Captivity or Flexibility: Complexities in a Dimensional Customization System

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Houses are essentially one-of-a-kind products that should reflect individualized differences of inhabitants who live in them. Homebuyers and homebuilders alike are thus captivated by the difficulties of housing customization. Achieving customer satisfaction depends on the flexibility of customized solutions, though the challenge of flexibility lies in the complexity of design validation. Constraints may be seen as design limitations, but they could provide for the efficiency of design validation. This paper addresses the complexities in the adoption of mass customization in the housing industry, and presents a dimensional customization system which would effectively use building information modeling (BIM) software, parametric design, and automatic verification of dimensional constraints to merge customization and validation.

Keywords: Mass Customization, Housing Industry, Building Information Modeling, Parametric Modeling, Automatic Constraint Satisfaction

INTRODUCTION

Social and cultural norms affect the way people house themselves. Although houses (or apartment buildings) can be characterized by sameness, it is the socio-cultural heterogeneity that differentiates our needs. Noting this lack of variety in housing, Kolarevic (2015) points out that customer demands tend to be heterogeneous, while physical buildings are largely homogenous.

The sheer necessity and the high demand for housing after the Second World War made architects and homebuilders rely on the economies of production from other industries. Economic reality was the real reason for applying industrial methods based on efficiency and economy of production in quantity. Mass production, as a Fordian paradigm of the 20th century, was embraced by the housing industry focusing on affordability and low-cost production. Repetitively-produced housing, however, was recognized as monotonic and was noted for its failure to provide for variety.

From a technological perspective, the recognition of disparity between physical homogeneity and cultural heterogeneity compels one to search for a customization system. As part of ongoing research, this paper proposes a framework for developing a flexible customization system that could allow for both individuality and profitability through customer participation in design, while fulfilling the viability of individualized housing solutions. Specifically, this paper focuses on the challenge of customer participation at an early stage of the design process. It argues that dimensional customization is a suitable paradigm for the housing industry; houses essen-
Mass customization, as a post-Fordian paradigm, is a way of delivering highly customized products or services while still maintaining mass production efficiency. The term "mass customization" was originally coined by Stan Davis in (1987) as a business strategy in which "the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously [...] be treated individually as in the customized markets of pre-industrial economies" (Davis 1987, 169). Similarly, Joseph Pine (1993) defines the goal of mass customization as providing enough variety in products and services at reasonable prices.

Over the past decade and a half, there were several attempts to embrace mass customization in architecture (e.g. Kieran and Timberlake 2003, Larson, Tapia and Duarte 2001, van den Thillart 2004, Duarte 2001). Due to potential design complexity, different and lengthy review and permitting processes, and inherent fragmentation in the building industry, homebuilders hesitate to allow greater customer involvement in the design process. In the building industry, homebuilders want to maintain the efficiency of production process by using standard models, though homebuyers demand houses that are individually configured and reflect their personal needs (Nahmens and Bindroo 2011, Hofman et al. 2006). Such an approach, however, does not provide for flexibility and variety and may not result in customers finding the solution they are looking for. Thus, the challenge remains how to satisfy customer demands and insure profitability without sacrificing the efficiency of mass production. The following section discusses customer participation as a fundamental of mass customization and its challenges in the building industry.

CUSTOMER PARTICIPATION
Mass customization is not merely product variation, as customers play a key role in housing customization. Alvin Toffler (1990) identifies the term "prosumer" to describe the producing and consuming role of the customer in which the customer becomes the co-designer. Mass customization should allow customer participation in the design process to define and modify individualized solutions (Piller et al. 2004, Salvador et al. 2009, Franke and Piller 2004).

Mass Customization Challenges
The basic application of mass customization in the housing industry, which has been growing in popularity, is to offer customers a limited number of choices in the forms of either printed or electronic catalogues, using a multiple-choice approach. Sears, Roebuck and Co., from 1908 to 1940, can be seen as the most established company that offered a catalog of house plans with added advantage of modification possibility (Thornton 2004). In web-based customization systems, homebuyers are allowed to navigate housing solutions at different levels, including layout, elevations, and interior elements. For example, Resolution: 4 Architecture’s website [1] offers ‘modern modular’ homes by developing a series of predefined typologies based on the possibility of variation within a standardized system. Living Homes’ website [2] offers several stylistically different house designs with various customization options regarding exterior/interior elements including finishing, appliances and HVAC systems. BluHomes’ website [3] offers standard modular prefabricated homes, and allows customers to make decisions within a "conceptual design" process, and manual 'code and
zoning research’ at the final step.

Multiple-choice approach offers customers limited number of solutions to choose from. Due to the complexity of the design process, homebuilders prefer to limit the solution space, as the entire range of alternatives would have to be designed up front. Because the designs are created without customer involvement, there is no promise of customer satisfaction - which is highly contingent upon the flexibility of solution space. Increasing the number of options could potentially increase the chance of finding satisfactory solutions; however, it could also be argued that having to choose among a large number of solutions could substantially increase the complexity of the customization process. The potential complexity inherent in the flexibility of solution space could lead to information overload, which is seen as a drawback (Huffman and Kahn 1998, Zipkin 2001). One consequence of information overload is ‘mass confusion’, i.e. customer’s inability to cope with making a decision among a large number of solutions, making it more likely that the customer will become confused (Pine 1993, Huffman and Kahn 1998). If customers are dealing with a great variety (making it appear complex), they may not be able to explore all possibilities and therefore may not find the ideal solutions. In either scenario, customers might become dissatisfied and uncertain about their ability to continue participating in the co-creation process and thus turn back to standard options (Huffman and Kahn 1998, Franke and Piller 2004).

Another drawback of customer participation is the customer’s inability to match needs with customizing products. The success of customer participation is highly dependent on the stability of customer preferences, customer awareness of their preferences, and customer ability to transfer them into product specification (Simonson 2005, Kramer 2007). Customer need-related information is attributed as sticky, where the stickiness is defined as “the incremental expenditure required to transfer that unit from one place to another in a form that can be accessed by a given information” (Franke and Piller 2004, 404). Simonson asserts that many customers cannot precisely determine their needs, and their decision could be changed based on situational cues (Simonson 2005). In the conventional design process homebuyers and the designer become involved in a back-and-forth process for several design iterations to find satisfactory solutions. Every transaction implies information exchange, which depends on understanding customer need-related information. Customer preferences, however, are often ill-defined, and as noted by Zipkin (2001), ”customers often have trouble deciding what they want and then communicating or acting on them [...] There are situations in which customers clearly articulate their requirements. More commonly, however, customers are unsure" (Zipkin 2001, 82). Thus, translating preferences into product specification determines customer satisfaction and, in fact, is bounded by the efficiency of communication between customers and the designer. Therefore, this becomes the source of additional cost for the company to transfer customer’s needs into the product specification. Dealing with the challenge of need elicitation and product specification, mass customization is subject to shift design tasks to customers by allowing them to express their needs and participate in the design of their own product (Thomke and von Hippel 2002, von Hippel 2001).

From the company’s perspective, customer participation in the design of individualized houses presents the challenge of design validation - ensuring that individualized solutions are viable. Due to the complexity of design validation, homebuilders offer filtered information about housing options and prefer to limit customer participation at the level of choice selection. None of the industrialized housing companies supports customization at the level of housing geometry. As noted by Lampel and Mintzberg (1996), the level of customization depends on customer involvement. Tailored customization is identified as the customer involvement in customizing a standard product at an early stage of the design process (Lampel and Mintzberg 1996). Tailored cus-
tomization at the level of determining various dimensions of the house's exterior and interior offers the highest level of customization. The deeper the level of customization, however, the higher the complexity of design validation. Customizing the overall spatial layout of building geometry is extremely contingent upon substantial design verification process to ensure that variations comply with design, engineering and manufacturing constraints. The process of manually evaluating and adjusting changes against constraints is error-prone, costly and time consuming, and could be a major driver of complexity. The most prominent approach is to offer customers a flexible solution space from which they could explore infinite number of housing alternatives, while ensuring the validity of customized solutions.

**PROPOSED SYSTEM FRAMEWORK**

Dimensional customization in the building industry requires customer involvement at an early stage of the design process so that a house could have a unique shape and form; building geometry can be tailored individually using dimensional parameters. The flexibility offered by such a large solution space can be enhanced by technologies that could provide for customer participation in the design of mass-produced but still highly customized houses.

Implementation of a dimensional customization toolkit is based on using building information modeling (BIM) software for a parametric definition of the geometry, a simple but layered interaction with the parametric model, and automatic verification of design variations. BIM technology could enhance the communication between the customer, designer, and manufacturer from the schematic design of customized products (houses) to construction documentation (Garber 2014). Every single modification could be automatically replicated within the entire model, and geometrical (and other) information of customized solutions could be extracted and transferred directly for manufacturing purposes, using file-to-factory processes.

In dimensional customization, maintaining relations between elements of the model and parametric variation of essential dimensions are essential to derive geometry numerically. Parametric modeling enables the customer to explore design variations by applying different dimensional parameters to a single model. This process can produce an infinite number of individualized solutions that differ from each other, but remain within the boundaries defined by the designer. Instead of designing multiple houses or offering limited number of options, the designer becomes involved in designing a 'meta' house, providing for the flexibility of solution space within an infinite number of dimensional variations. The customer could then interact with the parametric model via an interactive toolkit to design their individualized houses.

Dimensional customization system introduces a deeper level of customization by providing parametrized geometry that complies with design constraints. Design and performance limitations, rules and regulations imply constraints. In a traditional process, if customized houses do not comply with rules and regulations, the designer may need to consult other team members (i.e. engineer, manufacturer), and inform the customer how to appropriately modify the design so that it complies with the constraints. If the proposed solutions do not satisfy the customer (as if often the case), the entire customization process needs to start over. Automated constraint checking could significantly benefit the process of design validation as the entire model is automatically updated to accommodate changes. Companies could benefit from constraint-based parametric modeling, in that customization is performed over a single model that allows the customer to explore a vast number of solutions, while simultaneously complying with design rules. To realize this, all constraints should be quantitatively embedded into the parametric design model and represented at an early stage of the design process. Doing so helps ensure that essential features are maintained as design changes to avoid evaluation reworks.
SYSTEM IMPLEMENTATION
The prototype discussed in this paper is implemented within Autodesk Revit®, the most commonly used three-dimensional building information modeling software in the industry. The plug-in is implemented through API based on three main functions: dimensional constraint definition, spatial zone definition and the satisfaction of constraints. The following sections present the technical characteristics of the system and the implemented interface.

Product Architecture and Structural Hierarchy
Mass customization in housing reflects the dynamic configuration of housing elements within the static context of the building. In this way, the form is interpreted on the basis of the possibility of different combination of elements made by the customer, rather than conceptual definition of what constitutes a building. As a fundamental element in mass customization, product platform refers to a set of components, modules, or parts that are physically connected and allow the efficient development of derivative products (Meyer and Lehnerd 1997). Modularization refers to organizing complex products by decomposing them into simpler parts, so they can be managed independently (Ulrich 1995). Supplementary to product platform is product family, which refers to a group of related products where product derivatives can be obtained by customizing the components of product family while maintaining the basic product platform.

The concept of a product platform and a product family in the building industry can be approached through industrialized building systems. By dividing a building into two distinct parts, support (chassis) and infill, John Habraken (1972) proposes a new concept to support flexibility in building. While chassis refers to the platform that constitutes permanent and shared parts of the building, infill refers to the interchangeable elements of the building. The support should be flexible enough to accommodate changes in infill that could derive from social, cultural, or technical issues, and are intended to "accommodate and outlast infill changes, to persist largely independent of the individual occupants' choices, while accommodating changing life circumstances" (Kendall and Teicher 2000, 33).

The flexibility of housing configuration is attributed to its hierarchical structure, which in turn is determined by how a house could be decomposed. The definition of hierarchy enables the designer to determine the design context and the relations between configurable elements, and in turn governs the ways in which elements could be configured.

In dimensional customization, a building is defined as an assembly of spaces. A building, \( P \), is defined by a set of spatial zones (modules), \( Z_1, Z_2, \ldots, Z_m \), each of which could also be comprised of several subzones, \( Z_{i,1}, Z_{i,2}, \ldots, Z_{i,j} \). A building is also defined as a set of elements, \( E_1, E_2, \ldots, E_p \) referred to as customizable components, which are considered as members of spatial zones. A configuration can be explicitly represented over the components' attributes reflecting in the form of dimensions, which are associated with building elements. The same set of elements can yield different configurations when dimensions of elements are modified. This hierarchy of a building is used as a fundamental basis for classifying variations in all sorts of dimensional configurations.

The definition of hierarchical structure is implemented through the "Zone Definition" function, and an overall hierarchical structure of zones is represented through the "Configuration List", so they can be selected, providing access to the elements of the selected zones for the configuration process.

Geometric and Dimensional Relation
A dimensional relation is an explicit representation of a geometric object's placement relative to others. In the dimensional customization system, the definition of a dimension is a bilateral relation that determines a distance between two elements placed axially along \( X \) and \( Y \) directions.

Identifying a dimensional relation is highly con-
tingent upon logical properties of a geometric relation supported by internal functionality of Revit®. Thus, the interchanging of elements is supported through three types of geometric relations between elements: parallel, perpendicular and axial (i.e. aligned). Figure 1 illustrates six scenarios supported by Revit®, where the first two show unconnected elements, and others show geometrical relations among connected elements. The transformation of an unconnected element (image i and ii) does not make the other elements move. Maintaining the topological relation of connected elements is held by joining geometry. When elements intersect, Revit® creates a join by default, in that one of the joined elements cut the other and a union between two shapes is created; elements connected at the time of transformation. If two elements are connected axially at their edges (image iii), Revit® automatically joins them, eliminates any edges, and makes them a single element. In L-shape connection, where two elements are connected on the basis of two edges, the transformation of either element involves changes in the length of the other. In T-shape connection, where two elements are connected based on one edge, the transformation of horizontal element, A, involves changes in the length of vertical element, B, (image iv). If three elements (or more) are connected along their edges, only two elements can get joined by Revit®. If two axial elements are joined, they become a single element and act as T-shape connection between two perpendicular elements. Joining between two perpendicular elements, however, acts as L-shape connection, but without any relation to the third element (image v). In that case, not only the third element is not joined, but also it is totally detached from others, and therefore the transformation of elements results in topological violation.

**Constraints in Design**

There have been several researches exploring the essence of constraints in architectural design. A constraint specifies relations that must be maintained. According to Kolarevic (1993, 61), constraints are defined “as user-defined dependencies or relationships among one or more entities that are maintained by some kind of constraint satisfaction mechanism.”

Applications of constraints can be distinguished between constraint solving and constraint checking approaches. The constraint solving method uses constraints as a design driver to explore validated solutions. This method is typically used when a generative approach to design is applied, where architects can encode design rules that can be then explicitly recorded as constraints. In this approach, the generated solutions fully meet the design constraints, although the customer has no influence in the design process. Constraint checking, on the other hand, allows for customer participation. What makes constraint checking compelling in the customization of housing is that it offers a promise of automatic design verification to see if individualized solutions meet all the constraints, and adjusts the solutions if necessary. For example, Niemeijer (2011) explores the application of automatic constraint checking in the building industry for simplifying communication between the customer and the design. The system prototype deals with entering and checking constraints on an imported IFC model created by commercial CAD packages. Embedding design codes and laws, the system checks the model to determine if it meets all the constraints, and adjusts it if necessary. Constraint checking is an appropriate approach in mass customization as it allows the customer to interact with the customizable house, while compliance with constraints prevents design errors and conflicts at an early stage of the design process.

**Dimensional Constraints.** Autodesk Revit® supports dimensional constraints in two discrete environments, the conceptual mass and the main modeling. The former, conceptual mass environment, allows a user to create 3D complex geometries and define dimensional constraints in the form of parametrical equations, and the latter supports geometrical modeling in the BIM environment. The conceptual mass environment, however, is not supported by BIM technology. Similar to traditional CAD tools,
this environment does not govern non-geometrical information used to create a real building such as price, fabrication and schedules. The created geometry could then be exported to the main modeling environment, but that results in the loss of dimensional constraints. The Revit® BIM environment supports a limited range of dimensional constraints; first, there is a *lock* constraint, which is applicable over aligned, linear and angular dimensions; second, the *equality* constraint determines equal length over several dimensions; and third, the *level* constraint references the top and the bottom of an element to a horizontal plane whose height can be controlled by the user. The challenge is yet to define a set of dimensional constraints in the form of parametrical representation.

Based on the research in the prefabricated housing industry, the most commonly used dimensional constraints have been identified and implemented in the system: $C_{\text{Fix}}$, $C_{\text{GreaterThan}}$, $C_{\text{LessThan}}$, $C_{\text{Between}}$, and $C_{\text{Mtp}}$. First, the fixed constraint, $C_{\text{Fix}}$, ensures that the dimensional value $v$, as a distance between two elements, remains always fixed, as represented in the equation $\{v = v_{\text{fix}}\}$. What makes this constraint different from Revit’s lock constraint is that it also limits the movement of the selected element. With the lock constraint, if an element is moved, the other element moves too, maintaining a fixed distance. With the fix constraint, neither of elements can be moved, and if they do, the system would return them back to the position where they were. The other two constraints, $C_{\text{GreaterThan}}$ and $C_{\text{LessThan}}$, enable customers to explore an infinite number of possibilities, with dimensions that are either equal/higher or equal/lower than a value, $\{v \geq v_{\text{min}}\}$ or $\{v \leq v_{\text{max}}\}$, respectively. The fourth constraint, $C_{\text{Between}}$, ensures that the dimensional value $v$ is always within a particular range of minimum and maximum values, or $\{v_{\text{min}} \leq v \leq v_{\text{max}}\}$. The last constraint, $C_{\text{Mtp}}$, ensures that a dimensional value, $v$, is always a multiple of an increment value, as shown in $\{v v_{\text{mtp}} \in N_{>0}\}$. The applicability of such a constraint is determined by the limitations of manufacturing systems in the prefabricated housing industry. Each element can have multiple dimensions assigned to it, each of which can only be associated with a single constraint. Each constraint $C$ involves some subset of the variables and specifies the values these variables can simultaneously take.

The definition of dimensional constraints is implemented on the basis of two steps: first is the "Dimension Labeling" function, where the designer needs to apply desired labels to dimensions, and second is the "Constraint Definition," which enables the designer to apply dimensional constraints. Dimensions are not interrelated and each of those can only get associated with a single constraint. Figure 2 illustrates an example of a dimension labeling panel and constraints definition dialog box, in that the first column (parameter) shows dimension names associated with the selected element, the second column (constraints) enables the designer to select among five constraints, and the last column (value) is where the parametrical values are entered.

Figure 1
Six types of building element relations.

a) Unconnected Elements

b) Connected Elements

\[ \overline{2500} \]

A

\[ \overline{1500} \]

B

\[ \overline{4500} \]

A

\[ \overline{4200} \]

B

\[ \overline{4205} \]

C

i) Parallel

ii) Perpendicular

iii) Two elements (Axially)

iv) Two elements (L-shape & T-shape)

v) Three elements (T-shape)
Constraint Satisfaction

The implementation of automatic design validation is based on the constraint satisfaction problem (CSP) paradigm. According to a general definition of CSP, a model is composed of a set of dimensional parameters, $D_1, D_2, D_3 \ldots D_m$, each of which has a domain of possible positive values ($D_i$) and sets of constraints ($C_k$) which specify the allowable combination of values (Russell and Norvig 1995). In that fashion, given a set of dimensions and constraints, the problem is finding the dimensional values associated with building elements (walls, doors, and windows) that could satisfy all dimensional constraints.

Constraint satisfaction is implemented based on linear equations using numerical algorithms fulfilling the reconfiguration process. The propagation of changes is performed through recursive evaluation of constraints and the dynamic update algorithm to arrive at validated solutions.

Reconfiguration

The reconfiguration of building elements can be supported in two ways: numerical manipulation of dimensional values and interactive manipulation of building elements. Both types of reconfiguration require pre-selection of a single element over which the changes are applied. In the first method, once an element is selected, the system activates the associated dimensions of the selected element. A user can then easily change dimensional values numerically. The second method allows interactive reconfiguration within the model by two types of Euclidean transformations of translation and stretch. Once an element has been selected, the former allows a user to simply relocate a building element while the latter enables the user to change the length of an element at the points of free edge.

The process of manipulation is implemented based on changes to a single element at the time. The geometrical reconfiguration, however, can be limited by several dimensional constraints, due to the fact that an element can be associated with multiple dimensions. Thus, the overall geometrical reconfiguration is the result of constraint satisfaction involving all dimensions associated with the selected element.

In the reconfiguration process, constraint explanation and solution recommendation are essential to derive at valid configurations. If there is a constraint violation, the system simply refuses to carry out a transformation that results in conflicts. Dealing with conflict resolution, the user could be overwhelmed by the complexity of reconfiguration process. Building on that line of thinking, the dimensional customization system provides for the explanation of constraint violation through a notification message in the natural language, and then recommends a satisfactory solution complying with the constraints.

TEST CASE

For the test case, we used a typical two-story house. The model was created in Autodesk Revit® and then integrated with the customization toolkit. The building is divided into six zones, with a total of 15 sub-zones. The first floor includes three zones. The first zone consists of a garage; the second zone consists of a den, powder room, stairs and hallway; and the third zone includes a living room, dining room and a kitchen. The second floor includes three zones. The first zone consists of a bedroom, laundry room and a bathroom; the second zone consists of a bedroom, stairs, hallway and a storage space; the third zone consists of a master bedroom, en-suite bathroom and a walk-in closet. The perimeter boundary of the building is limited by the site conditions to 12x20 m². Figure 3 illustrates the 3D representation of the model and the 2D representation of the...
DISCUSSION AND CONCLUSION
This paper presents an ongoing research project that explores the complexities associated with the application of mass customization in the housing industry, with a particular focus on dimensional customization. The apparent disparity between heterogeneous customer demands and a rather homogenous housing fabric provides an impetus to search for a dimensional customization system that could allow for the design of one-of-a-kind houses. Homebuyers and homebuilders alike are “captivated” by the difficulties associated with housing customization, such as burden of choice selection and design validity of individualized solutions.

The proposed constraint-based dimensional customization system should provide greater customer satisfaction by allowing customers to have a much greater influence on the overall design of their houses, including the variation of key dimensions associated with the exterior and interior of the house. Constraints may be seen as a limitation, but over the course of design-configuration-validation, it offers a promise of ensuring design viability, i.e. that a designed house is affordable, producible, and safe.

The potential benefits of BIM technology have been proven in the mass customization, but none of the architectural design tools have been explicitly designed for this purpose. As a consequence, there are several technical impediments in implementing customization features within existing tools. Two major issues have been identified in Autodesk Revit®. The first is topological violation; Revit® does not maintain connectivity (the “join” constraint) between more than two elements connected at a single edge. The second flaw is editing the footprint of a roof; specifically, a pitched roof is supported differently from the walls. Revit® does not provide an API to edit the roof boundary, and its changes can only be performed by mapping model lines in an edit mode. Thus, dimensional customization is tightly limited by the inherent characteristics of Revit® and the resulting issues cannot be addressed using the existing API. Dealing with such Revit® difficulties implies the necessity of either offering customers limited flexibility for design customization or having the designer perform post-processing purification in the design.

Future work will focus on understanding social and cultural challenges that influence customer decision making. Allowing the customer to be more involved in the design of individualized houses, while dealing with various technical difficulties that may emerge, raises questions about the acceptance of such a system by the population at large. In co-creation activity, the professional designer is replaced by the customer who may not have the sufficient domain knowledge and the necessary skills and confidence to perform the (re)configuration tasks. There seems to be a trade-off relation between a perceived value that a customization system could provide and its perceived complexity. The customer might be faced with either the risk of uncertainty or dissatisfaction; in both scenarios, the role of the
designer is crucial to ensure that not only the customized solutions are valid, but also that the process of housing customization brings value to the customer. As argued at the beginning, affective factors associated with the design experience of customization could potentially bring a higher valuation to the entire process from the perspective of the customer. Additional research is needed to better understand customer behavioral intentions when using the dimensional customization system and how customer attitudes are shaped to close the gap between customization, validation, and efficiency.

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