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Mass Customization of Housing: A Framework for Harmonizing Individual Needs with Factory Produced Housing †

Basem Eid Mohamed [1,*] and Carlo Carbone [2]

1 Zayed University, Abu Dhabi 144534, United Arab Emirates
2 École de Design, University of Quebec at Montreal, Montreal, QC H2X 3X9, Canada; carbone.carlo@uqam.ca
* Correspondence: basem.mohamed@zu.ac.ae; Tel.: +971-504-771-234
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Abstract: Integrated processes for design and fabrication have guided mass customization of architectural systems and components. Providing affordable and accessible housing, a vital segment of the building industry, is a multifaceted process that witnessed various manifestations towards individualization over the past few decades. Design flexibility in housing systems is becoming a crucial aspect, informed by consumers' lifestyles, demographic patterns, and lifecycles change at a rapid pace. As the housing market demands more personalized, efficient, and agile strategies, prefabricated building systems have always presented a viable alternative for flexibility and customization, following a rise of interest in the last decade focused on new modes of digitized design and production. This paper presents an overview and appraisal of various practices to implement customization in the housing industry, with specific focus on empowering a systemic approach. We then propose an open framework that could accommodate emergent design technologies and production protocols, with the aim of taking advantage of advanced research efforts, and coupled with current industry application.

Keywords: architecture; housing; prefab housing; mass customization; digital design and fabrication

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1. Introduction

Industrialized building systems, prefabrication of architecture, or off-site fabrication of sub-assemblies generally employ some strategy of modularization though different scales of components to achieve a level of adaptability and personalization. Back in the early 1940s, the fertile partnership between Gropius and Wachsmann for the General Panel House Corporation exemplified how component modularity would allow a multitude of design options from some simple basic additive or subtractive choices from component-based choices [1].

Today, the building industry is highly industrialized; it offers complete customization and adaptability without any strategic link to systemic rationalization from one prototype to another. Architects and builders pick and assemble continuously produced components (doors, windows, beams, finishes, etc.). This high level of custom building infers a perceived uniqueness of buildings, which repeat a highly inefficient design and construction process for each building generating waste and loss of productivity [2].

The desire for an industrialized building process that optimizes construction efficiency, costs, and mass-production while offering potential for personalization has spanned eras. Modernity in architecture proposed the union of architecture and industry through variable component building systems. Mass production, wartime technological advances, and post-war building programs created the conditions for rapid expansions in modularity and repetition to the building industry. In architectural theory, modularity became synonymous with the potential to create variable architecture from a set of systemically coordinated parts. From Gropius and Wachsmann's packaged house and Walter Segal's self-build house to Ken Isaac's living structures, designers sought to combine the advantages of mass production with architecture's need for singularity and uniqueness [2]. Dimensional and modular coordination, first proposed by Bemis in the 1930s, is still the framework for applying modularity in architecture.

Along with the rise of computer technologies in the 1960s, the notion of diversity, difference, and individuality in production of consumers' good emerged, with the aim of offering an alternative to mass production. This new paradigm directed a shift in various domains and was thought of as a potential player to inform new systems for quality customer- focused production. Toffler's 1970 book "Future Shock" [3] anticipated these changes as technological capacities, and then further described them as a "third wave" in a subsequent study [4]. Also referred to as mass customization by Stanley Davis in his 1987 book "Future Perfect" [5], this process was formally systematized by Joseph Pine in 1993 [6].

Many segments of diverse industries have shifted their business model towards greater customization in response to increasing consumer demand. The ability to achieve a certain level of customization has percolated investment goods such as machinery and telecommunication systems to consumer goods such as cars, furniture, personal computers and watches. Given the principal importance of customer satisfaction, and an informed marketplace, the implementation of such a production strategy has proven attractive to companies seeking to remain competitive.

Pertaining to the building industry, mass customization has been a topic of interest in the past decade given that buildings are unique and highly customized products. However, the building culture including the prefabricated housing industry, which is the focus of this research, has been relatively slow in adopting new strategies. It has alternatively opted for developing a model based on either offering custom designs, or repetition of certain typologies.

Mass customization of housing aims at shifting standard production practices towards customized types and patterns, enabled through clearly defined design and production parameters. It is continuously discussed that recent applications of digitally integrated processes in the form of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) have resulted in a remarkable shift in production ideology. Individual building components can now be mass customized in a model that goes beyond was previously possible. Such an approach allows for optimal variance in response to differing contextual conditions, such as uniquely shaped and sized structural components or variable openings [7,8].

While factory-controlled production is widely considered to be a viable approach to achieving mass customization, it is argued that industry has been facing economic and cultural limitations in the past few decades that have inhibited the complete adoption of such an approach. The prefab housing industry has been challenged with age-old connotations associated with repetition, low quality and flawed designs [9]. The industry has also had a difficult task of competing with a low overhead fragmented highly flexible construction industry. It is believed that mass customization could offer a new way forward, given its principal purpose is the production of high-quality housing at an affordable cost. This notion of quality relates not only to the level of user satisfaction in terms of basic users' needs, but also to the functional and aesthetic criteria of a house, achieved through the integration of advanced production techniques, coupled with adaptive design processes that deploy computer-aided strategies. In that sense, the question becomes how can the housing industry benefit from emergent developments in design and fabrication technologies towards achieving mass customization, thus leverage housing quality? Such a question has been always pertinent to advancements in modes of productions. Nevertheless, it is fair to mention that the housing industry have not yet taken full advantage of such trends.

Based on the previous challenges, we present an open framework for mass customization of housing, one that could accommodate advanced design and fabrication technologies mutually. The framework aims at highlighting technological enablers in design and fabrication as crucial modules for successful implementation of mass customization. The research pursues the following methodology: first, we analyze some of the key research efforts to implement customization in architecture and housing, and then we highlight a series of successful industry applications. The analysis is supported by reference to the concept and process of mass customization from an operational and technological point of view, with specific focus on enablers. Second, given the objective of offering high level of customization, we devise a framework structured as a series of sequential procedures that reflects a comprehensive understanding of previous and current efforts, industry applications, while considering the potential of accessible enabling design and production technologies. Finally, the framework is then reimagined with the aim of embracing emergent design and fabrication protocols, such as integrated generative design models and 3D printing, towards a conceptual model for implementing mass customization within the housing sector. Figure 1 represents the research methodology towards structuring the framework.

In order to respond to the research objectives, the paper is structured in four parts. The first part introduces the topic, and defines the problem and subsequent research question. The second part is the theoretical background, and it explores the concept and process of mass customization, then highlights the applicability in architecture. Then, the section also highlights some of the key research efforts on mass customization of housing, as well as acknowledge a series of industry applications. Part three is dedicated to explaining the proposed the framework, and elaborates on various steps. A subsection is then developed to possibly reimagine the framework and present potential applicability. The paper then is concluded by explaining the contributions of the framework, and future research.

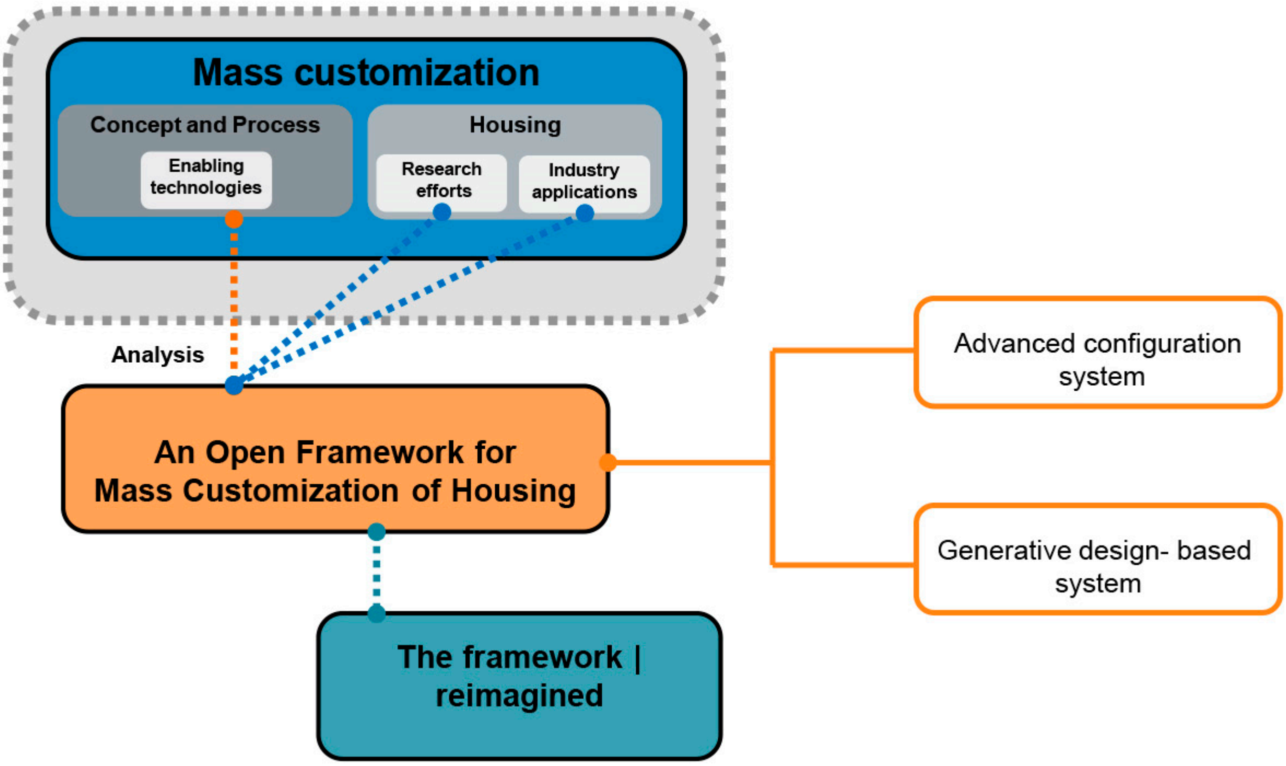


Figure 1. Diagrammatic representation of the research methodology towards devising the proposed framework.

2. Mass Customization: Concept and Process

Mass customization as a concept is based on aligning an organization with its customers' needs. In other words, it is not possible to achieve mass customization through reaching an understanding of the needs of individual customers and then producing customized goods to fit this description. Rather, it is more strategically about implementing technological and organizational capabilities that can direct a business towards specific goals [10].

The process of mass customization is comprised of a set of interlinking activities denoted with first collecting customers' needs, and then translating them into a physical product to be manufactured and delivered to them. This process could be broken down into a series of sub-processes based on the nature of the product, role of designer and producer, and level of customer involvement in the value chain [11]. Blecker and Friedrich [11] identified six sequential sub-processes necessary for implementing mass customization: development, interaction, purchasing, production, logistics, and information.

Salvadro et al. [10] explained that implementing a process for mass customization requires a certain level of technological enablers, defined as a platform of interlinked processes for appraising the technical and cultural procedures of a specific design and production strategy. The configuration of this platform allows companies to implement mass customization efficiently by gathering customers' needs and managing information transfers between various entities, thus leading to the manufacturing of custom products.

2.1. Mass Customization in Architecture

Pertaining to architecture, Kieran and Timberlake [9] argued that mass customization has increasingly inspired construction processes and architectural products over the past few decades. Mass customization in architecture is considered an industrial by-product designating adaptable and flexible models of production. This adaptability encompasses the capacity to integrate individuals' desires within a system articulated to production agility. Architecture and mass-customization strategies are connected through industrialized building systems as these systems imply a business model of mass production coupled with the ability of building variability through some type of modularity, either dimensional, systemic or a combination of both [12].

Nevertheless, one major challenge in applying mass customization strategies to architecture relates to the evaluation of product flexibility, and the way it is built. It must be concurrently customizable, properly designed, in concordance with design codes and regulations, and accurately manufactured. Consumer products are usually modularized in a way that partially limits customization due to technical constraints [9]. The field of architecture is distinct in its networked structure. In the design, production, and verification processes of creating a building, there is usually no single party that has the necessary specialization in all areas to manage such a project. Accordingly, realizing mass customization in a design and fabrication environment requires an integrated level of communication between users, designers and manufacturers [12]. Fragmentation poses a major obstacle, as fabricators in the building industry generally consist of small- to mid-size companies whose production volumes are normally insufficient for generating the economy-of-scale effects of the modularized production setting in a typical mass customization model.

Richard [13] defined four significant aspects to enable mass customization in architecture:

- Flexibility of the product: Concerned with the spatial variations of the product while in use;
- Flexibility of the tool: Concerned with the ability of the tool to become the generator of diversified products, by operating on different levels. This includes cutting-edge digital manufacturing techniques;
- Multipurpose framework: Concerned with product platforms that could accommodate different options, either through the addition of particular components, or the introduction of secondary modifications;
- Combinability: Defined as the possibility of generating a multitude of combinations from a set of standard components produced in a large quantity. This concept operates through modular coordination and simple interfacing rules for the joints.

These aspects were derived from general theories and approaches to mass customization and situate the user, designer, and manufacturer in a complementary relationship via either direct or indirect communication. However, buildings can be singular products, whose design involves typological, cultural, and social aspects that have yet to be robustly accounted for by the customization process.

It is evident that recent advancements in design technologies, which employ specific digital design environments and the related manufacturing processes, have influenced most of research efforts and industry applications exploring the realm of mass customization in architecture. Information technology, parametric design and new modes of collaboration such as BIM (Building Information Modeling) have paved the way for more control over the building process through supporting the notion of integrated design and file-to-factory protocols. These technologies allow for flexible collaborative environments to increase efficiency in the design, fabrication, and assembly of components [8].

2.2. The Case of Housing

Research efforts exploring the potential of implementing mass customization in housing are mostly technology-focused due to the correlation of the two matters: customization and design and fabrication technologies. The literature review on the topic reveals heterogeneous concerns, where some approaches focus on modes of homebuyers profiling, design generation through computational methods, link between design and production through digital collaborative environments, and emergent fabrication techniques and machines to support the delivery of customized housing and others examines various fabrication tools and machines to enable efficient production of products with remarkable variations. Within this diverse milieu, some particularly pertinent research is highlighted in this section. We highlight specifically the relevant research work and industry applications in relation to the previously discussed challenges specifically related to technological, economic and cultural obstacles in the prefabricated housing sector.

One of the early efforts is the work by Duarte [14], where he proposed a comprehensive model for the mass customization of housing built around an interactive computer program that generates housing designs following a given language. The design system used description and shape grammar as technical mediums for coding design rules. The grammar reflecting on his extensive analysis of Alvaro Siza's mass housing project in Malagueira, Portugal. The work by *House_n* [15], a former digital media and housing research group at MIT's Department of Architecture defined three necessary elements for the mass customization of housing. First, a *preference engine* for customer profiling. Second, a *design engine* that employs computational set of rules encoded into a shape grammar to generate design solutions in response to the profiling process. Finally, a *production system* that relies on digitally controlled machines for construction. Later, Duarte [16,17] presented different versions of his work that looked deeply into the computational model.

Realizing the internet's potential as an interactive medium for information management and transfer, Huang [18] developed a model to support homebuyers' participation in the design of their dwellings based on a decision support system. This model employed an interactive questionnaire that guided users in a sequential process towards finding the appropriate solution, relying on a catalogue of prefabricated modular housing systems. As housing prototypes were built in BIM software, a library of housing variants with coordinated modularly was established, allowing for interchange of components. Further to the focus on prefabricated housing system as a possible medium to support mass customization, Benros and Duarte [19] proposed an integrated system that tackles the linkage between design and production with the aim of lowering cost through serial production. To achieve such integration, a computer program was implemented for customers to explore and visualize design solutions and the subsequent automatic data generation required for production. Rules for both design and fabrication were systemized and then encoded into the computer program.

Friedman et al. [20] proposed an advanced configuration system for mass customization of prefabricated housing, built around the idea of using information technology to engage homebuyers in the design of their homes. As defined by Blecker et al. [21], product configuration systems are information tools that automate the order-taking process, thereby recording customer requirements without the need for external human intervention. Hippel [22] described product configurators in terms of "tool kits", whereby customers are provided with necessary tools to configure a product as per their needs. Configuration systems are generally implemented in the online interface between a producer and its customers. These systems are responsible for supporting customers in the configuration process, so as to develop a product in accordance with their particular and individual requirements.

Along with continuous advancements in web-based technologies, Puusepp et al. [23] proposed an online configurator prototype to involve homebuyers in the design of prefabricated homes. The process starts with offering architects the ease of creating configurable models using BIM/CAD, combined with a decision support system for spatial configuration, and a pricing module. Clients can then access the model via a web-based configurator and customize the design, while getting live feedback about geometry design, energy efficiency, and cost articulation. However, choices are outlined and limited by the architect. Finally, the configuration data is then sent to the architect for verification, and recreation of the configured mode in the preferred design software.

Given that mass customization is more of a business model, and only enabled by technological capacities in design, production, and delivery, while considering customers satisfaction, Larsen et al. [24] presented a comprehensive review on various research topics including mass customization in housing, modular off- site construction, supply chain, and customer satisfaction. The review highlights potential application of mass customization in housing, as well as challenges in application due to lack of use industrialization in construction, and limited use of automation and digitalization. Additionally, the paper underlines challenges in perception of industrialized housing, despite its proven benefits including saving in cost and time and improving quality. Additional research efforts on mass customization of housing include Eid Mohamed and Carbone [25] and TT Lo et al. [26].

Concerning the manufactured housing industry, one that has always been considered a suitable sector to adopt mass customization, numerous global producers have established collaborative partnerships with architects, computational specialists, and fabrication technologists towards advancing their design, visualization, and manufacturing processes in response to market demands. The aim has been focused on offering a level of customization to fulfill social and cultural needs of homebuyers, while leveraging affordability, quality, and environmental performance. These efforts resulted in exploring the application of internet-based interactive configuration systems as means of effectively communicating with homebuyers.

Online configurators within the prefab housing domain could be considered as a network of platforms that takes homebuyers through a decision-making process to customize their dwellings. Such a trend has been implemented by various prefab housing companies in Europe, Japan, and the United States, subsequent to similar implementations by automotive, clothing, and computer companies. Typically, the structure of the customization platform relates to the level customization, or, in other words, the level of customer involvement in the value chain and the applied customization strategy. Eid M. [27] classified possible levels of customization in the prefab housing industry as follows:

- Layout design: highest level of customization, where a company develops a custom design as per homebuyers' needs;
- Room block modification: homebuyers get to modify room blocks from a predefined option, or library of spaces;
- Layout alternative selection: homebuyers choose from different spatial organization of a specific housing prototype;

- External/ internal finishes: homebuyers are offered the option to selecting external and internal finishing materials;
- Appliances and systems: homebuyers are only offered to customized appliances and systems to be integrated within the house.

A diagrammatic representation of levels of customization is shown in Figure 2.

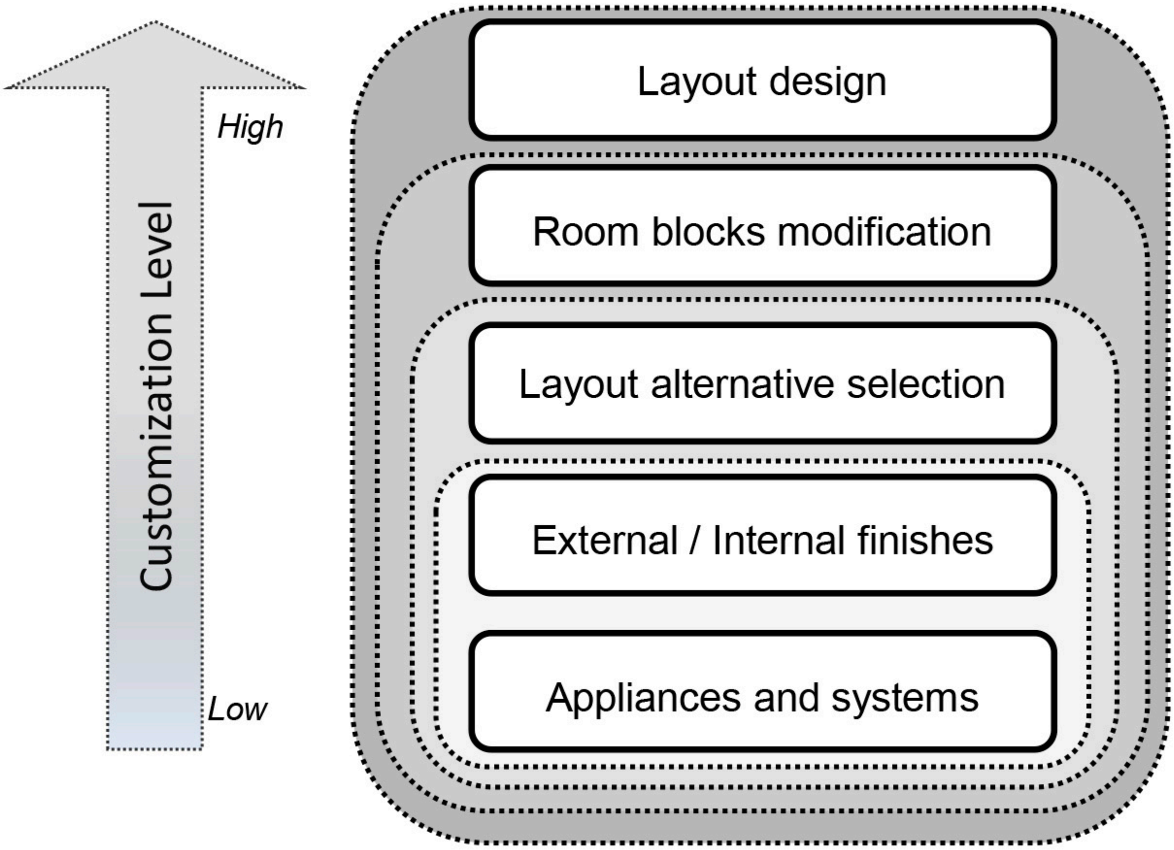


Figure 2. Levels of customization in housing organized sequentially from low to high, as a series of decisions offered to homebuyers.

On the first hand, the highest level of customization; layout design, offers unique homes corresponding to individual homebuyer's demands, yet it requires the longest time to complete and costs the highest price due to loss of economies of scale. On the other hand, lowest level of customization could be considered as the most common one, as builders develop a fixed set of housing prototypes (a catalogue or pattern book of house types) in response to an intensive analysis of market demands and offer homebuyers few items to modify such as appliances. The advantages of such a trend include reduction of both the lapsed time and the cost of construction. Intermediary, levels of customization in between combine take advantage of the economy of pre-designed housing models, coupled with the flexibility in customization through sort of limited pre-defined modifications to features such as room blocks, layout alternatives, external or internal finishes, and other systems.

However, given that the level of customization relates to enabling technologies, many prefab housing companies have opted for a mid-level of customization, one that that could be efficiently implemented without overwhelming the company's operational and financial capacities. Commonly, prefab housing companies operating in North America, and engaged in this field of customization tend to build and invest in a database of variable housing prototypes that are searchable by type, area, average cost, and number of bedrooms. Once a housing model is selected, homebuyers can access an online configuration tool that offers selections of different exterior/interior finishes, roof styles, and systems. Some pioneering examples in the US housing market include *livinghomes* and *bluhomes* as shown in Figure 3a. While *livinghomes* employed a static website that relies on pre-rendered images, *bluhomes* developed a 3D home configurator that homebuyers can navigate interactively to walk through the housing model, and customize various features [27]. Recently, *plantprefab* [28] (originally known as *Livinghomes*) collaborated with a user-experience (UX) company to develop a 3D configuration that allows homebuyers customize their dwellings through a visually-interactive sequence of decision making for various elements including exterior and interior finishes as shown in Figure 3b. The process is also supported by a pricing module that translates homebuyers' decisions into price estimate, thus act as decision support system. Configurators in the prefab housing sector make it possible to visualize choices in real time, thus facilitating the customization process, and making the whole house procurement process less tedious for the uninitiated buyer.

The review of various research efforts and industry applications highlights the fact that interest in the mass customization of housing was influenced by two dynamics: first, significant developments in information technology, and computational design and fabrication protocols. Second, demand for more individualized housing, sparked by parallel trends in consumer goods market. While these dynamics signify an opportunity for a comprehensive approach to implement mass customization in the housing industry, yet it has not been exploited to the full potential. In fact, we argue that customization in prefab housing has not changed much over the years. On the one hand, the online configurator could be considered as a line that was never crossed by prefab companies. On the other hand, the majority of production processes remain limited to the notion of bringing conventional processes inside the factory, despite the potential offered by automation and digitalization. Automation specifically makes it possible to increasingly identify nuanced production adjustments within the same overall process particularizing the assembly line further offering potentials for mass customization to be economically feasible.

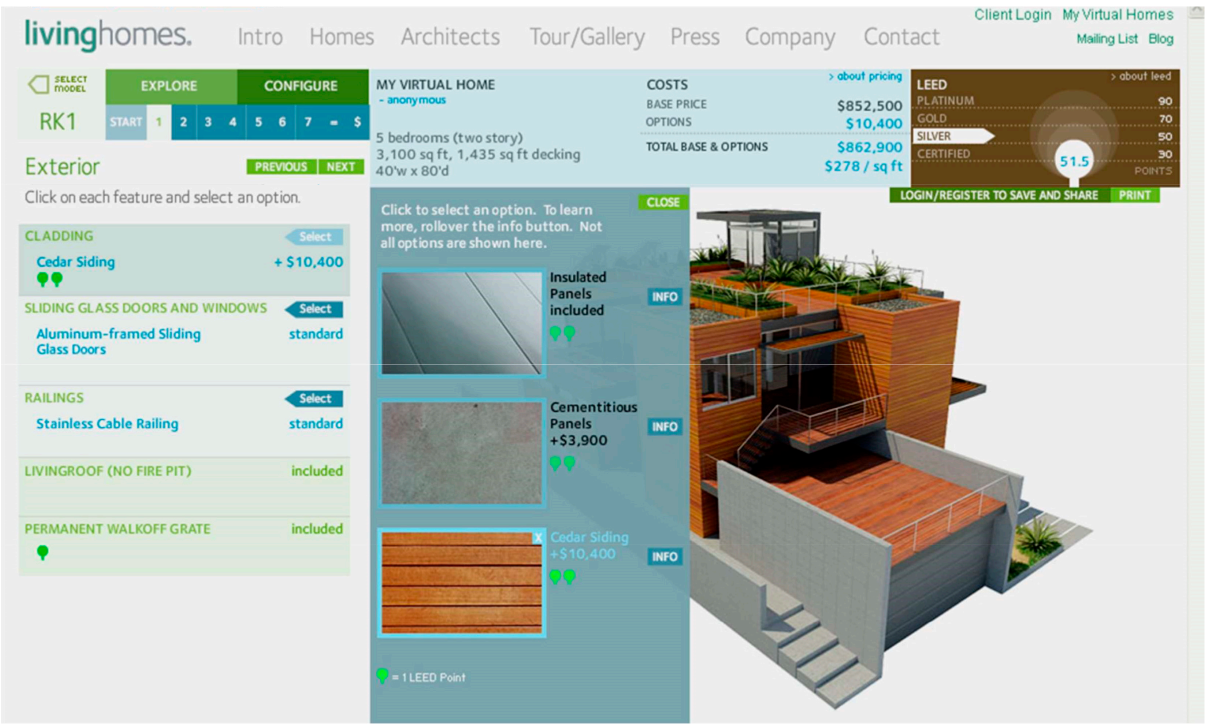
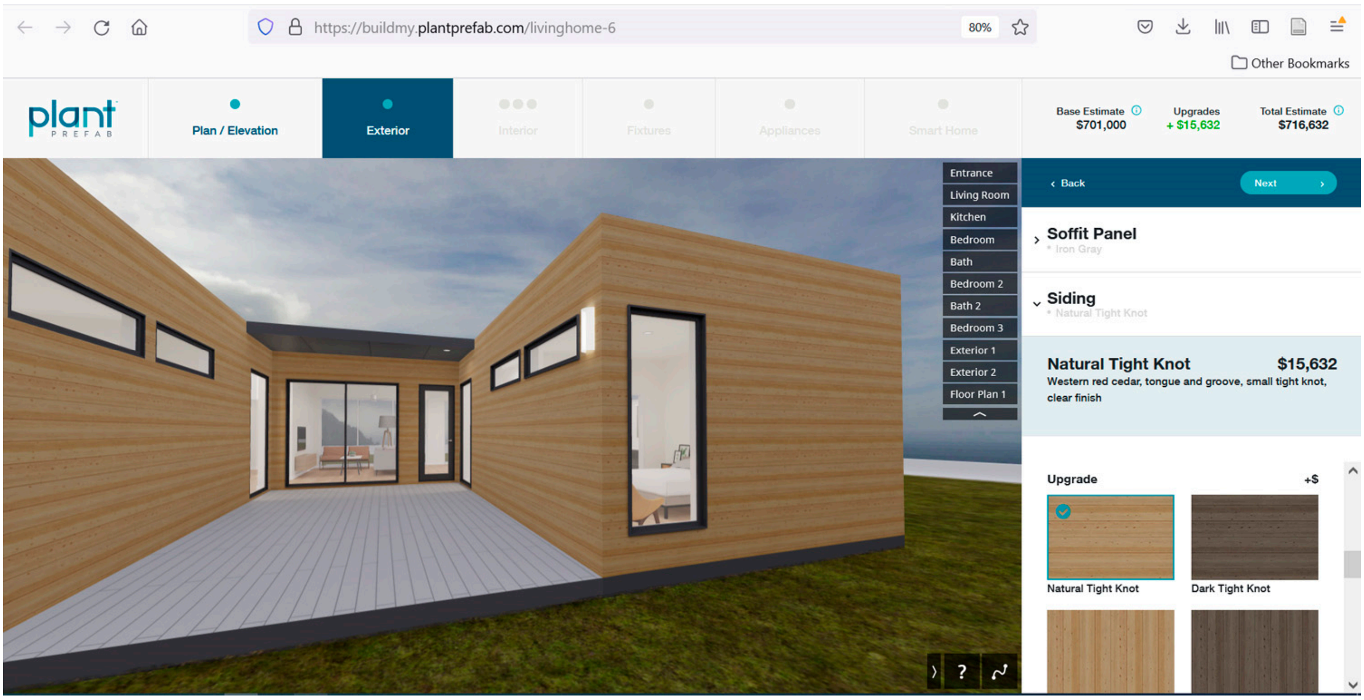


Figure 3. *Cont.*

(**a**)



(**b**)

Figure 3. (**a**) A printscreen of the configuration system by two companies in the US market, *Livinghomes* and *bluhomes*. (**b**) A recent screenshot of *planprefab* (livinghomes) with a more advanced 3D configurator.

In response to recent developments in technological enablers for mass customization in the form of computational design systems and fabrications tools, we believe in the significance of constructing an open framework that could accommodate such developments effectively, without being limited to a specific method. The framework builds on previous efforts, while being flexible to accommodate future endeavors.

3. An Open Framework for Mass Customization of Housing

Salvador el al. [10] defined three common capabilities required for the successful implementation of mass customization: (a) *Solution space development*, defines the amount of possible product variants in accordance to customer needs, (b) *robust solution space*, relates to the flexibility of the design, and (c) *choice navigation*, supports customers in making while minimizing difficulties in making these choices.

When examining prefab housing companies that offer a certain level of customization through an online configurator, it is apparent that they have opted for a strategy that is based on offering choices on multiple levels. First, homebuyers can select from a set of housing typologies varying in design style, spatial layout, number of bedrooms, area, and finishes. Then, the configurator guides homebuyers systematically through structured decisions with regard to exterior and interior finishes, appliances, and systems. We believe such a strategy is subject to considerable limitations as developing design variations that could accommodate wide choices is considered an exhaustive process and labor intensive. As a result, the number of alternatives in some cases must be kept limited to avoid additional overhead cost. Additionally, the multiplicity of choices may confuse or intimidate some homebuyers.

Despite various research efforts that have highlighted the potential of advanced design and fabrication tools to enable higher levels of customization, we could argue that currents practices have failed to embrace these technologies. In that sense, we propose a framework that aims to facilitate a new relationship between homebuyers and prefab housing developers, through focusing on relevant information, and employing design and fabrication tools in a comprehensive manner.

Within the proposed framework, homebuyers, the architect, and the manufacturer are the three main active participants in the customization process. The framework emerges as a possible evolution of previously analyzed research efforts and industry applications in mass customization of housing, towards highlighting new opportunities that relies on advanced technologies in design and fabrication. Figure 4 represents a schematic diagram of the proposed mass customization framework.

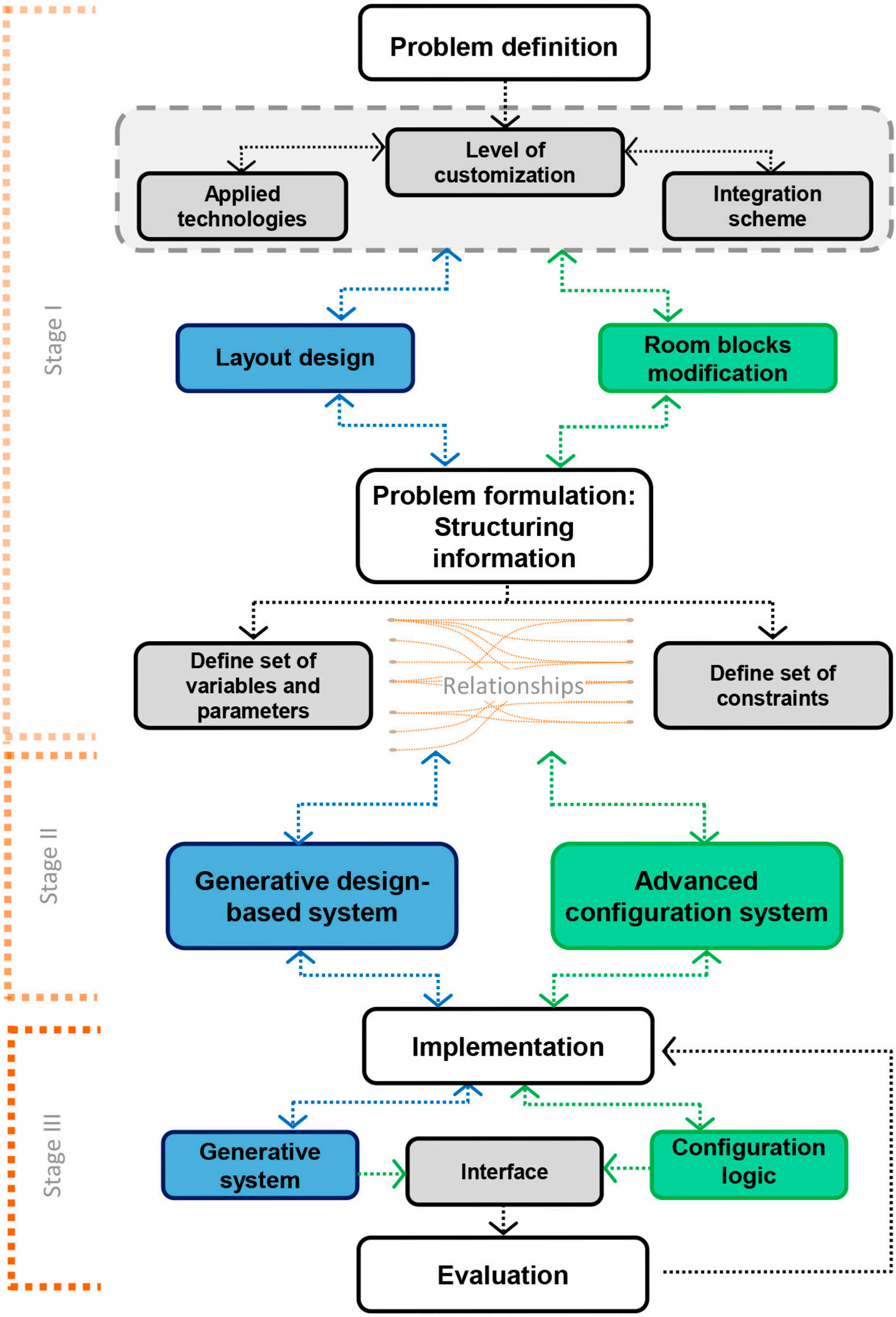


Figure 4. A diagrammatic representation of a proposed open framework for mass customization of housing.

As per the diagram above, the proposed framework is structure on three main stages:

- Stage I: Initiated by defining the problem which relates to understanding various levels and activities that constitute the mass customization of housing, based on the study of mass customization as a concept and process and supported by the analysis of previous research, and industry applications. The primary objective is to identify the level of customization denoted with the homebuyer's point of involvement in the process. This is then correlated to the housing company's readiness for customization with regard to technological capacities, and modes of communication with homebuyers with the aim of effective integration. At this point, the process branches into two possibilities. On the first hand, the case of room blocks modification is designed to allow homebuyers modify spatial attributes within a predefined, and pre-engineered housing layout. On the other hand, layout design requires the use of generative design model that has the capacity to generate housing design solutions based on homebuyer's data, and constrained with a specificities of the design and production system. For both levels of customization, the process entails developing relationships between variables and parameters that encode users' needs and requirements, and design and production constraints. For instance, homebuyers' profiles, socio-cultural backgrounds, budgets, and desired spaces and activities could be translated into precise programmatic data to direct the selection of a housing unit, that could be then customized. Additionally, design and production constraints in the form spatial relationships and proximity, building length/width, height, and area; all could be used to drive the process of generating a design solution.
- Stage II: Explores the process of selecting a methodology to formulate a solution space for the selected level of customization. The selected methodology is intended to focus towards users, while being tailored to the specific customization approach, and considering the company's readiness. First, the case of layout design involves employing a generative design system that relies on computational logic to generate housing designs that would comply with inputs defined at the previous stage, in addition to the generative rules of the algorithm, and the specific set of constraints built into the representation formalism. The study of previous research reveals the use of various possibilities for generative design systems including for instance shape grammars, evolutionary algorithms, or even combining both, yet the proposed framework does not endorse a specific system given that it is a continuously evolving technology. We believe that the selection criteria would rely on the company's housing design language, and production scheme. Second, an advanced configuration system entails the use of an interactive interface through which homebuyers could exchange room blocks as per their preferences. The process relies mainly on a knowledge base component a, which is further divided into two subcomponents: the database and the configuration logic. While the database comprises the whole set housing variants in the form of component types and their instance, ones that the housing company intends to offer for customization, the configuration logic identifies the existing constraints between different components, to ensure valid product variants. Within the framework, the proposed configuration system aims at overcoming current industry practices through taking the customization process a couple of steps forward. For instance, in the previously described cases, homebuyers select from a series of prototypes based on their own preferences. However, within the proposed configuration system, homebuyers' profiles are matched with specific housing prototype through a search engine. Moreover, the decision-making process goes beyond materials and finishes selection towards customizing room blocks with the aim of more suitable spatial configuration of the matching housing prototype.
- Stage III: Denoted with implementing various enablers, and then verifying their capability to deliver a solution space in response to the selected customization path, and in compliance with the requirements defined in the preceding stages. Branched into two possibilities as per each of the previous stages, implementation is only possible once

the system is clearly articulated and understood. Layout design level of customization requires selecting then coding a generative design algorithm that has the capacity to generate design solutions as per a specific brief, and complying with a production model. However, this requires defining the system operator and degree of automation. With regard to an advanced configuration system, the configuration logic becomes the core component of the process, supported with a profile- matching model that seeks the most suitable housing variant in compliance with homebuyers' profiling outcome, then a hierarchically structured product configurator that allows homebuyers to customize the matched housing prototype based on specific sequence [25]. In both cases, an interactive interface would be used in order to establish a relationship between homebuyers and the builder. The role of the interface is to guide homebuyers throughout the customization process. We believe that building such a system would involve a concentrated and interdisciplinary collaboration between experts from various disciplines, including prefab housing, architecture, computational design, BIM, and user-interface design. The collaboration would aim to identify the required type of information at each stage. For instance, prefab housing producers would set out required parameters and constraints of the building system, that the computational designer, and BIM specialist could utilize to feed the generative system. Then, the user-interface designer would initiate a user-friendly interface that brings all the steps together in a visual format.

Towards Embracing New Technologies

Recent growing roles of generative design tools in architecture, coupled with new modes of fabrication, imply new possibilities for customization in the housing industry. On the one hand, automated design tools supported by algorithmic modeling [29], such as Finch3D [30], Higharc [31], and others, could be considered as an extension to current parametric CAD/BIM tools. These tools rely on computational design logic, coupled with the power of Artificial Intelligence (AI) to automate the design process towards a well-informed decision-making model. Such an approach could be integrated within the process of customization, thus allow for a more efficient process of generating design solutions.

On the other hand, large-scale robotic fabrication is reforming conventional construction through offering a new production paradigm. This technology-based construction ideology that relies primarily on industrial-scale robotic systems has been extensively investigated in the past few years, and have inspired innovative research efforts in academia, as well as erection of real-scale prototypes. From bricklaying to components assembly and large- format 3D printing, industrial robots are continuously expressing the ability to offer a new alternative to traditional serial production. For instance, 3D printing has been applied to produced facade elements, structural components, and even entire buildings. In that sense, we anticipate emphasizing the power of integrated generative design tools, supported by emergent fabrication machines within the proposed framework logic towards enabling customization of building components. We present, in Figure 5, a reformed version of the proposed mass customization framework, with the possibility of embracing emergent design and fabrication technologies.

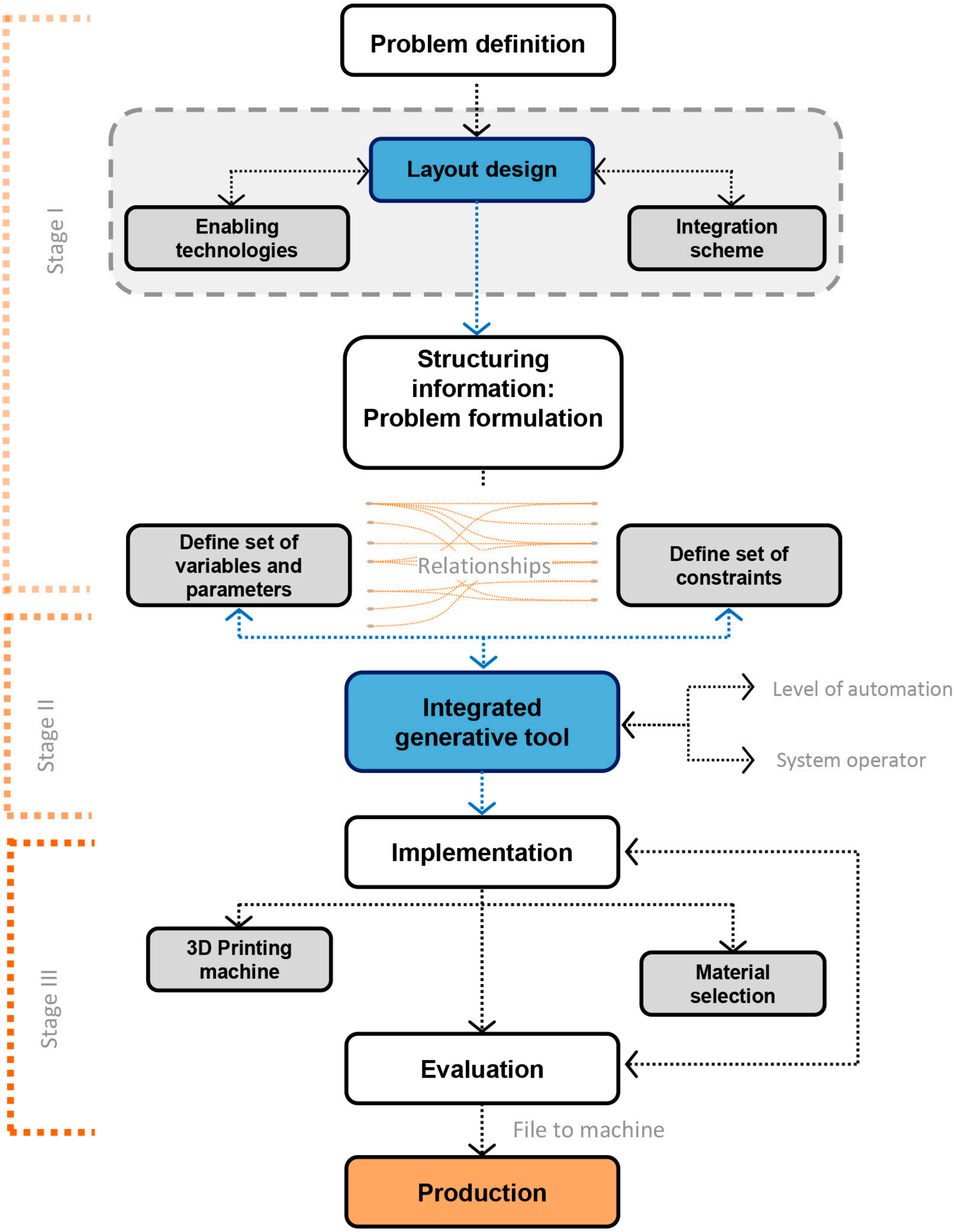


Figure 5. A diagrammatic representation of the a mass customization framework targeting higher level of customization in response to n emergent design and fabrication technologies.

4. Conclusions

The analysis of research efforts and industry applications reveals a sort of disparity between two approaches to mass customization of housing. First, research efforts on mass customization of housing are typically driven by advancements in computational design and fabrication technologies in architecture, leading to exploring how these technologies could effectively enable customization on various levels. Given that customization is centered around fulfilling homebuyers' needs, different computer-based design systems were proposed, thus relying on their capabilities to devise housing designs in response to specific' inputs, and following a specific design language. Additionally, other efforts explored the possibility of integrating a synergy between advanced design tools and numerically controlled machines for efficient production of customized housing. Second, industry applications are centered around employing configuration systems, and being encouraged by the rise of information technology tools, and parallel applications in other market segments. The use of 2D static/3D dynamic configuration systems are intended to provide homebuyers with an interactive decision-making interface to offer the selection from predefined housing layout options, and then modify external or internal finishes, appliances and systems.

As a result of studying both approaches, it could be argued that mass customization of housing is a remarkably complex process that requires building up multiple levels of information between homebuyer, architect, and manufacturer, relating three fields that are rarely convergent. Research efforts on mass customization of housing have not yet offered a comprehensive model for implementation; rather, they have focused mostly on enablers. On the other hand, industry applications have been reluctant to integrate technological enablers as described by research efforts, and still limited to the notion of using simple product configurators.

The work presented in this paper could be seen from two angles. First, we present an open framework for mass customization of housing as a systematic approach to assist prefabricated housing companies rethink their production ideology, with focus on integrating technological enablers towards implementing mass customization effectively, rather than celebrating the production of custom homes. The system framework is conceptually structured on three phases. The first aims to explore the problem through defining the desired level of customization, required technological applications, and method of information transfer between various actors in the customization process. The second concerns the selection of an appropriate methodology to devise a solution to the formulated problem. The final stage is concerned with implementing the design system and evaluating its ability to generate valid design solutions.

Following the analysis of various research efforts, we believe that the framework could offer a road map to overcome technical limitations and difficulties that are typically correlated with implementation of customization of housing, thus stagnating its potential factory production. The framework, thus, represents an opportunity to respond to housing market demand for high quality customized housing, by implying a robust process for information management and transfer. Within this framework, the levels of customization and corresponding company's technological capacities can be clearly identified. To this end the proposed framework would bridge the ever-extending conceptual divide between individualization and traditional factory produced architectural systems.

Second, we then reimagine the framework through advocating for the possible application of automated and integrated design tools, coupled with robotic 3D printing towards a more efficient interaction between architects and producers, and leading to wider application of customization in the housing industry. In this case, 3D printing could be utilized to produce either a full structure or prefab components. We believe that such an approach represents a viable alternative to current prefab housing production, and an exemplary model for mass customization given that various activities are digitized in a file-to-machine fashion, thus leading to a high level of customization as previously described classification. Our argument could be exemplified in recent projects delivered through 3D printing such as the ongoing large community of 3D printed homes by Icon [32]. Future research efforts are intended to further develop the framework, and simulate the outcome through collaborating on real-life projects.

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