AN OVERVIEW OF CONFIGURATORS FOR INDUSTRIALIZED CONSTRUCTION: TYPOLOGIES, CUSTOMER REQUIREMENTS, AND TECHNICAL APPROACHES

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Abstract

To improve productivity, the construction industry is increasingly adopting methods of industrialized construction. A key strategy to support industrialized construction is to leverage an adaptable product development platform, i.e. a configurator. Although many benefits of configurators (e.g. mass customization) have been witnessed in the manufacturing industry, the application of configurators in construction is limited and immature. This paper reviews eleven configurators in academic research and four configurators in industry practice. First, using a comparative analysis, the authors generalize three strategic typologies of configurators developed and implemented for industrialized construction. Second, stakeholder requirements are identified for each typology. Finally, the technical approaches, including related methods and theories, are reviewed using a framework of three-tier architecture decomposition. The findings contribute to practice by allowing AEC stakeholders to understand strategic typologies and customer requirements for configurators. This can assist in guiding the future development of mass-customized configurators.

Introduction

The current construction industry is filled with opportunities and challenges. According to the 2013 McKinsey Global Institute's report, the world will spend $57 trillion on infrastructure by 2030 (Dobbs et al., 2013). With increasing demand for a new building market, the industry also faces increasing construction costs, decreasing labour supply, and long development cycles. In response to these challenges, some stakeholders within the industry are exploring the use of industrialized construction. The industrialized construction process draws from lessons of the manufacturing industry. Following a design-manufacturing-assembly approach, industrialized construction assembles buildings comprised of prefabricated components. These components range from structural elements to volumetric modules. They offer competitive pricing, quick turnaround time, and increased quality.

Some pioneering architects are leading the charge (Lubell, 2018). Traditionally, architecture has held to the stereotype of modular buildings as dull, repetitive and unreliable. Recent architectural design using industrialized construction have been successful to avoid the negative aesthetic perception of "modular", "box-like", or "cookie-cutter" architecture. However, despite some success stories, there is still a steep learning curve that prevents new stakeholders from entering this currently niche market.

Digitalization and automation are key strategies to increase participation. New models of automation can increase efficiency by integration and optimization while enabling new human-machine collaboration and creativity (Pittman, 2018). One such form of automation to increase participation in industrialized construction is the development and use of product configurators. Product configurators, first initiated in the manufacturing industry, are widely applied in many domains, such as electronics, automobile, and aerospace. As a successful application of artificial intelligence, a configurator eases the creation of complex systems by assembling a set of components, or kit-of-parts, under certain constraints within the scope of design specifications, production capabilities and product operative performance. By decomposing the building into subsystems (e.g. floor slabs, walls, roofs, etc.) product configurators enable designers to generate and evaluate a variety of building layouts, while retaining confidence that the final design can be effectively manufactured and assembled using industrialized processes.

However, the application of configurators in construction is limited and immature. Existing configurators do not satisfy many requirements of industry practitioners (Haug, Hvam, & Mortensen, 2012; Nielsen, Brunoe, Jensen, & Andersen, 2017). Furthermore, even though application strategies of configurators have been proposed by some studies, a critical analysis comparing the similarities and differences in configurator approach has not been done. Consequently, without clear knowledge of configurator-based workflow, many construction companies are unwilling to apply configurators in projects, due to the uncertainties and potential disturbance to their original project delivery processes and technical environments. As configurators emerge in the construction industry, there is a need to understand their purpose and application. This

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research conducts a comparative review of configuration development and implementation from academia and industry practice. Drawing from eleven configurators in academic research and four configurators in industry practice, we present an overview of configurators for industrialized construction. In doing so, we seek to answer three fundamental research questions:

1. What are the strategic typologies of configurators developed and implemented for industrialized construction?
2. How do these strategic typologies differ in their approach to meet stakeholders needs?
3. What are the technical approaches to develop configurators for industrialized construction?

To answer the above questions, the paper is organized as follows. At first, we presents related concepts and research gaps. Then, the research methodology is illustrated. Next, the results from the study are presented, followed with a discussion. Finally, we provide our conclusion, as well as suggested directions for future research .

Point of Departure

In the late 1980s, due to increased demand for product variety, the manufacturing industry transitioned from mass production to mass customization (Pine II, 1993). Mass customization is a widely adopted business strategy that identify and fulfill customer needs without sacrificing efficiency, effectiveness and low costs (Pine II, 1993). Mass customization maintains the main advantage of mass production, i.e. economies of scale, and meanwhile is enriched and complemented by theories of modularization, product family architecture, and reconfigurable manufacturing systems (Hu, 2013). To achieve mass customization, a crucial technical support, first proposed in the manufacturing industry, is a product configurator. Product configurators have also been referred to as design systems, co-design platforms, and toolkits (Robertson and Ulrich, 1998; Piller, 2004; Salvador and Forza, 2007). A product configurator is an intelligent information system that supports the creation of products with variations using a set of modules, as well as rules influenced by companies' marketing strategies and available resources (Haug, 2007; Aleksic, Jankovic and Rajkovic, 2017). Those modules and rules stored in a knowledge base form a product family architecture (PFA) that drives the product design in configurators (Mitchell M and Jiao, 2001; Blecker *et al.*, 2004; Wikberg, Olofsson and Ekholm, 2014).

Configurators in construction projects

In the construction industry, buildings are one typical type of product. Unlike products in the manufacturing industry, buildings combine both product-level information and project-level information (Ramaji and Memari, 2016). The product-level information includes prefabricated modules' design dimensions, engineering attributes, and production processes. The project-level information includes site planning, site properties, site-built elements, and on-site activities. Thus, a configurator suitable for construction industry should support both product-level and project-level information management. As the information is stored in Building Information Models (BIMs), configured solutions should be represented as BIMs in different configuration views, with multiple possible design and manufacturing options, as well as construction schedules.

A vast of benefits of applying configurators in construction projects have been illustrated in three aspects: product, process, and people, as shown in Table 1.

Table 1: Benefits of Configurators applied in industrialized construction

	Benefits of Configurators
Product	Increases flexibility (Thuesen and Hvam, 2011; Jensen *et al.*, 2014; Bonev, Wörösch and Hvam, 2015; Smiding, E., Gerth, R., Jensen, 2016)
	Ensures product manufacturing and assembly of solutions is possible (Bonev, Wörösch and Hvam, 2015; Said, Chalasani and Logan, 2017; Jansson, Viklund and Olofsson, 2018; Yuan, Sun and Wang, 2018)
People	Minimizes the need for manual involvement (Frank et al., 2014; Jansson, Viklund and Olofsson, 2018; Lee and Ham, 2018)
	Smooths the learning curve (Jansson, Viklund and Olofsson, 2018)
Process	Reduces time and cost for design and production (Thuesen and Hvam, 2011; Frank *et al.*, 2014; Bonev, Wörösch and Hvam, 2015; Smiding, E., Gerth, R., Jensen, 2016; Said, Chalasani and Logan, 2017; Jansson, Viklund and Olofsson, 2018)
	Enhances coordination efficiency (Malmgren, Jensen and Olofsson, 2011; Xu *et al.*, 2018; Yuan, Sun and Wang, 2018)
	Develops construction documents efficiently (Jensen, Olofsson and Johnsson, 2012; Smiding, E., Gerth, R., Jensen, 2016; Jansson, Viklund and Olofsson, 2018)
	Preserves and reuses knowledge for the next product (Frank *et al.*, 2014; Jensen *et al.*, 2014)
	Increases reliability of schedule (Wu *et al.*, 2010; Larsson *et al.*, 2015)

However, most implementation strategies of configurators in the academic study are only validated by one or two construction projects, and several are only tested within certain building systems, such as wall systems (Smiding, E., Gerth, R., Jensen, 2016; Said, Chalasani and Logan, 2017). Often, existing configurators are tailor-made for companies after a long period of development cycle, leading to investment risk and high initial software cost. In this context, the limitations of configurators can only be partially exposed and may not be representative to support future development. This results in several unknowns regarding the implementation of configurators. It is unclear when, how, and for whom configurators should be developed. Furthermore, there is need to develop our understanding of how configurators can meet the requirements of AEC main stakeholders, including clients, designers, manufacturers and assemblers. Finally, it is necessary to understand the common technical approaches used to develop configurators.

Methodological Approach

To investigate these gaps, this paper conducts a preliminary review on the development and application of configurators in the construction industry. We first review eleven academic papers that describe the development of configurators to generate mass-customized products in the AEC sector. However, due to the nature of academic research, many of the proposed configurators are still at the conceptual or testing stage. We therefore supplement our review with four existing web-based housing configurators from industry practice. We analyze the trial or demo version of these existing commercial web-based configurators.

Source Data

The data for this comparative review comes from two main sources. First, we identify previous academic literature in which industrialized construction products are configured. The literature was gathered if it meets two criteria. Firstly, because the term "configurator" is not widely adopted in AEC literature, we widen the literature search to also include several similar concepts such as platforms and design system that are identified in the academic literature. We categorize those IT tools into configurators if they are in line with the following definition: "a software package composed of a knowledge base that stores the generic model of the product and a set of assistance tools that help the user find a solution (Aldanondo and Hadj-Hamou, 2003)". Secondly, since our goal is to study how configurators could be used in the AEC sector, we further narrow the literature to only include configurators for construction, with a specific focus on industrialized construction (otherwise referred to as prefabrication, preassembly, modularization, and/or off-site fabrication). Eleven research studies, including nine journal papers, and two conference papers, are identified in the literature. They represent configurators of building products and services from a variety of AEC sectors (see Table 2).

Next, we identify existing cases of configurators from industry in order to supplement early research concepts with more advanced-stage implementation cases. We identify four web-based housing configurators, which were commercially available and had demo or trial software available for testing (shown in Table 3). By configuring a simple product sample from start to finish, the authors can evaluate the configurators' functionalities and limitations.

Table 2: Configurators in the previous academic research

AEC Sector	Configured Product
Design (Yuan, Sun and Wang, 2018)	Precast concrete buildings
Design (Taborda *et al.*, 2018)	Floor plans
Design (Farr, Piroozfar and Robinson, 2014)	Curtain wall systems
Real Estate Developer (Veloso, Celani and Scheeren, 2018)	Floor plans
Manufacturer (Bonev, Wörösch and Hvam, 2015)	Precast concrete panels
Manufacturer (Said, Chalasani and Logan, 2017)	Timber walls
Design & Construction (Jansson, Viklund and Olofsson, 2018)	Floor plans
Design & Construction (Wikberg, Olofsson and Ekholm, 2014)	Buildings
Engineering Consulting (Jensen, Olofsson and Johnsson, 2012)	Timber walls & floors
Construction (Wu *et al.*, 2010)	Construction schedules
Design & Engineering (Wee, Aurisicchio and Starzyk, 2017)	Plant rooms

Table 3: Commercial web-based configurators

Web-based Configurator	Configured Product
HiStruct	Steel structures
AGACAD	Wood & Precast concrete elements
Creatomus	Private homes and apartments
My Projectfrog	Wood panelized buildings

Comparative Analysis

From the fifteen identified cases, we conduct a comparative analysis. First, we assess the characteristics of each configurator, along the following five dimensions:

- Who are the main users of the proposed configurator? (who?)
- When are configurators used in a project? (when?)
- How is configuration performed / what are the

key activities? (how?)

- What are the typical targeted products suitable for each strategy? (what targets?)
- What are the expected outputs generated by configurators? (what outputs?)

The result of this comparative analysis is the identification of three strategic typologies.

Second, for each strategic typology, we assess which customer requirements each configurator in our analysis attempts to meet. The requirements include the perspective of the client/owner, the designer, the manufacturer, and the assembler for the project. Through this, we try to understand how the strategic typologies of configurators attempt to meet the customer requirements of the many fragmented stakeholders found in AEC.

Third, we consider that the development and application of configurators are likely interlinked. We next evaluate each of the fifteen configurators by their technical approach. We do so using a framework of three-tier architecture decomposition (Figure 1), widely adopted in software architecture for web applications. The three-tiers include (1) the presentation tier, (2) the application tier and (3) the data tier. The presentation tier consists of a graphical user interface (GUI), which receives input and displays the different model views to users. Through API requests, the presentation tier calls the application tier to carry out core functionalities provided by configurators. The application tier visits the data tier, which stores a single source of truth (SSOT) of information managed in configurators. This separation between data and applications enables much flexibility for development teams to upgrade, add or replace components in other tiers. The resulting comparison summarizes and analyses the technical approach for configurators from each these three tiers.

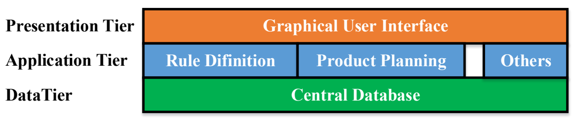

Figure 1: Three tier of architecture of a configurator

Findings

This section presents the results of the above analysis. First, we demonstrate three strategic typologies of how configurators are implemented in projects. Then, we present what customer requirements each type of configurators could fulfill. In the end, we illustrate how to organize the software architecture of configurators by three tiers to satisfy those requirements.

Strategic Typologies of Configurators

From our review, three different strategic typologies emerge (Table 4).

Table 4: Typologies of configurators in the construction industry

	Typology 1	**Typology 2**	**Typology 3**
Who	Real estate developers, Landscape planners, Architects	Architects, Engineers, Fabricators	Engineers, Fabricators
When	Concept design before creating BIMs	Design stage when creating BIMs	Detailed design after creating BIMs
How	1. Codify configuration logic 2. Generate configuration by low-level representations 3. Convert the representations to BIMs in CAD applications	1. Codify configuration logic 2. Enter configuration parameters into the UI of a plugin 3. Generate BIMs, as well as documents automatically in CAD applications	1. Codify configuration logic 2. Perform component optimization on the developed BIMs 3. Cluster components with similar sizes and apply standard modules with higher performance
Target	Site plan, Floor plan	Prefab elements	Prefab elements
Output	Sales models	3D parametric models	Standard modules
Cases	MyProjectfrog, HiStruct, Creatomus	AGACAD	-
	(Wikberg, Olofsson and Ekholm, 2014; Jansson, Viklund and Olofsson, 2018; Taborda *et al.*, 2018; Veloso, Celani and Scheeren, 2018)	(Jensen, Olofsson and Johnsson, 2012; Farr, Piroozfar and Robinson, 2014; Yuan, Sun and Wang, 2018)	(Said, Chalasani and Logan, 2017; Lee and Ham, 2018)

Typology 1 represents configurators for projects at the planning stage. Stakeholders for typology 1 typically include real estate developers, architects, and landscape planners. The major objective of applying configurators is to generate diverse development plans, such as site plans and floor plans, for decision-makers to select. Because engineers typically do not participate in this step of the process, the plan representations can be graphic illustrations with low-levels of detail, such as images and wireframes. Compared with a traditional design strategy, the reviewed literature claims two advantages. First, real estate developers allow customers to interactively design their desired houses by offering available selections based on the companies' capability and economic analysis. Second, intelligent algorithms can identify more feasible or advantageous floor plans using the embedded configuration rules. Some configurators can convert these representations to building information models, which could be exploited to build a linkage between the sales stage and the design stage.

Typology 2 represents configurators at the project design phase. This is the most widely-applied situation for configurators. In this scenario, architects, engineers, and fabricators are involved. The targeted products include prefabricated modules, assemblies, and parts. Users need to define related rules and constraints by configurators in advance. Usually, the rules and constrains can be stored and reused for future product development. The effort spent on this process depends on the complexity of products and the configurators' rule translation capabilities. Once those rules are embedded in the system, operators just need to enter the necessary design parameters via a user interface. 3D building information models can then be automatically generated, along with related data and documentation such as G-codes for NC machines, permit drawings, and a manufacturing bill of materials.

Typology 3 is less applied in commercial configurators then the other two typologies. Related research work has been done in the design for manufacturing and assembly (DfMA) domain. Engineers and fabricators usually adopt DfMA principles in the detailed design stage before the manufacturing process. To gain the scale of economy as much as possible, users perform component optimization on the prefabricated parts by configurators. The main procedures involve clustering components with similar geometric features and assigning standard modules to each cluster with higher building performance, such as structural capacity. As a result, the degree of standardization increases. However, due to a lack of M&A knowledge base, designers seldom consider DfMA in the early design stage, when decisions greatly affect the project performance, such as ease of manufacturing and assembly, project cost and duration, quality issues, etc.

Customer requirements for Configurators

To support the selection of configurators, we match the above three typologies with customers' requirements from main stakeholders, including clients, designers, manufacturers, and assemblers. In Table 5, we review which are the customer requirements for each typology. We use " ● " to represent the requirements met by configurators in academic research (Table 2), and " ▲" for the requirements met by commercial configurators (Table 3).

Table 5: Customer requirements for strategic typologies of configurators

Customer Requirements	Typology 1	Typology 2	Typology 3
Clients			
Visualize design options	●, ▲	●, ▲	●
Select variant types of elements	●, ▲	●, ▲	
Output time and cost estimates	▲		●
Designers			
Perform parametric design	●	●, ▲	●
Perform parts' connection		▲	
Perform structural analysis		●	●
Perform clash detection		●	
Perform component optimization			●
Input building regulations	●	●	●
Input product constraints	●, ▲	●, ▲	●
Output 3D parametric models	●, ▲	●, ▲	
Output engineering drawings		●, ▲	
Manufacturers			
Output production drawings		●, ▲	
Output bill of material		●, ▲	
Output NC operational codes		●	
Assemblers			
Output schedules			
Output assembly instructions		●	
Output site layout			

Three specific findings can be pointed out. First, typology 2 satisfies most of customer requirements. These configurators are targeted at automating AEC specialists' work, which accounts for a large portion of construction activities. Second, some functional requirements exceed the scope of configurators which are defined by manufacturing industry initially, such as shop drawing creation. The reason could be that the AEC sector is fragmented, so an integrated and multifunctional platform is sought by all stakeholders. Third, typology 3 which focus on DfMA is less realized in existing configurators. One of identified reasons is few design metrics are defined and standardized to measure the manufacturability and ease of assembly for products.

Technical approaches to build Configurators

After addressing the customer requirements, the development process starts with the design of software architecture. Similar to other web-based application, we find that the configurators in our study can be analysed based on three-tier architecture. This includes a Presentation tier, Application tier and Data tier, as shown in Figure 1. The technical approaches to build software components on each tier are described as follows.

- **Presentation tier**

The user interface (UI) on this tier enables customers to be involved in the design process. Determined by product specification processes, the UI enables different levels of freedom for the non-expert and expert collaborative design. The main product specification strategies are select variant, configure to order, modify to order, and engineering to order. With the delaying of the customer order decoupling points, the design flexibility enabled by UI becomes more limited. There are four typical design activities, namely selecting standard elements, editing design parameters, arranging spatial layouts, and defining configuration rules. Table 6 presents the relationship between customer order decoupling points (CODP) of web configurators and corresponding available design activities.

- **Application tier**

The application tier, also called business logic tier, process main functionalities of configurators. Each of function could be programmed as a reusable component. Here, a component is a software "unit", which could be a block of reusable code or an independent application, so as to support the customized combination of multi-functionalities required by different customers. In this research, the rule definition component and product planning component are reviewed based on previous configurators. Other application components found (e.g. economic calculation, 3D model creation) are not included in this research.

The rule definition component takes charge of translating the knowledge from domain experts to computer operable language to guide the product configuration. Technical approaches to formalize the configuration knowledge includes the parameter-driven approach, constraint satisfaction problems (CSP), shape grammars, and genetic algorithm. Table 7 shows what types of rules embedded, as well as how those rules are represented and formalized in examined configurators. The component can be built via either API functions and general programming languages, such as Autodesk Revit API, or CAD built-in functions, such as the Boolean operators used in TactonWroks Studio.

The product planning component guides engineers in building a product architecture, which is made up of independent modules and modules interfaces (Jensen, Olofsson and Johnsson, 2012). Here, a module is a cluster of building elements which could be produced by mass production approach. Mechanisms that indicate a strategic reason that a module should be created are called module drivers (Lange and Imsdahl, 2014). Previous studies have highlighted that modularization is the foundation for product planning in the climate of mass customization, and various approaches have been proposed to tackle various module drivers. For example, Wee et al. (Wee, Aurisicchio and Starzyk, 2017) made use of three tools, including Design Structure Matrix (DSM), Modular Identification Matrix (MIM) and Generational Variance Index (GVI) to build module-based product architecture of plant rooms based on 15 module drivers, including technical specification, common unit, transportation, maintenance, etc. Said et al. (Said, Chalasani and Logan, 2017) set up a genetic algorithm to cluster timber walls with similar geometry for fabrication efficiency.

Table 6: Design activities under various CODP scenarios

Configurators	CODP	Select standard elements	Edit design parameters	Arrange spatial layouts	Define configuration rules
Creatomus	Select variant	Available	Limited	Not applicable	Not applicable
My Projectfrog	Configure to order	Available	Available	Limited	Not applicable
HiStruct	Modify to order	Available	Available	Available	Not applicable
AGACAD	Engineer to order	Available	Available	Available	Available

Table 7: Configuration rules' representation and formalization

Configurators	An example of Configuration rules	Rule representation methods	Programming tool
Floor plan configurator (Taborda *et al.*, 2018)	The kitchen must be placed either at the front of the house or next to the living room	Genetic algorithm	Java
Floor plan configurator (Veloso, Celani and Scheeren, 2018)	A spatial division rule is to divide the apartment into private, social and service areas.	Shape grammars	Rhinoceros + Grasshopper
Façade configurator (Farr, Piroozfar and Robinson, 2014)	Variations of forms, materials, openings, and relative locations of openings within the façade	Parameter-driven approach	Revit built-in functions and families
Scheduling configurator (Wu *et al.*, 2010)	The number of workers, the number of concrete pumps and the number of falsework equipment for pouring concrete	Constraint satisfaction problems	General programming language

- **Data tier**

The central database maintains a single source of truth (SSOT) of information managed in configurators. The rule definition component, product planning component, and other applications store and retrieve data here. However, few configurators separate their database from various applications. In that case, any updates occurring in one place - such as 3D models in Revit – cannot be reflected in other scenarios, such as bill of materials (BOM) in PDM systems. As a result, repetitive data exchange between various applications is necessary and data inconsistency is inevitable. To solve the issue, a neutral data format or schema would be needed for cloud-based cross platforms (Afsari, Eastman and Castro-Lacouture, 2017).

Discussion

Industrialized construction is gaining more share in the construction market. More stakeholders adopt this approach by delivering their products from design to manufacturing and assembly. Configurators provide a common environment to integrate data, functions and processes during the project life cycle. However, due to the lack of scalability, the examined configurators can only be fit for one generation of products from one company. This requires a better understanding of customer requirements and product upgrading knowledge.

This paper makes a contribution to practice by allowing AEC stakeholders to understand their strategic typologies and customer requirements of configurators from Table 5. This can assist in guiding the future development of customized configurators. Without further development in academia and in practice, it is unlikely that the potential benefits of configurators can be adopted by greater segments of the construction industry.

Conclusions and Future Work

Configurators are important IT systems that support mass customization. This paper presents a preliminary review of the development and application of configurators in the construction industry. Based on fifteen configurators, we first generalize three typologies of configurators by clarifying when, how and for whom the configurators are developed for. Next, a framework of customer requirements for construction configurators is proposed to understand what customer requirements could be met by each type of configurators. Finally, to support the further development of configurators, we review the technical approaches, including related methods and theories, to build each component of configurators from three aspects, i.e. Presentation tier, Application tier and Data tier.

Future research should be done in two perspectives. First, an integrated framework of configurators should be studied. Stakeholders in the construction industry are seeking for an integrated and multi-functional platform to support design, manufacturing and assembly processes. However, examined three types of configurators could only fit for a certain phase of projects lifecycle, and lack connections between each other. Second, previous studies identify multiple module drivers, such as module connections, transportation distance and production time (Anvari, Angeloudis and Ochieng, 2016; Said, Chalasani and Logan, 2017; Salama et al., 2017). However, due to the uniqueness of construction projects, module drivers should be identified, and more importantly, quantified for different building types. In the end, those drivers could be embedded into the configurators, so as to optimize the modular architecture of buildings.

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