefits. *Journal of Engineering design*, 14**,** 295-313.

GERSHENSON, J. K., PRASAD, G. J. & ALLAMNENI, S. 1999. Modular product design: a life-cycle view. *Journal of Integrated Design and Process Science,* 3**,** 13-26.

GHARBIA, M., CHANG-RICHARDS, A., LU, Y., ZHONG, R. Y. & LI, H. 2020. Robotic technologies for on-site building construction: A systematic review. *Journal of Building Engineering***,** 101584.

GIL, N., TOMMELEIN, I. D., STOUT, A. & GARRETT, T. 2005. Embodying product and process flexibility to cope with challenging project deliveries. *Journal of construction engineering and management,* 131**,** 439-448.

GOODIER, C. & GIBB, A. 2007. Future opportunities for offsite in the UK. *Construction Management and Economics,* 25**,** 585-595.

GRAHAM, I. 1994. *Object oriented methods,* Addison-Wesley Longman Publishing Co., Inc.

HALL, D. M., WHYTE, J. K. & LESSING, J. 2020. Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. *Construction management and economics,* 38**,** 322-339.

HAYES, R. H. 1979. The dynamics of process-product life cycle. *Harvard business review***,** 127-136.

INNELLA, F., ARASHPOUR, M. & BAI, Y. 2019. Lean methodologies and techniques for modular construction: chronological and critical review. *Journal of Construction Engineering and Management,* 145**,** 04019076.

ISHII, K. 1998. Modularity: A key concept in product life-cycle engineering. *Handbook of Life-cycle Engineering***,** 511-530.

JACOBS, M., DROGE, C., VICKERY, S. K. & CALANTONE, R. 2011. Product and process modularity's effects on manufacturing agility and firm growth performance. *Journal of Product Innovation Management,* 28**,** 123-137.

JIANG, R., MAO, C., HOU, L., WU, C. & TAN, J. 2018. A SWOT analysis for promoting off-site construction under the backdrop of China’s new urbanisation. *Journal of Cleaner Production,* 173**,** 225-234.

KIM, M. J., CHI, H.-L., WANG, X. & DING, L. 2015. Automation and robotics in construction and civil engineering. *Journal of Intelligent & Robotic Systems,* 79**,** 347.

KUO, T.-C., HUANG, S. H. & ZHANG, H.-C. 2001. Design for manufacture and design for ‘X’: concepts, applications, and perspectives. *Computers & Industrial Engineering,* 41**,** 241-260.

KUSIAK, A. 2002. Integrated product and process design: a modularity perspective. *Journal of Engineering Design,* 13**,** 223-231.

LANGSTON, C. & ZHANG, W. 2021. DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia. *Sustainability,* 13**,** 9219.

LAWSON, M., OGDEN, R. & GOODIER, C. I. 2014. *Design in modular construction,* CRC Press Boca Raton, FL.

LU, W., TAN, T., XU, J., WANG, J., CHEN, K., GAO, S. & XUE, F. 2021. Design for manufacture and assembly (DfMA) in construction: the old and the new. *Architectural Engineering and Design Management***,** 1-17.

MACCORMACK, A., RUSNAK, J. & BALDWIN, C. Y. 2007. The impact of component modularity on design evolution: Evidence from the software industry. *Harvard Business School Technology & Operations Mgt. Unit Research Paper*.

MAO, C., SHEN, Q., PAN, W. & YE, K. 2015. Major barriers to off-site construction: the developer’s perspective in China. *Journal of Management in Engineering,* 31**,** 04014043.

OMIGBODUN, A. 2001. Value engineering and optimal building projects. *Journal of architectural engineering,* 7**,** 40-43.

PAN, W. & SIDWELL, R. 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics,* 29**,** 1081-1099.

PARNAS, D. L. 1972. On the criteria to be used in decomposing systems into modules. *Pioneers and their contributions to software engineering.* Springer.

PARRAGUEZ, P., PICCOLO, S. A., PERIŠIĆ, M. M., ŠTORGA, M. & MAIER, A. M. 2019. Process modularity over time: modeling process execution as an evolving activity network. *IEEE Transactions on Engineering Management,* 68**,** 1867-1879.

SCHILLING, M. A. 2000. Toward a general modular systems theory and its application to interfirm product modularity. *Academy of management review,* 25**,** 312-334.

SEAWRIGHT, J. & GERRING, J. 2008. Case selection techniques in case study research: A menu of qualitative and quantitative options. *Political research quarterly,* 61**,** 294-308.

SHEN, W., HAO, Q., MAK, H., NEELAMKAVIL, J., XIE, H., DICKINSON, J., THOMAS, R., PARDASANI, A. & XUE, H. 2010. Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced engineering informatics,* 24**,** 196-207.

SMITH, R. & REBOLLEDO, P. 2018. *A handbook for exploratory action research,* British Council London.

STRINGER, E. T. & ARAGÓN, A. O. 2020. *Action research,* Sage publications.

TAN, T., LU, W., TAN, G., XUE, F., CHEN, K., XU, J., WANG, J. & GAO, S. 2020. Construction-Oriented Design for Manufacture and Assembly (DfMA) Guidelines. *Journal of Construction Engineering Management*.

TAN, T., MILLS, G., HU, J. & PAPADONIKOLAKI, E. 2021. Integrated Approaches to Design for Manufacture and Assembly: A Case Study of Huoshenshan Hospital to Combat COVID-19 in Wuhan, China. *Journal of Management in Engineering,* 37**,** 05021007.

TU, Q., VONDEREMBSE, M. A., RAGU-NATHAN, T. S. & RAGU-NATHAN, B. 2004. Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective. *Decision Sciences,* 35**,** 147-168.

ULRICH, K. 1995. The role of product architecture in the manufacturing firm. *Research policy,* 24**,** 419-440.

VAN DE VEN, A. H. 2007. *Engaged scholarship: A guide for organizational and social research*, Oxford University Press on Demand.

VIANA, D. D., TOMMELEIN, I. D. & FORMOSO, C. T. 2017. Using modularity to reduce complexity of industrialized building systems for mass customization. *Energies,* 10**,** 1622.

VOORDIJK, H., MEIJBOOM, B. & DE HAAN, J. 2006. Modularity in supply chains: a multiple case study in the construction industry. *International journal of operations & production management*.

VOSS, C. A. & HSUAN, J. 2009. Service architecture and modularity. *Decision Sciences,* 40**,** 541-569.

WAGNER, H. J., ALVAREZ, M., KYJANEK, O., BHIRI, Z., BUCK, M. & MENGES, A. 2020. Flexible and transportable robotic timber construction platform–TIM. *Automation in Construction,* 120**,** 103400.

YUAN, Z., SUN, C. & WANG, Y. 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction,* 88**,** 13-22.

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