Mapping Mass Customization

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Mass customization (MC) and personal fabrication (PF) are current relevant topics in architecture offices practice and schools design research. Architects are adopting information based design and production techniques as a response to architectural century challenges. However, is not clear how various authors used and transformed the concept in practice, research and industry after three decades since the MC term was introduced by Davis (1987). Therefore, is essential to map the most relevant works in the field in relation to production and design control. The paper presents some of the results of the ongoing study through an evolving map that aims to visualize relationships, layering complexity and revealing difference.

Keywords: *Mass Customization, Personal Fabrication, Housing, Map*

INTRODUCTION

As parametric design and digital fabrication become increasingly established in both the profession and academia, alternative modes of production, such as Mass Customization (MC), emerge as feasible models for architecture and the building industry (Kolarevic 2013). The MC paradigm has been widely studied and adopted in manufacturing with the purpose of improving customer satisfaction by allowing the user to participate in the design of the product. It is a particularly fitting paradigm for the building construction industry, whose products are mostly prototypical in nature (Kieran & Timberlake 2003). Conversely, PF is the outcome of widely available information and means of production that empowers users to take the design and fabrication of objects, and eventually houses, into their hands. Consequently, control of production and design are key aspects to both concepts. But how has MC been implemented by architects and the building industry in theory and practice? And how do these experiences relate with one another and the MC concept in manufacturing? Are MC and PF overlapping concepts or are they mutually exclusive? These questions have had so far incomplete answers. Therefore, the present work uses a mapping method, that captures the production and design control level of both PF and MC. It is an ongoing work and this paper presents preliminary results. Examples of the implementation of MC and PF where limited to housing, to simplify the presentation and to fit the length restrictions imposed by the paper.

The term mass customization (MC) was first used by Stanley Davis in 1987, in his book Future Perfect, to define the possibility of mass producing customized goods, thus combining the advantages of mass-production, low price, stable quality and availability, with low-volume manufacturing advantages, accommodating personal requirements or preferences. One of the enablers of this possibility is the integration of digital design with file-to-factory processes, which provide “the ability to mass-produce irregular building components with the same facility as standardized parts" (Kolarevic 2001), but also instil the "logics of seriality" (Zellner 1999).

Computational design challenges the need for modularity in design and is often seen as an enabler of mass customization. Yet, in the literature of MC on manufacturing, modularity is seen as a complementary aspect of customization, or even one of the two prerequisites to attain it (Pine II 1993; Duray et al. 2000; Fogliatto et al. 2012; Piller & Walcher 2017), the other is digitization.

The definition of mass customization as originally proposed by Davis is considered visionary in the sense that he sees MC as the ability to provide individually designed products, as opposed to a more practical definition by Pine et all (1993) which propose that MC is the ability to provide diversity that meets specific needs of individual customers (Silveira et al. 2001). Da Silveira et al (2001) eventually proposed a dual definition model of visionary and practical MC, which was further developed by Kaplan and Haenlein (2006). Both definitions are similar in that they consider Mass customization to be a "strategy that creates value by some form of company-customer interaction" (Kaplan & Haenlein 2006, p.176/7). The main difference is the stage of the operations level at which this interaction takes place - at the design stage or fabrication / assembly stage.

There is not an agreement among researchers if MC can be applied to services as well as products. Some authors such as Pine (1993) consider it can be applied to both, whereas others such as Kaplan and Haenlein (2006) argue that services are inherently customized, for two of their main characteristics are perishability and inseparability, or in other words, they must be consumed at the moment of their production and necessarily involve the customer as a co-producer. Such is the case with the services of an architect, which are always offered on a personal customized basis, whereas the building construction industry is responsible for the manufacturing of the product. To mass customize these services would effectively mean offering customized services to a mass market in a cost-effective way, the opposite departure point of customizing a product that is mass-produced. Some authors (Kaplan & Haenlein 2006; Tien 2006) further suggest that mass-customizing is effectively a service that is embedded in the product, which supports Piller (2005) definition of MC as a co-design process. Architects, as independent professionals have direct relations with clients, which may or may not be the customers / building owners or even its users, and are bridging between the industry of building materials, the supply side, and the construction industry, the actual producers, whereas in most other industries the customer has no direct connection with the product designer and the manufacturer is the designer's client. So for architects to engage in MC there are three remaining options: to act as customers of the supply side, personalizing building materials into customized building components; to collaborate with or to become a building material / component manufacturer as in the Instant House (Sass & Botha 2006); or to integrate with engineers and contractors, overcoming the separation between design and construction phases of the architectural design process as in Duarte's work (Duarte 2005; Benros & Duarte 2009), reinventing the role of the "master builder" (Kieran & Timberlake 2003).

While architecture based on the logics of mass production is put into question, the most immediate applications of the MC paradigm have been mass produced housing, such as Duarte's (2005) discursive grammar, or pre-fabricated housing (Benros & Duarte 2009). In fact, MC requires integration of design and production in order to offer company-customer interaction at the operations level at cost levels that are similar to mass production (Kaplan & Haenlein 2006), hence it needs the control of the production tools and processes to be firmly on the manufacturer side (Gershenfeld 2005).

In 2005, Neil Gershenfeld announced a coming revolution of the digitization of fabrication, which will bring the programmability of the digital into the physical world. A shift from scarce means of production to increasingly affordable digital fabrication tools that will promote Personal Fabrication (PF). A precondition for PF is the open access to knowledge, made easier and widespread by information technology. While Gershenfeld vision of material assemblers might be still in the future, the “rudimentary” digital fabrication tools of today, CNC routers or laser cutters, are already widely available, and large scale 3D printers capable of producing large size building parts are becoming available. Architectural offices and design research groups alike have since increasingly adopted these tools, introducing prototyping into their workflows (Marble 2012). The increasing availability of digital fabrication tools and their connection with digital design allowed the exploration of the expression of the digital on the material and vice-versa, through programming and construction in what Gramazio & Kohler (2008) call a new “digital materiality”. In this process, other boundaries have also become blurred, the separation of the traditional roles of architect, engineer and builder, the difference between the prototype and the product and consequently the questioning of the role of the architect as a provider of services.

Thus, the literature review suggests that, while both MC and PF have been made possible by the integration of the digital fabrication tools with computational design, they depart from opposite directions regarding the access to information and the means of production.

METHODOLOGY

To map the most relevant works in the field of MC and PF, a method was adopted with the aim to analyse, organize and present relationships, layering complexity and revealing difference in the field of architecture and construction.

The mapping method is useful for showing and layering concepts and visualize relationships between different authors' approaches to MC and how they relate with PF. This can also portray tendencies and relations, sometimes revealing unexpected or unexplored fields (Sanders 2006). A map will also be useful to positioning our research in relation to previous work and to clarify new directions for future research.

In the reviewed literature, MC has been mapped in two ways: within the framework of the Product-Process Matrix (Pine II 1993), putting it into the context of volume (low to high) and diversity (customized or standardized) of production; and in the context of point of customer involvement and type of modularity (Duray et al. 2000), providing a clear differentiation between levels of MC. These matrices have some limitations, as they do not consider the access to the means of production, thus do not represent one of the key differences between MC and PF. Another way of looking at MC is framing it within the context of design and production control. Mapping MC in this way allows the possibility to put it into context with PF. In the field of design research, Sanders (2006) has used a bi-dimensional map as tool to clarify the design research landscape and to write about its state. The main difference between Sanders map and the previously used matrices in MC is that the quadrants are not discrete cells but areas, opening the possibility of placing concepts that overlap different areas.

The proposed map follows Sanders methodology and is organized in two axes: design control and production control. The vertical axis of the map - design control - ranges from design controlled by architects or building construction industry, at the top of the map, to design controlled by building owners or customers, at the bottom of the map. On the horizontal axis, the production control is portrayed from manufacturer control, on the left-hand side, to user fabrication on the right-hand side. This creates four quadrants (figure 1): (1) Manufacture/expert designed and produced; (2) Manufacture/expert design and produced and owner produced; (3) customer designed and manufacture produced; and (4) owner designed and produced.

To make the map clearer both axis need further discretization, so it is unambiguous how a building transitions from being expert designed to customer designed or it goes from being manufacturer produced to owner produced.

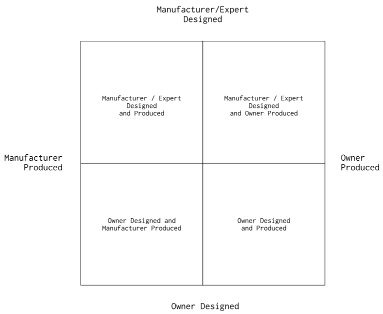


Figure 1
Mapping mass customization - underlying dimensions.

The design axis has parallels with the levels of mass customization which have been widely studied in the literature. Duray et al (2000) proposes a matrix of point of customer involvement and modularity in design of the product while Tien et al (2004) proposes a linear progression in terms of the customer order penetration point, that is at which stage the order interferes with the supply chain: customer, retailer, assembly, manufacturer, supplier. Figure 2 relates the levels of MC proposed by Tien with the level of design customization in the building industry. Partial MC and MC are coincident with the practical definition of MC by Kaplan (2006), while Real-Time MC is comparable with the visionary definition of MC by the same author but with some limitations. For Tien, Real-Time MC is instantaneous production and delivery of customer designed products. In the context of a design, real-time delivery of customized solutions is guaranteed by the adoption of digital design methods, and consequently only limited by the complexity of the computational configuration process and computational processing power available.

In a mass-produced building, customization occurs aftermarket - the customer can only inhabit the building or do renovations. At the retailer level the customer is offered different types to choose from (e.g. apartments with different numbers of rooms in a multifamily housing building or houses in different styles from a pre-fabricated building manufacturer).

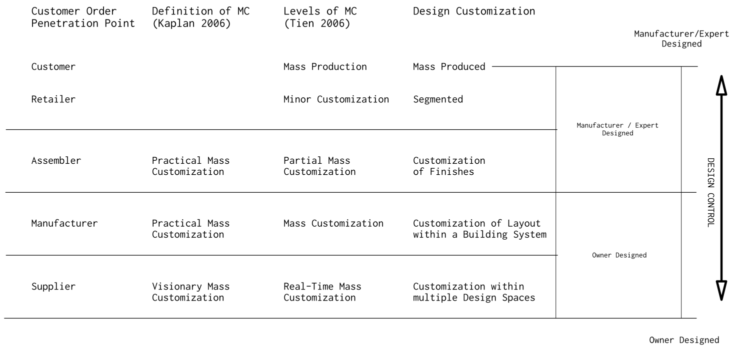
Design control at the assembler level includes the possibilities of the previous level plus the potential to change finishes or swap or add components in a modular system (e.g. adding a window), while at the manufacturer level changes in layout of the building are also possible which in turn have consequences on the manufactured building parts but may occur within a given building system. As proposed by Piller (2005) the design solution space is finite and all possible solutions belong to the same design space (Kolarevic 2013). Design control at the supplier level means that it is possible to choose amongst design spaces and consequently different building systems and different rulesets.

The midpoint of the production control axis is where the control moves from being on the manufacturer side to the owner/customer side. Tasks that are part of the operations level start to be undertaken by the customer. First the assembly (i.e. joining or installing previously manufactured parts or components into a new whole), then the fabrication (i.e: transforming inputs into outputs). On the left side, the manufacturer loses absolute control of the manufacturing process when the customer is given the possibility to make decisions that affect one of the stages of the operations level - first the assembly then the fabrication. Figure 3 integrates the previously discussed gradients of control in the map presented in Figure 1.

MAPPING MASS CUSTOMIZATION: PRELIMINARY RESULTS

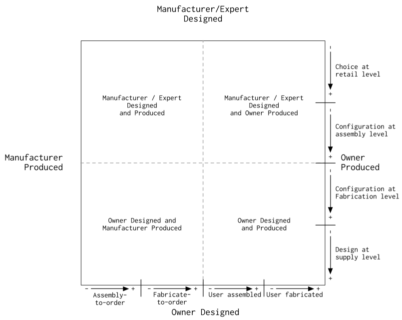
The use of the proposed methodology allowed to reveal the position of MC and PF and to illustrate that position with some examples in research and practice (Fig. 4). Since these concepts emerged outside the field of architecture, to put them into context, conventional construction space and mass production are identified. First, the reasoning for positioning the concepts is explained, then the position of the examples and their relations are explored. MC is divided into three areas, following the levels presented in Figure 2: Partial MC, MC and Visionary MC. Practice examples are limited to the Partial MC area, whereas research examples are concentrated on the MC area.

Figure 2
Design Control



To simplify the presentation, the examples of MC in research and practice are constrained to housing.

Figure 3
Levels of
Production Control
and Design Control



It is important to understand that in practice, architects almost always work for clients, so it is a very rare circumstance to have a building whose design is totally determined by the architect. But when the client will not be the owner, as is for instance the case in multi-family housing, the architect is designing for a mass market, eventually providing segmentation per some form of market analysis or insight. From the point of view of design control of the customer there isn't much difference between the previously explained example of conventional construction and pre-fabricated housing that only offers segmentation. The main difference lies in that the pre-fabricated manufacturer builds manufacture- or assemble-to-order houses with a specific design/building system whereas in the former example the building can be sold to the customer already built or, when the customer engages with the manufacturer before it is built or finished, the customer can have higher level of design and fabrication control.

Mass Customization requires some form of company-customer interaction, consequently a MC building can't be user fabricated and assembled. The opposite is true for Personal Fabrication, for the tools of production to be on the owner side, fabrication must be assumed by the owner: "With a PF [Personal Fabricator], instead of shopping for and ordering a product, you could download or develop its description, supplying the fabricator with designs and raw materials" (Gershenfeld 2005, p.4). Thus, PF is limited to the last forth of the production axis (see Figure 4). Along the Design Control axis, PF clearly occupies the lower three quarters. Even though Gershenfeld doesn't exclude the possibility of having PF that is expert designed, he states that "the promise of personal fabrication goes beyond consumption to invention." (Gershenfeld 2005, p.121).

The different levels of MC presented in Figure 2 also distribute themselves differently across the production axis. In Partial MC, customization only interferes with the assembly stage of production, customizing finishes or swapping modules does not

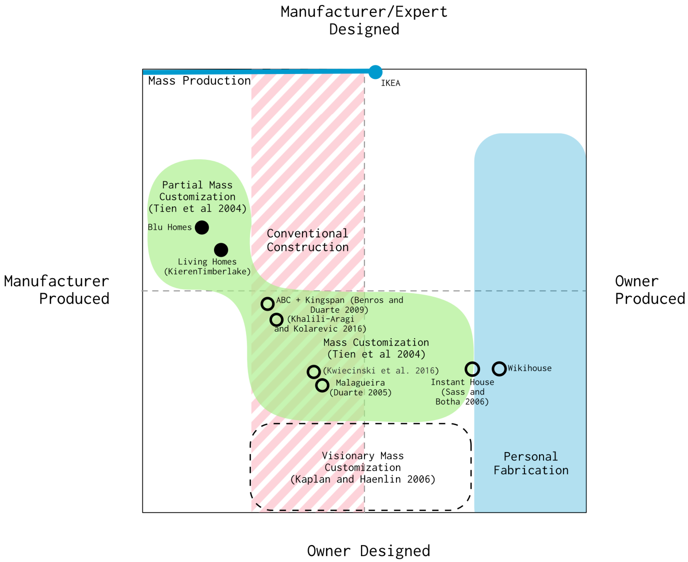


Figure 4
Preliminary Results: Concepts, Research and Practice examples

need to interfere with the fabrication stage, while in MC both stages, fabrication and assembly, are affected. The reason is that changes in the dimensions of the building or any of its parts do necessarily have consequences on the fabrication stage. It is also possible within a MC framework, as demonstrated by Botha and Sass's Instant House, that the assembly stage is performed by the owner. Even though the manufacturer is relinquishing some of the tasks he traditionally performs, there is still customer-company interaction at the operations level. This can be better understood with a parallel with IKEA, its products are still mass produced even if the customer is assembling the product.

Visionary MC, as seen in figure 2, can only happen at the lower quarter of the design control axis. From the point of view of architecture, Visionary MC means that the owner can customize the building across multiple design spaces, that is customization across different design families and different building systems. On the production axis, Visionary MC interferes at the fabrication level of production but the assembly might also be handed to the owner as in MC. Consequently, Visionary MC sits immediately below MC on the map. In the reviewed literature, no examples were found either in research or in practice.

Kolarevic (2015) points to several practical applications of MC in commercial housing, websites by builders of prefabricated houses such as Blu Homes, architect/builders like Housebrand's FAB House or architects firms like Resolution: 4 Architecture. Blu Homes is an example of Partial MC in pre-fabricated housing, in which the customer can customize interior and exterior finishes of predefined house designs. Another example is Living Homes, which offers LEED certified custom houses through a similar options selection process. But as Kolarevic points out, "none offers dimensional customization", although the enabling technologies are available and have been demonstrated to work in research.

The examples in research are concentrated in the MC area, within these examples two groups can be defined regarding the design process used: generative (Duarte 2005; Kwiecinski et al. 2016; Sass & Botha 2006) or parametric (Benros & Duarte 2009; Khalili-Araghi & Kolarevic 2016).

A common feature within the generative group is that the user of the system doesn't directly design solutions, but provides details that in turn are used by the system to generate solutions that are then presented to the user for inspection. Then the user has the option to review its original requirements. Even if the user is not defining dimensions it is still interfering with the layout of its house, so examples like Duarte's (2005) Malagueira discursive grammar or more recent work by Kwiecinski et al (2016) clearly fit in the MC area from the design control standpoint. From the point of view of production control, even though in Duarte's example is missing a physical grammar that translates designs into building specifications, these examples encode traditional construction systems that maintain the fabrication on the manufacturer side. The Instant House (Sass & Botha 2006) is a design production system composed by a design grammar and a subdivision grammar. Sass does not detail the design system, suggesting that different design grammars may be used to generate 3D houses, and the subdivision grammar by itself is not a customization system, but a way to generate valid construction details for generic customized solutions. The proposed implementation can be positioned in MC area, although on the right side of the vertical axis, since it requires the user to assemble the structure. But the authors recognize the system may evolve from MC towards PF: "Initially the process utilizes the end user exclusively for assembly purposes, but taking a page from Gershenfeld's (2005) Fablab and given sufficient local resources, the Instant House system could ship as an autonomous factory"(Botha & Sass 2006, p.210). Wikihouse, on the other hand, is an example of a construction system which clearly positions itself on the area of PF. It is freely available online and can be modified by the owner to meet its requirements, although it requires 3D modelling skills to do it successfully.

Benros and Duarte (2009), developed a different approach, based on a parametric model of the ABC system developed by Manuel Gausa and the Kingspan building system. It provides a computer system that integrates design and fabrication addressing that shortcoming of Duarte's previous work. The parametric system was conceived with the purpose of being used by architects and not customers and it has a smaller solution space than a generative system. Advantages include, being easier to implement and allowing a simultaneous feedback between the options made and the design changes. Although it allows layout configuration, it is limited to the modular grid present in the ABC system. Khalili-Araghi and Kolarevic (2016), propose a framework that aims to overcome this limitation providing dimensional customization in a parametric model. Another important difference is that this system is meant to be used by customers. It is composed by a design system, implemented in BIM (Building Information Modelling), and a configuration system that provides the user interface and a design validation process. Both these examples fit in the MC area, and although the latter example allows dimensional configuration, interior spaces maintain their topological relation, the former example allows topologically different solutions. A user of both systems controls design at the fabrication level and production control remains at the manufacturer side.

CONCLUSIONS AND DISCUSSION

In the reviewed literature and the selected examples of housing there is a clear gap between the implementations of MC in practice and in research. Since the technology and the knowledge of both production and design are available, one possible reason is provided by Kolarevic which suggests that customers might not be culturally inclined towards assuming the responsibility for designing their homes. From this point of view Duarte's approach seems more promising, since it doesn't require the user of the system to select options or configure dimensions but instead suggests possible designs solutions per user defined brief.

MC and PF are clearly mutually exclusive concepts from the point of view of production and design control, but as Sass's Instant House demonstrates, they might share methods and systems. What separates MC and PF is the openness of standards of design and production. Sass's Instant House also demonstrates the existence of an area of MC, where the assembly stage is handed over to the owner, that is not present in the reviewed literature of MC on manufacturing.

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