Information Exchange in Platform Approaches to Design for Manufacture and Assembly

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Abstract

Platform approaches to Design for Manufacture and Assembly (DfMA) advocate the mass-customization, repeatability and modularity from the downstream supply-chain to design process. It extensively relies on the design process to leverage the supply-chain to achieve best value of the project. However, current design decision making is often made inside the black box on account of a lack of effective information exchange originating from production systems. This research aims to enhance the information exchange from production systems to design as well as the interoperability and connectivity between design and production processes by linking Industry Foundation Classes (IFC) based Building Information Modeling (BIM) to data models for production. A literature review is conducted on current DfMA practices with a focus on industrialized building to formulate a synthesis in the framework of platform-based approaches. Propositions are made to identify the gap between conventional and platform-based DfMA approaches. In doing so, future research can be sought to formulate a robust and open approach for platform-based DfMA in industrialized building.

Keywords: Design for manufacturing and assembly, Building information modeling, Information exchange, Platform

1. Background and Introduction

There is an increased interest in Design for Manufacture and Assembly (DfMA) for the industrialized construction worldwide. In Singapore, DfMA is among the three key areas of construction industry transformation map (BCA, 2017: p.2-3). In Hong Kong, DfMA plays a vital role in implementing the offsite construction, particularly the modular integrated construction and weighs substantially in the performance metrics of innovation (DEVB, 2018: p.28 and 48). In the UK, from the *RIBA plan of work Designing for Manufacture and Assembly overlay* (RIBA, 2016) and recent response to Infrastructure Project Authority (IPA)'s call for evidence in new approaches for building (IPA, 2018), the UK's construction industry is transforming by maximizing the benefits from digitization, manufacturing and life-cycle performance including cost, sustainability and user experience (CLC, 2018). DfMA has become seen as a major process that underpins the industry transformation.

DfMA originates from embodiment design which is known as Design for X (Huang, 1996). Design for X has been developed as an "umbrella" for a range of specific purposes including manufacturability, inspectability, recyclability. It is composed of two parts, namely "lifecycle business process (x)" and "performance measures (bility)" (Huang, 1996: p.3). Pioneers studying Design for Manufacture (DfM) and Design for Assembly (DfA) have realized the great importance of design in product lifecycle performance. Especially cost effectiveness resulted from design is far more substantial than other processes (e.g. manufacture and assembly) (Bralla, 1996: p.14). An integrated approach combined platforms and DfMA for product management can contribute to the commonality and variety of product design by adopting repetitive, standard, modular details (Emmatty & Sarmah, 2012: p.699). Other benefits from the platform-based design have been also unveiled in many other industries in product development and production including cost effectiveness, time saving, reduced complexity, better capability in product updating and plant utilization (Simpson, 2004: p.4).

Platform-based DfX can incorporate various support systems including computer aided design and manufacture, computer aided process planning, and computer aided production management for efficient data exchange and decision making process during product development (Huang, 1996: p.4). More generic platforms can facilitate the systems integration not only in design and production, but also the back-end stages like the supply-chain management, reconfiguration, etc (Pirmoradi et al., 2014). Thus platform-based DfMA can be seen as a vehicle for information exchange across project delivery stages and systems. To ensure timely and precise information exchange becomes critical for design development. Several attempts in other industries have shown the great potential benefits in standardizing information exchange through configurable product design and platforms. In addition, the flexible manufacturing systems cannot succeed without the efforts from information systems and platforms for reconfiguration and information integration and collaboration in different stages of "product family extended platform" (Simpson et al., 2014: p.781).

In digitally-enabled industrialized building, Building Information Modeling (BIM) is often used for data and information exchange across domains and stages in project delivery. Industry Foundation Class (IFC) is the neutral BIM data exchange format and Information Delivery Manual (IDM) can store the required specification for information exchange in business process at particular timing (ISO, 2016). It has been regarded as a main approach to stream the design process by linking with different domain expertise. However, current challenges in the practice have threatened the information management without defining the base and exchange process (Lee et al., 2016). Inconsistency in the data structure and hierarchy as well as discontinuity in the data transfer between IDM and Model View Definition (MVD) also create barriers for information exchange. BIM data validation against the requirements of the MVD and the limitations of this data evaluation process have not been thoroughly studied, which results in syntactic problems, semantic errors, and unintended geometrical transformation (Lee et al., 2019).

The aim of this work is to review the current platform-based DfMA practices with a focus on information exchange based on literature in industrialized building. Different types of platform based DfMA are identified and classified firstly. Through literature review and synthesis (Webster & Watson, 2002), this research firstly summarized and classified the IDM-based information exchange patterns for industrialized building according to production strategies. The literatures were chosen with a particular focus on information exchange in platform-based DfMA for industrialized building. It then proposed to use the platform-based DfMA for more efficient information exchange. Finally, through cross analysis of literature, the limitations of conventional DfMA have been identified and discussed, while the corresponding solutions from platform-based DfMA have been proposed to address such problems.

This research acts a preliminary study for applying platform-based DfMA to information exchange in industrialized building, providing a new way for enhancing interoperability and connectivity between design and production systems (i.e. manufacturing and assembly) processes. The first research phase concerns theory development and is based on a literature review and conceptual modelling (logical reasoning). At first a thorough literature review was conducted in order to find the most relevant schemes and frameworks for information exchange of platform based DfMA for industrialized building. The second phase of the research concerns propositions of information exchange of platform based DfMA with a comparison from conventional DfMA practices.

2. Information Exchange for Platform-based DfMA

This part will mainly focus on current literatures on the DfMA and information exchange in industrialized building, as well as the platform-based DfMA framework in industrialized building.

2.1 DfMA and Information Exchange

The benefits of industrialized building come from the emergence of BIM in different perspectives including productivity, safety, quality, cost and efficiency (Eastman et al., 2009; Nawari, 2012). Existing research (e.g. information management for industrialized building) has shown their limitations in monolithic production strategy and lack of interlinkage with capability of production systems in the preliminary design stage. Key literatures are identified and summarized in Table 1 with regards to their different production and supply-chain strategies, key stakeholders and leading parties, and information management methods.

Standardization of information exchange between design, production, logistics and assembly processes in industrialized building has been a long-lasting topic. Information Delivery Manual for Precast Concrete (2009) is the first IDM standard for industrialized building based on the first version of US National BIM standard (NIBS, 2007). Then Eastman et al. (2010) further illustrated the rationales and a "use case" approach behind development of this national IDM standard. It is based three types of delivery methods in terms of different leading parties including engineer/architect, precaster and combination of the former both in the pre-construction stage. Nawari (2012) proposed a high-level IDM for offsite construction. The adopted production strategy follows Engineer-to-Order (ETO) process in which architect/engineer leads the decision-making process directly to the client before manufacturability studies carried out. An extended process to product modeling (xPPM) based on previous Georgia Tech Process to Product Modeling (GT-PPM) (Sacks et al., 2004) was developed aiming to improve the repeatability of information from both product model and architecture, and the IDM-MVD dataset (Lee et al., 2013). Berard and Karlshøj (2012) used an action research method to reengineer the information exchange process through engaging actors in the design and tendering with a focus on integrating product information. They argued that the success of IDM substantially depends on succinct terminology, modeling language and generic and flexible modeling process. A concept of product architecture model (PAM) is another key framework to facilitate in the DfMA information exchange in multistory industrialized building (Ramaji & Memari, 2015). Such a framework enables information exchange in both product-oriented and process-oriented approaches (i.e. the information exchange through the process maps, exchange models and task unit specifications) (Ramaji et al., 2017). The manufacturer and construction manager can be involved in a secondary way where the main decision is made in the architect and engineering domain. Despite the progressive development of IDM-MVD methods in industrialized building, current IDM-MVD practice has encountered barriers. These challenges include the complexity in producing process maps using Business Process Modeling Notation (BPMN), the poor traceability and reusability in exchange requirements and functional processes, the complexity in linking different information exchange files (Lee et al., 2013).

Table 1: IDM-based Information Exchange Patterns for DfMA in Industrialized Building

Production /Supply-chain Strategies	Authors	Industrialized building Method	Key Stakeholders and Leading Party (if any)	Information Management Method
ETO	Eastman et al. (2009) Berard and Karlshøj (2012)	Precast concrete components	• Architectural precaster • Or precaster-led • Or precaster as subcontractor	IDM-MVD
	Berard and Karlshøj (2012)	Prefabricated components	• BIM consultant • Product manufacturer • Contractor	IDM
	Ramaji and Memari (2015, 2018); Ramaji et al. (2017)	Volumetric modules (Composite steel and concrete volumetric modules, and others)	• Architect-led • Engineer • Manufacturer • Construction manager	IDM with extended MVD focus on integration and enrichment of building story and elements
	Yuan et al. (2018)	Prefabricated concrete components	• Architects led • Engineer • Assembly technician	DFMA-oriented parametric design
CTO (Configure-To-Order)	Malmgren et al. (2011) Jensen et al. (2012)	Configurable building system platform with prefabricated timber components	• Customers • Engineers • Product manufacturers • Assembly team	Product view method composed of the customer, engineering, production and site assembly views

ATO (Assembly-To-Order)	Nawari (2012)	Prefabricated components (concrete, steel, timber and others)	• Architect • Engineer • Manufacturer • Erector • Contractor	IDM
MTS (Made-To-Stock)	Berard and Karlshøj (2012)	Prefabricated components	• BIM consultant • Product manufacturer • Contractor	IDM

In order to address the obstacles, a configurable building system platform becomes an alternative solution to meet customization. It relies on early engagement of stakeholders' capacity to design stage. It also creates more flexibility in design while maintaining a high level of customization in fulfilling user needs. In a similar approach as MVD, multiple product views can visualize and facilitate the information exchange between stakeholders in different domains including customers, engineering, production and assembly (Jensen et al., 2012). Such CTO-based industrialized building has shown great capability in empowering customers value through standardized interfaces and products.

2.2 Platform-based DfMA in Industrialized Building

Mass customization is the main objective in fulfilling the most customer needs through a substantial number of products (Pine, 1993: p. 196). A platform-based product development is one of the tactics to drive mass customization (Simpson, 2004). Product platform often describes the product design practice using families with both competency in technological field and versatility in different customizing needs (Dodgson et al., 2008, p. 217). Current literature on technical platforms in industrialized building mainly focus on the product platform. Among different typologies of platform-based product design in industrialized construction research, the Jiao's typology remains a key reference in platform development which has been extensively used in earlier studies (Jansson et al., 2014; Jensen et al., 2013; Jensen et al., 2015a; Ramaji & Memari, 2016; Wörösch et al., 2015). Thus, this part adopts this method to summarize key literature covered in industrialized building in Table 2.

Table 2: List of Literature on Different Typologies of the Platform-based DfMA in Industrialized Building

Front-end Issues	Product architecture, product family and platform configuration, and product portfolio positioning
	➢ Product information in different production strategies (Winch, 2003) ➢ Configurable "products in product" method (Jensen et al., 2014) ➢ Product architecture model (PAM) (Ramaji & Memari, 2015)
Design and development issues	Balance standardization and versatility of building products
	➢ Housing product platform structure including product architecture, interface and standards (Veenstra et al., 2006) ➢ Technical and process platforms to standardize building product development (Lessing, 2006: p.187) ➢ Parametric models for configuration management of industrialized building systems (Jensen et al., 2012) ➢ Modular architectural view method to link the customer requirements to platform development (Wikberg et al., 2014) ➢ Exterior panelized walls platform optimization (Said et al., 2017)
	Design optimization:
	➢ A methodology for the optimal modularization of building design (Isaac et al., 2016) ➢ Exterior panelized walls platform optimization (Said et al., 2017) ➢ Tolerance: (Rausch et al., 2017) (Shahtaheri et al., 2017) ➢ Geometric variety control: (Rausch et al., 2017; Rausch et al., 2016)
	Decision support systems:
	➢ Modular suitability index integrated with the critical factors determining manufacturability, logistics and assembly (Salama et al., 2017) ➢ Managing information flow and design processes to reduce design risks in offsite construction projects (Sutrisna & Goulding, 2019) ➢ "minimization of the overall assembly geometric deviation, and (2) avoidance of rework caused by component aggregation. "(Rausch et al., 2016)
Back-end Issues	Manufacturability
	➢ Integrated prefabrication configuration and component grouping for resource optimization of precast production (Khalili & Chua, 2014)
	Metrics and Indices
	➢ Integrate the critical factors in manufacturability, logistics and assembly to the modular suitability index (Salama et al., 2017) ➢ Total fabrication cost and design deviation index (Said et al., 2017) ➢ Composite optimized assembly index and voting analytical hierarchy process (Gbadamosi et al., 2019)
	Supply-chain Management

	➢ (Hofman et al., 2009) ➢ Product modularity on supply-chain integration (Pero et al., 2015) ➢ Enhance supply network performance (Arashpour et al., 2017) ➢ Cost term and constant transfer term in production lead-time hedging (PLTH) (Zhai et al., 2016)

Front-end issues: Platform-based design methods are able to balance the commonality and the variety in industrialized housing production, which shares a common feature with automobile manufacturing (Gann, 1996). Implicit studies using product architecture for industrialized building can be dated back to 1990s, Japanese companies have deployed market specialists to represent customers in industrialized housing design and production, in which these specialist carried out market research through direct and indirect approaches with customers and clients (Gann, 1996). This brings another critical concept, project information flow induced by customers. The timing of customer involvement in the building design development may affect the production strategy. Similarly a decoupling point between planning and customer differentiates the production strategy (Barlow et al., 2003). Three types of production information flows were identified based on this (Winch, 2003). Thus the production information flow illustrated in the aforementioned case can be defined as new product development as only market research has been carried out and no actual customer relationship was established. And other two types of production information flows are tender and procurement on account of the integrity level of specification to satisfy customer needs (Winch, 2003). Design-to-order (DTO) or engineer-to-order (ETO) strategies are suitable for tender as substantial design development is required upon receiving the customer requirements. And concept-to-order (CTO) strategy applies to procurement if detailing of design is mature. Early attempts in parametric modeling in BIM can facilitate the cross discipline communication (Lee et al., 2006). For better information integration and developing a platform based design, a building information model (BIM)-based product architecture model (PAM) was established to manage the building components using a product-based design approach (Ramaji & Memari, 2015: p. 12). Ramaji et al. (2017) further developed this information integration platform as an information framework based on information delivery manual (IDM). This framework strengthened the inter-discipline information exchange by providing standard information to the right actors timely.

Design and development issues: How to interoperate functional requirements to product architecture is another critical issue in product platforms. Veenstra et al. (2006) employed the product platform structure to articulate the housing design and product development process following three steps, product architecture, interface and standards. In the first stage to capture the product architecture, modules and components were mapped according to the standard classification. And the interfaces were investigated via the design for variety method proposed by Martin and Ishii (2002). By comparing the metrics using generational variety index and coupling index in receiving and supplying specification flows, standardization of different modules can be optimized to better serve the platform (Veenstra et al., 2006). In industrialized housing construction, platforms in technical and process domains were also proposed to standardizing building product development (Lessing, 2006: p.187). Major purposes for such technical platforms are to reduce abortive work and complexity in design and facilitate the collaboration in different stakeholders at design stage. Jensen et al. (2012) applied the parametric models for configuration of building systems to improve the information exchange between designers/engineers, producers and customers. Different model viewers of engineering, production and customer can transfer the information flows to downstream and feedback the rules to upstream. Similarly, Wikberg et al. (2014) further proposed a modular architectural view method to link the customer requirements to the platform development. Such kind of design support system can transfer the information required from later stages to the initial design stage. Its great potential also lies in the operational stages.

To utilize metrics for assessing different building system platform is another research area. Salama et al. (2017) integrated the critical factors determining manufacturability, logistics and assembly to the modular suitability index for quantifying the competitiveness of different industrialized building. Post occupancy evaluation is expected to include for better customization. Isaac et al. (2016) applied the cluster algorithm and graph theory into BIM data model for design optimization in industrialized building. This optimization method can automatically break down building systems into prefabricated modules considering the rules related their repetition rate, interfacing connection number and renovation frequency. Khalili and Chua (2014) developed an integrated configuration decision support methodology against the requirements of manufacturing and assembly in prefabrication construction to support the design and production systems. Mixed integer linear programming (MILP) was used to improve the utilization of prefabrication molds during production.

Back-end issues: Current literature on this area still remains in an embryonic stage, and no systematic research has well covered in the back-end issues. Manufacturability (e.g. machining capacity) is one of the most common constraints in the design rationalization Austern et al. (2018). Despite to build such capability, design automation such as parametric-based approaches has been progressively benefited the also revealed in the rationalization process. Schmidt III et al. (2014) employed clustering and impact methodologies to analyze the building system architecture and changes respectively. The interdependences between building components were also articulated through a "Dependency Structure Matrix (DSM)" to show adaptability of the building system. Platforms can not only reduce the design effort, but also improve the productivity in productions (Jensen et al., 2013). Through a configurable design platform, the different construction methods can be assessed using product and process platform approaches through discrete event simulation on a bridge design and construction (Larsson et al., 2016). A process platform can support the supply-chain by systemizing the information and work flow (Lessing, 2006: p.171-172). Other areas stated in the back-end issues (Pirmoradi et al., 2014: p. 5-6) in platform based DfMA in industrialized building are not well covered in the current literature.

3. Propositions

3.1 Conventional DfMA Information Exchange

In the conventional DfMA of industrialized building, information exchange patterns are versatile and fragmented with regards to different building methods and production strategies. Different stakeholders exchange information through exchange models. Timing of customer involvement stimulates decoupling points for customer order and project information flow points for detailed specification (Jensen et al., 2012; Winch, 2003). Even though different production and supply-chain strategies may apply, information exchange patterns generally remain unchanged in conventional DfMA practice. Information exchange between different domain experts are not integrated and still rely on exchange models extensively. As summarized in Table 2, there is no integrated and comprehensive DfMA platform has been proposed or studied using the platform-based design methodology in industrialized building so far. Most of the literature only focus on limited areas in the platform development.

3.2 Platform-based DfMA Information Exchange

Table 3: Limitations of Conventional DfMA and New Opportunities in the Platform-based DfMA

	Limitations of conventional DfMA	Solutions in platform-based DfMA
Information Exchange Pattern	Random and fragmented	Integrated
Design Considerations	Only focus on one or several issues	Span from front-end issues, design development to back-end issues
Production Strategy	ETO	Closer engaged with supply-chain, ETO, CTO, etc.
Product Architecture	Various	Modular

Integrated design: The decision support and information exchange in ETO-based industrialized building among different domains is mostly achieved by providing exchange models with constraints. And the capacity requirements from manufacturing and construction are transferred in a later stage after receiving the preliminary architectural model worked out by the architect and engineer domains. "Silo" still exists in the design process even though periodical exchange can improve the communication between domain experts. Platforms can offer a vehicle to integrate the cross-domain information together. An integrated design platform can consist of information constraints from manufacturing, logistics and assembly in which enables a configure-to-order production and supply-chain integration. CTO is different from traditional ETO with its commonality to maximize the manufacturability and its variety for mass customization. Such a CTO-based platform can integrate with configurable product design and leverage the computational and optimization methods to rationalize the design. Even traditional ETO with integrated supply-chain can be further enhanced to become configure-to-order. It also demonstrates a greater capability for customization based on standard and modular components, compared with other supply-chain and production strategies (Jensen et al., 2012). Preliminary design and design development can be integrated once such information for specific projects are pre-defined. Similarly, CTO strategy embedded in platform-based DfMA can provide capacity for design and production teams to early plan for the standard components in which potentially induces shifting of the decoupling point towards planning (Barlow et al., 2003). Along with the emergence of advanced manufacturing (e.g. computer numerically controlled (CNC) fabrication) and design automation (e.g. parametric modelling), design rationalization has been developing in different forms in regards to its role in the design process integrated design approach can take advantages of simultaneous co-creation (e.g. with real-time design support methods (e.g. Austern et al. (2018)'s real-time rationalization).

Configurable product design: Product platforms have synthesized into scalable, modular and generational ones based on the product architecture (Zamirowski & Otto, 1999). We found there were few attempts to synthesize the product architecture for industrialized building. A modular platform is used to create variants through configuration of existing modules (Meyer & Lehnerd, 1997). A scalable platform facilitates the differentiation of variants that possess the same function with varying capacities (Simpson, Maier, & Mistree, 2001a). A generational platform leverages product life cycles for rapid next generation development (Martin & Ishii, 2002). One endeavor towards product platform development is to design product families in the way of "stretching" or "scaling" (Rothwell & Gardiner, 1990)". Integrated building products can be very complicated interfaces which has less chance to re-exist in repetitive standard platforms. In order to fit with the different projects on a same platform, building products can be designed in a configurable form. The platform-based DfMA is expected to show its great capacity for configuration management in early stage of design, which draws constraints and requirements from downstream supply-chain. It can combine CTO strategy to a global product architecture incorporated with function requirements to reduce design changes (Jensen et al., 2015b). Effective configuration management can offer informative change controls to other stakeholders in complex projects (Whyte et al., 2016). Parametric modelling in DfMA projects have demonstrated its effectiveness in prefabricated building (Yuan et al., 2018). With more flexibility shows in the product view method composed of the customer, engineering, production and site assembly processes, future research on IDM can consider mapping between different information constraints to configurable views for information exchange (Jensen et al., 2012). Information exchange in such design can be streamlined in an efficient way by reducing the manual interference (e.g. exchange models or requirements in IDM-MVDs).

Modular product architecture: Figure 1 shows a schematic modular product platform framework for industrialized building. In this framework, different assemblies (e.g. building module or integrated building component) can interact with other counterparts in an adaptive and responsive manner, by linking with the constraints from production systems. Modular or volumetric building has proved high modularity in assembly level. But the modularity at subassembly or higher (e.g. building layout design) levels can be a challenge for design due to limited flexibility induced by separated modules. Nevertheless, previous literature have found a modular product architecture shows the great flexibility to balance the commonality and variety in platform-based industrialized building (Jensen et al., 2015b) compared with the integrated and modular product architecture by (Ulrich, 1995). With more standardized interfaces, it can leave more room for making decisions towards customization.

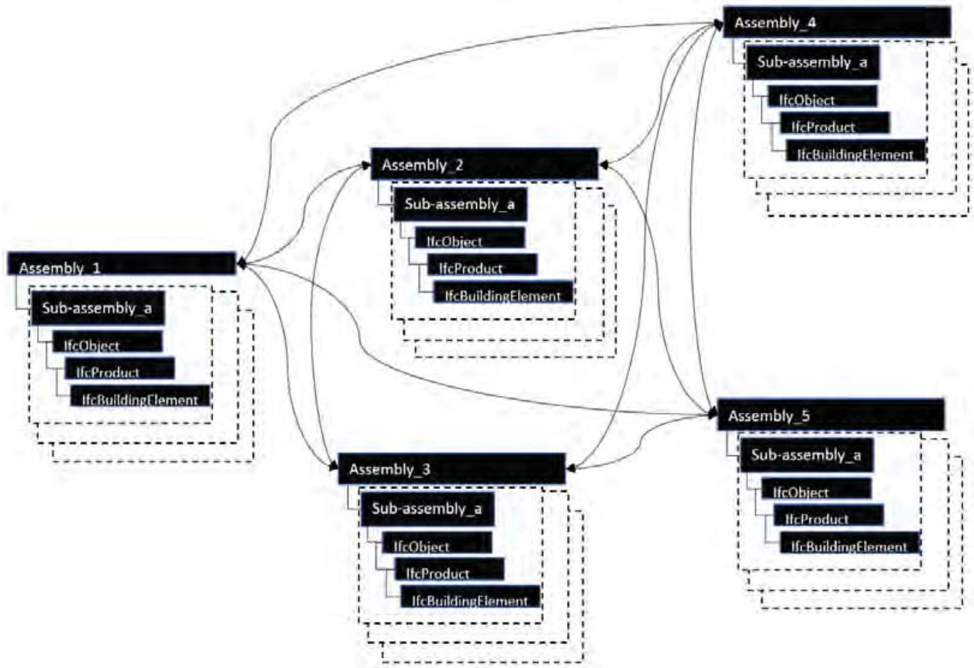

Figure 1: A Schematic IFC-based Modular Product Platform Framework through Configurable Design

4. Conclusions and Future Research

This research trajectory is important because it fills the gap between conventional and platform-based approaches of DfMA from an information exchange perspective. By summarizing and proposing the platform approaches in DfMA, potential benefits of design can be extended to the project lifecycle. More use cases of platform-based DfMA will be collected to validate the propositions drawn from this paper. Especially, to explore the information exchange in industrialized building by developing IDM and MVD is a key aspect for validation. Platform-based DfMA can incorporate decision making systems, metrics to show key features of building design as well as supply-chain management.

A platform for DFX has the capability to streamline other decision support systems to design stage and ensure the interoperability between different users and stages (Huang, 1996: p.6). One possible research area can be drawn on the real-time rationalization through simultaneous feedback and "parametric co-rationalization" between the design and manufacturing systems (Austern et al., 2018). Data-centric approaches like semantic techniques (e.g. linking BIM with product catalogues by Costa and Madrazo (2015)) and multi-objective optimization methods (e.g. Schmidt III et al. (2014)'s research) have shown potential benefits to support this research. There are also more opportunities to investigate the platforms' role in the industrialized building. Particularly, the technological platforms in the types of internal, supply-chain and industry types in regards to their different "constitutive agents", "interfaces", "accessible innovative capabilities" and "coordination mechanisms" (Gawer, 2014). The specific institutionalization of platforms for industrialized building is another key area for researchers to study.

The review and synthesis of the literature extend the knowledge of DfMA by linking construction, particularly industrialized building with product design and development platforms. Platforms in different contexts can effectively streamline the project lifecycle in certain ways, which need more evidence to support. Despite the emergence of modular platforms, an automobile-like generational platforms proposed by Zamirowski and Otto (1999), is yet to be developed. A study on this can potentially show the evolvement of building design practice. Novel design support systems can enable the rapid and iterative development of such platforms for industrialized building. To develop such systems needs an in-depth understanding of flexibility within platforms. Thus, it is worthwhile further studying using approaches of flexibility in engineering design.

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