A Choice Model of Mass Customized Modular Housing by Internet Aided Design

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Abstract
The Internet has increased the opportunities to apply the concept of mass customization to customer interaction by tailoring the content to individual needs. Within limited design parameters, customers can determine what options they wish by participating in the flow of the design process from the beginning. This concept has already been implemented in the computer, clothing, and automobile industries, but it has not been fully integrated in architecture, especially the housing industry which is more directly related to personal lifestyle. The industry lacks a process that will lead to the customization of homes that respond to the unique values and needs of the occupants.

The paper describes the relationship of client’s requirements and available design options of the proposed system by examples of its current prototype. By integrating the nature of modularity in prefabricated housing design, a proposed web-based design system will provide information filtering questionnaires to assist customers in selecting appropriate design components. A methodology has been developed that can generate design options based on the client’s needs and available modular components from selected product suppliers making it possible to simulate the final design before processing orders for assembling and manufacturing.

Keywords
advisory system; customer participation; interactive questionnaire, housing delivery process

1 Introduction
The design of industrialized housing has been a pre-occupation in architecture since the start of the industrial revolution in the nineteenth century. In the first half of the twentieth century, architects attempted to solve the housing shortage by introducing a production process based on the assembly line. The assembly line was initially developed for the automobile industry by Henry Ford, but soon became a paradigm for the housing industry (Duarte, 2001). For example, the Dymaxion House designed by Buckminster Fuller was trying to achieve the mass production goal by retooling the aircraft factory.

Prefabrication technology groups building components into larger-scale modular units, such as a prefab wall panel with window and door openings. Each module is made in the factory using assembly line techniques, and then transported to the building site to be installed on a permanent foundation. This is advantageous because it shifts portions of the construction process from the site to the factory where worker productivity is increased, quality is higher, costs are lower, and the overall need for labor is reduced. The construction of a new site-built home in the U.S. typically consists of 80% field labor and 20% material costs (Larson et al., 2004) – an extraordinarily high labor component compared to other industries.
prefabrication technology, the improvements of quality and efficiency are accomplished because factories can offer better working conditions, automation of many tasks, fewer scheduling and weather-related problems, and simplified inspection processes.

If mass production and prefabrication methods of the assembly line were the ideal of architecture in the early twentieth century, then mass customization and the development of digital technology are the recently emerged paradigms of the twenty-first century. The development of the digital revolution has already prompted the shift towards mass customization. In this new industrial model, computer-aided manufacturing facilitates variations of the same product. Mass production was all about the economy of making things in quantity, but mass customization does not depend on serial repetitions to be cost effective. It is about cultural production as opposed to the industrial output of mass production (Kieran & Timberlake, 2004). Within limited design parameters, it is possible for customers to determine what options they wish by participating in the flow of the design process from the beginning. This concept has already been implemented in the computer (Dell), clothing (Lands’ End), and shoe (Nike) industries, but it has not been fully integrated in the housing industry.

Today's information technology has become even more interactive and powerful than at the end of the last century. Integrating a participatory home design concept with web technology to create an online interface can become the design platform by which the clients can make more choices and establish a better communication with architects and/or manufacturers. Face-to-face meeting time between architect and client is always limited and time consuming, while a computational web-based design approach is infinitely patient and always available (Larson, Tapia, & Duarte, 2001). One of the problems that prefabricated housing industries failed to address in the twentieth century was the lack of variability and an individual identified design (Kieran & Timberlake, 2004). How prefabricated housing design can be evolved from mass repetitive production level to mass customization level to meet flexibility and variability is the primary issue to be explored in this research.

2 Background

2.1 Types of Modular Housing System

Generally, there are three different types of prefabricated housing systems: fully modular, sectional, and component. Figure 1 describes the basic modular types, features, and examples for each system. The complexity of on-site assembling and shipping limitation may be related with the scale of basic modular elements. This analysis will help us to understand the strength and potential of each system, and provide opportunities for customization and spatial adaptability.
(1) Fully Modular
All the components of a single housing unit are entirely made, assembled and finished at the plant; as three-dimensional modules (like boxes) requiring only simple connections to the foundations and main service conduits once at the site. The size of the modular unit is restricted by highway law or shipping constraints. Some examples are like Habitat ’67 in Montreal, Canada by Moshe Safdie and Nakagin Capsule Tower in Tokyo, Japan by Kisho Kurokawa.

(2) Sectional
Small and easy to transport sectional modules, but need a complementary component or process once they reach the site. Double-wide trailer is the typical example found along the North American highways. Sectional modular system has some potential for implementing with digital fabrication technology. ESG Pavilion by graduate students in Swiss Federal Institute of Technology (ETH) is an example of creating sectional modules.

(3) Component
By definition, a component system may be a panelized, precut, or kit-of-parts system. All building components are pre-engineered and designed to be assembled in a variety of ways. Components are sized for convenient handing or according to shipping constraints. The smaller of components may take longer time to be assembled on site, but that allows more flexibility for creating building variations.

2.2 Current Approach of Mass Customization in Modular Housing
At the beginning of the twentieth century, industrialized economies were focused on mass production, mass distribution, mass marketing and mass media. Presently, a combination of advances in information and digital technology is making it increasingly possible to rapidly respond to consumers with customized products at mass-production prices. The fundamental premise of mass customization is to no longer manufacture products "blindly" according to a predicted demand, but instead allow production to be directly driven by actual orders (Schodek et al., 2004).
Sears mail-order kit houses, from 1908 to 1940, can be viewed as the first customer-tailored mass product in the housing industry (Thornton, 2004). Sears provided a house plan catalog with the added advantage of modifying houses and hardware according to buyer tastes, and shipped the appropriate precut and fitted materials to the customer’s site. With today’s technology, the internet is the perfect medium for the dissemination of domestic design. Many pattern book companies now have big websites offering thousands of house plans stored on databases searchable by type, style, square footage, average cost, number of bedrooms and so on (Davies, 2005). Some websites also provide the design tool for customizing exterior and interior finishes after the clients have selected the base model from a house plan catalog. Figure 2 is an example of choosing different exterior finishes of a prefabricated modular house provided by the m-house vendor from London. Toyota also provides a customizable façade option from their Toyota Home’s website (Figure 3). These examples can be viewed as the current implementation of mass customization in the housing industry.

Figure 2: Example of Customizing Exterior Finishes from m-house
2.3 Problem Statement

Although the engagement of internet with pattern book concept can create a power of e-commerce for the housing industry, the end result of web surfing may or may not fit the client’s spatial needs. Unlike the other industries (shoes or watch), a suitable house design is not only judged by its appearance or architectural style, but also involves a series of architectural programming phases. Figure 4 demonstrates that by reversing the sequence of choosing a product image to get spatial features and functional details, a knowledge-based questionnaire can be a new format to collect client’s input. The interactive web interface will provide suggested design solutions based on client’s needs. The main goal of this research is to investigate the possibilities of customizing mass housing by internet and prefabrication technology beyond the finish material selecting process.

Figure 4: Difference Methods of Consumer-Product Interaction
3 Methodology

3.1 Conceptual Framework

In order to achieve the goal of mass customizing prefabricated modular housing, the conceptual design model must combine the results of two important parts: data collection of client’s requirements and a prefab system of design combinations. A web-based prototype can simulate this interaction between clients and the adoptable systems. The evaluation phase can include a series of case studies to demonstrate and revise the data-input method within the design interface. Finally, the resultant design can generate building specifications prepared for the manufacturing and assembly of the products (Figure 5). This research will be focused on the input methods of the end-users rather than relying on architects for finding suitable design solutions in the prefabricated housing.

![Conceptual Framework of the proposed i_Prefab Home System](image)

3.2 Existing Models and Proposed Model

Presently, only five percent of people in the United States typically hire an architect and pay them to design and build a home which is tailored to their preference (AIA Firm Survey, 2003). Instead, many people purchased stock house plans and hire a home builder for their new single-family houses. Besides the architect’s fee, clients also need to wait an interminable time for the completed process of design and construction. Factory-produced prefabricated housing systems have previously tried to solve this problem. However, most systems failed to address the issues of variability and individual needs. Plants closed because they could not achieve the large enough market needed to reduce the costs, and the prefabricated housing provided less flexibility and could not compete with the stick-built housing market.

Now, advanced digital technology makes it possible to communicate design ideas and concepts to others more effectively. The project delivery process leads to customization, embodying principles of lean production (Pine, 1993), flexible computer-integrated design interaction with clients, and reduced cycle times; all effecting rapid response between consumers and producers (Figure 6, bottom diagram). Demand-to-order is not a dream for prefabricated housing industry anymore. As long as people are motivated to accept this new concept, prefabricated housing will shift from the stereotype of “factory-like” repetitive industrialized products to flexible and customizable humanized products.
3.3 System Flow of Proposed Model

The internet-based prefabricated modular house design advisory system has two modes, basic and professional. The basic interface allows customers to query the suitable design options and customize the detail components as needed. The professional interface is designed for architects and home builders with the capability to organize the building site issues and review customer’s final selections. It also allows advanced users to exchange some digital data through different digital design applications in order to collaborate with engineering consultants and manufacturers.

The basic mode of the proposed system starts with a dynamic questionnaire – a series of questions to address the customer’s household profile, lifestyle, basic site context information, space requirements, and design style of home construction. Then, the advisory system will incorporate the customer’s input to find the most suitable design options from its database. Once the customer selects the matched model from suggested design options, the customization process begins. The online configuration tool provides the functionality to change or add design elements based on user’s preference. It contains four categories: space planning, construction, appearance, and appliances/equipments. Space planning is the most important component of these categories. Each individual room is treated as a replaceable “block”, and can be exchanged by a different layout of the same space type or a trade-off with different usage. There are some restrictions assigned to these room blocks to control the associated wall types which have to be compatible with their neighbors when those rooms have been rearranged. Room blocks can also be treated as additional space to extend the boundary of a suggested design floor plan.

Construction is the second category of the configuration tool. This is a general term for laypeople, and basically indicates any major change after the design plan has been decided. Regularly, the foundation of a prefabricated modular house will be prepared by the local
contractor on its building site. However, it is very important to understand the type of foundation (i.e. pier, strip or basement) to make space planning adjustment.

Appearance includes surface material, color and texture selection of exterior and interior components. Most of existing home catalogs and sales center have already achieved this service. The last category, appliance, may apply from kitchen appliances (refrigerator, dishwasher, oven and vent) to laundry and air conditioning equipment. Recently, the concept of sustainable design is getting more and more popular. Integrating solar panels and wind turbines with building design is no longer limited to commercial buildings. Energy renewal is becoming a desirable solution for residential projects and it can be applied for prefabricated modular housing as a new feature of the energy appliance option.

At the end of customization process, the advisory system will provide a price quote for review. Once the customer is satisfied with the design and estimated cost, he or she can meet with architect consultant to schedule a showroom visit for further modification. On the other hand, the professional mode of the proposed i_Prefab system is more straight forwarded from site planning to system and component selections. The important phase is when customer-driven design model is merged to the professional mode for architect’s review. All of the proposed modular house components are made by Building Information Modeling (BIM) application as a virtual building data file for professional analysis and simulation before factory manufacturing.

4 System Prototype

4.1 Decision Tree

Since the proposed model of the advisory system needs to provide the option of consumer driven participative design, a prototype interface which can guide consumers to make a clear decision has to be constructed. A decision tree is an idea generation tool that is used to identify the strategy most likely to reach a goal. It can also be treated as a support tool of data mining from the knowledge database, because the users can achieve the target item by passing a series of decision-making nodes. Personal Brain, created by TheBrain Technologies, is an easy-to-use system for organizing and sharing information. The first prototype adopts this application as a platform for a working model. The interface is divided into two portions: decision tree navigation and an input/ output dialogue window. The input/ output dialogue window includes the questionnaire (Figure 7) and design suggestions (Figure 8), which has been described in section 3.3. By utilizing the decision tree feature of its interface, the questionnaire answering process will be represented as decision trees in the upper views of the interface for guiding users to find the suggested design solution. The suggested design solutions would reflect the available systems of a specific vendor within the existing market.

A traditional decision tree pattern even shows the decisions which seem simple to the customer can create a large number of potential system states for the developer and a similarly large number of different connections and opportunities for failure (Thillart, 2004). For example, a decision tree with two systems states can generate eight systems states after only three decisions provided by the customer (Figure 9). However, some system states may repeat and the overlapping relation links will form as a decision network. The optimistic goal is to keep a minimal number of different system components which are capable of generating a maximal number of useful product variations.
Figure 7: Decision Tree Navigation (above) and Questionnaire (below)

Figure 8: Decision Tree Navigation (above) and Design Suggestion (below)
4.2 Digital Questionnaire

The proposed digital questionnaire model links a series of pre-established answers that define the architectural implementation from its database, and the users will receive real-time feedback to evaluate room layout and home design solutions from the digital interface. From general spatial need to detail preference, there are four different levels of questionnaire to be developed as the programming of this prototype system: (1) Generate a list of required spaces, (2) Determine each room size and relationship of plan by function, (3) Define the detail layout of individual spaces and the development of the plans and elevations, and (4) Customize material and color selections for exterior and interior components, Figure 10.

The first series of questions are trying to identify the household profile. By answering the household type and how many people in your new home can generate the basic requirement of spaces and sleeping arrangement. Furthermore, the questionnaires of life style, space adjacency preference, architectural options, and site context can help clients to provide more information and reflect the detail of spatial needs in a short period of time (Figure 11). For example, the eating style of the client’s family may determine the size, layout, and location of the dining area. If the client needs to work at home quite often, a home office or a den has
been considered. All human-machine interactive results can be viewed as design references. The clients have a right to revise any modular component during the design trade-off process. Finally, i_Prefab advisory system will provide available design suggestions from its database.

Figure 11: Questionnaire of Lifestyle and Corresponded Spatial Issues

4.3 Design Interface and Collaboration

The two main components of i_Prefab design interface are client’s requirement data “input” by answering questions and matching them with design options “output” from database. Figure 12 demonstrates the pre-design diagnostic website which is available anywhere with internet connections. All design suggestions are represented as virtual images online and advanced smart data are downloadable to BIM applications, like Autodesk Revit for coordination as the interface to the manufacturing and delivery system. The digital design model also can be exported from Revit application to Google Earth directly with exact site information for client to review as a four-dimensional experience. Figure 13 shows the expectation of housing delivery process from web-based programming to digital design collaboration and virtual environment simulation.
4.4 Modular System Variations and BIM implementation

Using the vendor weeHouse (Warner, 2007) as a case study, the design experiment of modular system variations starts with a 14’ x 56’ two-bedroom unit. This is the longest design model provided by the vendor under the category of weeHouse Solitaires – single module living, and carried by one truck to the building site. After spatial composition analysis, the whole house can be divided into two groups: living modular group (kitchen/ dining/ living) and sleeping modular group (sleeping/ bathing). If the individual modular group can be sub-divided by its real space units, like living room, dining room, and kitchen, etc, then there are four different reasonable configurations in the living modular group as below: (1) Living – Dining – Kitchen; (2) Kitchen – Dining – Living; (3) Living – Kitchen – Dining; (4) Dining – Kitchen – Living. Plus, there are two conditions of sleeping modular group: (1) Bedroom – Bathroom – Bedroom; (2) Bathroom – Bedroom – Bedroom.

Therefore, the system variation may end up with eight different compositions following the same linear building geometry. Next step is to label the ID tag for each modular unit with letters A to F, and numbers 1 to 4 on four sides of each unit. After carefully rearranging the basic module with architectural considerations and minor modifications of some modular units, like mirrored unit or adjusted adjacent wall conditions, the original six major modular
units can generate as many as 22 different configuration types of a 2-bedroom, one-story single family house (Figure 14).

The main goal to convert the 2D AutoCAD blocks to 3D Revit model groups is to see the potential of coordination and information database functionalities inside of Building Information Modeling (BIM) application. Figure 15 shows Revit is an object-orientated design application and embodied all required information along with any elements to simulate as a virtual building environment before the construction process. The Family Editor is an object making interface and can be used to create custom components for different parts of the building such as floor panels, aluminum frames, exterior cladding, mechanical components, connectors, and so on. In many instances, custom objects are assembled together to create larger object modules.

Referencing KieranTimberlake's experience with Revit, it seems that BIM's object-based approach is a natural fit for the modular approach to prefabricated architecture which should make it a lot easier to construct custom prefabricated buildings that don't have the "cookie-cutter" uniformity and monotony which have given prefabrication a bad reputation in the past (Khemlani, 2005).

If most of the individual prefabricated modular housing components that are standardized for interchanging and the other modular building elements were represented digitally as BIM models, manufacturers or suppliers could provide the information on their website to represent their product as accurately as possible for the final construction assembly. Modular housing systems could then be developed by assembling these components to create many different compositions, both digitally during design as well as physically during offsite construction to achieve the optimistic goal of mass customization of prefabrication without sacrificing time efficiency and the cost affordability that already exists in mass produced housing industry.
5 Conclusions

The results of this current phase of research establish the theoretical framework of a decision support system by dynamic questionnaire to find design solutions for future reference. The objective is to bring prefabricated modular houses to the next level to meet the goal of mass customization with digital technology. The interpretation of translating the client's need to match different spatial configurations of the design models from the selected prefabricated modular housing vendors is a little subjective. However, this is an online recommendation to replace the limited face-to-face first meeting time between architects and clients. Revising the modular unit to be more flexible and client responsive is the feedback to the modular housing architects and vendors. It is obvious that costs can be reduced in the architectural design and engineering consulting phase. Moreover, the factory-made modular houses can save the material waste and time spent on the construction site with tremendous labour cost. The future direction will be focused on the output format for manufacturing and the bi-directional linkage between the advisory system and Building Information Modeling applications to make a seamless design collaboration in the housing delivery process.

References


