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Platforming for industrialized building: a comparative case study of digitally-enabled product platforms

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ABSTRACT
Digitally-enabled product platforms are becoming prominent approaches for industrialized building. Such a platform is a collection of common and stable modules and interfaces that can derive products effectively using digital delivery. The usage of construction product platforms has been studied in the existing buildings literature; however, there is relatively less on firms' strategies of platform elements for *platforming*, which encompasses both the development and deployment of a digitally-enabled product platform. This paper examines how construction firms strategize for platforming, through a comparative case study approach with nine international case firms. Findings indicate that three typologies platforms that firms implemented: those rely on a kit of parts only; those have also developed structured interfaces; and those have also established design rules. Inferring from findings, this paper articulates the influential role of customer requirement certainties across multiple market segments in shaping these strategies. By offering a novel classification of platforming strategies under varied certainties of customer requirements across market segments, this paper contributes to the research on construction product platforming strategies. This has implications for practitioners and opens new areas for research, taking the characteristics of customer requirements within or across market segments into account in strategic decision-making on digitally-enabled product platforms.

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Introduction

Industrialized building is a way to construct buildings by leveraging technologies and principles from advanced manufacturing and digital delivery to achieve sustainability (Kedir & Hall, 2021; Zhang et al., 2022). Proponents of industrialized building have been learning from the manufacturing sector and applying its principles since the last century (e.g. Barlow et al., 2003; Gann, 1996). When industrialized building firms try to construct by reusing common modules to generate buildings for different market segments (Barlow et al., 2003; Gann, 2000), developing and deploying a *digitally-enabled product platform* becomes important; because firms need to reassess their strategies to derive products achieving economies of scale and scope (Barlow et al., 2003; Gann, 1996; Gann, 2000). Many governments and firms have seen the potential benefits of platforming as an approach to improve long-standing productivity and sustainability issues across projects, firms and the sector as a whole (HM Government, 2020; MOHURD, 2020; WEF, 2018; Zhang et al., 2019). Such a platform can configure the final products using a set of common modules (i.e. kit of parts), interfaces and design rules through digital delivery effectively (Lobo & Whyte, 2017; Meyer & Lehnerd, 1997; Mosca et al., 2020; Simpson, 2004; Ulrich & Eppinger, 2012).

The idea behind digitally-enabled product platforms has recently received attention in various countries, which is to address the productivity and sustainability deficiency the construction sector faces (WEF, 2016, 2018), as well as the demand for building more social infrastructure, such as affordable housing, quarantine camps, vaccine centres (e.g. Pancevski, 2022; The Standard (HK), 2022; Wilson, 2020). There have been substantial initiatives in Hong Kong, mainland China, Singapore and the UK (BCA, 2018; DEVB, 2018, 2020, 2021; HM Government, 2020; MOHURD, 2020), along with an increased interest in industrialized building in the US (Pullen et al., 2019). In response to the policies and firms' own needs to improve deficiency, construction firms face strategic challenges for the uptake of platforming.

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There has been some work on construction product platforming strategies, encompassing the development (e.g. Johnsson, 2013; Jones et al., 2022; Veenstra et al., 2006) and deployment (e.g. Jansson et al., 2014) of platforms. However, the trajectory of research at the firm level remains relatively immature (Glass et al., 2022), and there is relatively less understood about platform elements for platforming, i.e. the development and deployment in various market segment conditions. Therefore, the motivation of this paper is to examine how firms strategize the platform elements for *platforming* and related customer requirements of target market segments. To address the research question, this paper adopted a multiple-case study approach – using secondary and primary data from nine internationally leading construction firms with strategies for platforming.

Literature review

Industrialized building as a firm strategy

To transition into industrialized building, construction firms need to leverage technologies and principles from manufacturing (e.g. Hall et al., 2020; Zhang et al., 2019; Zhou et al., 2023). Proponents of industrialized building have advocated learning technologies and principles such as standardization, prefabrication, etc., from advanced manufacturing and digital delivery (Barlow et al., 2003). In transferring such principles into industrialized building, it is necessary to reuse modules to derive future buildings effectively, which makes the use of digitally-enabled product platforms become important (Barlow et al., 2003; Gann, 1996; Mosca et al., 2020).

Digitally-enabled product platform: three platform elements and customer requirements

Platforming encompasses the development and deploying of a digitally-enabled product platform (Meyer et al., 2018; Zhang, 2015), which is a set of predefined subsystems and interfaces that firms can use to develop a stream of derivative products using digital delivery effectively (Lobo & Whyte, 2017; Meyer & Lehnerd, 1997; Simpson, 2004; Ulrich & Eppinger, 2012). With the growing interest in industrialized building by learning manufacturing principles, research on product platforms began to emerge in buildings and construction literature recently. Because product platforms show potential benefits in building projects, there are calls for adaption to mobilize ‘product platform’ in construction, with the context nature such as project-based and complexity in the product system (Jansson et al., 2014). Veenstra et al. (2006) apply a platform framework by Meyer and Lehnerd (1997); Robertson and Ulrich (1998), constituted of modular product architectures, interfaces and standard design rules, to a building project, indicating potential benefits on cost and productivity. Jansson et al. (2014) argue the platform framework needs adaptation in construction, by suggesting the importance of a balance of platform knowledge, relationships and technical elements. However, how firms strategize for platforming is unclear.

This study is motivated to examine how firms mobilize platform elements inside product platforms for industrialized building. Thus, it synthesizes these common elements of digitally-enabled product platforms, i.e. *digitally-enabled kit of parts*, *digitally-enabled interface and digitally-enabled design rule*.

Digitally-enabled kit of parts

To group modules in a library in deriving future products, a kit of parts or product library is defined as a collection of discrete building modules that are pre-engineered and designed for manufacturing and assembly in a variety of ways as a finished building (Gibb, 1999; Gibb, 2001; Howe et al., 1999; Zhao et al., 2018). With a *digitally-enabled kit of parts*, modules (or components) can be engineered and defined before design and manufacturing pre-engineered using digital delivery (e.g. Cao et al., 2021; Gan, 2022b). A module is designed and manufactured, ready for onsite assembly with predefined interfaces, at varying prefabrication levels (Gibb & Pendlebury, 2006; Gosling et al., 2016; Peltokorpi et al., 2018). Different combinations of modules cover structural, mechanical, electrical and plumbing and other services. For example, structural modules can be composed of structural components, made of steel, reinforced concrete, timber, or other composite materials (Gosling et al., 2016).

Digitally-enabled interface

In this paper, *digitally-enabled interface* is defined as a set of digital and physical specifications or protocols to define interactions and relationships between modules (Chen & Liu, 2005; Ulrich, 1995), which can be digitally defined and codified using building information modelling (BIM) objects containing interface requirements (e.g. Jensen et al., 2012; Tetik et al., 2019). Digitally-enabled interfaces can store dependence requirements between modules, including engineering, architecture, production, assembly and others (e.g. Jensen et al., 2012; Wikberg et al., 2014).

Digitally-enabled design rule for future products

Digitally-enabled design rule refers to a set of digitally-codified protocols, standards and specifications for product reconfiguration and deriving future products (e.g.

Baldwin & Clark, 2006; Meyer & Lehnerd, 1997). These digitally-codified protocols, standards, or specifications are in a machine-readable format and mostly process information containing the design, manufacturing and assembly (including transportation) constraints (Soman & Whyte, 2020), which can be used for data-driven design such as generative design integrating with algorithms (Gan, 2022a, 2022b). Firms can use such digitally-enabled design rules to derive and reconfigure products based on defined kits of parts and interfaces across value chains (e.g. Jensen et al., 2012; Singh et al., 2019; Wikberg et al., 2014). Product platforms can embed design rules into product development for industrialized building, by effectively reutilizing past knowledge and processes (Jensen et al., 2012; Malmgren et al., 2011).

Customer requirement in product platforms

Understanding the customer requirements from specific market segments is important for industrialized building firms before platforming (Lessing & Brege, 2018; Wikberg et al., 2014). Investing in platforming for industrialized building firms can be expensive both in the development and deployment, partially due to uncertain customer requirements from target market segments in the development stage (Rasmussen et al., 2021). For platforming, firms need to decide the extent of customer requirements for the development (Bonev et al., 2015; Hvam et al., 2008), so that they can deploy such platforms into specific projects by configuring the kit of parts, interfaces and design rules (Bonev et al., 2015; Hvam et al., 2008).

A major assumption for mass customization in mass-production industries is based on knowing the customer requirements from specific market segments (Hvam et al., 2008; Johnsson, 2013; Rudberg & Wikner, 2004), where production is organized by flow (Hobday, 1998). Yet construction is unlike mass-production industries; products in industrialized building are produced in low volume or sometimes one-off, which often relate to complexities and uncertainties (Dubois & Gadde, 2002). These mean, high interdependences across modules, and relevant technologies, and tasks (Barlow et al., 2003; Gann, 1996), and uncertainties due to a lack of understanding of the resources and site environment (Dubois & Gadde, 2002).

Due to such complexities and uncertainties, construction firms may face challenges in mobilizing the platform elements while taking unpredictable customer requirements along the journey to develop and deploy platforms (Jones et al., 2022; Kudsk et al., 2013; Shafiee et al., 2020; Veenstra et al., 2006). In predefining product platforms, firms need to acquire adequate customer requirements in product development in alignment with the customer order across design and production stages (Johnsson, 2013; Rudberg & Wikner, 2004). Although Kudsk et al. (2013) advocate top-down as a preferred approach for product platform development to take customer requirements in the beginning, firms may have established modular kits of parts for those transitioning into digitally-enabled product platforms (Jones et al., 2022). Yet how firms develop and deploy these platform elements in varied certainties of customer requirements across market segments is unknown. All of these calls for a more granular understanding of how firms mobilize platform elements across market segments for *platforming*, including not only those modular kits of parts, but also interfaces, and design rules (Jiao et al., 2007; Simpson, 2004; Simpson et al., 2006).

Research methods

This paper adopts the multiple-case study, a recognized and established methodology in construction management research (Fellows & Liu, 2015; Schweber, 2016). The case study is appropriate because the research questions in the paper are about 'how' (Eisenhardt & Graebner, 2007). The case study is suitable for studying phenomena in which extant research might not be well explained (Benbasat et al., 1987; Edmondson & McManus, 2007). Across-case comparison in the multiple-case study can prove whether the emergent findings can be replicable (Eisenhardt, 1989)

Research setting

The study examines the leading industrialized building firms globally that developed and deployed digitally-enabled product platforms. The firms studied operated in Singapore, Hong Kong, and mainland China, the UK, and US. Internationally, there is a trajectory to adopt industrialized building to improve productivity in delivering buildings and infrastructure (WEF, 2016). In these countries or regions, there were incentives either from governments or capital investment to promote the adoption of industrialized building or digitally-enabled product platforms. Thus, construction firms operating in these countries (or regions) with interest in industrialized building.

Case selection

This paper used a purposive strategy to address the research question. The sampling boundaries and frame were set in the predefined criteria for case selection below (Miles & Huberman, 1994); they are: (1)

Table 1. Overview of case firms.

Case code	Type of firm (origin, primary business)	Digitally-enabled kit of parts	Location	Turn-over*
A	Specialist supplier and systems integrator with in-house product development and outsourced manufacturing	BIM-based; *non-volumetric preassemblies:* precast slab, façade, balcony; *volumetric preassemblies*: bathroom units, plant room module with interior fitting-out and MEP; *modular buildings*: residential flat modules	Hong Kong	Not available
B	General contractor with product development and manufacturing in-house	BIM-based; *non-volumetric preassemblies:* panel slab, hollow core slab, façade wall; *modular buildings*: Pre-fabricated bathroom unit, concrete PPVC module	Singapore	146 m
C	General contractor with own product development and manufacturing	BIM-based; *non-volumetric preassemblies:* 8 types: integrated floors, internal walls, external walls, integrated kitchens and baths, elevators, integrated interior decoration systems and intelligent building management systems	China /International	2 b (parent group)
D	Professional service firm with in-house product development and systems integration, and outsourced manufacturing	BIM-based; *non-volumetric preassemblies:* timber, steel, etc., mechanical & electrical module; *modular buildings*: school, office, prison, housing	UK, Singapore, Spain	70 m
E	General contractor with own product development and manufacturing	BIM-based*, non-volumetric preassemblies:* concrete floor, beam, MEP module, wall; *volumetric preassemblies*: Internal room pod, plant room	UK/International	3 b
F	Manufacturer or manufacturing system provider with own product development	BIM-based; *non-volumetric preassemblies:* structural component and system; *volumetric preassemblies:* modular mechanical, electrical and plumbing system, modular partition	China	84 b (parent group)
G	General contractor with outsourced product development and manufacturing	BIM-based; *non-volumetric preassemblies:* precast concrete units incorporating façade, precast trenches for MEP; *volumetric preassemblies:* DfMA (design for manufacturing and assembly) module, MEP module; *modular buildings:* MiC units equipped with plumbing and drainage	Hong Kong, Singapore	2.5 b
H	Digitally-enabled systems integrator with in-house product development and external manufacturing	BIM-based; *non-volumetric preassemblies:* door, windows, wall panel, metal deck; *volumetric preassemblies*: bathpod; *modular buildings:* school, healthcare, retail	US	3.7 m
I	Digitally-enabled systems integrator with in-house product development and external manufacturing	BIM-based; *volumetric preassemblies:* bathroom pods (modular electrical system, steel frame, plumbing system)	US	Not available

Remarks: * in USD, in Financial Year 2019, b stands for billion, m stands for million.

the firm was a regionally recognized industrialized building firm; (2) the firm maintained a modular kit of parts (or product library) for industrialized building; and (3) firms claimed they had digitally-enabled product platforms. The paper also used convenience sampling to select firms with which the researcher had links. This paper also considered diversified geographical locations to sample firms with international cases. A summary of case firms can be found in Table 1.

Data collection

This study relies on secondary data (e.g. archival material, firm websites, annual reports, official documents, slide decks, book chapters) and primary data (e.g. interviews). The data set includes different sources: 7845-page archival documents, consisting of annual reports, slide decks, etc.; 1062-minute videos and audios; 1627-minute recordings of 30 in-depth interviews with executives and product development leads; and seven factory and office visits (Pettigrew, 1990).

A protocol was used to structure the interviews, asking questions to understand firms' practices in developing and using a kit of parts, interface specifications and design rules. This protocol was partially developed based on a number of existing literature on industrialized building and product platforms, which contains questions about modular product architectures, interfaces, etc. (e.g. Gibb, 1999; Jonsson & Rudberg, 2014, 2015).

Data analysis

Data analysis was carried out by revisiting the data set and existing theories iteratively (Eisenhardt & Graebner, 2007). Firstly, data were synthesized into case narratives with a focus on platform elements, i.e. the kit of parts, the interface and the design rule. The emergent patterns of how each case firm developed its platform were identified. A number of emerging themes were coded, for example, related to the kit of parts, 'mechanical and electrical modules', 'modular mechanical and electrical installations', etc.

The platform elements and firms' practices were compared and contrasted. The practices of each platform element, used by each case firm were tabulated. Then, existing literature and data were revisited, to compare and verify the emergent constructs. This was complemented with additional data collection until theoretical saturation was reached. For example, existing theories on 'interface' in the product platform literature, data and emergent constructs on digitally-enabled interfaces were looked back and forth. This sharpened construct, theoretical relationships between constructs, and underlying theoretical (Eisenhardt, 1989).

Validation strategies

In interpretive research, it is usual to address validation by addressing the reliability, credibility and generalizability of the research (Miles et al., 2014). To increase the reliability, a protocol for the interview and maintained a database was developed for every investigator to access and check. In addition, findings were presented to international audiences at a range of international research conferences. A community of scholars discussed and negotiated the data collection, data analysis and findings from this research. By discussing with them, these informants agreed with the findings and theories. This paper also includes 'thick descriptions' (Miles et al., 2014) in the findings. For example, in-depth case descriptions were written to provide 'context-rich' data (Pratt et al., 2020). This can enhance both credibility and transferability (Miles & Huberman, 1994). This study investigated the 'common process' by selecting cases on the 'same focal phenomenon' (i.e. development and deployment of digitally-enabled product platforms) across different settings. This could enhance generalizability (Eisenhardt, 2021).

Case descriptions

The table below presents an overview of each case firm, including the type of firms, locations, turnover and primary materials of products. The following section introduces each case firm and its platforms.

Firm A: expanding kit of parts with a growing project portfolio

Firm A is an industrialized building specialist with government qualifications to design, fabricate and erect precast concrete components. It focused on the design, manufacturing and assembly of modules, and maintained a well-established kit of parts with its gradually diversified project portfolio. Its concrete slab product and modular integrated construction system were recognized and listed in the government funding pre-approval list, and concrete-based modular integrated construction systems were pre-accepted by the authority.

Firm B: loosely creating digitally-enabled kit of parts

Firm B is one of the A1-graded general builders in Singapore with over than 40-year track record of building industrial, residential and commercial facilities. It established a proven record in delivering public sector projects, with several awards in achieving excellence at the capacity of the main contractor. Firm B supplied a wide range of products in alignment with the kit of parts.

Firm C: one interface fits all market segments

Firm C is one of the largest multinational industrialized building firms based in China with a global footprint. Its product platforms are made of concrete-steel composite material. Firm C established a range of product platforms ranging from apartments, offices, schools, hospitals to dormitories. *PlatformC* (pseudonym) is composed of eight types of proprietary 'Eight Subsystems'. Such subsystems (or modules) are scalable and integrated internally with a predefined interface with other modules. Reliant on simple interfaces between beams and columns, the structural modules are flexible and can be used across product platforms.

Firm D: housing, school and office platforms for future projects

Firm D is a leading integrated design and engineering firm headquartered in the UK, with European and Asian branches. Its platforms cover market segments of offices, housing, schools, etc. Firm D has developed *PlatformDHousing* (pseudonym), *PlatformDSchool* (pseudonym) and *PlatformDOffice* (pseudonym) for housing, school and office market segments, respectively. These platforms support 'combination of project-level customisation, with space and component-level standardisation'. For schools, Firm D predefined modular buildings based on the service purpose, such as libraries, toilets, plants. Its product platforms stored those digital (BIM)-enabled kits of parts, digitally-enabled interfaces and digitally-enabled design rules.

Firm E: parametric kits for multiple market segments

Headquartered in the UK, Firm E is a leading construction firm with a global outreach in the Middle East, Europe, North America and Australia. It developed and maintained a proprietary kit of parts with proprietary framing solutions, such as steel-based and demountable concrete-based framing for retail, commercial, airport, housing and school market segments. Firm E predefined kits of parts and then digitally configured them for market segments of schools, healthcare and housing.

Firm F: versions one to three for multiple market segments

Headquartered in mainland China, Firm F is a spin-off of a global construction equipment giant. Its parent company is one of the largest global construction equipment providers with offices and R&D centres outside China. *PlatformF* was composed of non-volumetric and volumetric preassemblies. Their kits had 64 proprietary patents for structural systems, components and connection details. *PlatformF* has been embedded with decomposition rules to generate future products in compliance with its own standards.

Firm G: developing module drawings and reusing digitally-enabled kits of parts

Firm G is a construction conglomerate headquartered in Hong Kong with branches in Southeast Asia and over 60 years of history. It has carried out different industrialized building projects through DfMA, including data centres and quarantine facilities. Firm G offers non-volumetric preassemblies, volumetric preassemblies and modular-buildings modules, in which housing modules are preapproved by the authority. Its kits primarily focus on the housing market segment.

Firm H: continuously expanding to four segments

Firm H is a technology-based service provider of industrialized building in US. *PlatformH* (pseudonym) consists of several kits of parts. Its kits cover from the non-volumetric preassemblies to modular buildings, and volumetric preassemblies. In one of its bathpod modules, it reconfigured modular electrical systems, steel frames, plumbing systems and glass fibre reinforced concrete bases. There are also schools, healthcare centres and convenience stores in its modular building offerings.

Firm I: linking requirements in value chains using kits of parts and design rules

Firm I is an industrialized building specialist. *PlatformI* (pseudonym) leveraged parametric design (a digital technology to enable design using configurative parameters) and DfMA methodologies to develop a proprietary technology, *TechI* (pseudonym). *TechI* can be used to streamline the process data between each other in the value chain, including manufacturers, designers, architects, suppliers, etc. Its revenue mainly came from licencing fees by leasing its platforms to clients in the value chain. Till early 2021, its platform has a kit of parts for configurable volumetric preassemblies.

Findings: three types OF platforming strategies

Through this data set, findings show three types of firms that mobilize platform elements into their platforming strategies. By unpacking and evaluating the platform elements and their customer requirements of case firms, analyses suggest firms can mobilize platform elements in three types of approaches – driven by various certainties of customer requirements (as Figure 1 shows).

Findings show that firms with the Type-1 approach chose to develop the digitally-enabled kit of parts only. As customer requirements were largely from one single market segment and firms were less certain about requirements across other market segments, Type-1 firms did not seek to define or standardize interfaces between modules, or apply design rules. The platforms of Type-1 firms stored and reused existing modules, but the interface would be defined manually when there was a new design. As design rules were not developed, deriving of new products would be carried out manually. Considering expanding the customer requirements towards multiple market segments, it identified that firms with the Type-2 approach chose to develop the digitally-enabled kit of parts and interfaces. With an increased certainty of customer requirements across different market segments, Type-2 firms developed digitally-enabled kits of parts and established structured interface specifications. These firms, i.e. Firms C and E, developed interface protocols into standard details, while formalizing design rules into internal standards or design manuals. In contrast, this paper identified that firms with the Type-3 approach chose a complete digitally-enabled kit of parts, interfaces and design rules. This type of firm had a higher certainty of customer requirements from multiple market segments. As a result, these firms developed and updated their platform regularly to derive future building systems while accommodating new requirements from ongoing customer requirements. In addition, it found that an increasing number of interface specifications and design rules had been transformed into digitally-enabled interfaces and digitally-enabled design rules.

Because there were relatively more certainties on future requirements, firms used these Type-3 platforms to derive building systems by linking requirements from the value chain and users. Across three types of strategies, findings indicate all firms positioned digitally-enabled kits of parts at the core, while the digitally-enabled interfaces and design rules were of various completeness. Table 2 summarizes the platform elements in three typologies of platforming strategies.

Type 1: Digitally-enabled kit of parts with a focus on a single market

The first type, Type-1 firms, were identified that have only developed a digitally-enabled kit of parts (see more details in Table 3). Findings suggest that the customer requirements largely focused on the single housing segment, while the governments of the markets they operated in (i.e. Hong Kong and Singapore) mandated the use of industrialized building in the delivery of social infrastructure. With less focus on future customer requirements across other market segments, Firms A, B and G defined kits of parts into BIM models. However, they did not define interfaces between modules in the digital format or the design rules for creating future products.

Firm A focused on the housing market segment – predefining three main types of modular-buildings modules: studio modules, 1-room flat modules and 2-room flat modules. It reused these modules to accommodate specific project needs by recombining modules with bedrooms, living rooms, bathrooms and corridors. However, the requirements focused on the housing segment. With less ambition to derive future products for other market segments, Firm A has not turned interfaces or design rules into digital format. Its way to reuse these kits remained manual and *ad-hoc*.

Similarly, Firm B did not define any specific standard, specifications between modules, or design rules for configuring products. Firm B only defined commonly-used physical modules into digital modules. Firm B supplied a wide range of products in alignment with the kit of parts for the housing market segment, yet it did not specify other market segments the modules could be used for. Firm B heavily relied on the requirements given by their customers, and it usually did not influence the customer requirements. Thus, Firm B did not often reutilize the existing kit of parts outside other market segments, and it had not formulated a structured way to store and reuse the interface specifications. Firm G developed a digitally-enabled kit of parts with housing module drawings, and regularly updated those commonly-used building kits for MEP and structures. It has started to reuse its kits of parts and associated DfMA processes in newly-awarded projects. However, most of the modules were designed only for housing, and the requirements it used were focused on the housing market segment.

Type 2: Clearly-defined interface based on a digitally-enabled kit of parts

Type-2 firms were found to develop structured interface specifications based on their digitally-enabled kits of parts. Evidence indicates these firms started developing these specifications into digitally-enabled interfaces (see more details in Table 4). Using digitally-enabled interfaces, Firm E started to transform design manuals and typical drawings into digital tools to configure inter-module interfaces. Firm C drafted the internal standards specifying how to design the interfaces, and published them as industry standards.

By doing so, these firms were found to use digitally-enabled interfaces to configure plant rooms and interconnections between modules at the subsystem level. As for design rules, these firms were found to have drafted specifications such as codes of practice or design manuals and then started transforming these into digitally-enabled design rules. Because Firms C and E have started to witness the potential benefits from broader market segments, they started to take the customer requirements into interfaces and design rules while driving them to continue to bring digital delivery towards digitally-enabled product platforms.

With five market segments, including apartments, offices, schools, hospitals and dormitories, *PlatformC* is scalable and integrated internally with a predefined interface with other modules. The modules are flexible and can be used across market segments. In one of its school projects, the beam-column interface can be configured using the parametric feature in a digital tool, such as choosing different sizes of structural members. Firm C also developed internal codes of practice for the interface design and codified internal standards into drawing sets. It formulated 'one type of standard interface' and then used it across different market segments consistently. There were early attempts to transform codes of practice into digitally-enabled design rules to derive schools. Beyond the kit of parts, Firm E developed a roadmap that assists engineers and designers in using its kit of parts in different scenarios. It also developed digital tools for 'defined and repeatable interfaces' between modules to achieve quality and programme requirements. Using these parametric tools, it could customize products by putting manufacturing constraints. Its annual report stated, 'to move from

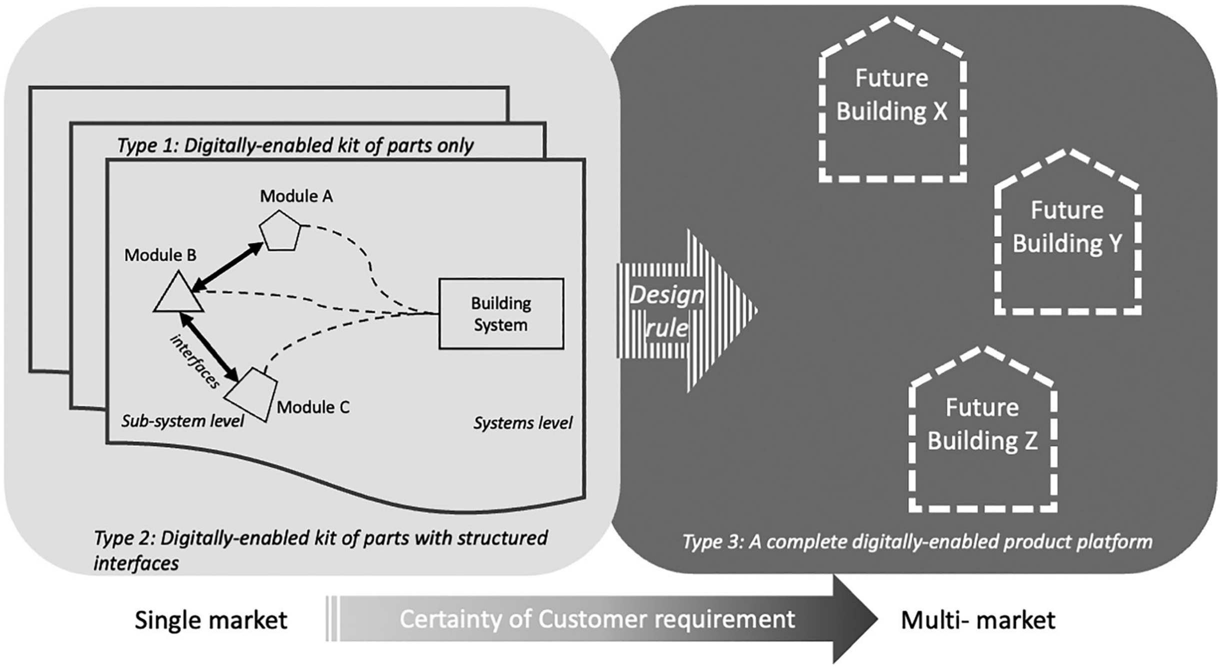

Figure 1. Three types of platforming strategies.

partial adoption of digital design tools […] to fully generative and parametrised design […] aligning with the requirements'. Firm E had developed a 'clear pathway' to better use the requirements from target market segments.

As explained above, Firm C had a higher certainty in the customer requirements from the beginning – scoping its eight subsystems for five various market segments. Having experienced the growth of the pipeline driven by the housing segment, Firm C further developed the digitally-enabled kit of parts with digitally-enabled interfaces, while currently pursuing digitally-enabled design rules. Such pipeline certainty of the other segments, such as dormitory, office and hospital segments, also drove Firm C to develop further. For Firm E, initially, the market segment was on the module level, now on the building systems level for multiple market segments, covering housing, school, commercial, etc.

Table 2. Overview of digitally-enabled product platforms by each case firm.

	Digitally-enabled kit of parts	Digitally-enabled interface	Digitally-enabled design rule	Characteristics of customer requirements	Cases
Type 1	Yes	No	No	Highly focused on a single market segment, with a low certainty about other market segments	Firms A, B and G
Type 2	Yes	Structured	No	Increased certainty across multiple market segments	Firms C and E
Type 3	Yes	Yes	Yes	High certainty on future building systems across multiple market segments	Firms D, F, H and I

Type 3: Towards cross-market platforms: a complete digitally-enabled product platform

Type-3 firms were found to develop a complete set of required platform elements. These firms were found not only to develop digitally-enabled kits of parts based on BIM tools, but also codified interface specifications into BIM as digitally-enabled interfaces, which can generate inter-module connections with a high level of detail (see more details in Table 5). This evidence indicates high certainty of customer requirements in developing and operating digitally-enabled product platforms, while considering multiple market segments and potential changes of future products. These firms also developed codes of practice and digitalized those manufacturing and assembly requirements in their platforms. Firms D, F, H and I can use their platforms to derive a variety of building systems in compliance with their code of practice and other building regulations.

PlatformDHousing can incorporate the rules of 'the manufacturers and also the design guidance of both

Table 3. Overview of Type-1 case firms.

Case code	Digitally-enabled kit of parts	Digitally-enabled interface	Digitally-enabled design rule	Characteristics of customer requirements
A	BIM-based; *non-volumetric preassemblies:* precast slab, façade, balcony; *volumetric preassemblies*: bathroom units, plant room module with interior fitting-out and MEP; *modular buildings*: residential flat modules	Typical details in drawings, yet not in a systemic way; not yet in digital format	Manually and *ad-hoc* to derive future products	Mainly on housing without any specific focus on other markets
B	BIM-based; *non-volumetric preassemblies:* panel slab, hollow core slab, façade wall; *modular buildings*: Pre-fabricated bathroom unit, concrete PPVC module	Not predefined, loosely stored interface specifications	Manuals, on manufacturing requirements	Mainly on housing without any specific focus on other markets
G	BIM-based; *non-volumetric preassemblies:* precast concrete units incorporating façade, precast trenches for MEP; *volumetric preassemblies:* DfMA module, MEP module; *modular buildings:* MiC units equipped with plumbing and drainage	Typical detail drawings but not in digital	No	Mainly on housing without any specific focus on other market segments

(clients) and architects themselves'. With such a future-ready approach, Firm D also developed product platforms for real estate developers. Another example is *PlatformDOffice*, in which kits of parts were 'designed in such a way […] taken forward and used on future projects'. Firm D had seen the great demand and certainty in customer requirements from the housing segment. It can generate various compliant housing and school building systems for users to select based on the user requirements, such as 'design guides and building regulations' in several minutes. Building upon its kits, Firm F developed modular MEP systems and modular partitions. *PlatformF* integrated digitally-enabled technical specifications, and patented digitally-enabled kits of parts, to achieve automated drawing production. *PlatformF* codified and standardized all processes from design, manufacturing to assembly into industry specifications. *PlatformH* can support reuse modules across different projects. It developed 'a catalog of buildings' for different market segments. By integrating interface specifications and design rules into the tool, *PlatformH* stores codified architectural design, schedule, pricing and engineering data. Similarly, Firm I leveraged parametric design and DfMA methodologies to develop a proprietary technology *TechI* for configuration. An example is its bathroom pod, in which *TechI* was used to link requirements computationally from customers as well as the value chain, such as manufacturing and logistics. Firm I utilized *TechI* for the detailed design of interfaces to meet manufacturing and other requirements. *TechI* automated these design rules for faster configuration. In one demo, the bathroom pod can be stretched digitally, in which modules and interfaces can be automatically reconfigured to suit the size of pods.

Witnessing the demand from the government procurement pipeline and incentives from government funding, FirmD developed *PlatformDHousing* and *PlatformDSchool*. With certainty across multiple market segments, *PlatformF* was developed to be digitally configured for healthcare, offices, schools, housing, etc. Firm H, as explained, indicates its multi-market segment platforms based on the known requirements of these targeted segments. Firm I started with a clear understanding of customer requirements for 'mass customization', *TechI* was developed with the idea of 'mass customization', and its CEO further added, 'the customers will use your product being center that we can take this group of people, they could all be product owners'. Firm I targeted, 'residential, multi-story, residential […] cross-laminated timber or mass timber' (CEO) at

Table 4. Overview of Type-2 case firms.

Case code	Digitally-enabled kit of parts	Digitally-enabled interface	Digitally-enabled design rule	Characteristics of customer requirements
C	BIM-based; *non-volumetric preassemblies:* 8 types: integrated floors, internal walls, external walls, integrated kitchens, and baths, elevators, integrated interior decoration systems, and intelligent building management systems	Standard drawings, technical standards and interfaces between modules can be digitally configured	Follow standards, but no digital rules to generate future products	Across five segments (office, housing, hotels, hospitals, schools)
E	BIM-based, *non-volumetric preassemblies:* concrete floor, beam, MEP module, wall; *volumetric preassemblies*: Internal room pod, plant room	Roadmap; Design guide for modules	In development, no formalized approach yet; some digital configuration rules, '*achieve quality and programme requirements*', '*manufacturing constraints*' (Firm website)	Across three segments (housing, school then office)

Table 5. Overview of Type-3 case firms.

Case Code	Digitally-enabled kit of parts	Digitally-enabled interface	Digitally-enabled design rule	Characteristics of customer requirements
D	BIM-based; *non-volumetric preassemblies:* timber, steel, CLT panel, line boards, M&E module; *modular buildings*: school, office, prison, housing	Connection details between modules or components were defined and configured digitally	Different building systems can be generated using BIM and design rules, for schools and housing	Expanded across five segments (pharmacy factory, then school, housing, office)
F	BIM-based; *non-volumetric preassemblies:* structural component and system; *volumetric preassemblies:* modular MEP system, modular partition	Connection detailing tools, composed of proprietary codes of practice for design, manufacturing an assembly; compliant interface specifications can be generated	Different building systems can be generated; incorporating structural analysis, manufacturing and assembly constraints	Initially across seven segments (healthcare, housing, research, commercial, academic, housing, underground)
H	BIM-based; *non-volumetric preassemblies:* door, windows, wall panel, metal deck; *volumetric preassemblies*: bathpod; *modular buildings:* school, healthcare, retail	Codified architectural design, schedule, pricing and engineering data	Future building systems can be generated using predefined algorithms and design rules, for different types of schools, restaurants	Gradually expanded to four segments (school, housing, education, healthcare)
I	BIM-based; *volumetric preassemblies:* bathroom pods (modular electrical system, steel frame, plumbing system)	Interfaces can be generated digitally	Different bath pods can be generated considering manufacturing, logistics, supply chains, engineering rules	Not predefined, but used for different segments

multiple market segments. Firms D, F, H and I codified the interfaces into digital specifications; and developed digitally-enabled design rules in addition to the digitally-enabled kit of parts and interfaces.

Discussion

By theorizing and synthesizing firm strategies for platforming, i.e. development and deployment of digitally-enabled product platforms, the main findings contribute to the industrialized building and construction platforming strategy literature (e.g. Hall et al., 2020; Jones et al., 2022; Lessing & Brege, 2018).

Shaping three platforming strategies: certainty of customer requirements

First, the three typologies of platforming strategies this paper identified relate to existing construction product platforming literature (e.g. Jones et al., 2022; Veenstra et al., 2006). It found that all three types of firms developed the digitally-enabled kit of parts as their first priority, while adopting relatively different approaches to mobilize interfaces and design rules. Findings show that Type-1 firms, facing uncertainties across other market segments, chose to develop the digitally-enabled kit of parts only, while developing and using interfaces or design rules in an *ad-hoc* and unstructured way. The possible reason is that the market demand for housing was steadily high, and customer requirements were regulated by the government consistently. Because all three firms were required to get pre-approval for their modules (mainly volumetric preassemblies or modular buildings) from governments – based on the commonly-used requirements for the specific housing segment. Thus, this suggests that, in the context of relatively stable and clear customer requirements in a specific market segment, which was largely driven by governments in promoting and regulating the use of kits of parts for industrialized building, preferably for housing. Yet, compared with other market segments such as hospitals or hotels, the customer requirements and demand from these segments were relatively uncertain. Such differences in certainties across market segments could hamper the willingness towards further development of digitally-enabled interfaces and design rules. The Type-2 firms, instead, with a growing certainty of customer requirements across multiple market segments, chose to develop further into structured interfaces. It found that Firm C and Firm E targeted at multiple market segments along with the product platform development and deployed projects. The Type-3 firms, with a high certainty of customer requirements across multiple market segments, developed a complete digitally-enabled product platform.

For platforming, firms may need clear or even specific customer requirements for market segmentation (Hvam et al., 2008; Johnsson, 2013; Lessing & Brege, 2015; Rudberg & Wikner, 2004). Findings on these three typologies of platforms show the role of requirement certainties can influence the predefinition of platform elements. Inferring from this, platform elements, i.e. the kit of parts, interfaces and design rules, need to fit the uncertainties of customer requirements, arising from single or multiple market segments in construction. Depending on the certainty of such requirements across market segments, findings suggest industrialized building firms can develop different types of platforms and deploy such platforms into specific projects. To develop platform elements into a complete set of digitally-enabled product platforms, these three typologies suggest that firms need a substantial level of certainty on customer requirements in their targeted market segments to develop a well-defined and complete digitally-enabled product platform. When such requirements are not well defined and uncertain, construction firms are not able to develop their interface specifications or design rules into well-defined digitally-enabled interfaces or design rules. Due to the complexities and uncertainties in terms of customer requirements from the 'demand' side, unlike those firms in 'flow'-based industries, construction firms appear differing potential towards platforming.

Through analyses of platform elements used by case firms, this paper extends the literature on construction product platforming (Jones et al., 2022; Kudsk et al., 2013; Shafiee et al., 2020; Veenstra et al., 2006), by identifying three strategies that firms iteratively developed digitally-enabled product platforms, not even of various completeness. It found these three firm typologies chose to develop the product platforms while utilizing their incomplete platform elements to deliver projects by developing an 'iterative' approach. This iterative approach concurs with the study by Jones et al. (2022) on platforms development in construction, showing that construction firms can develop product platforms 'iteratively' based on customer requirements, instead of developing the product platform in a relatively standalone approach (i.e. top-down or bottom-up) (e.g. Meyer & Lehnerd, 1997; Simpson et al., 2001).

Conclusions

The overall contribution of this paper is to offer a novel classification of platforming strategies – linking the platform elements developed and deployed by firms and the customer requirement certainty across multiple market segments.

Three platforming strategies depending on customer requirement certainty across multiple market segments

The key contribution of this paper is to classify three strategies in firms' development and deployment of digitally-enabled product platforms. This study extends the construction product platforming literature (Jones et al., 2022; Kudsk et al., 2013; Shafiee et al., 2020; Veenstra et al., 2006) showing a novel relationship between customer requirement certainty and firms' platforming strategies.

By examining nine internationally leading construction firms and their platforming practices, this study synthesizes three types of platforming strategies, including: Type-1 firms mobilizing kit of parts only with a certainty of a single market segment, yet lower uncertainties across other market segments; Type-2 firms clearly defining the interfaces based on a kit of parts with increased certainties across multiple market segments, and Type-3 firms: towards a complete set of platform elements with high certainties across multiple market segments. The analyses suggest that customer requirement certainties across multiple market segments matter. This study highlights the influencing and emerging role of customer requirement certainties in the construction industry producing complex product systems. With various levels of such certainties, the study shows how firms can mobilize platform elements into three platforming strategies. This study also concurs with the 'iterative' approach (Jones et al., 2022), in which firms can take customer requirements in the platform development along with the ongoing deployed projects, instead of developing the platforms in a standalone approach.

Implications for policy and firms

This paper has implications for government policy-making. Given that governments in the UK, China and Singapore periodically update their policies on industrialized building and digital delivery, this paper provides insights for policymakers through an in-depth analysis of firms across an international context. The reason why firms have varied platforming strategies can relate to the demand certainty in market segments. Firms may tend to develop and deploy a complete set of platform elements when the demand is consistently predictable and stable, preferably across multiple market segments. Similarly, Construction Innovation Hub (2022) argues 'predictability' of demand (including the nature and volume) or 'pipeline' is an important antecedent in shaping platform strategies. Policies and public owners should be aware of this to ensure the stakeholders foresee the customer requirements and the demand volume. Possible actions can include: providing clear and foreseeable tender notices in the longer term; a collaborative approach for procurement with the key stakeholders along supply chains; interchangeable specifications which take the requirements of different target market segments (e.g. schools and housing), the long-term relationship across stakeholders to determine the requirements.

This paper has implications for executives. For those firms developing and deploying digitally-enabled product platforms, understanding the targeted market segment matters, as firms may need certainties of product requirements, preferably from multiple market segments, before making strategic decisions to invest in product platforms.

Limitations and new directions for scholarship

This study explores how firms mobilize platform elements as their digitally-enabled product platforms by synthesizing three types of platforming strategies. More in-depth future research can address why firms choose these different strategies from other perspectives. For example, future research can consider the economics of the 'demand' side rather than the 'supply' side (Gawer, 2014). As this study has not considered the difference between firm sizes, future research can study how firm sizes can influence platforming strategies. Other studies can consider a longitudinal analysis of the Type-3 platforms with a complete set of platform elements to explore the market consequences of future generations of products. With more firms transitioning towards platforming and accumulating a diverse project portfolio covering multiple segments, performance (e.g. sustainability, economic metrics) can be better understood. With a complete set of platform elements, future research can explore how firms can derive future products based on updated versions of digitally-enabled product platforms using a generational approach.

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Data availability statement

Data not available due to ethical restrictions. The Interview Protocol and Data Collection Summary are available from the corresponding author on request.

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