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MASS CUSTOMIZED PRODUCTS FOR INDUSTRIALIZED CONSTRUCTION: CHALLENGES AND OPPORTUNITIES

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ABSTRACT

Developing mass customized products for industrialized construction (IC), including single- and multi-family modular housing, requires multidisciplinary, collaborative, and iterative approaches from the first stages of product development. Despite this, decisionmaking based on data pertaining to companies' capabilities and increasing diversity of customers' needs in IC is still in its infancy. Catalogs of houses are often extensive yet fail to take advantage of IC strategies (such as mass customization (MC), product platform, modularity, and product families), thereby undermining the competitiveness of IC against traditional construction. An opportunity exists to enhance communication among stakeholders, fostering decisions about catalog offerings based on clear understanding of their requirements, robust data analysis, and continuous improvement. This paper discusses practices, challenges, and opportunities related to the development of products and integration among stakeholders in the IC context. The research method comprised three steps: developing theoretical understanding, conducting two ongoing studies in Brazil and the United States, and leading a workshop with experts to identify practices, challenges, and opportunities regarding the development of IC products. The preliminary results indicated the imperative need for stakeholders to work together on improving product development and production system, fostering a more competitive IC industry.

KEYWORDS

Mass customization, industrialized construction, modular construction, product development, collaboration.

INTRODUCTION

Early developments of industrialized construction (IC), especially in the house-building sector, were strongly based on the Mass Production paradigm, resulting in a negative perception from customers due to the high degree of standardization, focus on cost reduction, and poor quality of products (Nadim & Goulding, 2011). More recently, Mass Customization (MC) has emerged as an approach to improve value delivery in house-building projects (Noguchi, 2003). MC aims to provide a certain degree of flexibility, while keeping production cost and delivery time within

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acceptable limits (Pine, 1993; Da Silveira et al., 2001). It seems that recent developments in IC, combined with the adoption of MC represent an opportunity to achieve high levels of efficiency in the building industry (Larsen et al., 2019) and, at the same time, to accommodate different customer requirements (Yashiro, 2014).

Product platform, modularity, and product families are key concepts in MC to respond to the diversity of demands (Salvador et al., 2009; Khalili-Araghi & Kolarevic, 2018). Those concepts can change the way in which new products are developed in the construction industry, e.g., by pre-defining a range of modular components to be used and creating a certain degree of process repetition (Brege et al., 2013). This allows the delivery of a limited variety of product solutions while sharing parts and production steps within the manufacturing capabilities, achieving economies of scale and scope (Robertson & Ulrich, 1998; Tseng et al., 2017).

The development of this type of solution requires early identification of stakeholders and collaboration among them, so that both customers and operations' requirements are considered in the definition of a finite solution space (SS) (Piller, 2004; Ferguson et al., 2014). The SS is a limited or stable space in which customization offers can satisfy the needs of customers (Piller, 2004). This involves the alignment between three MC areas: (1) customer integration, (2) product design, and (3) operations management (Rocha, 2011; Ferguson et al., 2014), with information exchange and knowledge dissemination between them being critical (Hentschke et al., 2020). The capacity of combining these elements in a meaningful way may have a strong impact on competitive advantage (Piller, 2013; Schoenwitz et al., 2017).

Companies apparently fail to understand how relevant information can support decisionmaking for SS definition (Hentschke, 2021) at a strategic level. There is often a lack of integration among different stakeholders in IC, such as developers, designers, manufacturers, general contractors, and regulators, and solutions are often defined considering the perspective of only a single one (Rocha, 2011). Only a few previous studies have addressed this fragmentation (e.g., Jiao & Zhang, 2005; Rocha, 2011; Ferguson & Olewnik, 2014; Andújar-Montoya et al., 2015; Schoenwitz et al., 2017; Khalili-Araghi & Kolarevic, 2018; Sjobakk et al., 2018; Hentschke, 2021; Popovic et al., 2021). The lack of understanding of market- and customer demand prior to the definition of a building system causes the need for later adaptations to projects, resulting in problems related to poor quality, occurrence of waste, and failure to implement continuous improvement. Manufacturers end up absorbing the issues resulting from the lack of refinement of design solutions which results in limited process efficiency (Popovic et al., 2022). Therefore, the development of solutions for capturing, analyzing, and presenting information about customer requirements, together with the understanding of operations management constraints may improve decisionmaking in product design, resulting in an effective way of developing and adjusting the SS (Sjobakk et al., 2018).

The aim of this paper is to report on a study to identify practices, challenges, and opportunities related to development of mass customized products in the IC context. The topic was approached from the perspective of the MC areas and their integration, which depends on the collaboration among stakeholders. This paper is distinct from previous research due to the emphasis on the need of deeply understanding customers' demands. This study is based on a literature review, two ongoing Empirical Studies, one in Brazil and the other in the United States (US), and insights from a workshop involving leading IC experts from California, US.

LITERATURE REVIEW

MASS CUSTOMIZATION (MC)

Trading off standardization desired by IC against flexibility required by customers is challenging (Schoenwitz et al., 2012). Nevertheless, MC attempts to fulfil these contradictory requirements (Pine, 1993). The level of customization allowed in the SS (Von Hippel, 2001) depends on the analysis of customers' requirements and existing operational capabilities (Da Silveira et al., 2001), and it is defined at the customer order decoupling point (CODP) (Rudberg & Wikner, 2004). In construction, it is not uncommon to have more than one decoupling point (Rocha, 2011), which allow different levels of customization of the same production system, depending on the market segments.

For MC to be feasible, a fixed- but still flexible SS is necessary (Ferguson et al., 2014). Differently from personalization, in MC value must be delivered with no need to reinvent products or processes for every new customer (Piller, 2004). Although customers may get the impression that the product is customized, several standardized components are being used in project delivery (Gibb, 2001). The definition of SS must be based on customer requirements, which are captured, analyzed, and translated into product specifications (Piller et al., 2004). Product solutions must also respond to the regulations, site, and climate conditions of different locations (Popovic et al., 2021). According to Otto et al. (2013) it is necessary to design products for specific market segments or customer clusters, instead of defining a general product that tries to meet all possible needs.

Maximizing repetition helps MC to achieve efficiency and lead-time reduction not only in production, but also in sales, design, and logistics (Tseng & Jiao, 2001). Economies of scale and scope are reached through commonality and reusability of both design and process capabilities across modules, tools, knowledge, processes, components, and specific market segments with respect to repetition in customers' needs (Tseng & Jiao, 2001). The reuse of solutions furthermore allows continuous improvement to be pursued, and facilitates the dissemination of practices within the company (Kotha, 1996).

DEVELOPMENT OF MASS CUSTOMIZED PRODUCTS FOR IC

The development of products for Industrialized House-Building (IHB) should be very different from traditional construction (Jansson et al., 2014). Structured solutions to handle multiple projects simultaneously, integrated decisionmaking, short lead-times, and adoption of new concepts, such as MC, modularity, and platform (Meyer & Lehnerd, 1997; Thajudeen, 2023), and a large number of engineering design activities, are necessary for manufacturing and site assembly (Lennartsson et al., 2021). These solutions may help companies that use MC reach competitive advantage (Hvam et al., 2008).

Product-platform and modularity concepts have been used to manage product variety in many other sectors (Hvam et al., 2008; Salvador et al., 2009) by sharing parts and production steps (Robertson & Ulrich, 1998). However, the application of those concepts requires much product development[5] effort (Bonev et al., 2015), involving several stakeholders throughout several project stages (Lessing, 2006). There is a need to shift to multidisciplinary product development from the early design stages (Jansson, 2013).

The term product platform refers to the collection of assets that are shared by a set of products (Robertson & Ulrich, 1998) or production lines (Meyer et al., 2018), allowing companies to offer products that show front-end variety based on back-end commonalities (Eriksson & Emilssson, 2019). These assets can be divided into components, processes, knowledge, people, relationships (Robertson & Ulrich, 1998), subsystems and technologies (Meyer et al., 2018). Lessing (2006) suggests that IHB development should include a Technical- as well as a Process Platform. The first consists of modularized solutions for building parts with interfaces that allow interchangeability and parts that can be combined to create a variety of end-products. The latter includes modules for collaboration, logistics, and information flow. Lessing also states that collaboration in multidisciplinary teams is a powerful way to develop solutions, methods, and tools designed to fit together.

[5] Product development is a set of activities to create, design and market a product (Ulrich; Eppinger, 2000).

The modularity concept is used to decompose complex products and processes into smaller and simple parts (Hvam et al., 2008). The ability to modularize a catalog of products is of great importance to offer a wider range of solutions for customers (Hofman et al., 2006). Voordijk et al. (2006) pointed out three different types of modularity: product-, process-, and supply chain modularity. The distinction between a modular- and an integral architecture is associated with the flexibility of the system to absorb changes. The first allows changes to impact only one component, whereas the second may see changes reverberate globally to several components of the system (Ulrich, 1995), making it harder to adapt products for diverse customers' needs without incurring penalties in product development costs and lead times.

RESEARCH METHOD

The point of departure of this investigation was a literature review on the management of information in the development of IC products, including the capture, processing, analysis, dissemination, and use of information to support decisionmaking among MC different areas. Our investigation also draws on learnings from two ongoing studies conducted in IHB companies (Table 1). Each case study involved two companies. The difference is that in Empirical Study 1, product development is carried out by the manufacturer, while in Empirical Study 2, it is carried out by the seller and real estate developer. In both studies, the companies delivered single-family houses. Those companies were chosen because they had been implementing some Lean Construction concepts, and also were interested in implementing an integrated approach in product development strongly based on the concept of modularity.

Table 1: Empirical Studies 1 and 2

<table>
<tr><th colspan="2"></th><th>Empirical Study 1
(Company A + B)</th><th>Empirical Study 2
(Company C + D)</th></tr>
<tr><td colspan="2">Duration</td><td>23 months</td><td>3 months</td></tr>
<tr><td colspan="2">Country</td><td>Brazil</td><td>United States</td></tr>
<tr><td colspan="2">Building System</td><td>Panelized</td><td>Volumetric</td></tr>
<tr><td colspan="2">Construction Type</td><td>Wood frame</td><td>Steel frame</td></tr>
<tr><td rowspan="3">MC area</td><td>Customer Integration</td><td>Company A
(manages and sells)</td><td rowspan="2">Company C
(develops, manage, and sells)</td></tr>
<tr><td>Product Design</td><td rowspan="2">Company B
(develops, manufactures, assembles and deliver)</td></tr>
<tr><td>Operations Management</td><td>Company D
(manufactures and assembles)</td></tr>
</table>

Multiple sources of evidence were used in both Empirical Studies, including open- and semi-structured interviews with companies' staff, direct observation on construction sites and manufacturing units, analysis of existing database of customer profiles (Empirical Study 1), participant observation in meetings, and seminar participation for discussing results.

The literature review and the learnings from both Empirical Studies grounded the proposition of the questions about product development in the IC context that guided the discussions described in this paper. These questions were presented for discussion in a workshop with expert practitioners and academics selected based on their practical or academic experience in recent developments in IC in California and also for their complementary backgrounds (Table 2). This study is part of a collaboration between the Federal University of

Rio Grande do Sul in Brazil, and the University of California, Berkeley in the USA. The goals of the workshop, held at UC Berkeley, were to create a collaborative learning environment and provide an opportunity for IC representatives to share thoughts, convey practices, and suggest opportunities to overcome industry challenges.

The workshop started with a presentation with the aim of (1) sharpening the understanding of MC strategy and key concepts related to the IC context, e.g., product platform, modularity, product family; (2) reporting the research gap regarding the integration between MC areas in the development of IC products; and (3) introducing the practical problem based on insights obtained from Empirical Studies 1 and 2. A set of questions were posed to the experts in order to identify practices, challenges, and opportunities to overcome the challenges. The experts wrote their contributions in Post-it® notes that were grouped on a large panel on the wall. After that, the academics who facilitated the workshop carried out a discussion with the experts to get additional understanding of their answers. Last, experts presented their work and proposed topics to be explored in future collaborative initiatives among companies and universities.

Table 2: Workshop participant roles and companies

Expert	Role	Company Type
E1	Director General, PhD candidate	Volumetric modular construction manufacturer
E2	Co-founder and CEO	Software for offsite construction
E3	Principal	Global non-profit organization in sustainability
E4	Senior Associate	Global non-profit organization in sustainability
E5	Sr. Manager for Lean Project Development	General Contractor
E6	Director of Product Design	Global volumetric modular construction manufacturer, designer, and contractor
E7	Senior Technical Advisor, Researcher	Research and Policy Center for Housing Innovation
E8	Distinguished Professor of Engineering and Project Management	University
E9	PhD candidate	University

FINDINGS

EMPIRICAL STUDIES: A BRIEF SUMMARY

The practical problem noted in Empirical Studies 1 and 2 is that companies use an extensive catalog of single-family houses with low adoption of the MC strategy and related concepts, such as product platform, modularity, product families, and standardization. Other problems included: (a) a wide variety of products developed by using a traditional design approaches that do not adopt multidisciplinary work from the early design stages; (b) low levels of commonality, leading to rework and incompatibilities that tend to be identified late in the detailing design or construction stage; (c) engineering overload due to the need to detail many projects with low reuse of solutions; (d) uncompetitive prices; (e) very limited flexibility offered to the customers; (f) continuous improvement hindered by the low reuse of solutions. Most of these problems stem from the lack of understanding and proper communication of stakeholders' requirements from the early design stages onward.

Seeking a solution to these problems, in both studies companies have been working together on making some changes to reduce the size of catalogs, offering more flexibility and reaching economies of scope and scale through repetition. The changes include: (1) improving the capture, structure, analysis and communication of key customer information; (2) defining clearly the levels of customization to be offered for each market segment, based on data analysis; (3) exploring opportunities to implement IC key concepts and strategies; (4) understanding and communicating operations management constraints; and (5) improving communication and collaboration among stakeholders that represents different areas in order to iteratively develop solutions.

INSIGHTS FROM THE WORKSHOP

The most prominent issues raised by the experts during the workshop are discussed in this section. The insights were structured according nine questions posed to the experts, following a "Practices", "Opportunities", and "Challenges" sequence. The expert who suggested the issue is labelled by means of a code (e.g., E4 in Table 2).

How to reduce the gap between what customers want and what IC companies have offered? (Question 1.1)

One way to narrow the gap between wants and offers is to incorporate design practices that facilitate the reuse of solutions (E4). These practices would allow for changes or additions later on, suggesting a more flexible design that enables adjustments as customer needs evolve.

By contrast, a set of challenges were identified. First, the experts recognized that understanding customers and market needs remains underexplored in companies. "We don't know our customers" (E7) is a shared perception. Second, the customers of many IC companies are not the users (e.g., multifamily developers) (E7). Demand analysis is often carried out by developers based on their perception of the market, rarely on customer requirement data and structured analyses. Third, the dynamic nature of market preferences over time, influenced by factors such as tastes and macroeconomic cycles, further hinders efforts to align offerings with customer expectations (E3). Moreover, it is challenging to predict how family structure and living groups will change in the future (E4), requiring a forward-looking approach. Fourth, the siloing of design, engineering, manufacturing, and customers is identified as a crucial challenge (E9). Fifth and finally, the challenge of "sharing ideas and solutions across projects" (E9) may be associated with the lack of commonality between products and the reuse of solutions.

The experts recognized two opportunities to bridge this gap. First, solutions can be drawn from past and current projects (E9), leveraging lessons learned and successful strategies. Second, the prospect of establishing a nationwide industry coalition (E7) emerges as a strategic opportunity. Such a coalition could serve as a collaborative platform, fostering knowledge exchange, innovation, and the collective development of solutions to overcome challenges and reach economies of scope and scale.

How does a company define the level of product customization to be offered? Does it vary according to the business model or market segment? (Question 1.2)

Experts have highlighted a variety of practices employed by companies in determining the level of product customization. One is the informal and subjective case-by-case assessment (E1), suggesting that these decisions are often based on individual circumstances and unique project requirements. Another is based on business-to-business (B2B) customer catalogs (E1), by using predefined options from previous projects to guide customization levels. This definition is also based on the business goals, which means that companies with high product output tend to offer less flexibility in order to maximize efficiency and effectiveness (E6). Furthermore, a dynamic strategy involves initially paring down options based on specific requirements and subsequently increasing options as needed (E2). This strategy was adopted by Companies A and B from the Empirical Study 1 in order to gain understanding on the adopted concepts (e.g., modularity, product family, among others) from a more restricted product platform and then increase the level of customization according to the level of maturity of the company.

Maintaining focus and establishing a robust strategic definition is a challenge (E6). The lack of clarity about the level of flexibility to be offered in each market segment and the urge to ensure the sale leads companies to allow customers to make small adjustments, overloading the product development and engineering departments, and expanding the catalog.

Companies invest too little effort in customer data capture and processing, hindering the ability to fully understand market demands (E2). Additionally, shifts in market-segments, demanding adaptive strategies (E7) and continuous data capture and analysis. It is even more difficult to deal with this type of complexity due to the different perspectives brought by different stakeholders, and also by a limited understanding of manufacturing processes (E1). The lack of suitable performance metrics, which should be time-dependent, such as fabrication capacity and required slack, further complicates decisionmaking (E8).

The prospect of reducing fragmentation in decisionmaking (E7) and unlocking focus-goals related to manufacturing capabilities and planning (E6) stands out as another strategic opportunity. Research and Development (R&D) and prototyping emerge as promising avenues (E7) to explore innovative solutions, clarify questions about the construction system, help in the visualization of the product, and collect customer data. The development of a coherent product platform is also an opportunity (E1) to understand the boundaries of each market segment and its level of customization based on specific orientations, rules, and standards.

How to manage trade-offs between customization (generating value to customers) and operational efficiency and effectiveness (keeping costs low)? (Question 1.3)

Work in multidisciplinary teams was highlighted as essential to manage trade-offs, fostering collaborative, and iterative decisionmaking (E7). Another practice is to allow for customization options in simple areas and maintaining consistent interfaces in the same location between them (E6). This helps to isolate complexity in a specific function or subsystem, which means that exercising an option will not affect the whole system. A third practice emphasized by the experts was the importance of balancing intention with high customization expectations (E6), recognizing that achieving extensive modifications on a daily basis may not be realistic. This approach emphasizes balancing product flexibility and streamlined processes, ensuring that customization efforts align with operational efficiency and effectiveness.

One challenge involves identifying large segments of common opportunities (E3). This requires the understanding of customer needs and market trends to effectively tailor products or services without compromising operational capabilities. Another is providing the perception of flexibility and choice while keeping boundaries (E6), and the escalating redundancy and complexity associated with having more interfaces between modules (E2). Experts highlighted the difficulty of resisting revenue opportunities, particularly for early-stage businesses, even if the product may not align well with efficient manufacturing (E1). One challenge, but also an opportunity, is to secure a long-term pipeline of customer orders (E7). This includes proactively managing projects and establishing stable and reliable supply chains to secure long-term contracts, to support product platform standards, and to ensure a sustained workflow.

One strategic opportunity involves the development of trade-off models with virtual reality interfaces to explore various what-if scenarios (E8). These models, accompanied by associated cost and process models for both customers and producers (E8), offer a powerful tool for evaluating the impact of product development choices on both value generation and keeping costs low. These models could enable early visibility on production impact (E2).

What are the best data sources to understand what the market and customers want? (Question 2.1)

Experts suggested a diverse set of practices to understand the market and customers' needs, such as: large historical databases, permitting data at both local and regional scales, experience of homebuilders whether private or fragmented and market research (E3); past projects, surveys, interviews, and market trends (E9); sales data in the company (E6). Hiring skilled and innovative designers with a discerning aesthetic sensibility was mentioned as a good practice to support the understanding of the demand (E1).

Experts identified several challenges in finding the best sources of demand data. Some examples include: variability of data, both regionally and over time (E3); fragmentation and cost of data sources (E3); distortion of company data, introducing potential biases that require careful examination (E6). Additionally, some customer segments do not allow for choice, as in affordable housing, where limited options constrain data-driven decisionmaking (E7). The unavailability or proprietary nature of certain data sources adds an additional layer of complexity (E7). Fragmented and prescriptive building codes were highlighted as a challenge that affects the three questions regarding customer information to support product development (E7). Specific regulations for transportation and minimum dimensions differ across states, cities, and allotments. Structuring a database with these diverse regulations can assist companies in determining which parameters to adopt in order to accommodate various contexts.

Opportunities exist in terms of (1) understanding the focal points of the sales team, aligning product development efforts with areas of concentrated sales activity for optimal market responsiveness (E6); and (2) providing the development of solutions that address urgent, critical situations (E7). The National Association of Home Builders of the US (NAHB) was suggested as an opportunity to access market information and industry trends (E7).

How should this information be captured, analyzed, and communicated to the company and stakeholders? (Question 2.2)

Experts recommended registering, analyzing, and communicating information through workshops, trainings, customer-company meetings (E9), surveys, and analysis of sales data (E1). 'Dogfooding', which means experiencing the company's products or services first-hand, provide quantitative, qualitative, and experiential perspectives of customer information through the test of solutions in the market (E1). Another practice suggested was creating functional and features description without specific product details or brands, as done with Target-Value Design (E6). Presenting customer information as a cohesive story supported by visual aids can contribute to a clear and impactful communication strategy among stakeholders (E6).

Challenges include diverse workflows among companies, requiring different processes (E2) often for the same project, hindering standardization. "Skewed data can tell the wrong story" (E6). Informal and incoherent sales information poses hurdles in effectively translating insights back to the design phase (E1). Another challenge is privacy concerns that require handling or lack of access to sensitive customer information (E7).

Communicating the cost impact of the customization options offered to customers, particularly in the early stages of product development, presents a tangible opportunity (E2). Moreover, strategically positioning the product to align with current customer needs (E6) undermines companies' ability deliver value to customers and to compete effectively with more traditional design and construction processes.

How to use customer information to support decisionmaking regarding product development? (Question 2.3)

One approach involves leveraging customer data to define Minimum Viable Products (MVPs) for different product families (E6). This ensures that product development efforts are targeted, aligning with the most critical requirements. Another approach is assigning the responsibility for managing customer information and making it available to support decisionmaking (E7).

A major challenge is to have different stakeholders and customers represented in decisionmaking, especially in multi-family housing (E4), in which contact with customers is rare. By designating someone to present customer perspectives in the decisionmaking process, companies can foster a customer-centric culture that prioritizes and integrates customer insights into every stage of product development, enhancing overall responsiveness to customer expectations. However, who should do the customer analysis (E5) is still an open question. Customer preferences (stated preferences) may not always be associated with customers' choice (revealed preferences), i.e., people are not necessarily good at defining what is more important for them vs. their willingness-to-pay (E3).

A persistent challenge manifests in the lack of a steady project pipeline, complicating the consistent integration of customer demand into product development and among projects (E5). The pipeline and the development of a product platform from a collaboration effort among universities and companies were suggested as opportunities (E5).

How to manage trade-offs between stakeholders' interests (i.e. developers, manufacturers, GC, customers) in product development? (Question 3.1)

According to the experts, finances often dictate decisions (E1). Based on that idea, building close, long-term partnerships emerges as a key strategic practice (E7) to promote the mutual understanding among stakeholders, as well as fostering an open forum for transparent discussions about trade-offs, spanning from ideation to test sign-off (E6). Another important practice is to prioritize designs that are not necessarily easy to install but hard to install incorrectly, aiming to minimize issues related to GC and site crew errors (E3).

The challenges include fragmented and frequently conflicting interests across various stakeholder groups (E1, E2). Misalignments in interests require a moderator to control and guide the conversations, managing divergent priorities (E6). Moreover, a challenge emerges from the lack of performance metrics that are time-dependent (E8).

Overcoming these challenges implies the opportunity of fostering industry collaborations and coalitions (E2). This can create a better understanding of constraints across stakeholders, facilitating decisionmaking (E1). Another opportunity arises with organizations that encourage collaboration for collective change. One example is the Builders Lab, an initiative that supports developments from start to scale through the launch of tools for political decisionmaking or the modernization of construction methods (E7). Experts also mentioned the use of Lean Design tools to identify the best solutions among various options (E6). This approach enables a data-driven assessment of design alternatives, streamlining the decisionmaking process.

What are the best strategies adopted to support the design decisions in the IC context, considering operations' requirements from the early design stages? (Question 3.2)

Design Thinking (E6), Integrative Design, Interactive Effects, and Option Value (E7) were mentioned as practices adopted by the experts to support design decisions considering operational requirements from the early design stages. According to E7, Option Value considers the future evolution and potential trajectories of the project, assessing how current design decisions may either preclude or enable future developments.

Regarding challenges, the dynamic nature of design can result in a long design process, leading to low engagement levels among stakeholders (E6). Moreover, measuring the impact of design decisions can be hard, especially across projects (E7). Another challenge mentioned by the experts is the cost impact, as costs rapidly rise as Levels of Development (LOD) increase (E2). These challenges emphasize the need for approaches that address temporal, evaluative, and financial aspects of product development.

The prospect of platform integration of code requirements, potentially facilitated by artificial intelligence (AI), stands out as a promising opportunity (E4). Additionally, the development of product platforms offers an opportunity to structure design decisions through rules and guidelines that promote flexibility within a standardized set of solutions (E1). Cross-training initiatives among design and manufacturing representatives is another opportunity to foster a shared understanding of possible solutions in both domains (E9). Experts emphasized the importance of R&D and prototyping as strategies to support design decisions (E7).

How to fulfil demand for customization in product development while achieving operational efficiency in fabrication and assembly? (Question 3.3)

The experts reiterated previously-mentioned practices in answering this question, such as iterative improvement (E7), competent software(s) integration (E7), use of tools to continuously measure the impacts of customization on fabrication (E2), and establish robust product platform boundaries (E6) to ensure that both customer wants and operational demands are achieved.

By contrast, the first-time fabrication poses several unknowns (E2). Some of the opportunities raised to respond to these challenges were cost transparency (E7), designing and engineering with the understanding of what is a good operational performance and how to achieve it (E9), and utilizing projects to build platforms when possible (E1, E6). This suggests utilizing individual projects not only to fulfil immediate requirements of a specific context, but as opportunities to develop more consistent product platforms for use on subsequent projects.

DISCUSSION AND CONCLUSIONS

This paper discussed practices, challenges, and opportunities related to the development of single- and multi-family modular housing products and integration among stakeholders in the IC context. Results of this study can be summarized and categorized into five topics:

1. There is a need to align decisions and interests from different stakeholders at a strategic level. This includes defining someone in charge of managing conflicting interests and ensuring that customers and companies’ requirements are considered and aligned with the level of customization and the defined business model goals;
2. Ensuring collaboration among stakeholders from the early design stages is imperative for improving product development and production system design. It is also necessary to use data on customer requirement and production capabilities, in order to foster a more competitive IC industry. This includes the implementation of initiatives for a better visualization and understanding of constraints, and the analysis of trade-offs;
3. Capturing, structuring, analyzing, integrating, and presenting information about customers’ needs, companies’ capabilities, and distinct code requirements within and among companies is crucial to support decisionmaking and for the IC industry to work together to overcome the challenges of competing with traditional construction;
4. Developing product platforms to define SSs can help IC companies to establish the boundaries of each market segment and its product families while reaching economies of scope and scale through repetition. The product platforms should be flexible to absorb changes over time and intuitive for the stakeholders to follow standards;
5. Promoting continuous improvement and learning through iterative development of products and reuse of solutions. This includes measuring performance across projects; prototyping and using MVP to shorten cycles or refinement; investing in data capture and analysis; understanding and communicating what good performance is and how to achieve it; and what is the response of the market to the offers.

The following steps of this investigation include the development of prescriptive knowledge that can be used to support the development of mass customized products for IC, and conducting a second round of interviews with experts to assess the utility and applicability of those prescriptions. Finally, suggestions for further research include to improve understanding on how to capture, structure, analyze, communicate and use design, engineering, manufacturing, and customers' requirements to support product development and production system design.

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