The Development of Platforms for System Innovation by Modularization and Vertical Integration of Production Systems

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Abstract
Vertical integration strategies are found to be critically significant firm performance and innovation (Teece, 1996). Although modularity in product platforms generally enables or even accelerates innovation by reducing coordination efforts between sub-systems, existing literature has indicated such modularity may hamper the capability for systemic innovation (Teece, 2018). The effect of different vertical integration strategies to modularization within platforms for systemic innovation remain unresolved. This paper aims to explore how systemic innovation can be enabled by the co-existence of vertical integration and modularization strategies at the firm level. We find evidence for such co-existence in our emerging case studies from the digitally-enabled manufacturing of complex product systems in construction firms. Propositions depending on the degree of vertical integration may also potentially relate to openness of platform development.
The Development of Platforms for Systemic Innovation by Modularization and Vertical Integration of Production Systems

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Abstract

Vertical integration plays an important role in firm performance and innovation. Although modularity in product platforms generally enables or even accelerates innovation by reducing coordination efforts between sub-systems, existing literature has indicated such modularity may hamper cooperation and the capability for systemic innovation. The effect of different strategies for modularization and vertical integration within platforms for systemic innovation remain unresolved. This paper aims to explore how systemic innovation can be enabled by co-existence of vertical integration and modularization strategies at the firm level. I find evidence for such co-existence in our emerging case studies from the digitally-enabled production of complex product systems in construction firms. Propositions depending on the degree of vertical integration may also potentially relate to openness of platform development.

1. Introduction

Platform approaches are still emerging in the construction industry. Digital information fundamentally changes the project delivery models (Whyte, 2019). Such changes include radical transformations of new integrated solutions, supply chains and stakeholder relationship (Whyte, 2019). One of these transformations can be the emerging integration of product architectures and organization architectures (Tee et al., 2019), and how to manage such modularity in construction firms for the adoption of digitally-enabled production systems (Hall et al., 2019).

A product platform is defined as “a set of assets organized in a common structure from which a firm can efficiently develop and produce a stream of derivative products” (Gawer & Cusumano, 2014). In the manufacturing industry, it has proved to leverage reutilization of products, processes, knowledge, and people and relationship for competitive advantages (Kristjansson et al., 2004; Meyer & Lechner, 1997: p.7; Ulrich, 1995). Since the last century, lessons from the manufacturing industries have been applied in industrialized building (Gann, 1996). Replies to the UK Infrastructure and Projects Authority (IPA) (2018) call for evidence on new approaches for building, platform-based approaches have articulated potential benefits to the life-cycle value and certainty of project cost (ICE, 2019: p.7), the new supply chain to local suppliers and the professional service export (RIBA, 2019).

Previous platform studies have unveiled the interactions of system architectures between building products and production systems. These studies conceptualized production systems through either classifying off-site production (Jonsson & Rudberg, 2015) or supply chain structures (Doran & Giannakis, 2011; Hofman et al., 2009; Pero et al., 2015; Voordijk et al., 2006). However, such conceptualizations of production systems were constructed without considering the system architectures across and within firm boundaries. In this paper, efforts are made to investigate how modularity of system architectures between platform assets and production systems. In addition, initial findings indicate digitally-enabled product platforms provide new opportunities for such vertical integration across firms.

The research explores strategies to manage the modularity in product platforms for the digitally-enabled production systems. The next section gives theoretical background drawn on production systems, product platforms and modularization. Then this paper presents the
research methods used. Later this paper shows emergent findings from the early case studies. Finally, potential contributions and limitations are discussed.

The research setting of platforms in this research is on product platforms. Such platforms exist at the level of firms (i.e. internal) and supply chain (e.g. assemblers, suppliers) (Gawer, 2014). Digital platforms (e.g. Google or Facebook) defined by Gawer are different from platforms studied in this research. In addition, the research setting also focuses on linear and planar reinforced concrete residential building systems due to its common use. In the Cast Consultancy (2019)’s categories of industrialized building, it represents five out of seven categories.

2. Theoretical Background

2.1. Product platforms in construction

A product platform is defined as “a set of assets organized in a common structure from which a firm can efficiently develop and produce a stream of derivative products” (Gawer & Cusumano, 2014). Platforms (or internal platforms) are classified as internal, supply chain and industry depending on openness of interfaces, coordination mechanisms and accessible capabilities (Gawer, 2014). By this classification, to the best knowledge of the author, only product (or internal) platforms within firm boundaries were investigated in the industrialized building literature.

Platform assets are interpreted as components, knowledge, process and relationship (Meyer & Lehnerd, 1997; Robertson & Ulrich, 1998). Research on platform assets shows a wide range of focuses. Veenstra et al. (2006) applied product platform structures to articulate the housing design and product development process following three steps, product architecture, interface and standards (Veenstra et al., 2006). Such product platform architectures have effectively enhanced the communication between design and customers for mass customization. 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). Technical and process platforms were testified for lean, agile supply chain management (Lessing, 2006). Process platforms were found to support the supply chain by systemizing the information and workflow (Lessing, 2006: p.171-172).

Another key factor in product platform development is the supply chain and production strategy. Commonality and variability of products can be predefined in four levels in product platforms (Hansen, 2003; Hvam et al., 2008). This synthesis of product platform precondition could be associated different production strategies and decoupling points of customer order specification. This also provided theoretical framework to the later explorations on the product configuration in the platform-based industrialized building. A decoupling point between planning and customer can differentiate the different production strategy (Barlow et al., 2003). These supply chain models were constructed as stockholding decoupling point (Barlow et al., 2003) and customer order specifications decoupling point (Hansen, 2003; Hvam et al., 2008).

Platforms supported by views of engineering, production and customer can transfer the information flows to downstream and feedback the rules to upstream (Jensen et al., 2012; Malmgren et al., 2011). Such flow of information has dramatically changed the configuration of industrialized building compared with traditional approaches. Design rules and constraints were used to develop modular building products effectively by reutilizing the past knowledge and processes (Malmgren et al., 2011).
To reach a balanced point between commonality and variety is crucial for production systems performance (Gann, 1996). Jansson et al. (2014) studied the commonality of such platform assets across firms. The platform assets were insufficient for industrialized building in engineer-to-order production systems. Thus, platform support methods (i.e. design planning, collaborative design, design optimization, and requirements iteration) were found complementary for platform use.

2.2. Production systems in construction

Previous platform studies have unveiled the interactions of system architectures between building products and production systems. These studies conceptualized production systems through either classifying off-site production (Jonsson & Rudberg, 2015) or supply chain structures (Doran & Giannakis, 2011; Hofman et al., 2009; Pero et al., 2015; Voordijk et al., 2006).

Barlow et al. (2003) classified the production systems in industrialize house building with a focus on customer order decoupling point (Hoekstra & Romme, 1992) in the supply chain. The classification was based on mass customization theories and utilized the level of customization from “pure standardization” to “pure customization” to differentiate production systems (Barlow et al., 2003). Jonsson and Rudberg (2014) categorized the production systems by considering the “manufacturing outputs”. This concept of “manufacturing outputs” was generated by literature review on drivers and barriers during implementing manufacturing systems. Six criteria affecting such outputs were “delivery, cost, quality, performance, flexibility, and innovativeness”. There were other classifications of production systems with a focus on product architectures e.g. levels of off-site production. (e.g. Jonsson & Rudberg, 2015).

2.3. Modularity between product platforms and production systems

The mirroring hypothesis between technical and organization structures lies in the organizational and product design (Colfer & Baldwin, 2016). Such hypothesis claims organizations should position interdependent within a common organization group corresponding to the technical system architectures. Mirror in project level also hampers cooperation though it improves coordination (Tee et al., 2019).

Modularity also exists between products, processes and supply chains (Fine, 1998). Voordijk et al. (2006) investigated such modularity in construction by highlighting product platform architecture as a potential research focus. In a more in-depth study, Hofman et al. (2009) examined system architectures between products and contractor–supplier relationships in industrialized building. Drivers for such matching were identified including: “the degree of variety in customer demand, the extent of the required supplier investment, the extent of dependence on supplier knowledge, and the intentions of both the supplier and the buyer in a relationship”. Through examining the modular supply chain, Doran and Giannakis (2011) identified modular product architectures and supply chains can be complemented with high-level supply chain and process integration.

2.4. Systemic innovation in construction

Concept of architectural (systemic innovation) innovation was originally proposed by (Henderson & Clark, 1990). This concept broke-through the binary setting of innovation by that time (i.e. either incremental or radical innovation). Systemic innovation fundamentally
recognized the significant impacts resulted from the connection between the core concepts and the components in a product or process innovation.

Mirror (in terms of modularization) in technical and organization structures weakens the generation of systemic innovations (Henderson & Clark, 1990). Early findings suggest that fragmented construction industry was impossible to implement systemic innovation which requires efforts across firm boundaries (Sheffer, 2011). Mirrored industry structures constrain the penetration of new opportunities to the technical structures (Sheffer, 2011). Mirror breaking strategies are formed to avoid firms to get trapped. The need for mirror breaking comes from changing and complex technologies existed in the technical and organizational systems (Colfer & Baldwin, 2016). Breaking such mirror can dramatically improve the performance and create competitive advantages (Colfer & Baldwin, 2016). Prior study in three construction firms unveiled three strategies to break the “mirror” for systemic innovation. Relational, project-based spin-off and vertical integration were identified as enablers in the adoption of systemic innovation (as digitally-enabled production systems an example) at the firm level. Modular design (which resulting in modular product architecture), instead, can complement with integrating practices for collaboration in industrialized construction (Tee et al., 2019).

Table 1: Key concepts and definitions

<table>
<thead>
<tr>
<th>Concept</th>
<th>Definition</th>
<th>Key References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product platform</td>
<td>“a set of assets organized in a common structure from which a firm can efficiently develop and produce a stream of derivative products”</td>
<td>Gawer and Cusumano (2014); Shipilov and Gawer (2019).</td>
</tr>
<tr>
<td>Modularity</td>
<td>“a particular design structure, in which parameters and tasks are interdependent within units (modules) and independent across them”, also refers to “a particular pattern of relationships between elements in a set of parameters, tasks, or people. Specifically, modularity is a nested hierarchical structure of interrelationships among the primary elements of the set”</td>
<td>Baldwin and Clark (2000: p.11 &amp; 88).</td>
</tr>
<tr>
<td>Vertical integration</td>
<td>a firm can be defined if a firm “encompasses two single-output production processes in which either (1) the entire output of the &quot;upstream&quot; process is employed as part or all of the quantity of one intermediate input into the &quot;downstream&quot; process, or (2) the entire quantity of one intermediate input into the &quot;downstream&quot; process is obtained from part or all of the output of the &quot;upstream&quot; process”</td>
<td>Perry (1989: p.185).</td>
</tr>
<tr>
<td>Product architecture</td>
<td>“the scheme that enables the function-to-component mapping, with design rules and interfaces” (Baldwin &amp; Clark, 2000: p.73; Ulrich, 1995). The interfaces determine the “boundaries of modules”</td>
<td>Baldwin and Woodard (2009: p.23); Baldwin and Clark (2004: p.73); Ulrich (1995)</td>
</tr>
</tbody>
</table>

3. Research Methods

3.1. Research strategy

The research adopts a multiple-case study design (Eisenhardt, 1989; Eisenhardt & Graebnor, 2007) to understand how firms manage the modularity in product platforms for production systems, then efforts are drawn to compare and contrast the cases to examine the different modularization strategies within the separate settings of production systems. The unit of analysis is the product platform used by a construction firm for industrialized reinforced concrete residential building.
3.2. Case selection

This study adopts a purposeful sampling strategy for sampling. Cases were selected to best meet the predefined criteria (Morse, 1989: p.127). Criteria for selection are as follows: (1) recognized industrialized builders with capability of digitally-enabled design and production; (2) deliver a collection of industrialized reinforced concrete residential building platforms; (3) representative regional industrialized building capability; (4) vertical integrated supply chain. However, three firms adopt various levels and types of production systems. Particularly, they indicate different relationships with production systems through either directly ownership or contract-controlling. Table 2 shows the details of case firms for the case study.

Table 2: Background of builder firms studied

<table>
<thead>
<tr>
<th></th>
<th>Firm A</th>
<th>Firm B</th>
<th>Firm C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Hong Kong</td>
<td>Singapore</td>
<td>China</td>
</tr>
<tr>
<td>Market</td>
<td>Local</td>
<td>Local</td>
<td>Middle East, Japan</td>
</tr>
<tr>
<td>Production</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Annual Turnover</td>
<td>Not applicable</td>
<td>152 million USD</td>
<td>1.2 billion USD</td>
</tr>
<tr>
<td>Ownership of supply chain</td>
<td>No</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Product Platforms</td>
<td>Housing apartments</td>
<td>Housing apartments</td>
<td>Apartments, dormitories</td>
</tr>
</tbody>
</table>

3.3. Data collection

Table 3: Early data sources (Remark: TBC means to be continued)

<table>
<thead>
<tr>
<th>Source</th>
<th>ID.</th>
<th>Details</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Documents</td>
<td>MD1</td>
<td>BIM Execution Plan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MD2</td>
<td>Building systems catalogues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MD3</td>
<td>Building systems drawings</td>
<td>1 set of 50 slides</td>
</tr>
<tr>
<td></td>
<td>MD4</td>
<td>Project information management systems (supply chain, design, production, logistics and assembly)</td>
<td></td>
</tr>
<tr>
<td>Semi-structured interviews</td>
<td>MS1</td>
<td>CEO and Chief Engineer</td>
<td>12 Jun 2019, duration 90 mins</td>
</tr>
<tr>
<td></td>
<td>MS2</td>
<td>Director (R&amp;D)</td>
<td>12 Jun 2019, duration 90 mins</td>
</tr>
<tr>
<td>Site visit</td>
<td>MV1</td>
<td>Office</td>
<td>1 visit, on 12 Apr 2019</td>
</tr>
<tr>
<td>Firm B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Documents</td>
<td>SD1</td>
<td>Building systems catalogues</td>
<td>1 set of 28 slides</td>
</tr>
<tr>
<td></td>
<td>SD2</td>
<td>Building systems drawings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD3</td>
<td>Project information management systems (supply chain, design, production, logistics and assembly)</td>
<td></td>
</tr>
<tr>
<td>Semi-structured interviews</td>
<td>SS1</td>
<td>Chief Innovation Officer</td>
<td>4 Jul 2019, duration 64 mins</td>
</tr>
<tr>
<td></td>
<td>SS2</td>
<td>Planning Engineer</td>
<td>4 Jul 2019, duration 64 mins</td>
</tr>
<tr>
<td>Field visit</td>
<td>VS1</td>
<td>Office and manufacturing facilities</td>
<td>22 Oct 2019</td>
</tr>
<tr>
<td>Firm C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Documents</td>
<td>JD1</td>
<td>Building systems catalogues</td>
<td>2 sets (total 34 pages)</td>
</tr>
<tr>
<td></td>
<td>JD2</td>
<td>Building systems drawings</td>
<td>TBC</td>
</tr>
<tr>
<td></td>
<td>JD3</td>
<td>BIM models of the building systems</td>
<td>TBC</td>
</tr>
<tr>
<td></td>
<td>JD4</td>
<td>Production line specifications and drawings</td>
<td>2 Sets (total 42 pages)</td>
</tr>
<tr>
<td></td>
<td>JD5</td>
<td>Project information management systems (supply chain, design, production, logistics and assembly)</td>
<td>TBC</td>
</tr>
<tr>
<td>Semi-structured interviews</td>
<td>JS1</td>
<td>Chief Engineer</td>
<td>TBC</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-----</td>
<td>----------------</td>
<td>-----</td>
</tr>
<tr>
<td>Site visit</td>
<td>JV1</td>
<td>Office and manufacturing facilities</td>
<td>1 visit, 27 Apr 2018</td>
</tr>
</tbody>
</table>

Data was collected from three firms. Site visits and semi-structured interviews were conducted with chief engineers or chief innovation officers for product development from each of these firms. Data collected included firm archival records, product catalogues, technical drawings, documents and transcribed factory tours. A protocol and a database for the case study have been built to ensure the research reliability (Yin, 2009: p.43). The drafts of the case study descriptions were verified by the respondents from each of the three case firms for the construct validity (Yin, 2009: p.43).

The scoping interviews used a protocol with starter questions including: How do you partition an industrialized building into systems (i.e. assemblies such as modules or panels) and then sub-systems (i.e. sub-assemblies)? How do you manage (1) interdependencies within individual modules and (2) interdependencies across modules (e.g. panels)? How do you integrate the systems (i.e. assemblies) and the sub-systems (i.e. sub-assemblies) to finished products (i.e. buildings)? How to develop new products (for product platforms) in order to meet the needs of new or potential projects? What kinds of assets in terms of products, technologies, knowledge and processes or others have you considered in product platforms? How do you mange these assets between product platforms and production systems?

### 3.4. Data analysis

#### Preparation for analysis

The interview audio records were manually transcribed. Interviews conducted in Chinese were manually translated into English. The research data collected was processed in a coding process (Strauss & Corbin, 1990). Firstly, open coding was conducted to identify and develop concepts. Observations, sentences and events with similar concepts were categorized (Strauss & Corbin, 1990: p.101-102). Then categories at the same level of dimension and properties were grouped into new categories (Strauss & Corbin, 1990: p.142: p.142). This process was to formulate relationships between concepts and sub-concepts. Pattern matching was conducted to find the similar evidence to construct and enhance the internal validity (Yin, 2009: p.175). Similar findings across cases were categorized to support the theory building. Construct validity of this research were enhanced through verification by the industry experts and consultants to triangulate the findings from the case study (Yin, 2009: p.43).

#### Within-cases analysis

The settings of production platform were referred to the product definition with focus on assets including products, knowledge as well as processes and relationships. Particular focus was drawn on identifying the building systems decomposition and integration, interface definition, in the product development process. Particular attention was drawn to process maps to manage the knowledge, technologies and products. Thus, a case dynamics matrix can be established to link coded dataset and categories with explanations (Miles et al., 2014: p.148).

#### Across-case analysis

Three firms selected have implemented different strategies to manage modularization in their different levels of vertical integration of production systems. The vertical integration level has indicated different practices (e.g. process) between production systems and product platforms. Such practices may affect product development strategy and arrangement. Thus, a variable-by-
variable matrix will be constructed to articulate the interdependences between design and production systems. This matrix can be descriptive and exploratory for later stage exploration of reasons (Miles et al., 2014: p.220-221). Conceptual ordering resulted from axial coding will be carefully allocated to columns and rows.

4. Emerging Findings

4.1. Within-case analysis

Firm A:

Background
The study has been conducted in three case firms. In the first firm Firm A, the firm’s supply chain is contractually controlled. They have strong digitally-enabled design and digital integrated solutions experiences in the industrialized building industry. Although the firm did not own the supply chain (manufacturer and logistics), they could still sustain and further evolve in the competitive industry. Firm A’s manufacturing facilities are located in mainland China and Malaysia. It has developed a digital integrated system to monitor and control the logistics and assembly processes in the production systems.

Product platforms
Firm A has been focused on developing innovative building products and maintained a well-established product library. In the past 5 years, the product library has been extended with its diversified project portfolio. Firm A has delivered the first-ever fully-prefabricated reinforced concrete (RC) building project for Hong Kong Housing Society. In this project, Firm A and the main contractor changed the original design by proposing a fully prefabricated RC structural system. This structural system is composed of linear and panelized components, including (1) semi-precast: panelized components: structural walls, balconies, slabs and parapet walls, and (2) precast: staircases and refuse chutes. Firm A also extended its product platforms by developing innovative products.

Production systems
Evidence shows that Firm A has a scalable and reconfigurable process across projects. Firm A has developed and adopted digitally-integrated systems across production systems. During design, manufacturing, logistics and assembly onsite, collaboration and coordination has been facilitated within and across firms. Production systems are aware of the design and planning information communicated on such digitally-integrated systems.

Product platforms of Firm A rely on a range of contractually-controlled production systems. These production systems are across firm boundaries while product platforms clearly define the interfaces and product architectures for each production system. This setting can be considered as vertical integration across firm boundaries. Internal supply chain has been integrated with external firms in such production systems.

Firm B:

Background
Firm B is one of the A1 general builders in Singapore. In the past, it relied on overseas manufacturing facilities to provide industrialized building products. Its involvement in the decision making of industrialized building design was constrained. Firm B is one of the early adopters of Integrated Construction Prefabrication Hubs (ICPHs). ICPHs were launched by
Singapore’s Building Construction Authority to build the local digital manufacturing capacity. ICPHs consisted of a series of vertical and mix-used industrialized buildings.

**Product platforms and production systems**

Firm B’s ICPH is a three-storey building complex, including 2 production floors and 1 office floor level. Firm B’s manufacturing capacity has been uplifted through this ICPH. Product portfolios have been further expanded ranging from linear, planar to volumetric industrialized building products. Recently, Firm B strengthened its capacity production systems by acquisition of a precast concrete manufacturing facility in Malaysia. Digitally-integrated solutions are substantially used by Firm B to streamline the coordination and collaboration between product platform and production systems.

**Firm C:**

**Background**

Firm C is one of the largest multi-national industrialized building firms in China. Their annual turnover has reached over USD 1.2 billion in 2018. The annual advanced manufacturing capacity has met 1 million square meters (refer to floor area) for linear and panel (or 2D) products. is a vertical-integrated builder by operating their own material production, manufacturing, and logistics. Relying on their own expertise and manufacturing capability, they have also diversified their business by providing advanced manufacturing production lines and green construction materials. Such production lines include automated rebar production line, and precast concrete panel production line. has also developed their digitally-enabled collaboration platform. This digital platform can support design, procurement, production, assembly and operation management.

**Product platforms**

Firm C has established a series of product platforms ranging from apartments, offices, schools, hospitals to dormitories. These platforms rely on building assembly systems that composed of eight types of sub-assembly modules. Modules are scalable and integrated internally with a predefined interface with other modules. These assemblies consist of integrated floors, internal walls, external walls, integrated kitchens and baths, elevators, integrated interior decoration systems and intelligent building systems. Table 4 shows two product platforms for residential purposes. The structural assembly system is highly flexible and has been applied in their product platforms. PEC-based platforms can reduce the site activities by achieving a prefabrication ratio to 90%. Relying on simple connection designs between beams and columns, these platforms can constrain the wet-trade activities substantially. Firm C has been developing many product platforms based on assembly and sub-assembly systems. This development is to combine different sub-assembly systems to meet different needs of product platforms (see Table 4). In the assembly level, three structural systems are deployed into different product platforms. For one specific product platform, the interfaces between assemblies and sub-assemblies are well defined. Thus, one sub-assembly can accommodate with several assemblies.

**Table 4: Product platforms in Firm C**

<table>
<thead>
<tr>
<th>Overall building system</th>
<th>Apartment</th>
<th>Dormitory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly level - Structural floor system</td>
<td>PEC</td>
<td>SST</td>
</tr>
<tr>
<td>Assembly level - Partition wall</td>
<td>CLS</td>
<td>CLS</td>
</tr>
<tr>
<td>Assembly level - External wall</td>
<td>PLC</td>
<td>PLC</td>
</tr>
<tr>
<td>Assembly level - Staircase</td>
<td>UCW</td>
<td>PCW</td>
</tr>
<tr>
<td></td>
<td>FBS</td>
<td>FBS</td>
</tr>
</tbody>
</table>
Assembly level - Fitting-out  |  PFD, ITB

Remarks: Overall structural system: PEC is a form of partially encased composite structural system; PS: a form of steel structural system; SST is a form of staggered truss structural system. Modular systems: CLS is a form of precast concrete laminated structural floor system; UFC is a form of modular structural floor systems; PLC is a precast lightweight partitional wall system; UCW is a modular curtain wall system; PCW is a modular concrete wallboard system; FBS is a form of precast staircase system; PFD is a form of prefabricated and prefinished fitting-out system; ITB is a form of prefabricated and prefinished integrated kitchen or bathroom system.

Production systems

Firm C adopts vertically integrated production systems. All manufacturing, logistics, onsite-assembly are owned and controlled under the firm. Firm C develops and adopts digitally-enabled and integrated systems to improve the overall performance and collaboration of production systems. Table 5 shows the production system is clearly arranged to suit the assembly and sub-assembly production needs. However, it also implies product platforms require integrated and coordinated production systems to produce corresponding assemblies and sub-assemblies. Production systems are generally specialized at assembly levels. Such modular product architectures are coupled with modular production systems except for the accessories. Integrated and coordinated production systems are found enabled by digitally-integrated systems.

Table 5: Interdependences between production systems versus assembly systems (Firm C)

<table>
<thead>
<tr>
<th>Production system type</th>
<th>Structural</th>
<th>External Walls</th>
<th>Accessories</th>
<th>Fitting-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall structural system</td>
<td>PEC, PS, SST</td>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural floor system</td>
<td>CLS, UFS</td>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partition wall</td>
<td>PLC</td>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External wall</td>
<td>UCW, PCW</td>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td></td>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fitting-out</td>
<td></td>
<td></td>
<td></td>
<td>PFD, ITB</td>
</tr>
</tbody>
</table>

4.2. Cross-case analysis

Table 6: Summary of emergent cross-case findings

<table>
<thead>
<tr>
<th>Firm</th>
<th>Vertical integration</th>
<th>Control</th>
<th>Firm boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Contractually control</td>
<td>Inter-firm</td>
<td></td>
</tr>
<tr>
<td>B</td>
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Emerging findings in this paper only cover the vertical integration patterns between product and production systems. Vertical integration in three firms has indicated different inter- and intra-firm patterns (see Table 6). Different boundaries of firms in vertical integration could relate to the modularization strategies of platform assets. This will be further analyzed in later stage of research. In addition, as all firms have implemented modularization and vertical integration for digitally-enabled product platforms and production systems, such co-existence between vertical integration and modularization have contributed to the systemic innovation (i.e. digitally-enabled production systems).
More analysis will be conducted to investigate how platform assets are articulated under different vertical integration across. Particularly, production systems with direct controls by firms could articulate different mirroring between product platforms and production systems (i.e. strict or partial).

5. Discussion and Conclusions

5.1. Contributions to the theory

This research is expected contribute to the knowledge by articulating the significance of platform strategies in construction firms. The research explores strategies to manage the modularity in product platforms for the digitally-enabled production systems. The emergent implications from the modularity between product platforms and production systems are also complemented by vertical integration and digitally-integrated systems.

5.2. Contributions to the practice

By examining the various platform strategies, this research will better inform construction industry stakeholders from a firm-level perspective for strategic decision making. Innovation strategies for construction firms can be better enriched by studying fundamental enablers behind platforms.

5.3. Limitations

This research is drawn on digitally-enabled product platforms and production systems. Generalization of the theories built can be a threat as the data sources are collected in a mature industry and only from industrialized residential reinforced concrete building.

5.4. Future research plan

The within-case analysis will continue to investigate how platform assets (i.e. products, knowledge as well as processes and relationships) are articulated across projects across projects and product platforms. In the cross-case analysis, focuses were drawn on vertical integration levels in production systems. Case findings adopting different vertical integration were compared and contrasted across and within firm boundaries. Their impacts to product platform need to be further analysed in cross-case analysis.

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