A Digital Platform for Mass Customization of Housing

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Abstract

Introduced in the early twentieth century, mass production created the conditions for rapid expansions in modularity and repetition to the building industry. Since the 1960s, and with the integration of information technologies, digitization brought the possibility of customization. Diversity, difference, and individuality could now be implemented with the same ease as mass production. Accordingly, building components could be mass customized, allowing for optimal variances to respond to differing local conditions, and enabling the production of uniquely shaped and sized structural components. Ever a vital sector in the building industry, housing has witnessed a renewed surge of interest in the last two decades, especially following these new approaches to modes of design and production. While this interest has taken many forms and constituencies, digital design and manufacturing strategies have inspired the most diverse research and pragmatic solutions to contemporary industry challenges. However, there is marked gap between proposed research approaches and current production practices, specifically in the prefabricated housing industry, which otherwise represents an ideal model to adopt mass customization.

Although unrecognized within standard housing production, current research acknowledges the need for advanced computer applications for enabling mass customization in the housing industry. This thesis thus proposes a novel framework and a systematic group of methodologies for constructing a computational design system that could support homebuyers' participation in the design of their dwellings. This framework derives its novelty by analyzing mass customization theories,

technological enablers, various research endeavours in housing, and the standards currently adopted by the prefabricated housing industry. The aim of this framework is to redefine the traditional relationship between homebuyer, architect, and manufacturer. Consequently, this thesis proposes not only a computational tool, but also a comprehensive approach for customization.

The framework is simulated by two case studies dedicated to customization in the early design stages. This leads to the development of both an advanced configuration system and a generative tool-based customization system. These simulations arise from an analysis of the profile and practice of a leading prefabricated housing company in Quebec, and thus create a platform that is intimately responsive to the contemporary needs of the industry.

The proposed framework provides a rigorous method of customizing prefabricated housing, particularly through an advanced configuration system that builds on existing industry applications. However, the relevance and engagement of a generative tool-based system may still be questioned, especially depending on the available degree of automation and the system operator, among other factors. Implementation requires a fundamentally multi-disciplinary approach to technological dialogue; one that the prefabricated housing industry requires further time and effort to assimilate.

Résumé

Introduite au début du XXe siècle, la production de masse a créé les conditions favorisant l'expansion rapide de la modularité et de la répétition dans l'industrie du bâtiment. Depuis les années 1960, et avec l'intégration des technologies de l'information, la numérisation a permis la personnalisation, c’est-à-dire que la diversité, la différence et l'individualité ont pu être mises en œuvre avec la même facilité que la production de masse. Ainsi, les éléments des bâtiments peuvent être adaptés aux besoins de masse, permettant aux variances optimales de répondre aux différentes conditions locales, ce qui favorise la production d'éléments structuraux de formes et de tailles uniques. Grâce à l’arrivée de nouvelles approches de modes de conception et de production, on s’est de nouveau intéressé lors des deux dernières décennies à l’habitation, toujours un secteur vital dans l'industrie de la construction. Bien que cet intérêt ait pris de nombreuses formes et structures, ce sont la conception numérique et les stratégies de fabrication qui ont inspiré les recherches les plus diverses ainsi que des solutions pragmatiques aux défis de l'industrie contemporaine. Il existe cependant un écart marqué entre les approches de recherche proposées et les pratiques actuelles de production, en particulier dans l'industrie des maisons préfabriquées, qui représente par ailleurs un modèle idéal pour l’adoption de la personnalisation de masse.

Même si on estime qu'il existe un besoin pour les applications informatiques de pointe qui permettrait la personnalisation de masse dans l'industrie de l’habitation, la présente thèse propose un cadre original et un groupe systématique de méthodes pour construire un

système de conception computationnelle qui pourraient inciter les acheteurs à participer à la conception de leurs habitations. Ce cadre tient sa nouveauté du fait qu’il analyse les théories de personnalisation de masse, les facilitateurs technologiques, divers projets de recherche en matière d’habitation, ainsi que les approches adoptées actuellement par l'industrie des maisons préfabriquées. L'objectif de ce cadre est de redéfinir la relation traditionnelle entre l’accession à la propriété, l’architecte et le constructeur. C’est pourquoi cette thèse propose bien plus qu'un simple outil de calcul, mais plutôt un processus assisté par ordinateur complet pour la personnalisation.

Deux études de cas consacrées à la personnalisation à des stades précoces de la conception ont servi à la simulation de ce cadre avec lesquelles on a pu élaborer à la fois un système de configuration avancée et un système de personnalisation génératif basé sur des outils. La logique de ces simulations découle de l'analyse du profil et de la pratique d'une importante entreprise de maisons préfabriquées au Québec, ce qui a créé une plateforme qui répond intimement aux besoins actuels de l'industrie.

On fait valoir que le cadre fournira une méthode rigoureuse pour adapter des maisons préfabriquées, notamment à travers un système de configuration avancée qui s'appuie sur des applications existantes dans l'industrie. On peut toutefois s’interroger sur la pertinence et l'engagement d'un système génératif basé sur un outil, en fonction de facteurs tels que le degré d'automatisation disponible et l'opérateur du système. Avant d’adopter ce type d’approche multidisciplinaire, l'industrie des maisons préfabriquées a besoin d’y consacrer plus de temps et d'efforts.

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Part I: Overview

1.0: Introduction

1.1 Problem Overview

Recent social, economic, and environmental changes have significantly changed the way individuals acquire dwellings. On one hand, demographic transformations and economic downturns have continuously affected the housing market's supply and demand cycles, resulting in an increase in costs and a consequential affordability gap. According to the Canadian Home Builders Association (CHBA, 2010), the average size of a single-family detached housing unit nearly doubled from 1050 square feet in 1975 to 1950 square feet in 2010. However, an analysis of the changes in household characteristics reveals that households have become smaller in recent decades. This trend is primarily due to an increase in one and two-person households and a concomitant decline in the number of large households. A recent census of population report reveals that single-person households constituted 27.6% of all Canadian families in 2011, evincing an increase of 9.3 % since 1961. Within the same period, the portion of large households composed of five people or more decreased from 32.2% in 1961 to 8.4% in 2011 (Figure 1.1 and 1.2) (Statistics Canada, 2011).

On the other hand, the urge to conserve natural resources introduced new measures of innovation into residential design and construction. Towards this end, architects and builders have explored cost-efficient measures, as well as environmentally sensitive materials and techniques to respond to the changing needs of homebuyers on a tight budget.

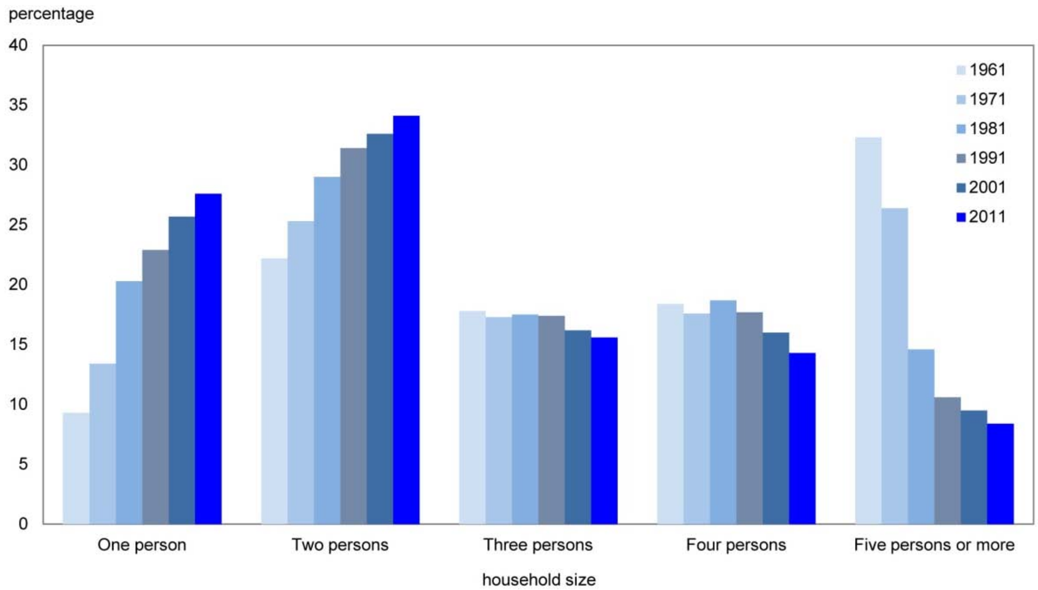

Figure 1.1: Distribution in percentage of private households by household size, Canada, 1961 to 2011 (Source: statistics Canada, 2011).

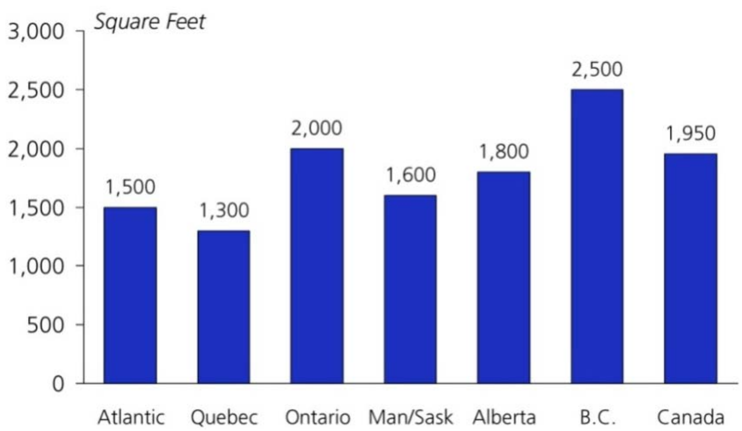

Figure 1.2: Average size of new single-family homes in Canada in 2010 (Source: CHBA, 2011).

Coupled with demographic transformations, affordability contributed to the need to foster greater interaction between the homebuyer, the architect, and the builder in an indirect way. This was aimed at producing a better fit between homebuyers' needs and their chosen dwellings. By the nature of its design and production methods, the prefabricated homebuilding industry has demonstrated a proven ability to respond to these challenges with efficiency and ingenuity. Prefabrication and standardization minimize the number of one-off components and streamlines the process, so as to reduce cost and time. Consequently, the breadth and scope of these industry practices have dramatically expanded within housing markets. For instance, in the past decade nearly one in five new homes in the United States have been manufactured in a controlled factory environment and then transported to an external site (Smith, 2010). According to the Canadian Manufactured Housing Institute (CMHI), factory-built housing production in Canada has followed a similar trend over the same period (2011). Recent market analysis revealed that in 2011, factory-built housing accounted for 12.5% of all single-family housing starts; a significant increase over the 9.5% market share of the year 2010. A detailed study of the Quebec prefabricated housing market is presented in Chapter 5.

In addition to affordability, prefabricated housing has the potential to offer new levels of personalization to its clients. However, this possibility is complicated by the difficulty of achieving robust and effective communication levels between homebuyers and manufacturers. The challenge remains to enable the design and production of unique products that fit the specific needs of a client while still maintaining the affordable cost of prefabrication methods.

Enhancing user participation in design is not new, and has historically produced only limited success for the industry. The notion of offering choices to homebuyers dates back to the 1960s, when mass-produced dwellings during the post-World War II era incited architects to reflect on the traditional delivery methods of their designs. Seeking to integrate buyers into the shaping of their dwellings, architects experimented with participatory strategies and tools such as sketches, drawings and physical models. Nevertheless, these efforts experienced limited success and were not accepted by the industry at large. Accordingly, Kieran and Timberlake (2004), and Davies (2005) argue that the North American housing industry of the twentieth century failed to adopt mass production as a viable approach for producing dwellings. This was due to the lack of personalization options for the industry's clients, as mass produced homes were usually considered monotonous and poorly designed.

However, contemporary homebuyers are becoming more demanding, as a "one-size-fits-all" approach no longer satisfies their preferences and needs. According to Clayton Research (2006), the domain of custom homes is a growing segment within Quebec's prefabricated housing market. While the application of advanced design and manufacturing technologies has made the delivery of customized products feasible, the housing industry has been slow to adopt such a paradigm, despite successful research efforts and a number of industry applications throughout North America. Accordingly, this thesis explores the possibilities of developing a comprehensive, computer-based system to allow homebuyer's participation in the design of their homes at a very early stage, thus facilitating the production of uniquely customized dwellings.

1.2 Rationale of the study

The concept of mass production was developed in the early twentieth century by the Henry Ford Motor Company. Also called "serial production", this method was based on the construction of large standardized components and the systematization of production processes. Ford's contribution improved on existing methods of sequential production and integrated electric power into an assembly line of factory workers performing repetitive operations. Systematic repetition of components and processes lowered costs through economies of scale. The most notable outcome was the continuous flow of the mass production of Ford's product, making the Model T a remarkably affordable car. The success of Henry Ford's ideas resulted in the wide adoption of both the automobile and of mass production techniques in American life and industry (Davies, 2005).

Since the development of mass production, there have been various responses on the part of housing companies and architects who have questioned the applicability of this paradigm to architectural practice. On the one hand, housing companies took advantage of the reduced costs and rapid construction processes of this method. For example, between 1908 and 1940, Sears, Roebuck and Company sold around 75,000 houses through their mail-to-order Modern Homes Program. The company designed a variety of 447 housing models, where potential homebuyers could choose a model that suited their specific needs in regards to style and budget. Furthermore, sales offices were able to offer homebuyers personalized services, where they could modify floor plans and materials. During the post-World War I housing boom, sales increased from an average of 125 units a month in 1920, to more than 250 units a month in 1929. However, after the stock market crash of 1929 the company faced financial difficulties. Sales declined to only 54% of the firm's total business in 1930, and by 1940 this branch had shut down completely (Stevenson & Jandl, 1986).

Consequently, Architects since then have sought to understand why factory production has revolutionized the creation of formerly hand-crafted objects such as clothes, shoes, and household products, as well as modern mobility, such as automobiles, planes and ocean liners, while the building industry has been largely resistant to such transformation. Such an enquiry informs the work of many architects, resulting in a wide field of notable experimentations in mass production techniques and their implementation (Kieran & Timberlake, 2004).

The exploration of the potential of off-site building components involves and includes many of the most storied names in the history of architecture. Le Corbusier, Walter Gropius, Frank Lloyd Wright, Bukminster Fuller, and Jean Prouvé all designed various projects based on this concept. Additionally, these architects were also concerned with offering design variations on different levels (Armstrong, 2008). In 1923, Le Corbusier demonstrated his interest in standardization and mass production through the solutions he devised for the housing challenges of the time. Defining a house as a "machine for living", Le Corbusier re-examined the technical problems of production and streamlined construction procedures. His project created structures that were easy to assemble and could be completed quickly with the application of efficient tools and non-professional workers. The 1925 Workers' Housing in Pessac, France, applied these principles and is based on a set of model houses that could be repeated on a large scale (Figure 1.3). Le Corbusier's overriding objective was to design houses wherein the prototype, basic units and elements, standard plane, and composition could be mass produced to lower costs through the standardization and industrial production of components (Hsu & Chih-Ming, 2006).

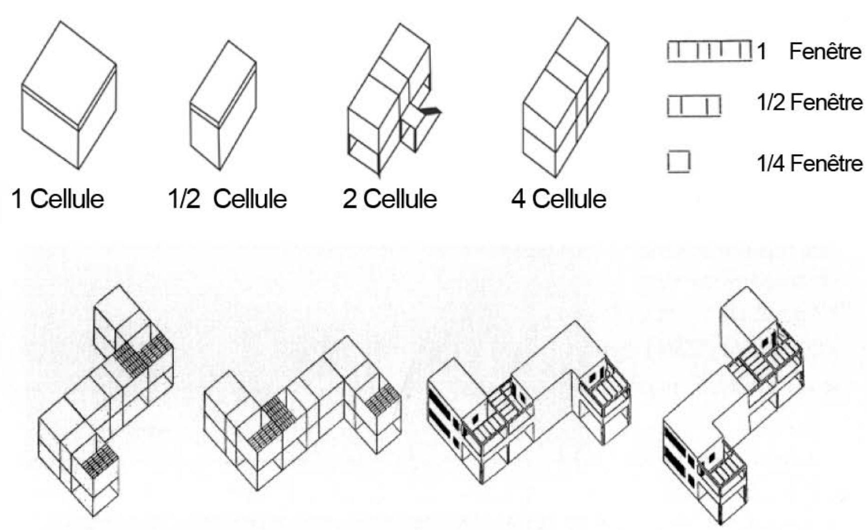

Figure 1.3: Le Corbusier's conceptual sketches for the Pessac project (Source: Hsu & Chih-Ming, 2006).

While Le Corbusier focused on urban scale, the German architect Walter Gropius' priority was to preserve the artistic nature of the architect's role. He was equally concerned with the consumer of the house, as prefabrication implied that a house would no longer be the product of a relationship between an architect and a client. Instead, it would become an impersonal transaction between an architect and an undifferentiated mass of consumers. Gropius believed in the necessity of variations; he foresaw a system wherein future homebuyers could order specific housing components from a central warehouse so as to meet their unique needs and interests (Armstrong, 2008). In his 1926 design for Torten Estate in Dessau, Germany, Gropius elaborated an open-ended system enabling the architect to work closely with middle-class clients to produce a building that would express their particular individuality. The concept was based on the development of a few select model houses, which would be prefabricated and then repetitively produced in mass volume, but constrained by parts dimensions and a specific design scheme for construction. Gropius also sought to apply these means of lowering cost in order to generate affordable housing. However, in addition to other approaches to mass-producing houses during the inter-war period, these efforts were mostly experimental in nature and only a few projects were realized. These examples include Buckminster Fuller's Dymaxion unit project of 1927, which was based on the mass production of components, low maintenance, and light materials. Similarly, Walter Gropius and Konard Watchsman's 1941-52 Packaged House system consisted of a palette of ten different types of panels laid out on a modulated space frame (Bergdoll, Christensen, & Broadhurst, 2010).

Advances produced by post-war prefabrication models did not emerge from new techniques, but were rather characterized by improvements in business models. Following World War II, the return of soldiers created a high demand for housing. At the time, the U.S. federal government issued an emergency housing initiative that required the production of 850,000 prefabricated housing units in less than two years. As the economy transitioned from its military focus to a more consumer-oriented market, more than seventy companies, some of them producing 1,000 units per month, constructed more than 200,000 prefabricated houses. This boom consisted of upwards of 12% of the total housing market in these years (Smith, 2010).

This initiative resulted in some significant shifts in post-war housing design, including a tendency towards more compact and efficient houses that used more innovative materials and construction techniques. Marked improvements in the affordability and construction productivity of mass produced houses, combined with effective marketing strategies, convinced consumers that these products were a reasonable housing solution (Smith, 2010).

Builders developed a production paradigm for the serial fabrication of houses called a “Kit-of-Parts”. This process was optimized over time, and costs were further reduced by the proliferation of individual companies dedicated to manufacturing single components. In 1948, the Lustron Corporation, led by Chicago industrialist and entrepreneur Carl Strandlund, began the production of all-steel houses in airplane factories. Although the houses had a traditional design and appearance, they featured innovative construction materials and processes (Figure 1.4). However, due to communication complexities, integration proved ineffective and cost control became jeopardized. To make matters worse, the aesthetic appeal of the houses was decidedly lacking. After building only 2,500 housing units, the company went bankrupt and ceased production in 1950 (Fetters, 2002).

Figure 1.4: One of the Lustron homes models, made out of steel coated with porcelain enamel (Source: Bergdoll, Christensen, & Broadhurst, 2010).

Efforts to employ mass production techniques in the housing industry continued throughout subsequent decades. However, they lacked variation and individual personalization. Consequently, a new participatory paradigm in design and production was initiated, with the aim of allowing homebuyers' input into the design of their homes. In the 1960s, architect, theorist and educator John Habraken was working in the Stichting Architecten Research (SAR) (Foundation of Architects Research) group in the Netherlands. He developed the "Theory of Supports", which was both a significant contribution to the field of mass housing and also based upon the principle of user participation or user control. This theory presented a vision of housing wherein a dwelling would utilize a process that supports and adapts to user decisions within a larger framework of communal services and infrastructure. The theory distinguished between two fundamental components, which were "supports" and "infills". A "support" was regarded as a physical entity, or the rigid part of the building. In short, this entailed the structure and infrastructure that users agreed not to change. The "infill" was the flexible part that could be adjusted on different levels: social, industrial, economic and organizational (Figure 1.5). The system was designed to facilitate variations to floor plans over time, while also accommodating the design of dwellings to meet the diverse standards of normally accepted housing in any particular society. Accordingly, in this system the designer of the "support" would be tasked with providing an open-ended infrastructure, which at a later stage would be creatively customized by the resident using their own independent decision-making processes (Habraken, 1972). This foundation further developed and promoted Habraken's open building method, and thus marked the first attempt towards personalization on a mass scale in the Netherlands (Habraken et al., 1976). Following these efforts, Kendell and Bailey (2000) have subsequently explored various trends towards open buildings. They have also proposed flexible and economical methods for implementing these systems in levels, based on analysis of realized projects around the globe.

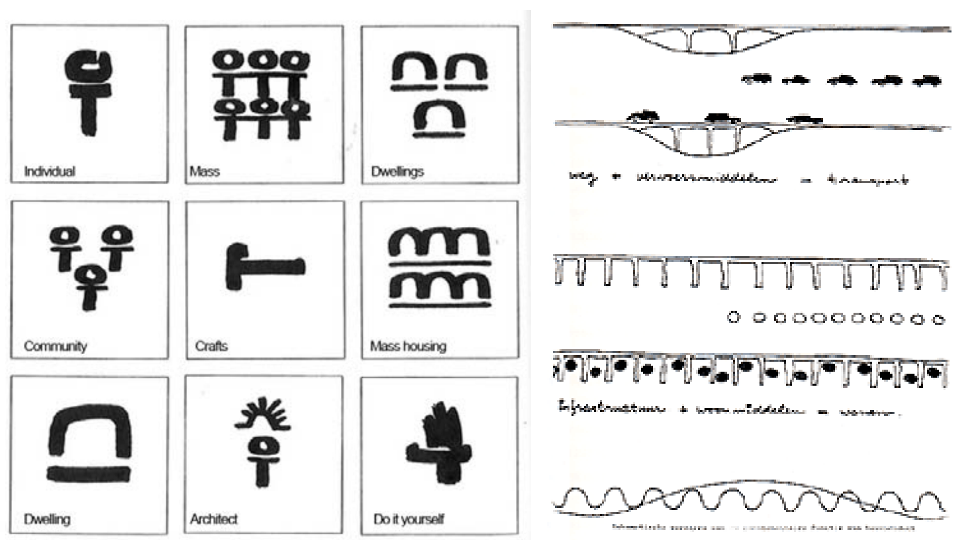

Figure 1.5: Conceptual sketches by Habraken for Supports (Source: Habraken, 1972).

While lagging in the housing industry, the viability of mass production techniques rose and fell in other economic sectors over time. By the 1970s a sharp increase in demand for personalized goods and products contributed to the decline and obsolescence of the standard mass production paradigm. In its place, a new production model was introduced during the 1970s, primarily by Toyota in the automotive industry. First known as the Toyota Production System (TPS), this method became broadly referred to as *Lean Production*[1] by the 1990s.

As a result of advancements in manufacturing technologies, this new paradigm was received enthusiastically. Furthermore, Toffler's 1970 book "Future Shock" anticipated these changes as technological capacities, and he further described them as a "third wave" in a subsequent study (Toffler, 1980). Also referred to as *mass customization*[2] by Stanley Davis in his 1987 book "Future Perfect", this process was formally systematized by Joseph Pine in 1993.

Many segments of diverse and variable industries are currently moving towards greater customization in response to consumer demand. Given the principle importance of customer satisfaction, the adoption of such production strategies has proven attractive to companies seeking to remain competitive. Mass customization can and has been applied to a wide range of products, from investment goods such as machinery and telecommunication systems to consumer goods such as cars, furniture, personal computers and watches.

Pertaining to the building industry, mass customization would seem to hold great potential, as buildings can become superbly unique and highly customized products. Utilizing design and fabrication tools such as Computer Aided Design (CAD) and Computer Aided Manufacturing

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[1] Lean Production was aimed at reducing waste that existed in serial production. One of the main concepts of the process is Just-In-Time (JIT) production, where parts are produced in response to direct orders to reduce storage space. JIT production employs an information system that links the client directly to the production structure, and thus offers a degree of customization in which customer satisfaction is no longer dependent on stock availability (Schodek et al., 2005).

[2] Pine (1993) defines mass customization as a production strategy that integrates mass production principles with the process of producing custom products. It is a strategic mechanism that has been applied to various sectors of the consumer goods market. while delivered through different approaches.

(CAM), modern digitally integrated production processes have produced a paradigmatic shift in production ideology. Individual building components can now be mass customized in ways previously considered impossible. This method permits optimal variance in response to differing local conditions, such as uniquely shaped and sized structural components or variable openings (Kolarevic, 2003).

A surge of interest in new approaches to prefabrication over the last two decades parallels the rise of customization in the housing industry. The rapid adoption of digital production techniques within the design and construction industry also facilitates new possibilities for off-site fabrication. Given the potential to achieve the high level of precision expected from design products, together with new formal and structural experimentation through digital *parametric design*[3], these conditions could make prefabrication available and compatible with customization. this would respond available to a wide variety of applications, including consumer preferences, climate, and site and manufacturing conditions (Bergdoll et al., 2010).

While prefabrication is widely considered to be a viable approach to achieving mass production, the industry has been facing challenging limitations in the past few decades that have inhibited the complete adoption of such an approach. It is believed that mass customization could offer a solution to these problems, as its principle purpose is the production of high-quality housing at an affordable cost. This standard of quality relates not only to the level of user satisfaction in terms of basic housing needs, but also to the functional and aesthetic criteria of a house. As a high level of customization leads to a correspondingly high

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[3] Parametric design implies the use of parameters to define a form, with greater focus on the relationship between elements of the form. Equations are used to describe the relationship between elements, thus defining associative geometry (Kolarevic, 2003).

degree of customer satisfaction, while also minimizing the costs associated with post-construction modifications, this method seems highly desirable. Additional cost controls could be further achieved through the integration of advanced production techniques that deploy computer-aided manufacturing processes to manage waste (Kieran & Timberlake, 2004).

The work described in this thesis explores the applicability of mass customization within the prefabricated housing industry, with the aim of overcoming persistent difficulties that manufacturers face in the transition to this production strategy. While these difficulties have been previously addressed in diverse research efforts (Larson et. al, 2001; Duarte, 2009; Matcha and Quasten, 2009) that have resulted in pragmatic computer-based systems to enable homebuyers' participation in the design of their homes, the industry has been slow to adopt such approaches. Consequently, this thesis explores the gap between research efforts and industry applications, proposing a distinct and comprehensive approach based on digital design and production technologies. This approach ultimately outlines a series of systematic procedures for companies to follow when developing their own systems of mass customization.

The main goal of such an approach is to involve homebuyers, architects, and manufacturers in a comprehensive dialogue that could simplify and ameliorate the internal and external complexities relevant to the process of customization. Internally, this method allows the manufacturer and architect greater control and precision within the customization process through efficient information management and transfer. Externally, this system involves and empowers relatively inexperienced homebuyers, in the design of their homes, offering options and suggestions through highly visualized product data sets. The success of such a system is contingent upon the ease and navigation within its interface.

1.3 Areas of Study

1.3.1 Mass customization

Salvador, Holan, and Piller (2009) argued that the key to success in mass customization is to view it as a process of aligning an organization with the customers' needs. In other words, mass customization is not achieved through reaching an understanding of the needs of individual customers and then manufacturing personalized goods to fit this description. Rather, it is more fundamentally about implementing technological and organizational capabilities that can direct a business towards specific goals.

The decision to implement mass customization may come from a variety of factors at multiple stages of industry development. While mass production companies work on the basis of a standardized model by making uniform components to stock, these companies may decide to shift towards mass customization in response to market pressures and customer demand for a broader product portfolio. Every approach of mass customization has to be adapted according to the company's profile, specific market and customer demands, and the technology available for efficient implementation. A value creating process is achieved through the direct integration of customers throughout the sales, design and production processes (Blecker & Friedrich, 2006). However, the challenge is to balance the system to an extent that would lead to a socially and technologically efficient environment, which would be of higher value for the customers and provide better business opportunities for the company. Table 1.1 demonstrates the main differences between mass production and mass customization.

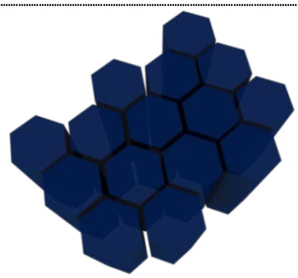
	Mass Production	Mass Customization
Focus	– Efficiency through stability and control	– Variety and customization through flexibility and quick responsiveness
Goal	– Developing , producing, marketing, and delivering goods and services at prices low enough that nearly everyone can afford them	– Developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly all customers find exactly what they want
Key Features	– Stable demand – Large, homogeneous markets – Low cost, consistent quality, standardized goods and services – Long product development cycle – Long product life cycles	– Fragmented demand – Heterogeneous market niches – Low-cost, high-quality, customized goods and services – Short product development cycle – Short product life cycle
Diagram		

Table 1.1: Mass production compared to mass customization (Source: Blecker et al., 2006).

1.3.2 Computation in architecture

During the 1960s, concurrent with the design methods movement and with the rise of computers as arithmetic and logical devices, researchers defined a new role for computers within the design process. The potential for new, synergetic relationships between designers and computers captivated the imaginations and research interests of many architects in this era.

One of the foremost pioneering efforts was that of Ivan E. Sutherland's SKETCHPAD system (1963), implemented on the TX-2 computer at MIT's Lincoln Laboratory. Using a point-vector to represent form, it allowed engineers to develop designs by operating an interactive graphic terminal, controlling drawings displayed on the screen using a light-pen and keyboard. In parallel with the early explorations of Sutherland, other interactive CAD systems were developed, leading to wide dissemination and use of this technology in various realms of mechanical, civil, electrical, and industrial engineering (Mitchell, 1975).

In regards to architecture, however, the application of CAD notably lagged behind other engineering fields, primarily due to economic reasons, but also from an ignorance of the potential contributions of these systems to design and production processes. The academic community, conversely, demonstrated early interest in CAD, with several publications actively investigating the concept from diverse angles[4]. One of the main areas of research at that time was space layout planning, employing CAD techniques for the spatial allocation of architectural features.

Although computers have played an increasingly prominent role in design, the nature of this role has constantly changed over time. Terzidis (2006) differentiated between two distinct roles that computers can play in architecture. Firstly, architects tend to use computers as an advanced representation tool, running programs that enable the production of complex 3-D models. This application, moreover, allows for tighter control of a digital model without going through the inner production process of an analog equivalent. Terzidis defined this method as "computerization", in which the computer acts only as a medium to process and manipulate ideas that were already conceptualized in the designer's mind. On the other hand, the second modality of "computing"

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[4] Moseley (1963) proposed a system for generating conceptual massing design with a focus on the spatial organization of various functions. Christopher Alexander (1964) described a systematic utilization of computer-based architectural design methods. Other CAD systems were also developed, such as Negroponte's URBAN5 (1964), and COPLANNER by Souder and Clark. In 1968, the Architecture Machine Group at MIT proposed an Artificial Intelligence approach to developing architectural computing applications, with the aim of producing a robotic architect (Mitchell, 1977).

or “computation” is defined through a more creative use of computers and an exploration of the potential of programming. In such cases, computers integrally assist in the design process. Computation modes have been intensively researched during the last few decades, with a focus on algorithmic methods as an approach to design. For instance, Gero (1995) investigated the notion of creativity and creative design as a form of computational model that could map emergence as a basic exploration process.

While early systems supported new ways of working with computers, later systems offered support to the conventional design process. Following ground-breaking research efforts and new possibilities in computational design methods, computer-based modeling and analysis methods have made it possible to support the synthesis of design solutions on various levels. These have provided designers with various frameworks for assisting in the decision-making process within various design activities. This has resulted in pragmatic solutions to architectural problems, especially in form finding and layout design (Coates, 2010).

1.3.3 Prefabricated housing systems

Prefabricated housing is a general term that describes housing built with factory-produced and assembled components. It may include manufactured housing, modular housing, mobile housing, panelized housing, and kit-of-parts. Elements of prefabrication refer to the form or configuration of the output: components, panels, and modules. However, this research focuses only on two types of housing: modular homes and panelized homes, as they are more common in the North American housing market, most specifically the province of Quebec, based on the simulation of the proposed framework.

Due to its flexibility with regards to design and production, and the relatively high quality control it engenders through building in a controlled environment, the prefabricated housing industry represents a prominent area of exploration to implement mass customization strategies.

1.3.3.1 Modular homes

The term *modular homes* refers to factory-built homes whose three-dimensional components are 95% completed in an off-site plant before delivery. Components range from a single room to an entire house. Modules are constructed on an assembly line track where components move from one workstation to the next, adding various elements and materials at each stage. While the house undergoes factory production, all necessary site work simultaneously takes place. Once all the components are fabricated, they are delivered to the site in three-dimensional sections, assembled, and then positioned on a full perimeter foundation using cranes (Smith, 2010).

Modular homes can be constructed in any number of component sections, which can then be used to build single or multi-family low-rise dwellings, such as townhouse developments or low-rise apartment blocks. The sizes of modules vary from one company to the next and depend mainly on two factors. The first is the company's internal production system and applied technologies, while the second is external building codes and highway regulations, which differ from province to province.

Modular construction has many benefits over conventional construction. Primarily, it has the advantage of speed, as site work is completed simultaneously with the production of modules. Secondly, its off-site location escapes the weather delays that inevitably plague open-air construction. Thirdly, it reduces waste, and thus cost, as the repetition and systematization of specific tasks results in standardization of quantity and quality. Finally, modular homes are built to higher structural standards than most site-built homes due to continuous quality control (Smith, 2010),

1.3.3.2 Panelized homes

Similar to modular construction, panelized home construction is a factory-based system that allows builders to benefit from the labour and assembly efficiencies of an indoor fabrication process. During production, building components such as roof trusses, wall frames, and structured insulated panels are prefabricated and shipped as two-dimensional components to the construction site, where they are then assembled on the foundation or fitted onto a site-built, load-bearing structural frame (Smith, 2010).

Panelized construction is considered to be more flexible than modular construction and easier to transport, and is thus better suited in many ways to urban construction. The panels' small size and two-dimensional qualities allow them to be stacked onto mid-size trucks and transported to urban sites, making them easier to handle than modular buildings. Figure 1.6 and Table 1.2 illustrates a comparison between modular and panelized systems.

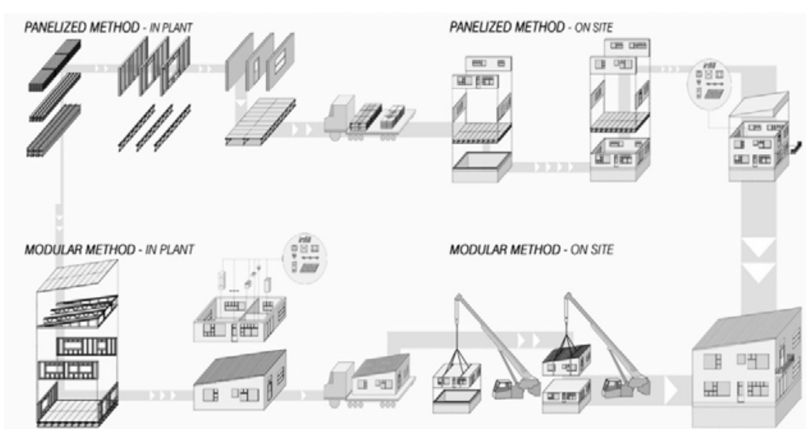

Figure 1.6: The in-plant and on-site production processes of panelized and modular systems (Source: Friedman, 2007)

	Advantages	Disadvantages
Panelized Housing System	Greater ease of shipping from the factory to the building site. Panelized components are compact enough for shipment by truck, train, or ship.	Moderate factory completion ratio. Approximately 50 % of building components can be completed at a factory. The other 50% of the construction still depends on craftsmanship on site.
	Flexibility in design. Panels do not restrict planners in the size or shape of the space, offering a greater range of styles and designs than the unit housing system.	Longer on-site construction period. Climatic conditions are influential in delaying the construction.
	More opportunity to allow homebuyers to do some of the assembly and finishing work by themselves.	Longer on-site storage period of building materials. Components are exposed to the environment; as a result, quality control cannot be maintained.
Modular Housing System	Higher factory completion ratio. Ninety % of the internal and external finishes can be prefabricated in the factory under optimum conditions. The quality control can be standardized, and units inspected before shipment.	Less flexibility in design. Units are made as fixed boxes, so that there are more dimensional limitations than in the panelized housing system.
	Better compliance with building codes. Shorter on-site construction period. The work progress is highly managed.	More traffic regulations. Transportation methods are restricted by regulations reflects on the shape and size of the units, limiting the range of distribution.
	Greater adaptability to industrialization. Automated production systems in the factory can be enhanced; the labour cost can also be reduced.	

Table 1.2: Characteristics of prefabricated housing systems (Source: Smith, 2010).

1.4 Research Objectives

As noted earlier, mass customization is a comprehensive method that involves managing various aspects of the design and production processes with regard to information management and technological applications. Unlike other products, housing requires a considered response to social and cultural issues when gathering clients' preferences. Architects and researchers observed developments in industrial design and the opportunities offered by the convergence of digital design and fabrication technologies. They then sought to rigorously apply these techniques to the process of creating architectural artefacts.

Housing has attracted special attention from proponents of mass customization due to its fundamental role in the building industry. On the one hand, researchers have attempted to develop computer-based design systems that could be employed by architects or homebuyers to customize dwellings on various levels. These range from direct participation in fundamental design concepts, such as unit layout, to more cosmetic choices such as the selection of finishing materials. On the other hand, efforts have been made to explore the potential of digital fabrication and how it could be deployed to produce customized housing. However, innovative computational techniques still require a further exploration of the many new opportunities that could offer mass customization of housing.

Due to limitations in technological capacity, customization, affordability, and quality, previous attempts at designing prefabricated housing systems failed to acquire more than an average share in the housing market. However, this thesis seeks to explore the potential for ameliorating these failings by skillfully repositioning design technologies within the process of producing housing. It proposes a mass customization model that would both suit manufacturers' profiles and respond to market needs by employing a digital platform to investigate computer-based design systems in architecture. The model elaborates a design system framework that would effectively integrate homebuyers in the process of designing their dwellings at an early stage. To that end, the proposed framework aims to bridge the gap between research endeavours and current industry applications of mass customization, finally delivering the great potential of mass customization to home buyers and industry leaders.

The key features of the proposed framework are:

a. The framework is fundamentally flexible, accommodating multiple levels of customization tailored to the manufacturer's own building strategies and capacities. Concordantly, this process facilitates a clear definition of homebuyers' involvement in the customization process and the upper limits of that participation.

b. The framework offers a methodology that seeks to build a synergetic relationship between the homebuyer, architect and the manufacturer through the use of advanced computational methods and techniques:

   - With regard to the homebuyer, the framework proposes a systematic method to build user profiles, which would help to identify particular types of control variables during the customization process. A clear understanding of users' requirements and needs is the starting point for successfully achieving mass customization, as customers should be considered partners in the value creating process. The challenge at this step lies in the integration of users' cultural and social preferences within the data gathering process.
   - With regard to the architect, the framework presents a process to develop a generative design tool, thus simplifying and organizing the various internal and external complexities of the customization process. Both the designer and the intended computational design system should thus be able to respond to the homebuyer's requirements. The challenge at this step lies in a critical analysis of the generative design paradigms; investigating their abilities to manage the complexities associated with the process of customization.
   - With regard to the manufacturer, the framework presents a methodology for conceptualizing and implementing this design system at the level of factory production in order to efficiently

realize customers' requirements. This is made possible by the radical changes in conception and production incited by the digital design and manufacturing technologies of recent years. These innovations create a direct link between what can be conceived and what can be constructed.

c. The framework employs technological advancements in design, and manufacturing as effective enablers towards customization. For example, BIM (Building Information Modeling) tools can play an important role in the process of customization, since they offer the capability to automatically and systematically track required materials and products, while merging all project information into a single file. Such a concept eliminates boundaries between design and construction, thus strengthening the connection between architects, manufacturers, and builders.

d. The framework does not propose a specific computational tool for the mass customization of housing, yet it offers a process; a methodology for implementing an efficient customization through computational techniques. Such a methodology could be pursued by manufacturers to enable integrating homebuyers into the process of designing their homes, while still maintaining high-quality products. Additionally, improving affordability by virtue of the many advantages of prefabrication techniques coupled with high customization.

1.5 Research Question

The goal of this research project is the comprehensive development of a process for constructing a computer-based mass customization environment that integrates the homebuyer, architect, and manufacturer with the common aim of producing high-quality and affordable housing. Customers in mass customization participate in this value-adding process on various levels, from the simple selection of pre-defined options, in the case of customized standardization, to the co-design of products in a pure customization strategy.

In light of the research objective and this goal, the primary research question is as follows:

> What should the structure of a digital platform be for the mass customization of prefabricated housing, based on the application of computational design methods?

The study of this question relates to diverse topics that are connected on various levels. These topics include mass customization theories, system design, and generative algorithms, leading to the following secondary questions:

> What is the process of developing this computer-based design system?
>
> Moreover, what are the core components of this system?

1.6 Research Methodology

Responding to the previously outlined research objectives and questions, this thesis proposes to develop a framework for implementing a computer-based design system, which will enable homebuyers' participation in the design of their homes. The methodology of the intended system framework is modeled from macro to micro concerns, leading to the definition of the design system framework (Figure 1.7). It encompasses the following stages:

a. *Introduction stage*: Identifies the research problem and various areas of study, including mass customization, computation in architecture, and prefabricated housing, in addition to the process by which to achieve the intended research goals.

b. *Analysis stage*: Represents the theoretical background of the thesis and thus performs a critical analysis of a series of topics and sub-topics from macro to micro concerns. The topics are as follows:

  - The fundamentals of mass customization with a focus on its theoretical and technical configurations. This includes relevant research efforts to enable mass customization in the housing industry, with a particular focus on efforts dedicated to the study of computer-based design systems and successful industry applications.
  - System theory and design methods, leading to a definition of design system concepts.
  - Generative algorithms as the core component of design systems, and with a focus on various approaches to problem-solving rather than form-finding methods.

  This second stage decisively explores the systems' capability to handle the complexities associated with the process of the mass customization of housing, thus laying the theoretical and technical base for the following phase.

c. *Synthesis stage*: Synthesizes the outcomes of the analysis stage, and couples them with research objectives so as to formulate the design system framework. Broken down into a set of hierarchical levels, the framework conceptualizes a comprehensive approach to constructing a computer-based design system for mass customization of prefabricated housing. The framework emerges as a logical consequence of the previous stages, following rational system design methods. Additionally, the framework derives its knowledge from the study of mass customization theories, and computational design models. It thus identifies technical enablers for building a design system that can allow homebuyers' participation in the design of their homes.

d. *Simulation stage*: Simulates the proposed design system framework within a real-life customization scenario from a leading prefabricated housing company in Quebec. The simulation calls for the highest levels of customization, and proposes two different prototypes amongst the design system framework, thus revealing its many opportunities and complexities. The first prototype simulates a configuration model for customization, while the second simulates a computational model for design synthesis.

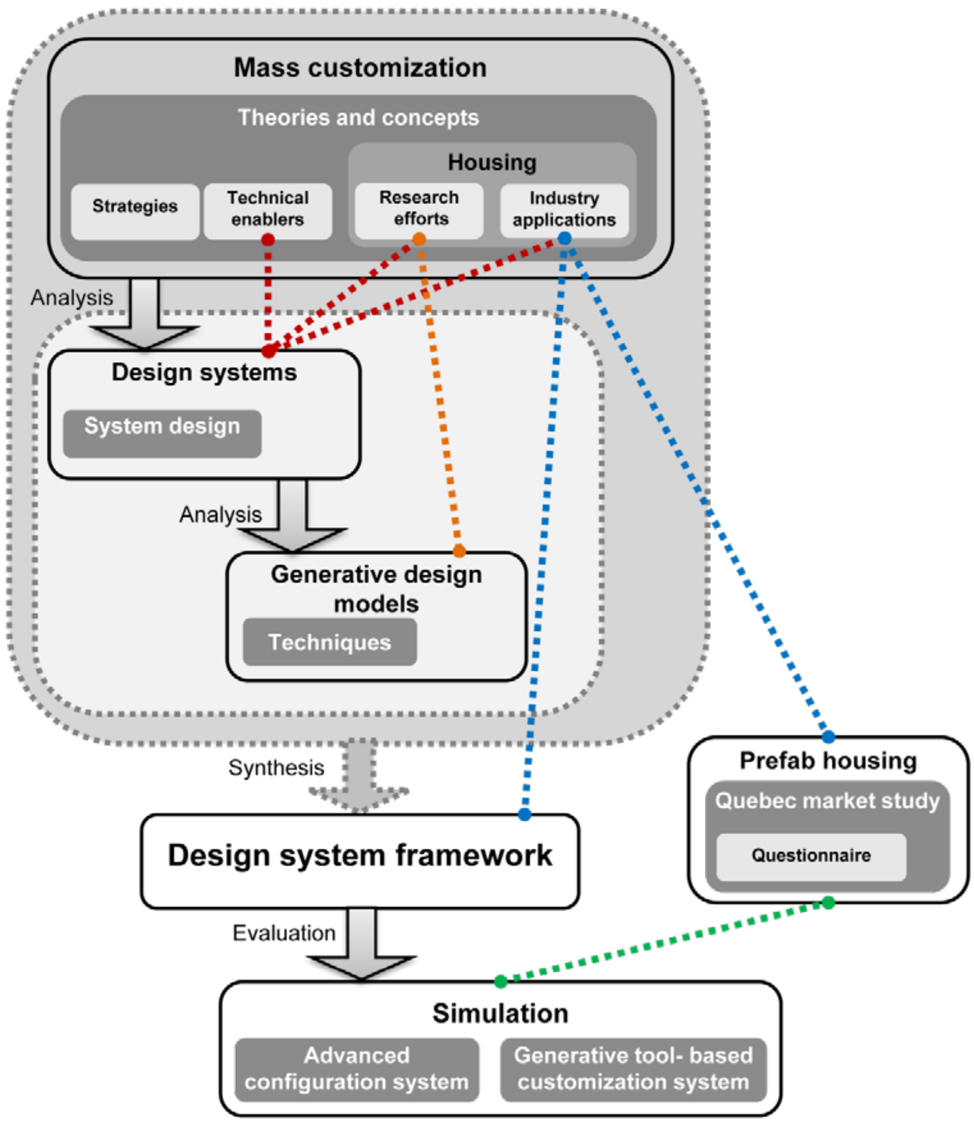

Figure 1.7: Diagrammatic representation of the research methodology. The process operates from a macro to micro scales, passing through sub scales in between.

The proposed framework is generic in nature, so as to ease its implementation in the customization of many other modes of housing. Nevertheless, it suggests a tangible series of systematic steps that, if implemented, would ultimately lead to the development of a comprehensive and integrated computer-based system for the mass customization of housing.

1.7 Thesis Structure

The thesis is divided into four main parts:

Part I: Overview

Consists of one chapter:

Chapter 01_Introduction: The first chapter describes the value of the topic, research objectives, methodology, and provides an overview of the study.

Part II: Theoretical Background

Represents major topics related to the thesis, and comprises three chapters:

Chapter 02_The concept of mass customization: Reviews the nature of mass customization and the various strategies and technical enablers required to implement it in an industry. Additionally, the chapter analyzes efforts towards implementing mass customization in housing, with regard to research and industry applications.

Chapter 03_Design systems: Describes the trifold relationship between design methods and processes, system theory and system approaches, and the design of a system that integrates these two fields. The chapter concludes with a preliminary set of components for building a design system for the mass customization of housing.

Chapter 04_Generative design models: Investigates various paradigms in generative design techniques with the aim of evaluating the relative capacities and merits of systems. This understanding is then applied to the management of the complexities associated with the process of mass customization of housing.

Part III: A Proposed Digital Platform

Describes the thesis' propositions, and is composed of two chapters:

Chapter 05_The prefabricated housing industry in Quebec: Presents a critical analysis of the Quebec prefabricated housing industry, with a focus on the application of technology in sales, design and production.

Chapter 06_A design system for mass customization: Introduces the thesis' framework as a series of systemic procedures for developing a comprehensive system for the mass customization of housing. It focuses on the design system's role within this industry framework.

Part IV: Simulation and Conclusion

Validates the design system framework through simulations, and then presents the conclusion of the research. It consists of two chapters:

Chapter 07_Simulation: Describes the simulation of the proposed framework to the highest levels of customization, as based on the profile of a leading prefabricated housing company operating in the Quebec market. The outcomes are two distinct systems: an advanced configuration system and a generative, tool-based customization system.

Chapter 08_Discussion and conclusion: Summarizes the thesis' conclusions, evaluates the process of developing the framework, and outlines avenues of future work.

Part II:
Theoretical Background

2.0:
The concept of mass customization

2.1 Introduction

Interest in mass customization of architecture principally evolved from advancements in computational design and fabrication technologies. Such an interest resulted in innovative concepts based on pragmatic design, manufacturing and shipping strategies. It also paved the way for new possibilities in digital applications that redefined the relationship between design and production. Yet despite these advances, mass customization remains a business and production model that needs further exploration of its strategies and processes, with the goal of developing a more comprehensive approach.

This chapter explores the theories and concepts of mass customization that are related to this thesis' research objectives. It represents an analysis of the various strategies and practices that enable the customization of products. The chapter ultimately presents a critical analysis of the diverse research efforts and applications in the adoption of mass customization within the housing industry. It also emphasizes the application of computational design methods that support future homebuyers' participation in the designs of their homes. Figure 2.1 illustrates the structure of this chapter within the overall organization of the thesis.

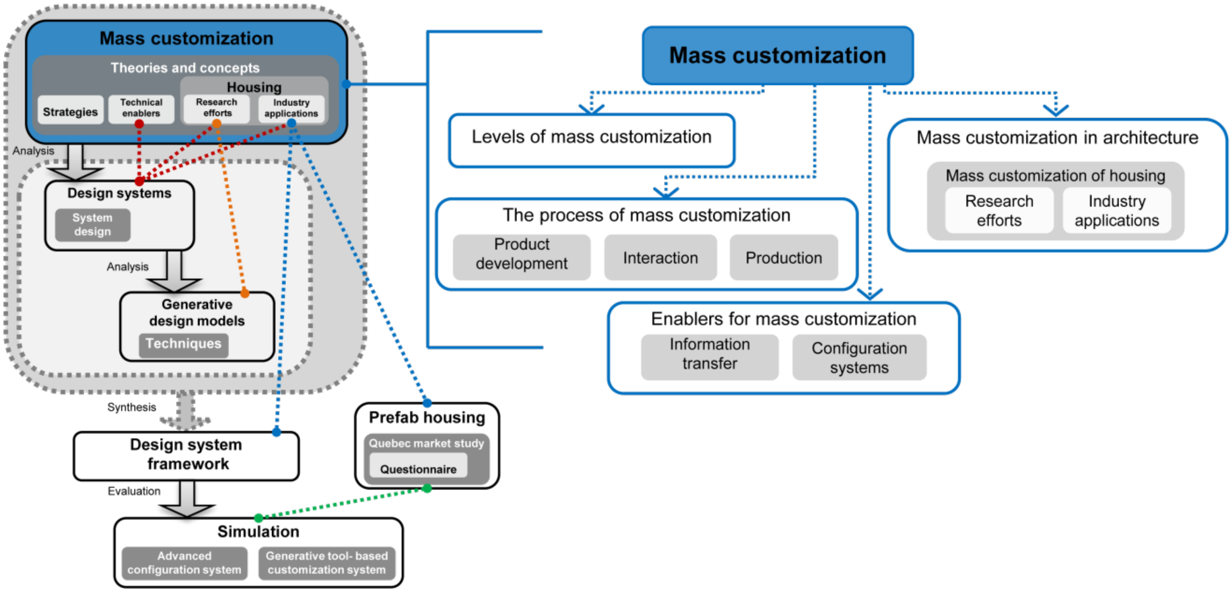

Figure 2.1: Diagrammatic representation of the chapter's outline, in relationship to research structure.

2.2 Levels of Mass Customization

The primary point of departure in the process of implementing mass customization lies in determining the levels of individualization, thus defining at which stages customization can occur within the *value chain*[1]. Different companies adopt mass customization strategies based on two main factors: the point of customer involvement within the value chain, and the type of modularity they intend to offer. These two factors assist companies in defining the configuration of processes and technologies that must be applied to produce mass customized products (Chandra & Kamrani, 2004).

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[1] In his book *Competitive Advantage: Creating and Sustaining Superior Performance,* Porter (1998) defined value chain as the series of activities that an enterprise performs to deliver valuable products or services to customers, towards achieving a competitive position in the market. In each phase of the value chain the product or service gains some value.

Pine (1993) identified four approaches to mass customization:

- *Collaborative customization*: Based on establishing a mutual dialogue between the consumers and the producer, so as to determine the consumers' needs and requirements
- *Adaptive customization*: Based on the production of standardized products, while still allowing for alterations by the user during operation.
- *Transparent customization*: Based on delivering customized products to customers, and promoting their awareness of the customization process.
- *Cosmetic customization*: Based on marketing the same product to different consumer categories, and essentially packaging standard products differently for each intended customer.

Lampel and Mintzberg (1996) further defined the four main stages within the value chain as that of design, fabrication, assembly, and distribution, all of which can be integrated with customization processes. While this involvement can range from simple adaptation up to total customization, processes in which customer involvement occurs early in the production cycle generally result in more customized products. Based on that definition, Tseng and Piller (2003) identified five standardization strategies, categorized by the stage at which customization occurs (Figure 2.2):

- *Pure standardization*: Standard products.
- *Segmented standardization*: Product assembly using standard parts.
- *Customized standardization*: Assembly of standard products, configured according to customer demand.
- *Tailored customization*: Products where the customer can choose materials or extra equipment, but where that choice is constrained by the basic design of the product.

- *Pure customization*: Products specially designed for a particular customer.

Pure standardization, containing the lowest level of customization, occurs if all stages of the value chain have been standardized. At the other end of the spectrum lies pure customization, which is achieved only when customers are able to have a near-complete impact on the design process. The other strategies are intermediate forms, and are situated between these extremes.

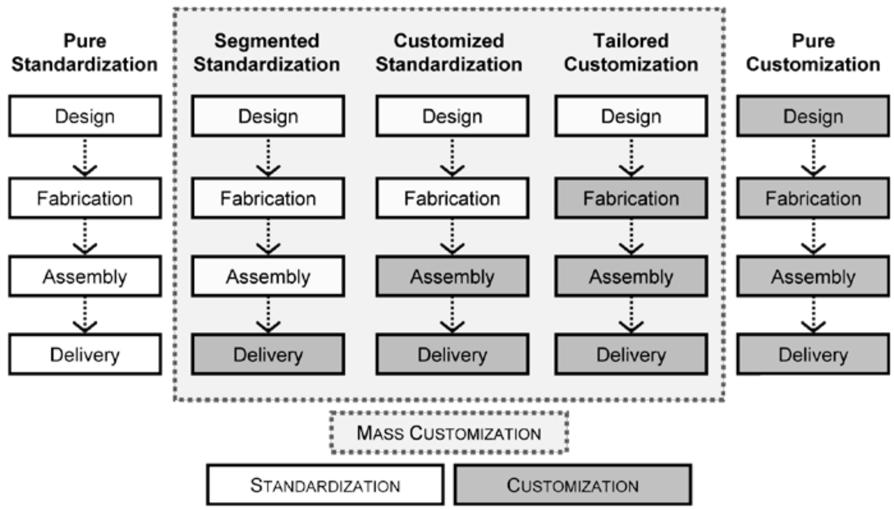


Figure 2.2: Mass customization strategies with regard to level of customer involvement (Tseng & Piller, 2003).

2.3 The Processes of Mass Customization

The process of mass customization is composed of a set of interlinking activities devoted to first gathering customer requirements, and then transforming them into a physical product to be manufactured and delivered to the customer (Figure 2.3). This process can be broken down into various sub-processes depending on the nature of the product, role of designer and producer, and level of customer involvement in the value chain (Blecker & Friedrich, 2006).

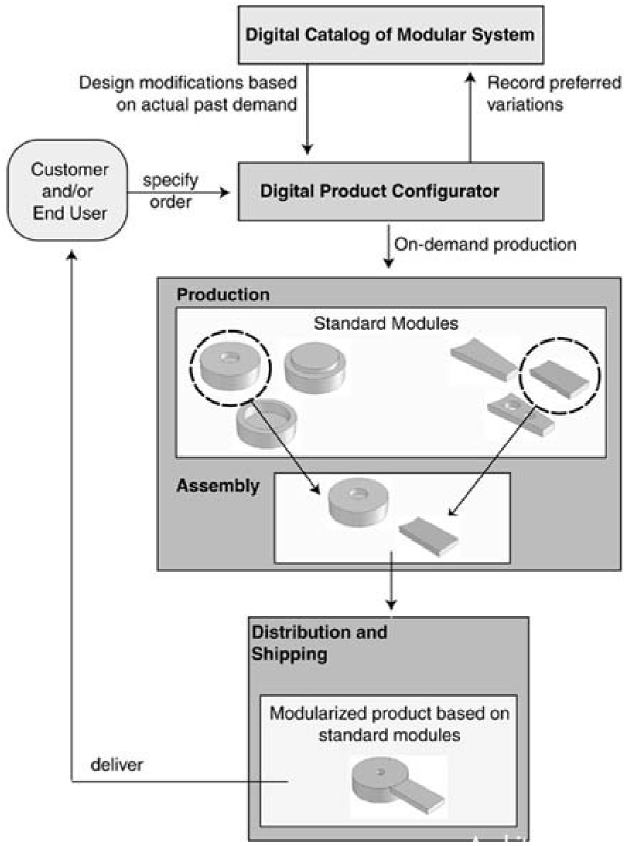


Figure 2.3: Schematic process of mass customization (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2005).

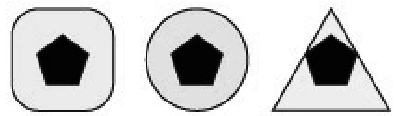
Blecker and Friedrich (2006) identified six sequential sub-processes necessary for implementing mass customization: development, interaction, purchasing, production, logistics, and information. In the interests of precision, this research specifically focuses on the three sub-processes that are intimately related to architecture and housing: product development, interaction, and production.

2.3.1 Product Development Sub-Process

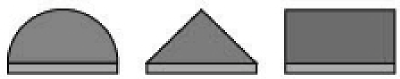
As the first step towards a transition to mass customization, it is advisable to analyze the customizability of an industry and its principle commodities. To be viable as mass customized products, goods and services must be developed in a way that can easily be adapted to diverse customer requirements at an affordable cost. Thus, after analyzing the patterns in market demand for customization, and a company's technological status, the initial step in the product development process is to develop generic product modularity from which a large number of product variants can be derived (Blecker & Friedrich, 2006).

For architecture to be interpreted via logic of mass customization, it must be understood as a modular product formed from a set of different components, which can each be treated as logical units. The scheme by which these components are organized is defined as the product's architecture. Following the research of Pine (1993), modular architecture can be seen as an example of a product that facilitates its own customization. Salvador (2007) argued that modular product design involves creating and selecting modules, in addition to designing module interfaces, so that more modular architecture can be achieved with fewer interactions among modules. Product modularity enables the manufacturing of a large number of product configurations by simultaneously taking advantage of the economies of scale and scope. Other benefits of modular design include ease of product development, increased product variety, decreased product order lead-time, ease of design, and ease of service (Blecker, Friedrich, Kaluza, Abdelkafi, & Kreutler, 2005). Figure 2.4 identifies various types of product modularity.

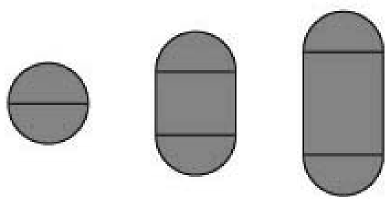
In addition to modularity, Tseng (2003) lists commonality and platform strategies as important factors for the increased reusability of components within mass customization systems. Commonality refers to the possibility of using a component both within the same product and between different products. The combination of modularity and commonality leads to a product platform strategy. This is a common module that can be implemented into a wide range of variants of the same *product family*[2].



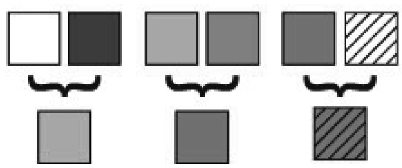
Component-Sharing Modularity: Common components are used in the design of a product. Products are individually designed around a base unit of common components.



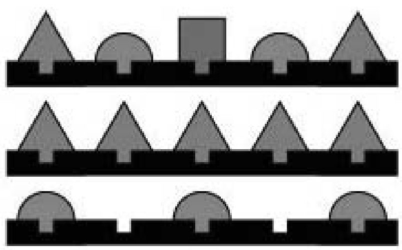
Component-Swapping Modularity: components that can be switched on standard products. Modules are selected from among a list of options, which are added to a base product.



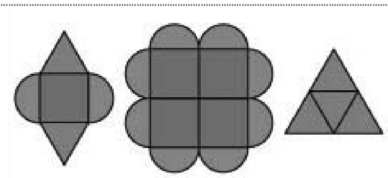
Cut-to-Fit Modularity: Dimensions of a module can be modified to combine it with other modules. It is employed with products having particular dimensions such as length, width, or height.



Mix Modularity: Similar to component-sharing, but it is distinguished by the feature of products losing their unique identity.



Bus Modularity: Characterized by a common bus to which physical components can be connected via the same type of interface.



Sectional Modularity: the assembly is realized by connecting the components to each other via identical interfaces.

Figure 2.4: Types of product modularity (Source: Flaherty, 2009).

Product development for mass customization requires definition of the degrees of freedom offered to customers. It is an attractive practice to

[2] Tseng (2003) defined product family as a group of products derived from a common product with similarities in components, as well as processes. A product family generally consists of both standardized elements (product platforms) and variable elements, to insure product variation.

producers as it normalizes the process of customization and minimizes cost. However, it also entails the surrender of a certain degree of control. Allowing customers to benefit from customized product development requires a high degree of external integration, and fundamentally considers customers as partners in the process of product innovation.

Within the realm of prefabricated housing, modularity in design was spurred by early twentieth century mass production techniques, which sought to simplify production and reduce building costs. With the advent of digital design and fabrication technologies, modularity in design has recently gained new ground by offering high degrees of flexibility in design, especially through the possibility of various assemblies of prefabricated components, as well as by allowing for material use optimization (Salingaros & Tejada, 2001).

2.3.2 Interaction Sub-Process

The product development sub-process focuses on the creation of a platform of product variants, thus increasing the chance that customers' needs would align with the features of an offered product. However, an additional interactive sub-process is required to collect and define customers' needs and demands. This sub-process researches and suggests the most appropriate end product for a consumer's unique requirements (Blecker & Friedrich, 2006). The level of this customer interaction can vary, from simply selecting predefined alternatives to the integral co-design of products. The complexity of the interaction sub-process lies in collecting the appropriate information to optimally match products with customer preferences. The ideal outcome of such an interaction is a completed product order with an accompanying list of supporting materials and components.

The internet has recently played an increasingly important role as an electronic medium of communication between producers and customers, thus offering new modes of interaction for customization in the form of an interactive, web-based interface. Many companies (e.g. Dell, Sony, NIKEiD) have developed internet-based customization platforms that provide customers with the tools to configure products to their needs. Among these companies is a group of prefabricated housing producers who have shifted towards offering web-based configuration platforms. As enticing as such an approach might seem, it nevertheless still limits customization to mere selections from a pre-determined model, with complementary customizations of a dwelling's cosmetic appearance, specifically affecting flooring, counter-tops, and windows.

2.3.3 Production Sub-Process

The application of mass customization requires a high degree of flexibility on the part of the manufacturer, as multiple product variants must be offered without the loss of competitive pricing. In practice, the feasibility of mass customization can be largely attributed to advances in the fields of flexible manufacturing systems and modular product architecture. In this context, product modularity is the primary building block of any manufacturing environment that may traditionally be regarded as flexible (Piller, 2003). Blecker (2006) identified two possible production systems for mass customization based on flexibility. The first relies on flexibility as generated by a modular product design. The second is based on embedding flexibility in the design process itself. Accordingly, both approaches influence the determination of customization levels, and thus the selection of customization strategies.

2.4 Enablers for Implementation of Mass Customization

Implementing a mass customization system relies primarily on developing a platform of processes and technologies 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 (Salvador et al., 2009).

Salvador el al. (2009) defined three common capabilities required for the successful implementation of mass customization:

- *Solution space development*: Concerned with the definition of the amount of product variants to be offered to customers A secondary concern is the creation of a software design tool, which serves as an innovation tool kit with which customers can translate their preferences directly into a product design.
- *Robust design process*: Concerned with the flexibility of the design and production processes.
- *Choice navigation*: Concerned with offering customers adequate support to identify their needs, requirements and solutions, while minimizing difficulties in making these choices. There are three main approaches to this pursuit, based on the application of software systems. First is an assortment machine, consisting of software that matches the characteristics of an existing product with a model of the customer's needs. Second is trial and error learning, consisting of an interactive system that builds a needs model, and then matches and tests it with available solutions. Finally, an embedded configuration, consisting of products that can be adapted and reconfigured internally to the customer's needs.

Contemporaneous to Salvador el al.'s model, Schodek et al. (2005) detailed the latest developments in Advanced Manufacturing Technologies (AMT), Flexible Manufacturing Systems (FMS), and communication and networking systems that have formed the basis for this shift towards customization. These technologies enable an effective linkage between work groups (i.e. analysis, design, manufacturing, and testing), thereby improving the response time to customer demands and integrating various components into the production chain.

Like other consumer products, the customization of housing requires an analysis of the different levels of information enabling its processes. These levels are considered alongside a homebuyers' profile, with a greater focus on *psychographic*[3] and demographic traits, in addition to the manufacturer's design and production data. Accordingly, the efficient implementation of mass customization in the housing industry hinges on the ability to clearly understand the dimensions of its multitudinous processes. This is including but not limited to enabling technologies that facilitate the development of users' profiles; mechanisms to match or generate housing solutions that are responsive to users' needs and requirements; and data management approaches that organize the transfer of information between the various entities involved in the process.

2.4.1 Enabling technologies at work: information transfer

The success of any mass customization program is largely determined by the efficiency of information transfer between customers, the manufacturer, and various production units. Tseng and Piller (2003) explored the notion of information transfer throughout the process of

[3] Psychographics refers to people's attitude, values, and lifestyle characteristics. It is intended to supplement the standard demographics description of people by adding the richness of social and behavioural science (Kahle & Chiagouris, 1997).

mass customization (Figure 2.5). Conversely, Frutos and Denis (2004) proposed a method for establishing an information system framework designed for responsive interaction between companies and customers in a mass customization environment. This was suggested through the following sequence of steps:

- *Defining the product catalogue to be offered to customers*: The catalogue identifies the degree of product customization. A greater number of possible options leads to a higher level of customization, thus requiring greater technological and developmental capacities on the part of the manufacturer.
- *Collecting and storing information on customer choices*: Gathering customer needs and requirements for a specific product could be done by sales representatives trained to guide customers through the decision process, or by means of a web-based interface. Alternatively, customers and designers might work side by side with one another to develop a product from scratch. The resulting information could then be stored electronically,
- *Transferring data from store to manufacturer*: Production orders are transferred to manufacturers through a digital link. Customer preferences are then used to create a product identification number (ID).
- *Translating customer choices into product design features and manufacturing instructions:* A well-developed digital design and manufacturing system fulfills the criteria outlined in the previous steps. Specifications in design elements are inputted into CAD/CAM systems, which translate this data into manufacturing instructions. Driven by computer-enabled responsiveness and flexibility, CAD systems allow customer-driven design modifications to be faithfully processed and transformed into manufacturing commands. Similarly, CAM systems expertly adjust to any variation in components without losing the advantage of production capacities.

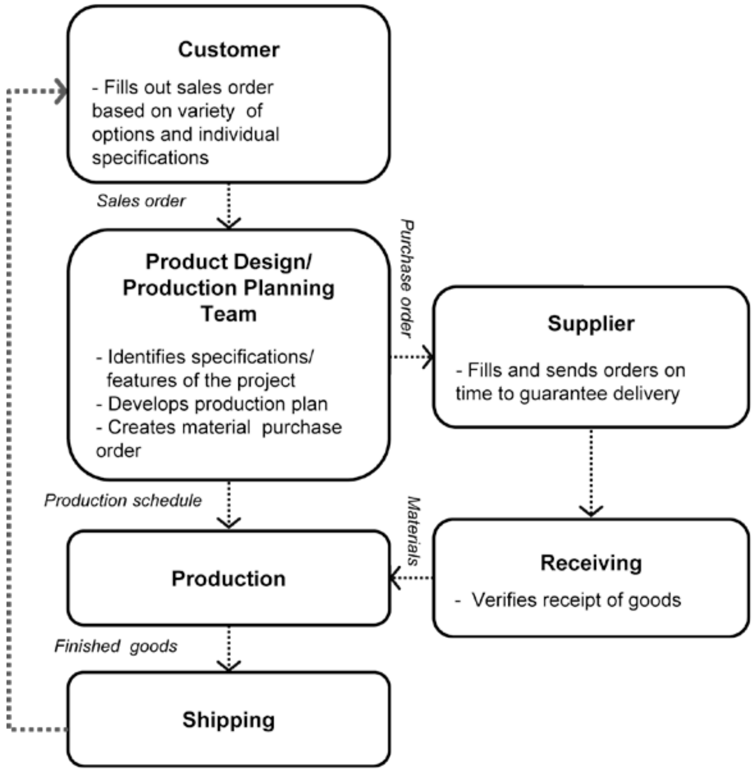


Figure 2.5: Information flow in mass customization (Source: Tseng & Piller, 2003).

The development of an information transfer framework within a mass customization system creates a dynamic environment that integrates customers with the design and production of customized products. For consumers, such a dynamic environment would facilitate their involvement in the design of their products at an early stage of the customization process. For manufacturers, such a system creates a reliable framework for pricing and managing production processes and data.

2.4.2 Configuration systems

Blecker et al. (2005) defined product configuration systems as information tools through which the order-taking process is automated, thereby recording customer requirements without the need for external human intermediaries. In his 2005 book *Democratizing Innovation,* Von

Hippel described product configurators in terms of "tool kits", whereby customers are provided with required tools to configure a product based on their needs. Configuration systems are commonly implemented in the online interface between a producer and its customers. These systems are aimed at supporting customers in the configuration process, so as to produce a product in accordance with their particular and individual requirements. Von Hippel (2005) further stated that the main technical component of a configuration system is a knowledge-base composed of two subcomponents: its database and its configuration logic. While the database comprises the whole set of component types, variants, and their instances, the configuration logic identifies the constraints existing between different components, which ensure valid product variants.

Belcker et al. (2005) classified configuration systems into various categories based on configuration knowledge, nature of interaction, solution search, and mass customization strategy. This classification was based on the concept of a *model configurator*; termed a "morphological box" by Zwiky (1996). The model was aimed at providing software engineers and producers with primary guidelines when designing a product configuration system. However, since customers may face a complex decision-making process when buying a customized product, effective support is required. Zwiky further proposed extending the configuration system through the addition of a supplementary component: an *advisory system*[4], to support inexperienced customers in the configuration of a product.

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[4] Advisory systems are defined as software systems that offer assistance to customers throughout the customization process, and according to their profiles and requirements. The system guides customers to select product variants which better fulfill their objective needs (Blecker et al., 2005).

2.5 Mass Customization in Architecture: New tools and Techniques

Erecting a building is often achieved through the assembly of various configured components, leading to the construction of a unique structure. Most buildings fabricate elements on-site by the direct processing of materials, such as concrete and masonry. More recently, following the extensive application of CAD/CAM techniques within the building industry, new opportunities have emerged that offer the development of comprehensive 3-D building models to increase efficiency in both the design and construction processes. Moreover, these same techniques assist in the management of the design and production of off-site fabricated components, which will later be integrated with on-site activities, thus further improving productivity (Smith, 2010).

In parallel with off-site fabrication, specialized manufacturers create customized products and components. This mode of production employs speculative models, which are produced by advanced digital design and manufacturing techniques in order to enable the fabrication of distinctive building components. In this industry, recent advances in software platforms, such as parametric modeling tools, have offered practical capabilities for presenting complex shapes accurately and enhancing fabrication through CNC techniques.

Kieran and Timberlake (2004) argued that mass customization has increasingly influenced construction processes and products over the past few decades. Most of the recent production approaches, which employ specific digital design environments and the related manufacturing processes, relate to the concept of mass customization, although this influence is at times discrete.

One major challenge in of applying mass customization strategies to architecture lies in the evaluation of the efficacy of a product. 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 pragmatism. However, the field of housing, 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, in order to realize a mass customization design and fabrication environment, a high level of communication between users, designers and manufacturers must be shared and integrated. 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 (Kieran & Timberlake, 2004).

Richard (2007) defined four significant aspects that serve to enable mass customization in architecture. Some of these factors have already been applied productively in the prefabricated housing industry and within the European Community:

– *Flexibility of the product:* Concerned with the spatial variations of the product while in use. This could be achieved through the use of movable/demountable partitions, mobile 3-D functional modules, and interchangeable exterior envelope panels.
– *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 CNC, and other 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 considered to be special products, whose design involves typological, cultural and social aspects that have yet to be robustly accounted for by the customization process.

2.5.1 Mass customization of housing

Noguchi (2004) classified homebuilders in the North American homebuilding industry into three different categories based on the level of customizability. He described the field as a mixture of production, semi-custom, and custom builders. Production builders specialize in a high-volume construction model in which they develop a fixed set of housing prototypes in response to an intensive analysis of market demands. Homebuilders, accordingly, construct homes as a part of a pre-sale strategy, allowing potential buyers to evaluate the quality of their intended new homes through physical interaction with a built-model, thus helping to ensure satisfaction. The advantages of this system include the reduction of both the lapsed time and the cost of construction. Moreover, high-volume work, either in subdivision housing developments or high-rise apartment blocks, offers trade contractors scheduling advantages that result in remarkable cost savings.

Custom-builders, on the other hand, tend to develop completely unique homes corresponding exactly to an individual homebuyer's demands, leading to a one-of-a-kind product. However, custom-built homes take the longest time to complete and cost the highest price due to intensive site work and lost economies of scale.

Finally, an intermediary, semi-custom approach allows builders to combine characteristics of ready-built and custom-built homes, drawing on both the economy of pre-designed plans for model homes, and the flexibility in customization through design modifications to features such as spatial layout, external or internal finishes, and other systems (Noguchi, 2004).

There have been several successful research explorations and production attempts that seek to use advancements in design and manufacturing technologies to go beyond a straightforward application of custom-build approaches within the housing industry. These explorations tackled the concept of mass customization of housing from two angles: design and production. The following section analyses these prior attempts and evaluates their successes and failures.

2.5.1.1 Survey of research directions

Interest in mass customization as a production strategy has recently increased in response to a demand for individualized products, along with the development of new technologies supporting the shift from a "one-size-fits-all" approach toward custom products. Researchers from diverse disciplines, including management, engineering, computational design, and architecture, were encouraged to investigate the potential of adopting such a production strategy, with the goal of resolving particular social and economic problems, improving housing conditions, diminishing final costs, and customizing dwellings.

A review of the literature on the mass customization of housing reveals heterogeneous concerns. Some approaches evince different levels of interest in developing models to integrate homebuyers into the early design stage of their homes. Alternatively, other approaches focus on the link between design and production, and how flexibility in manufacturing systems and emergent digital fabrication techniques could support the delivery of customized housing. Within this diverse milieu, this section explores related academic research with the thesis' research questions in mind. It seeks to study the application of computational design tools for enabling greater customization in the housing industry. This section focuses on methodologies specific to the implementation of design systems and related generative design tools. It also examines other interesting approaches that represent a milestone in the research of the mass customization of housing.

The work by *House_n*, a former digital media and housing research group at MIT's Department of Architecture, can be regarded as one of the leading investigations of how computational technologies, materials, and strategies for design can come together in the creation of dynamic, evolving places that respond to the complexities of life. In an article titled "A New Epoch: Automated Design Tools for the Mass Customization of Housing" (2001), the group's director Kent Larson, along with Mark A. Tapia, and Jose P. Duarte explored how automated design tools may help architects to develop better solutions for mass housing projects, facilitating a shift from mass production towards mass customization. The authors defined three necessary elements for the mass customization of housing:

- *Preference engine*: A framework to engage the customer in a dialogue to reveal profiles, requirements and values. This component would systematically lead users through a series of design diversions, images and diagrams, prompting and recording their choice of spaces, colours, and other design details. The system would also offer advice, as clients may not have prior experience with selection procedures. Finally, the preference engine should build a user profile by collecting and refining these responses.

- *Design engine:* A computational based design system that encodes data, collected by the preference engine, into a *shape grammar*[5] that defines the architectural strategy. As the design engine may not necessarily generate an ideal solution that meets all needs and expectations of the user, the process will also permit the user to make judgments about its proposal and critically evaluate possible solutions. The system will then follow up by generating more solutions. It is important to study the potential affordability of these solutions when linked to integrated, component based, CNC fabrication techniques.
- *Production system:* A digitally controlled production system that can extract information, including geometric data, from the digital design model.

These three elements form the abstract representation of a system for promoting and enabling the mass customization of housing. It is directly derived from models of mass customization in other industries. However, one of the limitations of the proposed system is that it only relies on a shape grammar, despite other reliable and pre-existing systems for design generation. Additionally, information transfer between the three elements was ambiguous, and thus open to potential error. Despite its limitations, however, *House_n's* approach provided a crucial constituent in the process of mass customization.

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[5] Shape grammar, defined as a rule-based computational approach to design, was developed by George Stiny and James Gips in 1972. The concept will be explored further in chapter 4.

Reflecting on this research and on an extensive analysis of Alvaro Siza's mass housing project in Malagueira, Portugal, Duarte (2001) proposed another comprehensive model for the mass customization of housing. This model was built around an interactive computer program that would generate housing designs following a given language, and matching certain criteria. The design system used description and shape grammar as technical mediums for coding design rules (Figure 2.6). Shape grammar is regarded as a well-defined formalism that facilitates the process of devising and structuring rule systems for design generation. However, it can be challenging and time-consuming to implement, as it requires specific expertise to tackle technical problems emerging from the complexities of shape recognition and rule application. Later on, Duarte (2005, 2006) presented different versions of his work.

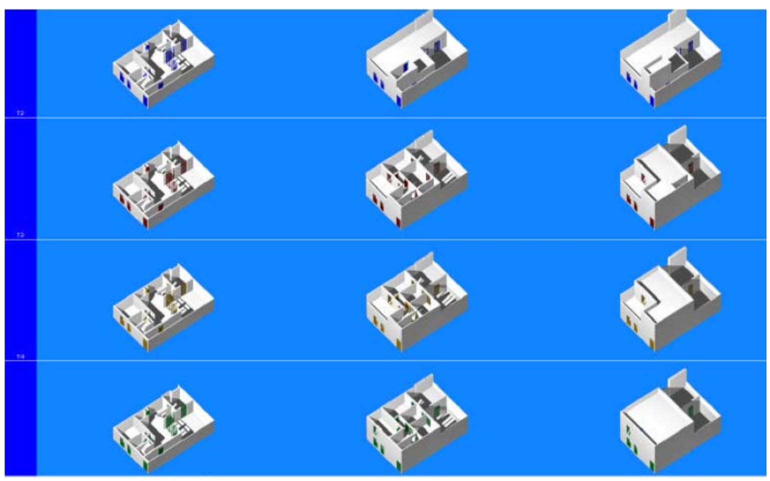

Figure 2.6 : Design derivations, and variations of the shape grammar modeled after Alvaro Siza's Malagueira Housing Project (Source: Duarte, 2005).

While Duarte focused on the design aspects of the process of customizing mass housing, Noguchi (2004) outlined a "*choice model*" to assist homebuilders in implementing innovative design and construction systems, as well as for industrialized building systems. Deriving its logic from an analysis of the Japanese prefabricated housing industry, the model focused on developing design alternatives that were based on integrating the concept of mass customization with value analysis techniques. It systemized a decision–making process for the selection of alternatives, which would facilitate the mass customization of the end product as either a housing unit or a development.

Explorations of computation techniques in design and manufacturing to enable customization in the housing industry resulted in interesting and distinct approaches to customization. In a different approach to Duarte's model (2001, 2005), Juan et al's (2006) computer-based design system investigated potential problems and solutions for housing customization in Taiwan, a market dominated by a pre-sale housing marketing strategy. The paper presented an information technology-based model to support decision-making in housing customization. It attempted to bridge the gap that might emerge between customers and builders at the communication stage, thereby shaping the choices of a large variety of possibilities for customization. The model employed a hybrid approach combining *Case-Based Reasoning* (CBR)[6] with *Genetic Algorithm* (GA)[7]. The system first used CBR technology to retrieve satisfactory housing layouts based on customers' needs. GA was then applied to search for satisfactory solutions to design options by optimizing cost and housing conditions. As CBR requires a pre-existing pool of cases for the system's analysis mechanisms, the system's efficiency increases as more cases are developed.

Botha and Sass (2006) proposed a design and fabrication system for mass-customized, emergency housing in their paper entitled "The Instant House." This system utilized generative computational methods and

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[6] Case-based reasoning (CBR) is a method for problem solving based on solutions derived from similar past problems (Maher, 1990). The concept is further explained in chapter 4.

[7] A Genetic Algorithm (GA) is an evolutionary algorithm that simulates the process of natural evolution (Bently, 1999). The concept is further explained in chapter 4.

CNC fabrication techniques to achieve design customization. This process is divided into five stages, namely shape design, design development, evaluation, fabrication, and construction. The product will be a customized, habitable, mono-material plywood structure, assembled manually with rubber mallets and crowbars. Although the process addressed a particular type of housing and construction system, it explored wider design and production systems, as well as the link between both systems, which is a critical detail in the mass customization of housing.

Along with a rising awareness of the internet's potential as an interactive medium that might be applied towards the customization of prefabricated housing in the North American market, Huang (2007, 2008) developed a model to support homebuyers' participation in the design of their dwellings, based on a decision support system. This model employed a dynamic questionnaire that guided users in a sequential process towards finding the appropriate solution, relying on a catalogue of prefabricated modular housing systems. The proposed consumer interface is based on four structural levels: firstly, the user's profile and list of required spaces; secondly, the unit typology and plan layout; thirdly, the detailed room layout and design; and finally, the selection of finishes and appliances. To test the applicability of these links between design and production, housing prototypes were built in BIM software. This lead to the development of a library of housing variants with coordinated modularly, so as to allow interchange of components. However, the success of this approach relied on the ability to cover various housing sectors and social standards within the set of design variants, which is a somewhat exhaustive process.

In addition to design and production, the critical linkage between design and production requires resolution before customization can be implemented efficiently. To that end, Benros and Duarte (2009) proposed an integrated system for enabling mass customization. It was comprised firstly of a design system encoding the rules for generating customized designs and secondly of a prefab building system allowing for production based on design system outcomes. To achieve such integration, a computer program was implemented by the researchers to allow for the easy exploration and visualization of design solutions and the subsequent and automatic generation of the data required for production. Rules for both design and construction were systemized and then encoded into the computer program, which operates through three distinct stages. First is the development of a three-dimensional model of the dwelling and the building; second is the creation of two-dimensional representations; and third is the production of a list of all construction elements required for erecting the building. What is distinctive about this system is that it uses a parametric design approach for knowledge representation. In short, this means that a set of variables and mathematical equations were used to represent shapes and spatial relations. The system also encodes building regulations and know-how principles to avoid redundant situations. The proposed framework thus opens new opportunities for the exploration of mass customized housing as it remarkably establishes a link between the design system and the building system.

Concurrent with advancements of parametric design tools in architecture, additional efforts targeted the customization of housing, while also focusing on integrating design and production. Matcha and Quasten (2009) conducted significant research on the development of a digital plug-in tool for generating vertically stacked single-family homes. This tool was subsequently implemented in Revit Architecture Software (Figure 2.7). The parameterized typology was aimed at providing more variety and individuality, while maintaining an efficient linkage between design and fabrication processes. The tool consisted of a parametric, rule-based algorithm that started with a building site and orientation, and which allowed the user to specify and input requirements, such as unit size or number of rooms. Information was then used to develop a 3-D model of the house, with its specific characteristics defined and controlled via building parameters and constraints. However, since these tools are remarkably complex, their implementation required the intervention of experts in the field of programming. Further setbacks arose due to the housing industry's ongoing limitations in its shift from manual to digital production.

Figure 2.7: Variations in parametric housing typologies (Source: Match & Quasten, 2009).

One of the important issues when offering high-level customization is to ensure that the selection process and design modifications comply with building system codes, and other design constraints. This is especially important when offering homebuyers choices on different levels, each of which may fall under different building codes. Neimeijer, Vries and Beetz (2010) explored the use of design constraints to control users' participation in the design of their homes. Their approach allowed users to independently modify their designs through an interactive interface, after which the result was automatically verified for potential building code violations. These constraints are presented internally as functions that evaluate a building through Boolean operations, where a building model will be taken as an input, then return as a true/false statement that indicates whether or not the design violates any of the constraints.

Unfortunately, such an approach requires both a large number of prototypes for testing its usability and also an arduous definition of the set of applicable constraints.

A review of various research efforts demonstrates that interest in the mass customization of housing emerged from significant developments in digital design and fabrication technologies on multiple levels. Such developments created the opportunity to connect information, people, and tools in a comprehensive manner, thus leading to a set of methodologies and approaches to facilitate the implementation of mass customization in architecture and housing. However, all of these efforts were focused on developing a tool- a computer–based design system to generate housing designs or assist homebuyers in the decision process. This thesis instead aims to propose a process for developing a design system framework to enable homebuyers' participation in the design of their dwellings at the pre-occupation stage. It focuses on prefabricated housing, due to the latter's accommodation of mass customization strategies.

2.5.1.2 Industry applications

The housing industry has witnessed a number of successful global innovations in the production of prefabricated housing. These methods deploy advanced design and manufacturing technologies in response to market demands, with regard to affordability, durability, and the social and cultural needs of homebuyers. Recently, advanced digital design and manufacturing technologies have offered new opportunities to facilitate the manufacturing of customer-tailored mass production. This section presents a brief description of a successful model in the area of customizing prefabricated housing. It evaluates prefabricated housing in Japan, in addition to some internet-based configuration systems in the United States.

a. The Japanese experience

While the United States dominates 26% of the global prefabricated housing market, Japan is regarded as the fastest growing prefabrication economy (Smith, 2010). In 2004, roughly one out of every seven new homes was prefabricated. This number has increased remarkably in recent years. Nowadays, the market is led by the “Big 5”, a group of companies including Shiga Prefecture, Sekisui Heim, Sekisui House, Daiwa, and Misawa, offering varying products with equally diverse methods of manufacturing. Recently, Toyota homes have also become a well-established participant in the market, transferring their success in the automotive industry and their lean manufacturing technique to prefabricated housing. The resulting method of lean architecture focuses on housing people through mass customization and the utilization of economies of scope (Barlow & Ozaki, 2005).

Japanese housing manufacturers, long considered as world leaders in industrialized housing, have succeeded in implementing cutting edge computerized design and inventory control systems, in addition to automated assembly-line production and advanced research and development. The outcome of these advances shifted production from a repetitive mass-produced mode to a mass customized system offering a wide variety of housing components for users to select from (Noguchi, 2003)

A number of researchers, such as Gann (1996), Barlow and Ozaki (2004), and Noguchi (2003, 2004), investigated how Japanese housing prefabricators managed to supply and deliver mass-customized housing. Gann (1996) investigated how the prefabricated housing industry in Japan could benefit from the use of advanced manufacturing techniques developed by the car industry. A comparison was made to assess the similarities and differences between Japanese housing and car manufacturing industries, leading to a knowledge-sharing model. Since customization requires the investment of significant customer resources on the front-end of the buying process, the concept of managing the interface with customers was introduced in parallel with the development of standardization and preassembly within the production process. The interface was designed to manage the various options in this process. To that end, customers are able to work with experienced sales and design staff to make modifications to CAD systems, which generally provide high-quality 2-D and 3-D representations. Each customized design is developed through a series of stages, wherein sales staff inform the customer of all cost, time and quality implications related to their choice. Salespersons also provide samples of materials, fittings, and furnishing (Gann, 1996).

Noguchi (2003) stated that the Japanese prefabricated housing industry has achieved market success by overcoming the poor image that was traditionally associated with industrialized houses. Early on, mass produced dwellings were monotonous, boxy units, and were perceived by the public as having an inferior quality. Japanese prefabricators have integrated specially-developed marketing, design, and quality-oriented production techniques with the aim of satisfying local demands. This has led to tremendous design flexibility in the task of customizing housing to buyers' choice.

The amount of choice that Japanese companies offer to customers depends on the firms' market orientation and the fabrication technology used. Typically, a firm will offer up to three hundred standard floor plan designs and elevations, which can then be personalized according to customer needs (Figure 2.8). Choice also extends to the external and internal specifications of the house. The outcome of this menu-driven philosophy will be a dwelling unit built with either a timber or steel frame, and finished externally with prefabricated cladding systems, and internally with the customer’s choice of finishing, fixtures and fittings (Barlow & Ozaki, 2005). These choices, however, are restricted by three factors:

- Firstly, one’s income imposes a noticeable constraint and is the starting point of all discussions with a potential customer.
- Secondly, the choices of external customization are restricted in part by homebuilders who offer only select options for a house’s cladding materials, so as to better achieve economies of scale. Other factors, such as building and planning regulations or the shape and size of a housing plot, further limit the breadth of possible customizations.
- Finally, interior customization is constrained by homebuilder influence on customers’ choice, which typically manifest in salesperson’s marketing suggestions and in predefined lists of available fixtures and fittings (Barlow & Ozaki, 2005).

Figure 2.8: Design options for a single- family, prefabricated housing unit in Japan by DaiwaHouse Group (Source: DaiwaHouse, 2008).

Offering a wide variety of interior layouts and products while delivering high-quality homes within a specified time frame requires an advanced production system. Suppliers employ standardization and preassembled components, while subassemblies move from a focus on economies of scale in production towards economies of scope. The latter introduces processes that facilitate the production of a variety of models using the same machinery and material inputs (Barlow & Ozaki, 2005).

With regard to production, Japanese prefabricators have employed CAD/CAM extensively in their design and production systems in order to make the product design lifecycle faster, more efficient and more accurate. This automates the detailed planning of the manufacturing process, which previously began with a set of drawings and specifications. CAD systems are used to realize conceptual images to certain dimensions in the design stage, and then electronic drawings can be shared through an online system within the company. Furthermore, CAM systems can transfer drawings into manufacturing steps that include technical planning, production scheduling, and automation control. CAD/CAM systems are the link to operating the CNC machine tool programs (Noguchi, 2003).

The key reason why the Japanese prefabricated housing industry has gained this notable success is its ability to adapt digital and material technology within the production processes for the purpose of delivering high-quality, customized housing. According to Smith (2010), the construction culture, collaboration, team-building, and integration of these businesses offers the possibility of overcoming numerous challenges, leading to the efficient production of better products. In fact, the success of the prefabrication housing industry in Japan goes beyond attributions of the perfection of their products or fabrication ideology. Instead, the lesson learned from such a system lies more fundamentally in its ethos of taking advantage of new technologies to deliver quality architecture.

b. Internet-based configuration systems

Advancements in information technologies encouraged companies to integrate interactive systems for participatory design via web technology, situating the online interface as the foremost site of contemporary design platforms. This networked interface engages customers in the design of their homes through a sequence of decision-making processes that ultimately lead to efficient customization. Various housing manufacturers in Europe, Japan, and the United States, following similar applications in the automotive, clothing, and computer industries, have implemented this approach. Housing companies engaged in this field must build and invest in databases of various housing prototypes, which are searchable by type, area, average cost, and number of bedrooms. Once a housing mode is selected, homebuyers are able to access a customization tool that offers selections of different exterior/interior finishes, roof styles, and systems.

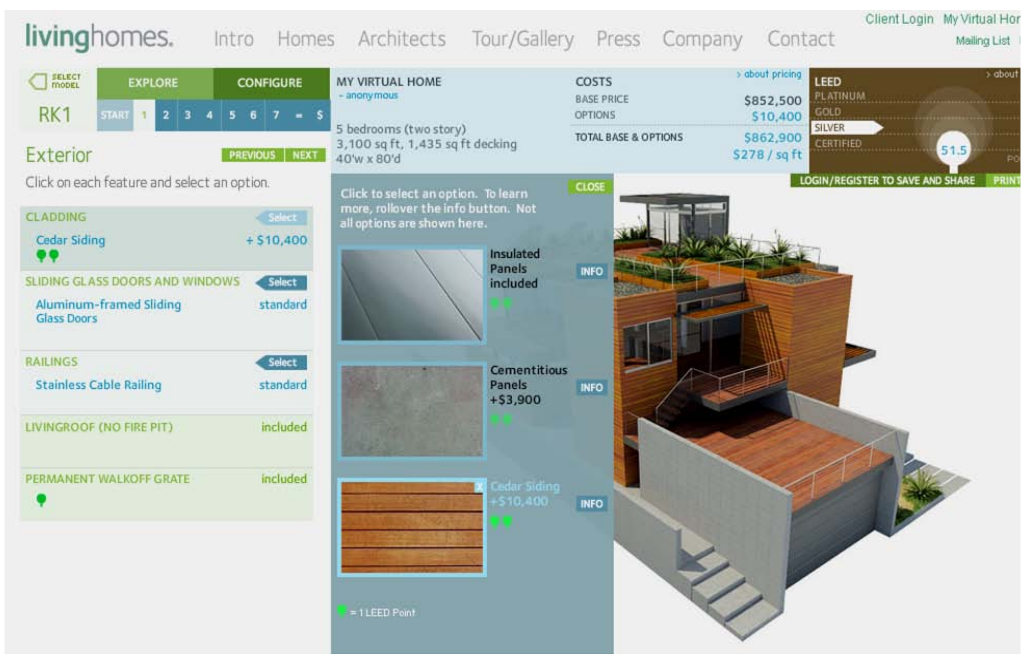
One such company is that of *LivingHomes*[8]*,* an environmentally-focused business that builds modern-styled homes with an unprecedented level of healthy, sustainable materials and energy conservation systems. The company and its products fill an important void in the housing market by offering a unique level of customization, considered design and production while also targeting consumers who value innovation, health, and ecological sustainability (Ozler, 2005).

The company has managed to bring a significant, interactive and web-based system for customization into practice. Homebuyers start the

[8] LivingHomes, founded by entrepreneur Steve Glenn, is a leading developer of prefabricated LEED certified green homes on the West coast of the United States. The company offers two lines of single and multi-family designs, one created by Ray Kappe, FAIA; the founder of the Southern California Institute of Architecture, and the other by KieranTimberlake, the AIA 2008 Firm of the Year (www.livinghomes.net).

process by creating an account, selecting a model, and then proceeding with the customization of the selected housing unit (Figure 2.9).

The online configuration system takes the user through a seven-step procedure entitled “my virtual home”, in which users can define their preferences. Throughout the process, an embedded decision support system provides homebuyers with up-to-date details regarding finishing materials and systems. For instance, any modification to the base unit is reflected in the energy performance of the dwelling, in addition to the total price of the unit. The process then continues to provide more options regarding a house’s living spaces, bathrooms, bedrooms, technical systems and landscaping. At the end of the process, homebuyers get a detailed analysis of all the modifications they have made and the final cost of the housing unit.



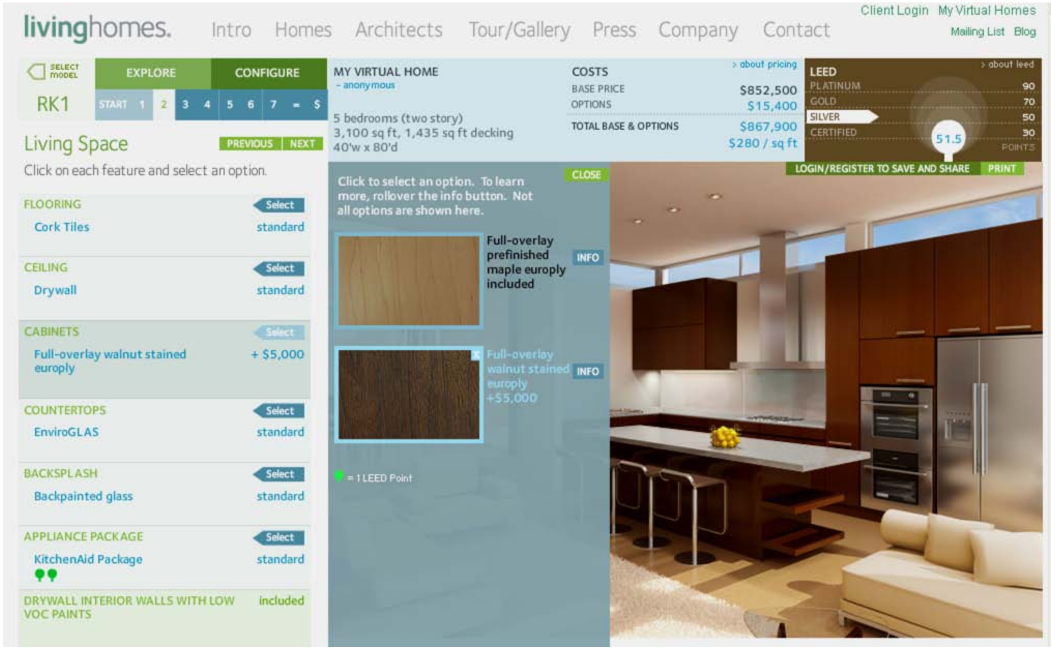


Figure 2.9: The first two steps in the configuration process of a standard LivingHomes model. The process has high visualization qualities (Source: http://www.livinghomes.net/configure.html?model).

In order to link design data with production, *LivingHomes* extensively employs BIM technologies: a software platform that enables interoperability and efficient data exchange and management. BIM further facilitates the realization of these conceptual projects through forging pragmatic links between design and production data. The successes of this approach have encouraged the company to expand its product family by introducing a new typology of customizable, multi-family housing units. In doing so, the company has actively involved itself in this rising sector of the housing market, while still maintaining the integrity and strengths of its configuration system (Ozler, 2005).

In a more advanced approach, *bluHomes*[9] has managed to push the envelope via the features and interactivity of their configuration system. The company offers a web-based plug-in called “design your home”,

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[9] Founded in 2008 by Bill Haney, bluHomes is a company operating in the North American housing market, manufacturing green and affordable dwellings that reply to various market sectors (www.bluhomes.com).

consisting of a 3-D configurator that can be downloaded from their website (Figure 2.10). This tool offers 2-D and 3-D immersive navigation with which users can interact with their chosen housing model. Potential homebuyers can select a space such as the living room, kitchen or bathroom, and see it visualized in a 3-D manner. These zones can be navigated and adjusted in real-time to reflect different finishes, appliances, and systems from a pre-determined palette. Additionally, this tool comes with a decision support system. Once the user makes a selection, the system suggests a family of matching materials, with their cost directly reflected in the price.

Figure 2.10: A snap-shot of bluHomes' interactive, 3-D configurator plug-in (Source: http://www.bluhomes.com/homeconfigurator/).

BluHomes also employs a BIM platform for 3-D modeling and analysis, allowing the design team to test energy consumption and CO_2 emissions, as well as optimize structural and material components of the homes prior to the manufacturing process. Such tools contribute to the lowered cost and heightened durability of these homes through an optimization of processes, offering efficient links between various material and components producers and the main production plant throughout the manufacturing phases of the homes.

2.6 Reflections

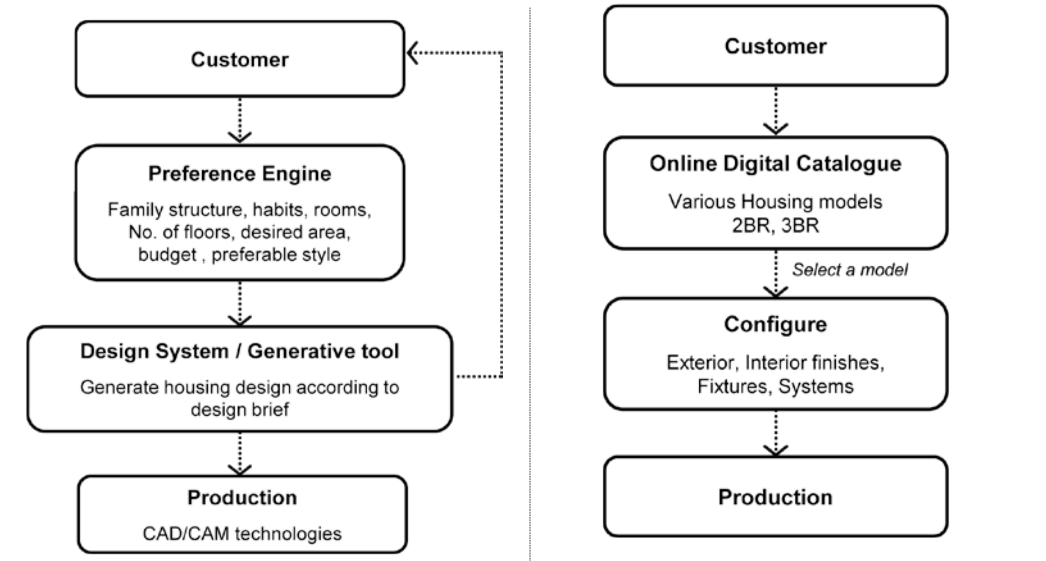
Mass customization approaches and strategies are classified according to the level of customer involvement in the value chain. Salvador et al. (2009) argued that there is no one ideal way to adopt mass customization, even if one is following from successful business models. In fact, companies should customize their mass customization strategies according to intensive market studies, customer requirements, product flexibility, and accessible design and production technologies. Despite the fact that the fulfilment of these factors is critical, it is still not a sufficient condition to guarantee mass customization success.

Based on the analysis of research efforts, as well as industry applications, two approaches to mass customization systems in housing could be defined:

- Firstly, research on the mass customization of housing has been largely stimulated by advancements in computational techniques in architecture, in the form of computer-based design and manufacturing systems. These techniques have offered the possibility of repositioning customization to an earlier stage in the value chain, specifically through the use of computer-based design systems, thus pushing the configurator approach to a higher degree of customization. Various systems have been developed to support further homebuyers' participation in the design of their homes (Figure 2.11 (a)). However, these systems raise various concerns in regard to their applicability and suitability for different contexts.

- Secondly, a common application of customizations within the housing industry lies in the use of product configurators (Figure 2.11 (b)). This model provides homebuyers with different alternatives in spatial layout, external or internal finishes, and other systems by providing the means by with which to navigate and make comparisons across these selection alternatives. For example, the homebuyer might be offered a choice between house layouts A, B, or C, kitchen blocks A, B, or C, an optional extra garage or even an extra story. This approach has been defined in housing research as *multiple choice housing*, and has taken the form of printed catalogues and more recently developed internet-based digital catalogues. However, such a trend is subject to considerable limitations. Creating an advanced design for all possible options is exhaustive and labour intensive. As a result, the number of alternatives in some cases has been limited to three or four options, in order to avoid additional overhead cost. Furthermore, the multiplicity of choices may confuse or intimidate some homebuyers. Even with countless options, there is still the chance that a customer’s desired design variations will not be offered, as the architect’s anticipated customizations may not necessarily accord with every customer’s individual demands.

The appraisal of extant research efforts and industry applications thus reveals a disparity between what has been proposed in research and its applications within the housing market. This thesis thus proposes a comprehensive approach for the mass customization of housing that would bridge the gap between research efforts and industry applications. It forwards a design system framework that can be pursued by prefabricated housing companies to enable homebuyers’ participation in the design of their dwellings at the early design stages, and thus achieve a high level of customization.



(a) The state of mass customization of housing in relevant research

(b) Current customization state within the prefabricated housing industry

Figure 2.11: A comparison between mass customization of housing in industry and research.

3.0:
Design systems

3.1 Introduction

The implications of computer-based design systems in architecture have offered architects and researchers a new territory of exploration with regard to its applicability to assist in decision-making within the design process. These systems tend to provide a medium that can translate a design brief into a solution for a specific problem, following a set of specific procedures.

Following the analysis of the concepts underlying mass customization, with focus on with research efforts to implement such a concept in the housing industry, it was found that one of the key enabling factors is the capacity to structure a computer-based design system that would provide an adequate solution space for prospective homebuyers. This chapter provides a conceptual understanding of design systems, in order to establish the theoretical background required to comprehend the process of developing an appropriate design system framework for the mass customization of housing. As design systems operate by modeling design methods to generate a specific output, the chapter begins with a brief description of various methods and processes. System definitions and theories are subsequently presented, in order to identify the necessary components that would constitute a design system that to enable the application of mass customization to the housing industry. Figure 3.1 illustrates the structure of this chapter within the overall organization of the thesis.

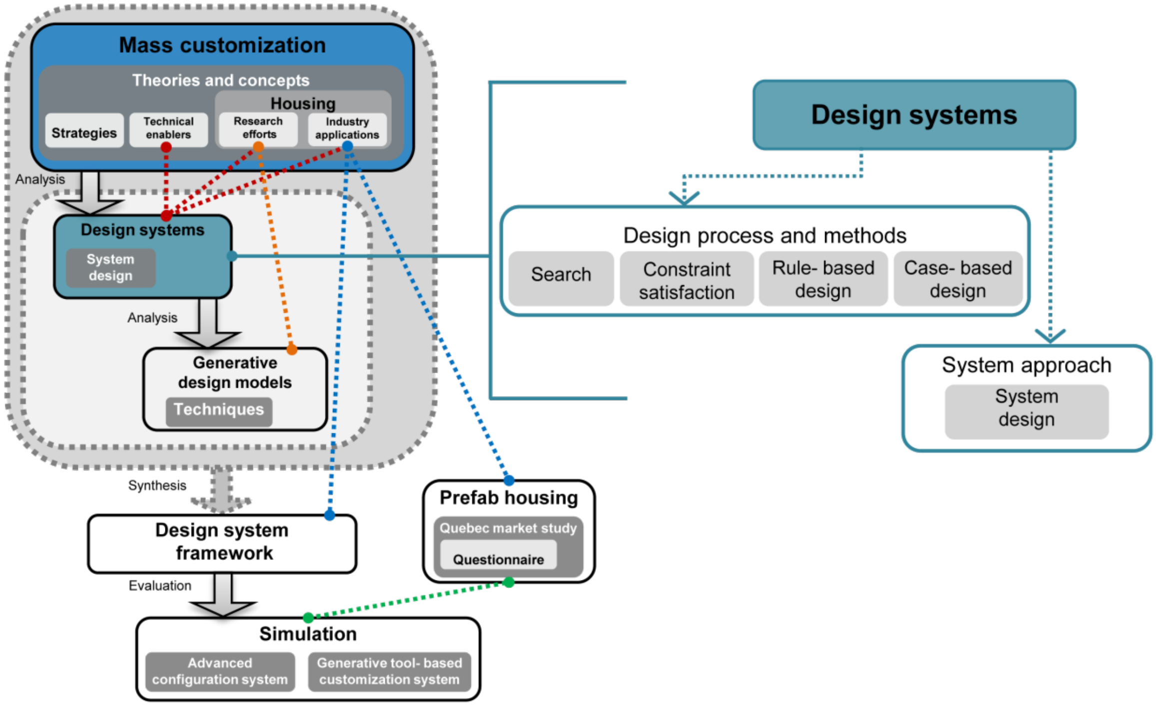


Figure 3.1: Diagrammatic representation of the chapter's outline, in relationship to research structure.

3.2 Design Process and Methods

The interest in *design*[1] as a field of research emerged in the 1960s along with a series of conferences on design methods. In 1968, the first international conference by the *Design Methods Group (DMG)*: *Emerging Methods in Environmental Design and Planning* explored design methods based on science, technology and rationalism, with the aim of systematizing the design process and methods. Additionally, it explored the application of computers to the design and planning fields, along with the rise of computers as arithmetic and logical devices, and Artificial Intelligence (AI) (Moore, 1968). AI techniques were perceived as a means to support the goal of developing designs that exceeded the

[1] Simon (1969) defined design as a problem-solving process, a natural human activity that entails the exploration of a problem as a distinct spatial state, with the aim of finding a design solution. For every problem there is a solution space that encompasses all possible solutions. Thus, problem-solving can be described as the process of searching through alternative solutions within this space to determine one or more that meet specific criteria. Later on, Jones (1992) defined design as a multi-disciplinary process which depends on combining art, science, and mathematics.

normal domain of humans. As a result, design science and methods were established as an academic subject for research, aiming to aid understanding of design skills, especially in schools of architecture.

Several attempts were initiated to model the design process by describing the pattern and sequence of activities that typically take place. Cross (1984) traced four stages in the evolution of design process studies:

- Prescription of an ideal design process;
- Description of the intrinsic nature of design problems;
- Observation of the reality of design activity;
- Reflection on the fundamental concepts of design.

While Mitchell (1990) notes that systematization of the design process dates back to the systematic search for design alternatives observed in the notebooks of *Leonardo da Vinci* (1452-1519), the *Rational Model* [2] by Herbert Simon, and Pahl and Beitz was by far one of the most robust efforts to describe design as a process. The model was based on a systematic step-by-step process starting with a clear definition of the problems, primary and secondary goals, objectives, and constraints, and leading to the formulation of a design tree of decisions. However, the model was widely criticized as being fundamentally unrealistic. Brooks (2010) objected on the grounds that it is difficult to describe design within the constraints of a single decision tree. During the design process the objectives and constraints are by their nature fluid and change continuously over time, thus affecting the nature of the solution space. Additionally, other critiques were concerned with the gap between the model and the professional practice of design.

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[2] The Rational model is based on Bounded Rationality, developed by Herbert Simon in 1975. The model defines decision making as a search process guided by aspiration levels, where the value of a goal variable which must be reached or surpassed by a satisfactory decision alternative (Brooks, 2010).

Jones (1970, 1981, 1992) suggested a prospective design process in the form of a basic structure of analysis, synthesis, and evaluation; a practice that was formalized in the 1960s (Figure 3.2). Jones elaborates on the following stages as an example of a systematic design model:

- *Analysis:* Uncovering the relevant issues and parameters of the problem-solving process, as well as the positions of other parties involved in the project. Information gathered from this process leads to the definition of specific goals for the solution and a plan to achieve them. Additionally, this analysis of the problem helps the architect to explore the project's physical context, as well as situate it within broader social, economic, and cultural dimensions. These can be expected to intersperse further constraints, which can be considered throughout the design process.
- *Synthesis*: Finding possible solutions and building complete designs requires structuring all of the collected information systematically, in order to make it valuable to this phase of the process. During the design process, divergence amongst competing requirements must be resolved and goals prioritized until an optimum solution is reached.
- *Evaluation*: Evaluating the potential of each alternative for fulfil design requirements, in order to select the optimum design solution.

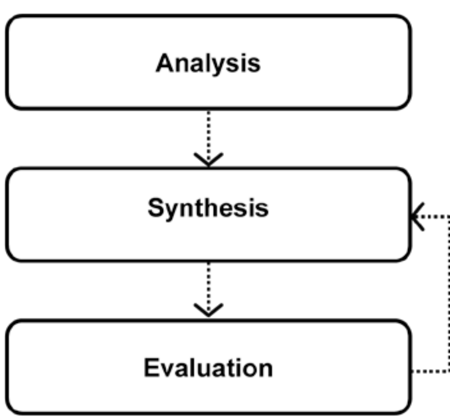

Figure 3.2: The typical 1960s design process (Source: Jones, 1992).

Cross (1984) provided a simple, yet descriptive, four stage model of the design process that consisted of exploration–generation–evaluation–communication. An integral stage within the design process, communication allows the exchange of information between design participants in order to keep them all informed of evolving goals and solutions. An iterative feedback loop exists between evaluation and generation, repeating until a satisfactory solution is reached. Such a model was further developed in more detail by Archer (1984), by inserting two stages prior to analysis: those of programming and data collection (Figure 3.3).

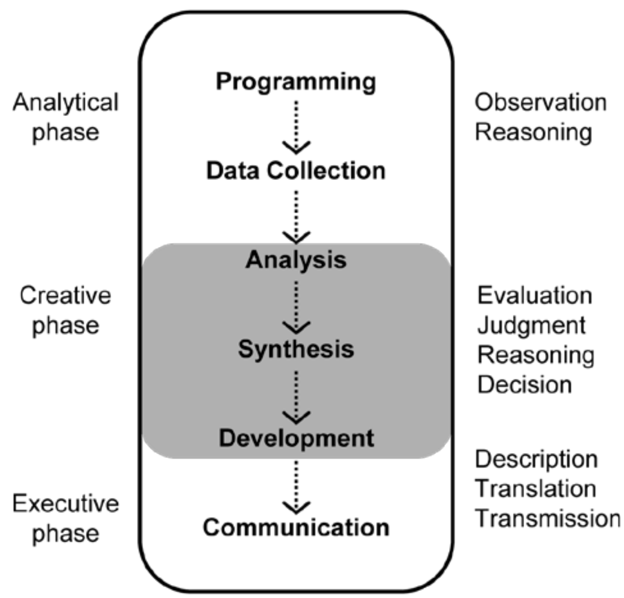

Figure 3.3: Design process by Archer with three broad phases: Analytical, Creative, and Executive (Source: Archer, 1984).

More complex models were later developed, with detailed and comprehensive descriptions of different tasks. Pahl and Beitz (1984) proposed a systematic model based primarily on the following stages:

- *Clarification of the task:* Extensive data collection of requirements and constraints.
- *Conceptual design:* Develop function structures, search for suitable solution principles, and combine them into concept variants.

- *Embodiment design:* At the concept stage, the designer defines the layout and form, developing a technical product or system in response to technical requirements.
- *Detail design:* Involves all technical design details and specifications, including form, material, and dimensions, in the generation of a complete set of production documents (Cross, 2000, Hurst, 1999).

While the systematization of the design process was considered as a significant step forward in design research, many researchers have argued that it is difficult to interpret a distinct design process, as it is typically a non-linear process that reacts to the continuous shift of requirements as the process develops.

3.2.1 Design methods

The interest in *design methods*[3] began as a critical element of the design research movement in the 1960s, where many researchers attempted to explore and formalize new methods of design. Alexander (1964) proposed a method based on using logical structures to represent design problems, and then break down the problem into components, allowing each component to be solved independently. Once solved, various solutions were then to be synthesized into a single solution. Within such method, Alexander emphasized the use of Cartesian rationalism, graphical representation, and computers. Alexander et al. (1977) further developed a more holistic method for the design of buildings and spaces in the book *A Pattern Language.*

[3] Cross (1984) defined design methods as any procedures, techniques, or tools employed for designing. They represent a string of distinct activities that designers might employ or combine towards an overall design process.

Jones (1981, 1992) classified design methods by dividing them into the two broad categories of creativity and rationality. Accordingly, three methods to design were identified: designer as a black box; designer as glass box; and designer as self-organizing system, depending on creativity, rationality, and control over the design process. While creative methods are inherently difficult to track and understand, it is possible to explicate the functioning of the rational methods commonly adapted from operational research, decision theory, management sciences, and computation.

Cross (2000) conducted research on a wide range of rational design methods covering all scales of the design process, based on a speculative survey of the literature from different disciplines. Akin (1986), and Kalay (2004) argued that the starting point for many design methods is the process of searching for a spatial solution to satisfies a set of goals and constraints. Accordingly, a set of approaches has been developed to model the practice of devising potential solutions to architectural problems. These approaches follow trial-and-error search, constraint satisfaction methods, rule-based design, and case-based reasoning. By focusing on these methods this chapter aims to create a relationship between the logic of design methods and computer-based design techniques, ultimately establishing a theoretical framework through which to approach the following chapter. Additionally, these methods relate to techniques commonly applied by research efforts in the mass customization of housing.

3.2.1.1 Search

The process of searching for a solution to a specific problem involves two phases. Candidate solutions are first evaluated against goals and constraints, followed by the selection of an appropriate solution for further development. The process remains in a state of continuous development until a final solution is considered adequate for all requirements and constraints. In the case that a candidate solution cannot be found, the solutions must be created by the designer before evaluation (Jones, 1992).

Jones (1992) outlined a sequence of steps to pursue while solving a problem by a systematic search approach (Figure 3.4):

- Identify the constituents of the problem:
    - Variables that can be manipulated by the designer.
    - Variables that cannot be manipulated by the designer.
    - Objectives and their relative importance.
- Identify the relationship between variables.
- Identify constraints or boundary conditions, thus limiting the values of the variables.
- Evaluate each decision variable with response to its resulting performance.
- Select values for the decision variables that would accomplish the highest value for weighted objectives, resulting in optimum design.

Kalay (2004) noted that the application of search techniques for solving problems has been regarded as an important field in computer science, specifically in Artificial Intelligence (AI). For instance, many problems can be solved through the intelligent application of search algorithms, which explore many possible solutions. Experimentation with AI techniques to solve architectural problems promises to yield a number of computational techniques, which are modelled on reliable design methods available for architectural application.

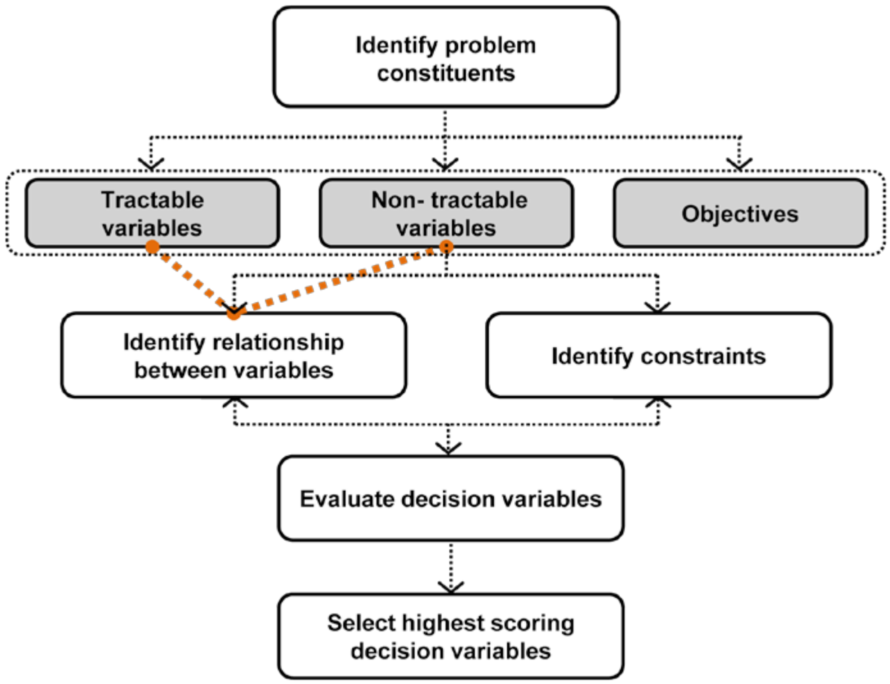

Figure 3.4: Systematic search approach to problem solving by Jones (Source: Jones, 1992).

3.2.1.2 Constraint satisfaction

In some cases, the size of a specific problem comprises a large number of candidate solutions, making it difficult to find a solution that best responds to the stated objectives. Constraints must then be imposed, in order to minimize the solution space enough to find a satisfactory solution. This process is defined as constraint satisfaction, an approach utilized by Artificial Intelligence (Kalay, 2004).

In many architectural design problems, the client, in addition to site conditions, usually formulate constraints. Designers then include additional constraints in order to make the design process more systematic. The logical addition of constraints and the designation of values for design parameters gradually minimizes the solution space and directs the process towards a particular solution.

3.2.1.3 Rule- based design

The rule-based design method is considered to be one of the most reliable procedures for achieving design objectives. Its success depends on the notion of establishing a set of concise rules and then applying them sequentially in order to accomplish specific tasks.

The earliest formalized design method can be traced back to Vitruvius Pollio's *De Architectura* (*Ten Books on Architecture*) in the first century BC (Mitchell, 1990). There, Vitruvius described a set of rules for all aspects of Roman design, including architecture, engineering, and city planning.

In the book *A Pattern Language* (1977), Alexander, Ishikawa, and Silverstein proposed a set of 253 rules that constitute a structured method for design practices capable of systematically approaching complex problems. The book described, in a practical manner, a detailed process for the design of towns and neighbourhoods. The language consisted of a series of patterns that described and categorized possible problems that occur within the built environment, and then presented the core of the solution to such problems. Like all languages, this language of spatial patterns contained vocabulary, grammar, and syntax, which were employed to formalize the process of solving a problem.

Since rules can be employed to describe any well-defined process, rule-based methods have been modelled in programming languages to instruct computers on how to achieve a specific task by following a set of rules. For instance, Mitchell (1990) proposed a logical syntax for architectural design in the form of a design grammar that would be implemented through the theory of computation. However, such an approach to design requires a clear definition of rules, thus limiting it to specific types of problems.

3.2.1.4 Case-based design

The similarities between the goals of many design problems make it possible to solve some of them by following a similar solution-finding process. Though, for instance, site conditions and other design parameters may vary, the main structure and components are almost identical. Case-based design, recognized as precedent-based design, has been applied to many disciplines including architecture, law, medicine, business, and engineering (Jones, 1992).

Within architecture, the capacity to refer to a previous case to solve a particular design problem depends on the similarity between the situation of the targeted problem and that of the reference case. The use of such a method in design is aimed at providing the designer with a foundation from which to initiate and develop the process for the new design. It also aims, like other design methods, to create a comprehensive linkage between the three different phases of the design process: analysis, synthesis, and evaluation.

3.3 The System Approach

System theory attempts to establish a conceptual understanding of systems. It aims to define principles, which can then be pursued to develop all types of systems. Many of the contemporary design problems in architecture are of such a magnitude of complexity that a systematic and rational approach is required. These problems usually comprise a large number of quantifiable and non-quantifiable variables. The system approach is intended to develop mathematical or computational methods, which deal systematically and rationally with the quantifiable parameters of a problem (Mitchell, 1990).

Aguilar (1973) defined a system as a collection of interacting components that work together towards achieving a specific task (Figure 3.5). Systems are sometimes classified according to the context of their application, size, and process orientation. When developing a system, it is crucial to define the nature of the system, the scope of its various components, and the interfaces that connect them. Commonly, a system is aimed at satisfying certain functions, and thus consists of abstract and physical parts, variables, or elements within the system. It also consists of aspects that define the properties of the system and the interrelationship between components. Papalambros and Wilde (2000) proposed system variables, parameters, constants, and mathematical relations between different elements as a set of model elements that are required for all systems. However, a clear distinction between variables and parameters is still necessary.

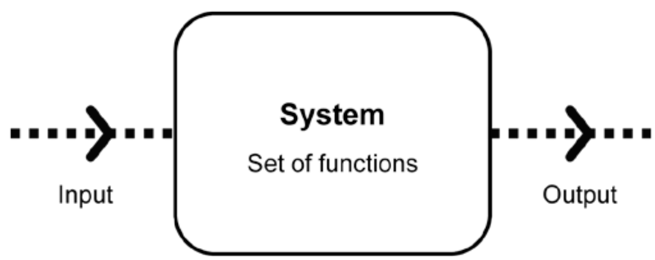

Figure 3.5: System diagram defined as a black box (Source: Aguilar, 1973).

Mitchell (1990) developed a system broken down into inter-connected subsystems that are assigned with specific functions to perform, in addition to the functional connections between different subsystems (Figure 3.6). Depending on the complexity of the system, subsystems can also be divided into numerous components, breaking down the system into a lower-level functional organization. In this way, the functions of each subsystem can be described through specific procedures, and then simulated by a computer model.

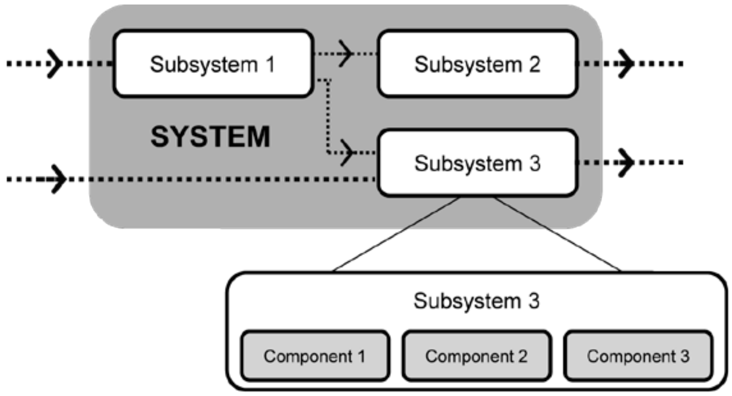

Figure 3.6: The organization of a system (Source: Mitchell, 1990).

The structure of a system and its subsystems can be broken down through either discrete or overlapping methods (Figure 3.7). In the case of a discrete structure, the relationship between the system, subsystems, and components is hierarchical. On the other hand, an overlapping structure represents a non-standard interconnection between components. In most cases, complex problems require overlapping and interlocking subsystems (Mitchell, 1990).

To devise a relationship between design and systems, Papalambros and Wilde (2000) considered the design itself as a system, defined by the geometric configuration, materials, and its assigned task. Considered in this way, design can be modeled mathematically, as models are developed to provide a good understanding of how systems work. Modeling a design mathematically involves assigning a particular value to each quantity, and then creating a mathematical relation to represent and evaluate the performance of a task.

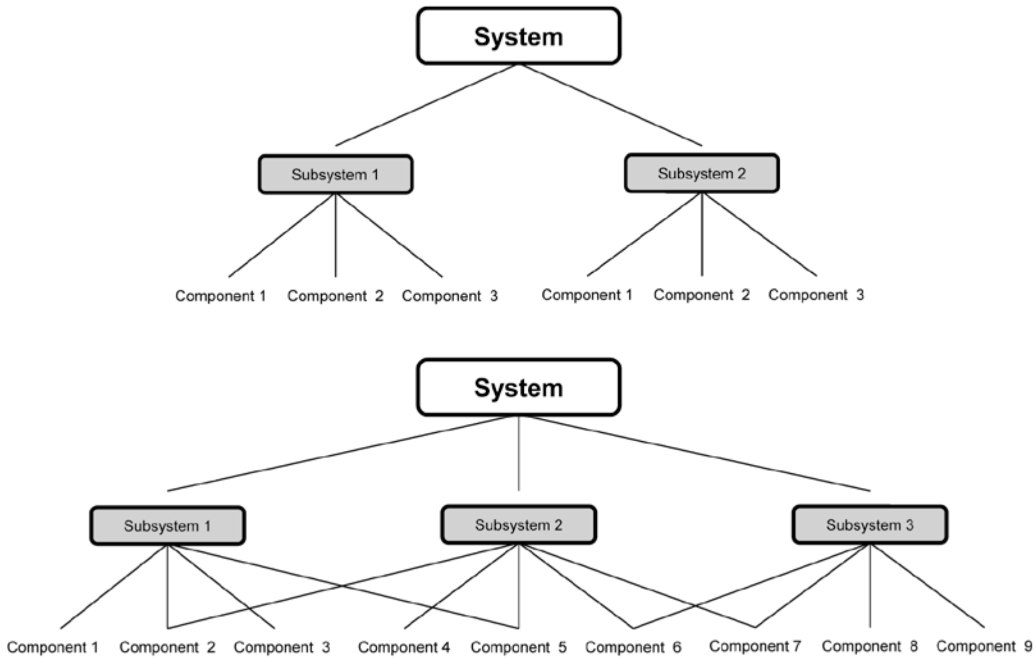

Figure 3.7: Different ways to break down a system, hierarchical subsystems, and an overlapping subsystem breakdown (Source: Mitchell, 1990).

3.3.1 System design

System analysis is an important step in understanding how a system is formulated. Aimed at assisting in the decision-making process, system analysis involves a detailed examination of the system in order to understand its nature and determine its essential features, especially via breaking down the whole system into its fundamental components. An alternative definition of system design is the process of selecting components, steps, and procedures to be pursued when producing a system, which would optimally address and resolve a problem. Every system has an architecture that is deeply interconnected by a sequence of inputs/outputs, and organized by a chain of influence and hierarchy in in relation to with the environment (Aguilar, 1973). Accordingly, system design can be considered to be an interdisciplinary process integrating concepts from system analysis, system architecture, and system engineering.

According to Aguilar (1973), there are important elements to consider when developing a system for complex problems:

- *A set of decision and state variables*: Set variables are under the complete control of the designer, while state variables are dependent on decision variables.
- *An optimization model*: Necessary to understanding the problem, this model involves analysis and synthesis, and consists of the development of a conceptual model designed to quantitatively evaluate a solution.
- *Measure of effectiveness*: Also called objective functions, it aims to evaluate the degree of success in fulfilling established goals.
- *Generation of alternatives and optimal solutions*: This is a methodology for generating both design alternatives and near optimal solutions.

Computer-based design systems were introduced to the architectural realm in the 1960s, along with the development of systems theory in computation by Von Neumann "*Von Neuman Architecture*" (Cross, 1977). Researchers explored the potential for employing computer-based design systems towards the objective of partially or fully automating the design process, in order to assist in both the analysis and synthesis phases of design. These efforts emerged concordant with a similar trend that was largely concerned with the systematization of the design process.

With recent developments in software platforms, computers are deployed with increasing frequency throughout the design process, offering intelligent knowledge-based processing of architectural information. Computer-based design systems attempt to model the design process, and refer to a specific design method in order to create a product (Figure 3.8).

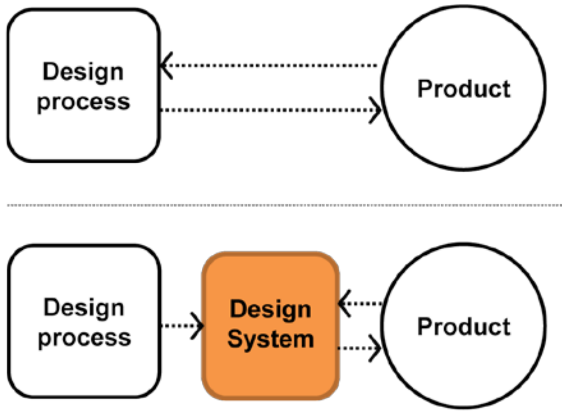

Figure 3.8: A design system should trace the design process to produce a solution**.**

While early studies of computer-based design systems employed computational tools in the design process, recent efforts have focused more on the computational tool, rather than the process itself. Coates (2010) argued that the recent application of computational techniques in architecture is considered to be very different than the methods developed in the late 1960s. In actuality, critically analyzing these approaches reveals that many of these ideas are conceptually analogous, with the primary differences residing in the computational methods, implementation models, as well as the coding and visualization strategies utilized. This in fact is an outcome of accessible software platforms that are offering designers a new perspective for solving problems. For instance, visual programming plug-ins open new territories of exploration in design, while not requiring experience in scripting or coding. Additionally, open-source programming languages have given designers access to a wide variety of pre-tested programs, which can be used independently, or as components of a complex program.

Computer-based design systems operate through different methods. Mitchell (1990) proposed that the process of finding a solution for a design problem through computation is, in some cases, a trial-and-error process. It is initiated by applying rules to generate candidate solutions, followed by computing predicates, in order to determine whether proposed solutions are acceptable (Figure 3.9). This process is commonly known as a generate-and-test process, which takes place in a search space.

In such a case, the position of synthesis in the design process shifts to the beginning, to be followed by analysis and evaluation. For a computational system to perform such a process, it requires a mechanism for generation, evaluation, and control. The focus of this thesis is to develop a computational design process rather than a tool. Therefore, a methodology to formalize design systems for mass customization is necessary, in order to examine the process by which computer-based design systems are developed for architecture.

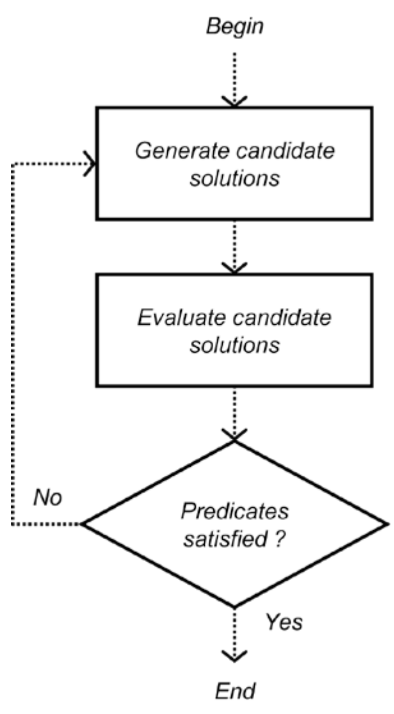

Figure 3.9: The basic trial-and-error structure of the design process (Source: Mitchell, 1990).

Krauss and Myer (1970) explored the required characteristics of CAD systems in order to assist a building designer, and proposed the following characteristics:

- The system should focus on geometric form.
- The system should permit the designer to select the scale at which to operate.
- The system should tolerate the processing of a large number of variables.
- The system should keep the designer in close contact with the problem-solving process.

Cross (1977) stated that the process of designing a design system primarily requires a clear definition of the design problem so as to produce a description of the system's objectives. Cross then proposed a comprehensive CAD System Checklist as a generalized systematic appraisal, to be applied by architects and CAD system designers before implementing a computer-based design system. The checklist was divided into sections, and each focused on different aspects of the design process in relation to human-machine interaction. The checklist's components were as follows:

System Design

How will the particular computer system be chosen?
What criteria will be used to select the system?
Who will be responsible for deciding on the particular system?
Who are the system designers and what is their experience and background?
What are the objectives of the system?
What is meant to be achieved?
Why is it being implemented?
What functions will the system perform?
How will the system functions be selected?

Efficiency

How are the expected increases in the efficiency of the design process and the reduction in man-hours predicted?

Design Process

What structure for the design process does the computer system assume and impose?
On what model of the design activity is the system based?
What structure to design problems does it assume?

What approach to design and problem-solving does it require its user to adopt?

Design solutions

What constraints will the computer system impose on the kind of buildings that can be designed?

What limitations are there on the shapes, forms, and arrangements that it can handle?

Relations with clients and other users

How will the computer system affect the designer's relationship with the project client and the building user?

Will the clients be able to participate in the computer-aided design process?

Will the computer system tend to 'democratize' or to 'bureaucratize' the design process? (Cross, 1977).

Additionally, Cross (1977) suggested a series of procedures to be adopted when developing a design system. These were based on the identification of functions to be performed by the system, and on the interaction of these functions in relation to the performance of both humans and machines (Figure 3.10).

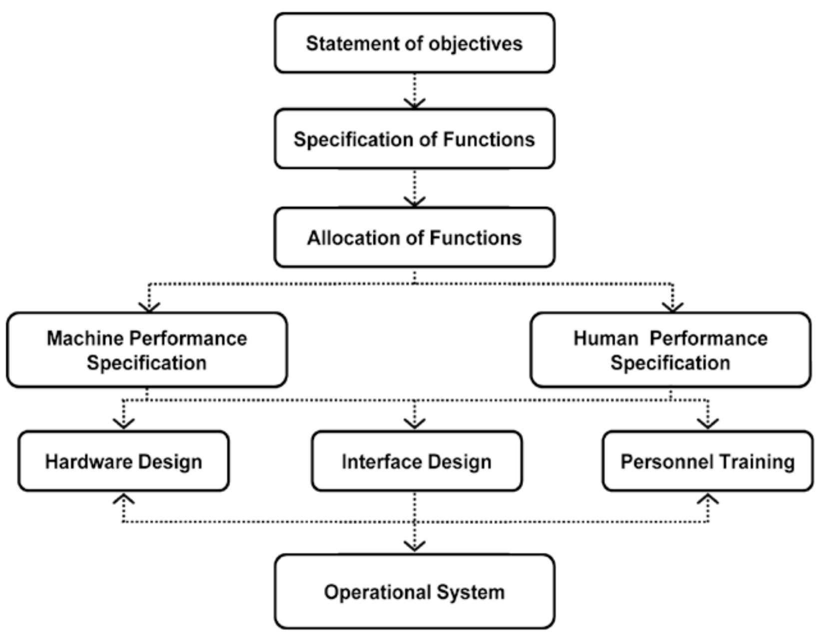

Figure 3.10: A process for the design of a computer- based design system (Source: Cross, 1977).

Following a different approach, Jones (1992) outlined the steps of a system design method that would achieve internal compatibility between various components of the system and its environment. These steps rely on a clear definition of the system's input, on functions that would transform input into output, on components capable of performing each function, and ultimately on the desired outcome of the system. Although the outline included the essential steps for designing a system, such a process can encompass enormous complexity and vast scale. Accordingly, one of the major difficulties that system designers face is how to partition a system into subsystems and components. Later, Cross (2001) came to re-examine how the machines could perform in the design process, requiring a closer look at the role that human design cognition played in designer-machine interaction, in order to construct efficient computational design systems.

Suh's (2001) axiomatic design presents one plausible system theory that might be pursued when designing for mass customization. Developed around the systematic analysis of the conversion of Customer Needs (CNs) into Functional Requirements (FRs), Design Parameters (DPs), and Process Variables (Pvs), axiomatic design is aimed at designing the principles of complex systems through the analysis of a problem's complexity, and then exploring the decision-making process. Within this framework, the first step to designing a system is to define the CNs, (the attributes defining the customer domain), that the system must satisfy. The FRs and Constraints (Cs) of the system in the functional domain are subsequently defined to satisfy these customer needs. Afterwards, the FRs of the functional domain are mapped onto the physical domain in order to identify DPs, which can be physical parameters or code modules. Once the DPs are defined, designers proceed to the process domain and identify the PVs, so as to determine whether it will be necessary to create a new process or whether an existing process will suffice. Accordingly, axiomatic design is the process of mapping between domains and developing a hierarchy from the system level to the detailed component level. Mapping here can be defined as the process of translating customer needs into technical specifications or functions (Suh, 1998, Alfaris, 2009).

While these aforementioned concepts could be considered outdated, they nonetheless demonstrate a valid approach to systems design and represent fruitful avenues for the exploration of what a design system could offer.

3.4 Reflections

The study of mass customization theories and approaches has revealed that a mass customization system would typically be composed of various subsystems, representing enablers of the process. In processes where a high level of customization is aimed, thus dictating a more complex solution space, a key subsystem would be tasked with providing customers with product variants, or a solution space to explore a product.

Within the context of housing computer-based design subsystem is required for the generation of housing solutions and must respond to homebuyer profiles. A study of design systems proposes the synthesis model as the core component of such a subsystem. Commonly defined as generative models, synthesis models are utilized to assist human designers in generating solutions for complex design problems by adopting a robust computational approach. These models simulate design processes and methods by encoding design knowledge into a computer system. Figure 3.11 illustrates a proposed breakdown of a mass customization system into its subsystems and components. The following chapter will explore various generative design models and techniques.

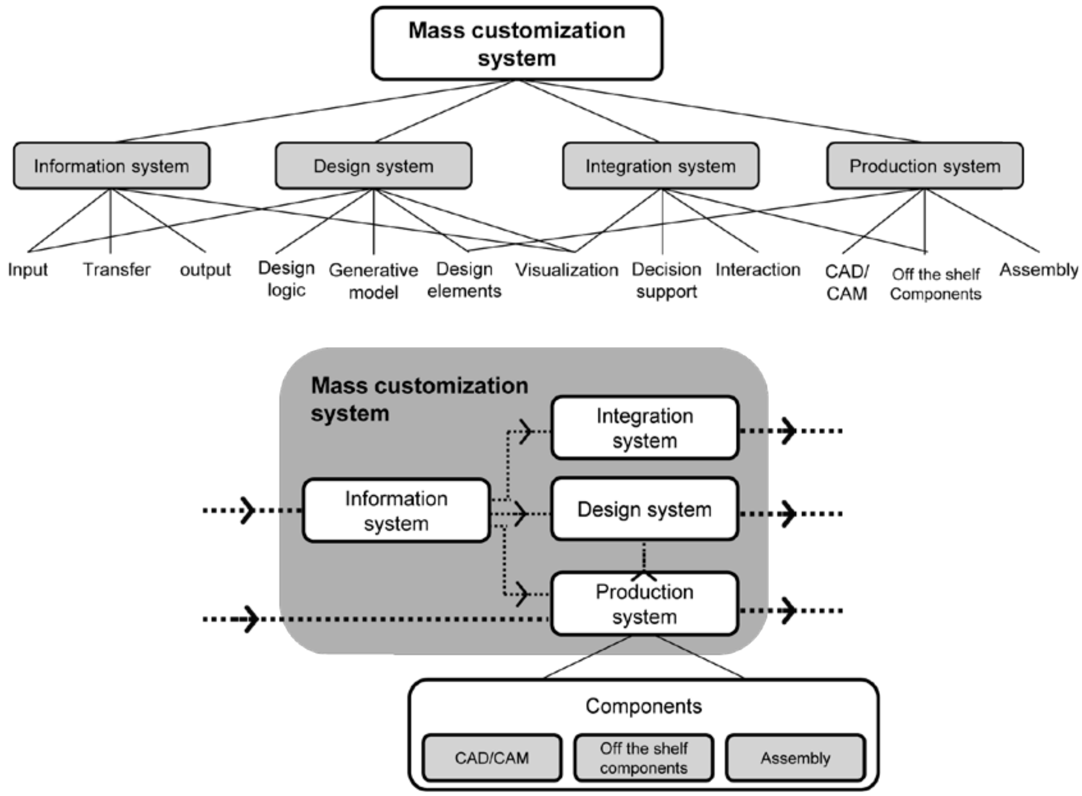

Figure 3.11: A diagrammatic breakdown of a proposed mass customization system into sub- systems, and components of each subsystem.

4.0:
Generative design models

4.1 Introduction

Structuring a design system for the mass customization of housing requires a clear understanding of that system's objectives, in addition to the different functions of subsystems. While many different design systems have been proposed to enable the customization of housing, the structure of these systems has traditionally been derived from the nature of the problem and from the intended goals, especially with regard to the level of customization, housing typology, construction system, and desired outcomes. The functions of the design system fundamentally evolve from the nature of the system's underlying, generative model.

This chapter explores various generative design models and techniques in order to develop a nuanced understanding of how these systems operate as synthesis models. A review of computation literature within the realm of architecture has presented a wide classification of generative systems with different terminologies, dating back to the development of computation techniques in design synthesis. This chapter's primary focus, however, lies in the systems that have demonstrated potential applications in customization research, along with other approaches that show promise for enabling homebuyers' participation at early design stages. Figure 4.1 illustrates the structure of this chapter within the macro organization of the thesis.

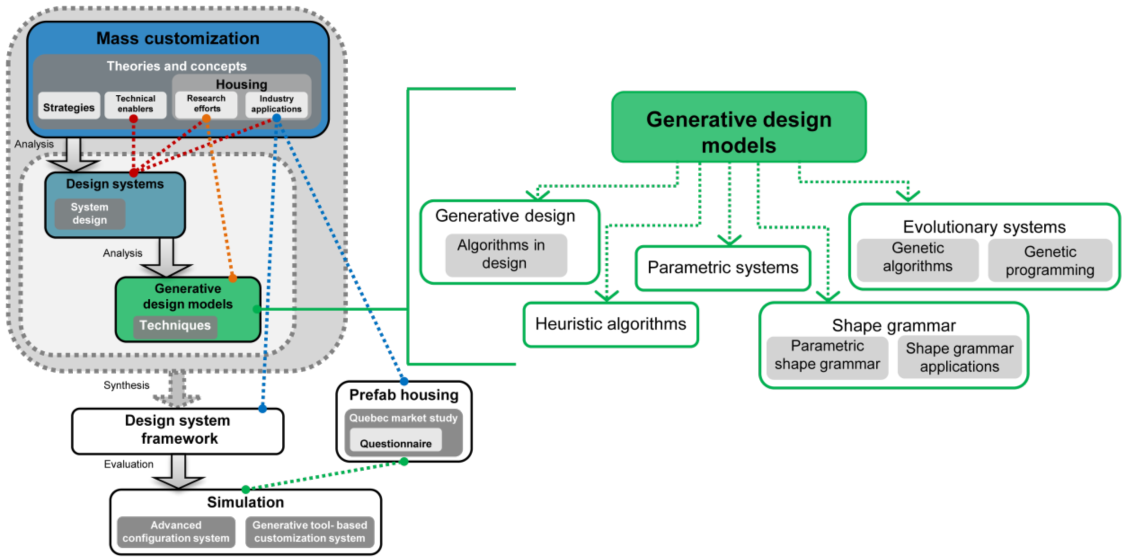

Figure 4.1: Diagrammatic representation of the chapter's outline, in relationship to research structure.

4.2 Generative Design

Constructing, then operating a generative system stems from the numerous benefits gained from producing many potential solutions to a given problem. This concept can be traced back to Aristotle, who described how the design of cities could be generated by deconstructing urban centers into their essential parts, listing the alternatives for each part, and then constructing speculative possibilities out of different combinations of these alternatives. Since Aristotle, generative systems have been deployed in multiple spheres, from fields such as philosophy to literary and music theory, to the development of engineering (Mitchell, 1977).

Within the discipline of architecture, a generative system is defined as an approach to developing applications that can generate, evolve, or design objects, architectural structures, or spaces with greater or lesser degrees of autonomy (Krause, 2003). The methodological use of generative systems in architectural design can be traced back as far as Leonardo da Vinci's work[1] on a schema for generating central-plan churches. More recently, the progression of computational techniques in architecture has shifted the means by which generative systems operate. New forms of generative models have offered architects and designers a vast range of problem-solving techniques. These systems can function upon different levels of autonomous actions, ranging from fully automated processes to step-by-step user-controlled tools. Such systems involve diverse procedures and steps, beginning with a decision of design rules, then adjusting starting parameters and shapes, subsequently navigating the derivation progression, and finally selecting the most suitable alternative.

4.2.1 Algorithms in design

Algorithms[2] form the core component of all generative design systems. They are malleable, able to deal with any type of unit within a system, and may have either fixed or flexible definitions. In computation, algorithms manipulate discrete units with fixed descriptions, identities, or boundaries. These units may consist of numbers, alphabets, or geometric elements, which are then used to compose functions or equations. The resultant collection of functions, including subtraction, addition, and other mathematical operations, leads to the development of techniques to achieve certain tasks. These techniques are defined as methods, which can be grouped and made to generate specific types of units. Accordingly, an algorithm can be regarded as a collection of

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[1] As described by Historian Paul Frankl (1968), da Vinci realized that if he began with simple spatial forms (square, octagon, circle, or dodecagon), he would arrive at a very conceivable central-plan church by automatic addition of circular, semi-circular, or octagonal ancillary spaces to the principal and cross axis of the basic shape. Later on, the means of classical approach to architectural design was formalized in the textbooks of Ecole Polytechnique and the Ecole des Beaux-Arts during the 19th century (Mitchell, 1977).

[2] An algorithm is a procedure for addressing a problem in a finite number of steps using logical if-then-else operations. It is either an expression of systematic problem-solving procedures, or a stochastic search towards potential solutions to a particularly known problem (Bohnacker et al., 2012).

methods that employs randomness, probability, or complexity- the outcome of which is undefined and unimaginable. They are systems that propose the means for the exploration, codification, and extension of the human mind, rather than its interpretation (Gero, 2006). Figure 4.2 illustrates an abstract process of a generative algorithm.

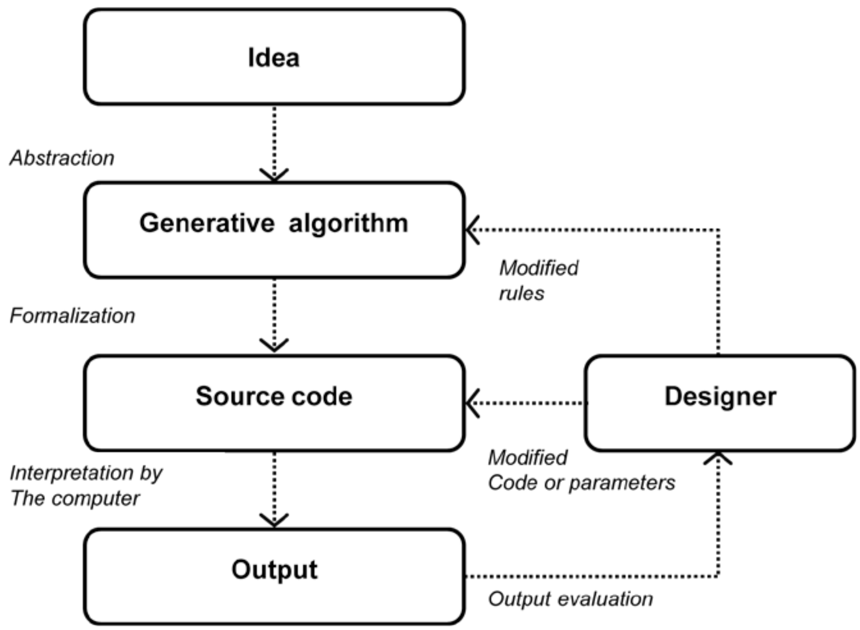


Figure 4.2: A diagrammatic representation of a generative algorithm process (Source: Bohnacker et al., 2012).

Algorithms also have their own vocabularies. The main linguistic components used in algorithms are constraints, variables, procedures, and libraries. An algorithm's basic operations are arithmetical, logical, combinational, and rational, and are arranged under specific grammatical and syntactical rules. These components are structured to accommodate the numerical nature of computers and the linguistic composition of logical models. When designing an algorithm, a designer may decide to employ fixed or changeable units, all of which have to be stored in units called placeholders. A fixed unit placeholder is called a constant, while a changeable unit placeholder is called a variable. A second-order, constant placeholder is a parameter. In order to control the operation of an algorithm, constraints must be introduced to diverging values. If applied inaccurately, constraints may eradicate potential solutions or interrupt the generation process (Zee & Vries, 2008) and (Terzidis, 2006). A further explanation of these terms is as follows:

- *Variables and parameters:* Variables are used to store values that are continuously changeable within the design process, while parameters are measures that are used to represent some characteristics of a modeled object, and can be linked to other factors. Parameters are considered to be more static, and, in some cases, can be regarded as constants that change only in cases where the object itself needs to be modified.
- *Constraints:* These can be defined as the restrictions on the degree of freedom within the process of finding a solution to a specific problem. Each constraint has to be considered carefully as it represents a potential way of controlling the design process.

Similarly, design can be perceived as a set of procedures leading to a solution to a specific problem. Rather than emulating manual design methods, algorithms can be developed as methodologies in and of themselves, complementing the human mind and thus extending its capabilities. For instance, within the realm of architecture there are some problems whose complexity level, vagueness, or array of potential solutions makes them difficult to handle through traditional techniques. In such a case, algorithmic strategies can offer assistance by ensuring a synergetic relationship between the human mind and its external concerns. The role of algorithms in design is highly variable, from exploration and organization to solving problems with increasing visual or structural complexities (Kalay, 2004).

Since algorithms are flexible, they can address numerous problems. A well structured algorithm, equipped with different parameters, can produce new and unexpected behaviours. When composing an algorithm for an architectural problem, design intentions, parameters, and variables are encoded into a symbolic language. The latter's vocabulary and grammar depend on the interaction between the human designer and the computer. This may include a description of quantitative components such as the required area, number of units, or geometric description of an object. Conversely, designers may also decide to formalize qualitative properties. This type of mapping is considered more difficult because it demands greater detail and different techniques for evaluation. In either case, an algorithmic design system requires the input of components to be interpreted, and subsequently generates various types of outputs, such as geometrical descriptions and properties (Zee & Vries, 2008).

Commonly, the structure of an algorithm largely depends on the problem for which it was designed. Accordingly, the most crucial factor of an algorithmic problem is that the problem must be describable and solvable through computation. In some cases, the operation of an algorithm reflects the human mind's way of thinking. As such, designs can be explored as mental processes by monitoring human behaviour over the course of a subject's interaction with a machine. The resulting algorithm will contain a complete set of instructions to be carried out by the computer without any human intervention. Until the first set of results is obtained, the decision-making mechanisms are largely built within the machine itself.

There are various synthesis algorithms that demonstrate potential significance in the synthesis phase of the design process. The application of any of these algorithms depends mainly on the problem, its complexity level, and the degree of creativity called for in the desired solution.

4.3 Heuristic Algorithms

Design synthesis methods are usually inspired by analogies and guided by architects' preceding expertise, which is gathered via tackling diverse design issues. The formalization of such methods, which draw upon fairly accurate knowledge, has been the base for heuristic methods and adaptive procedures. Mitchell (1975) described heuristic programs as akin to searching through a tree: root nodes represent initial solutions, alternative design decisions are present through branches, and finally terminal nodes represent final designs.

Heuristic methods are structured on experience and the notion of *trial-and-error* methods for finding a solution. Such techniques are similar to the *search-and-evaluate* process applied in architecture. In adaptive procedures, the computer accrues knowledge by establishing a database containing information based on external surveillance of the designer's conclusions. This approach became the basis for what was later defined as *expert systems*, in which expertise and knowledge about a specific topic are codified into a set of rules (Kokash, 2006).

Architectural design has a higher complexity than many other design processes, due to the difficulty of codifying multiple design elements. Accordingly, an architectural heuristic procedure not only depends on the information pertinent to the particular problem, but also on information that evolves during the search process, resulting in further decision-making on the part of the designer. However, heuristic methods cannot guarantee that the solution they produce will be the optimal choice. The reasoning of these algorithms may not be accurate, and the knowledge upon which they depend may contain logical gaps and discrepancies. These algorithms are therefore deployed to find a solution that is close to the best possible answer. Thus, heuristics examine problems in a holistic way, fundamentally derived from human observation and experience (Mitchell, 1990).

There are numerous heuristic methods for synthesizing solutions, some of which have been successfully applied in architectural design. These programs, which operate on the basis of analogical reasoning, were inspired by AI research. They were predominantly employed in space layout planning on different levels of complexity. These methods could be classified as follows:

- *Case-Based Methods*: A common method for finding new design solutions lies in adapting a previous solution from a similar case for the needs and circumstances of a current problem. Case-Based Reasoning (CBR) is a model of design that seeks to generate design solutions based on prior solutions from analogous and complete design problems. It employs design experience in the form of episodes rather than compilation or generalization. Designers accordingly tend to reason from past experiences rather than first principles. It is a subfield of AI that has tried to formalize and integrate the use of pragmatic knowledge, represented as cases within computers. A case typically consists of a problem definition, a solution, and an outcome. These three components create the basis for generating an index, which is later used to retrieve cases from a database. The process model for Case-Based Reasoning involves the following operations: (1) recall relevant cases from the case memory; (2) select the most suitable case; (3) construct a solution to the new problem; (4) test the solution; (5) evaluate the result; and (6) update the case memory with the new case. The adaptation process is interactive in a way that allows the designer to make modifications. However, the application of Case-Based Reasoning to the process of design synthesis requires a large design memory case, and thus the recognition of the relevance of each case, as well as its similarities to the design problem being addressed. Nevertheless, this method has been explored in many areas, spurring the development of numerous algorithms and programs (Maher, 1990).

- *Expert Systems*: Considered to be one of the most successful AI methods, Expert Systems are computational constructs that capture and represent the knowledge and experience of previous designers in the form of design rules, rather than in the form of cases. Consequently, they can offer interesting solutions to complex problems and even accommodate the addition of new knowledge. An Expert System's knowledge is usually encoded as rules in the form of IF-THEN couplets, each one representing an attribute of the problem or its solution. The collection of all rules is defined as the system's knowledge base, wherein its structure is classified at the Expert System's convenience. Such a system's operation is incremental- new rules may be added to expand the system's capabilities as more experience with the system is gained over time. The mechanism of applying the Expert System's rules is similar to the process of human logical thinking, as conclusions are developed on the basis of given facts. However, like other heuristic methods, Expert Systems cannot guarantee the arrival of an optimum solution for any given problem (Kalay, 2004).

4.4 Parametric Systems

By creating digital design environments with the use of hierarchal-based structures, one's design history can be recorded and listed. System tools allow for the variables presented at any step to be retroactively modified at any point in the design process. These capabilities are achieved through establishing a direct relationship, sometimes called a "parent-child", within the digital model's various elements. Subsequently, any further components added to the model either become attached to the whole structure or a parent whose characteristics are resultantly altered. If at any point the parent structure undergoes change, the children follow suit. This relationship is unidirectional, however. Changes to the child element do not affect the parent. A user can intervene within this hierarchal structure at any point. Parametric systems are based on the idea of synchronization between design elements, ensuring that various design elements can be formally interrelated and altered in a coordinated way (Woodbury, 2010).

While Woodbury (2010) defined many different approaches to representing parametric systems, graph-based approaches (Figure 4.3) and propagation-based systems are among the most interesting. A graph-based approach represents objects as nodes in a graph with their constraints evident as links between these nodes. Conversely, propagation-based systems are derived from graph-based approaches. Among the representations of parametric systems, they are considered the simplest. They presume that the user has already organized a graph in order to directly solve a problem. Objects are then structured in a directed graph so that known information is oriented upstream from unknown information. The system then propagates from known variables to help compute the unknowns.

While propagation-based systems excel in their simplicity, a more flexible and responsive methodology can be found in parametric variation, which can occur at any level of the design process. Parametric variation is accomplished by developing systems that are constraint-based and dimensionally driven. Additionally, specific rule structures, including formulas, are usually employed. Constraints may take the form of dimensions, angles, or several other relationships between these elements. Throughout a complex design process, some specific values may be fixed while other parts are repeatedly varied. These capabilities and qualities of design manipulation shape the platform for highly responsive digital environments (Schodek et al., 2005).

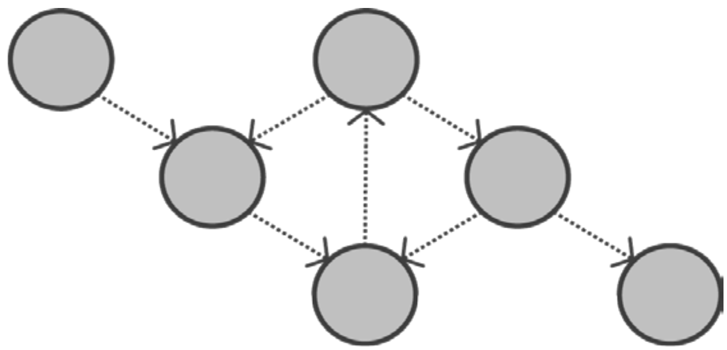


Figure 4.3: A graph has a collection of nodes joined by links. In a directed path, links join predecessors to successor's nodes. This graph is both directed and cyclic (Source: Woodbury, 2010).

Parametric design systems can be classified as a specific case of algorithmic systems. They were developed to overcome the limitations of conventional CAD software, and handle variations within various design and production environments. Within research on synthesis and generative models, parametric systems are sometimes classified as a dynamic feature of generative models. Almost all generative models can be parametric, as this categorization depends mainly on the implementation technique, thinking and coding.

With the introduction of new parametric software and its growing capabilities for geometric modeling (including CATIA, Generative Components, Solid Works, and Grasshopper for Rhinoceros) the notion of parametric design has prompted the interest of many designers and architects. Through the operation of this kind of software, architects and designers have able to generate geometries, configure data within hierarchies, and create dependency through relationships. This software is able to deform and control objects' properties by manipulating relationships, constraints, dimensions, and other parameters that may include building regulations, codes, and know-how principles. The true power of parametric systems, however, lies in the parallel development of fabrication technologies that enable mass customization.

4.5 Shape Grammars

Shape grammars are rule-based geometrical constructions for generating shapes based on distinct compositional rules. They are a specific class of production systems that describes how design can be generated from an initial shape through the recursive application of shape rules. The theory of shape grammar was first articulated by George Stiny and James Gips (1972) who illustrated the concept in an analysis of the original languages of artworks. This approach was subsequently elaborated in their 1978 book *Algorithmic Aesthetics.* By virtue of their work, shape grammars became an established paradigm in design theory, CAD, and other related fields. They were thus pioneers in formalizing a methodology for interpreting and creating design through computation with shapes instead of text or symbols.

Shape grammars consist of a vocabulary of shapes, a set of shape rules, and an initial shape. The rules, which are shown on the left-hand side of its visualization, are transformed and subsequently displayed on the right. When implemented, the computer becomes capable of handling the continuous tasks of shape computation, as well as rules, grammars, and the various design alternatives. The designer, conversely, specifies, explores, and develops design language, and finally selects the appropriate alternatives. According to Tapia (1996), the process of developing and employing the shape grammar can be divided into three logical phases (Figure 4.4):

- *Creating and modifying the shape grammar*: The designer sets up the rules and initial shape, and then specifies and changes the special and logical constraints.
- *Compiling the grammar*: While converting the grammar into internal forms, systems ensure that each rule always applies in only a finite number of ways.
- *Exploring the language of designs defined by the grammar*: The designer explores the language of designs, while generating designs, imposing additional constraints, backtracking to a previous design, or saving the current state. The designer may interpret the resulting design in a curvilinear form, and start using it as the basis for a new design.

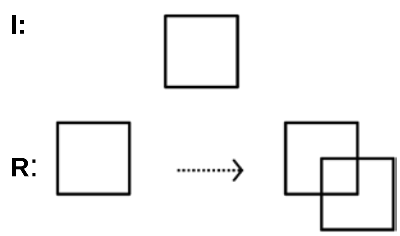
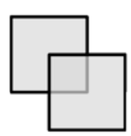
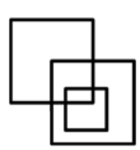
	This simple shape grammar generates forms on an orthogonal grid. The initial shape could be a square (**I**). The rule (**R**) specifies possible shape replacement operations, joining two shapes: a pattern, a square, and its replacement, the same square with the addition of a copy.
	Applying the rule to the initial shape yields a shape containing three squares: two the same size as the initial shape and one half the size, which emerges from the two.
	Applying the rule to the smallest square yields squares of three sizes: two the same size as the initial square, two half that size, and one a quarter of that size.

Figure 4.4: A simple grammar representation (Source: Tapia, 1999).

4.5.1. Parametric shape grammars

The concept of parametric shape grammars is based on the creation of parameterized rules, so that each rule represents a set of rules. It can be demonstrated thought-sequentially through five elements, which are called five-tuple (S,L,T,G,I). S is a set of shape transformation rules (in the form of A→B), which specifies that whenever a shape A is found in the design, it can be substituted by shape B. L is a set of labels that are employed to manage computation. T is a set of geometric transformations (rotation, translation, scaling, or any combination of these). G is a set of functions that assign parameters in rules. And finally, I is the initial shape to which the first rules are applied in order to start the shape derivation process (Knight, 1990) (Duarte, 2001).

4.5.2 Shape grammar applications

Shape grammars have been applied through two main methods: analytical and original. Analytical grammars were developed to describe and analyze historical styles and languages of designs. The first such grammar in architecture was that of Palladian villas (Stiny & Mitchell, 1978), which was followed by several others over the past twenty years, including Frank Lloyd Wright's Prairie house grammar and its three-dimensional compositional principles (Koning & Eizenberg, 1981). To create this kind of grammar, analytical studies using sets of existing designs are deployed to study and codify the language-corpus and rules germane to the system. The resulting grammar is then tested using the rules, in order to generate a design in the corpus and new designs in the language. Original grammars, conversely, focus on the creation of new and innovative styles of design without historical precedents. This is achieved by creating a new vocabulary and set of rules from scratch. The advantage of such an approach is that considerably complex results can be generated from a simple vocabulary and minimal rules. As such, shape grammars can be very useful tools for design innovation.

Shape grammars derive their generative advantage over other synthesis methods from their deterministic nature, wherein at each step of the process the designer can choose the rule to be applied. As a result, shape grammars allow for emergence: the ability to distinguish and operate on shapes that are not predefined, but rather evolve from several parts of shapes throughout the application of rules (Knight, 1999).

Since its development in the 1970s, there has been ongoing research into various aspects of shape grammar formalisms. For example, Duarte's (2001) exploration of Alvaro Siza's Malagueira houses made great efforts to demonstrate the generative application of shape grammars. Based on his research, Duarte applied this process to a proposed framework for customizing mass housing.

4.6 Evolutionary Systems

Evolutionary design is a process that has the ability to generate and evaluate various design alternatives. It expresses a technique inspired by evolution in biological systems. Natural evolution is the primary reference point for any evolutionary system, and has inspired human designers throughout history. Biological designs exceed those by human hands in complexity, performance, and efficiency. As such, biological systems can be a rich source of inspiration and potential solutions for the development of new methodologies in problem-solving (Bentley, 1999).

Within the field of computation, evolutionary design systems are expressed as advanced algorithms, and are employed by designers to automatically improve the performance of design processes. Such algorithms set the stage for numerous creative solutions, as they possess the ability to generate and suggest new design alternatives for a specific problem. Evolutionary algorithms are in some cases classified as heuristic algorithms, due to their search-oriented nature. They define a computational problem in terms of a search, in which the search space contains all possible solutions and a point in that space defines a solution. Evolutionary search algorithms express their full potential by simulating the process of natural selection and reproduction on a computer, thus shaping the evolution of solutions in response to a problem. These algorithms therefore consider a large group of solutions at once, rather than working with only one solution at a time (Bentley, 1999).

Evolutionary Algorithms (EA) employ regulations, in order to direct evolution towards more advantageous areas of the search space. This is achieved through evaluating every solution in the population, in order to determine its fitness (a mark that defines the degree of success in fulfilling the problem objectives, calculated by the fitness function). Fitter solutions are then further developed, with the intention of finding the optimum solution. Depending on the problem complexity level, however, reaching an optimum solution through this method may prove difficult.

Bently (1999) identified four main types of evolutionary algorithms in use, three of which were independently developed around forty years ago:

- Genetic Algorithms
- Genetic Programming
- Evolution Strategies
- Evolutionary Programming

Evolutionary computation is an important field of study, proving to be flexible, efficient, and robust. Throughout the literature on this subject, it is apparent that only the first two types of algorithms have been widely employed on different levels in architectural design. Accordingly, the following section will focus on discussing genetic algorithms and genetic programming exclusively.

4.6.1 Genetic algorithms

The technique of genetic algorithms was developed principally for problem solving and optimization for problems with clear definitions and explicit criteria to be fulfilled by successful solutions. Genetic Algorithms were developed by John Holland in the 1970s, in an effort to formally understand biological adaptation in nature. The main strength of these algorithms as a design principle is that they do not require an optimal solution generation method, but rather rely on the generates-and-test method (Eiben & Smith, 2003). At their heart, they are search systems for finding optimal solutions. In most cases, a near-optimal solution is provided and the task of improving the solution is classified as a search problem.

The process of genetic algorithms simulates the behaviour and adaptation of a candidate solution over time as generations are created, tested and selected through repetitive mating and mutation (Figure 4.5). Such algorithms employ stochastic search procedures. Bently (1999) stated that genetic algorithms use two kinds of abstract spaces: firstly that of the search space of the genetic algorithm, which comprises all possible coded solutions, or *genotypes* of a given problem, and secondly that of the space of actual solutions: the solution space. The genotype is a set of coded parameters that describe the *phenotype*, which is the population of solutions. A coded parameter is referred to as a *gene*, while the possible values of a gene are defined as *alleles*. Fitness functions are used to select the fittest phenotype from within the population of candidate solutions. Their corresponding genotypes are used to create new and possibly enhanced populations of solutions, through mating and mutation. The evolution process is guided by fitness assignment. Genetic algorithms require regulation to direct evolution towards better areas of the search space. This is achieved through evaluating every solution in the population to determine its fitness, and then enabling the fittest solutions to survive and reproduce themselves.

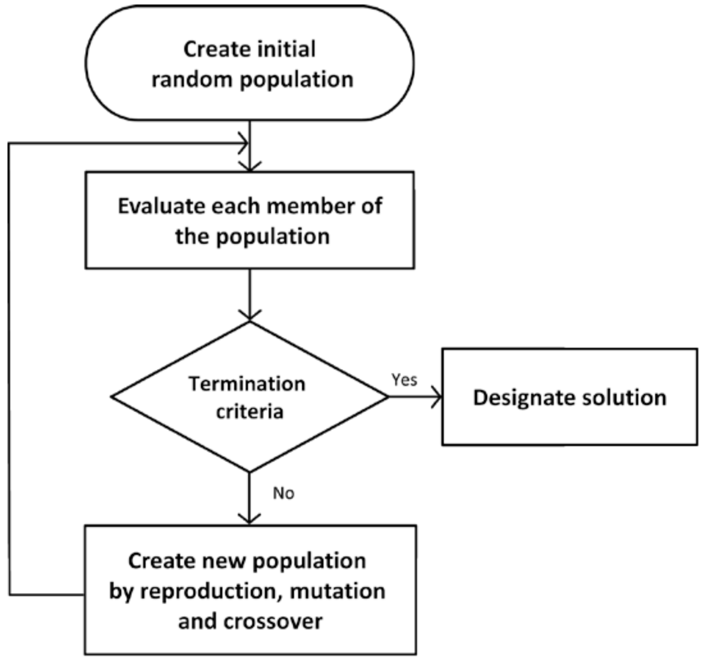


Figure 4.5: The process of a genetic algorithm (Source: Eiben & Smith, 2003).

4.6.1.1 Genetic representation

Representation serves as a link between the problem context and problem-solving space. In this context, individual units presenting possible solutions within the original problem context are defined as phenotypes, while their encoding and encompassing properties are defined as genotypes (Eiben & Smith, 2003). In this system the initial design step, representation, is aimed at defining mapping from the genotypes into a set of phenotypes. The ordinary representation of the genotype is a series of coded instructions stored in an array of bits called chromosomes. A phenotype is thus the interpretation of a genotype at the physical level. Consequently, it is important to choose the appropriate representation method to solve the problem.

This process begins with an initialization algorithm, which produces a set of solutions, defined as a population. The initial population is generated randomly and should cover all of the search space. Based on the nature of the problem, the population size is established with the aim of containing a sufficient amount of diverse elements. Accordingly, the initial population must be large enough to offer a varied pool of potential solutions in the search space. However, this process may be time-consuming, as a large population requires repeated generations.

4.6.1.2 Fitness evaluation

A fitness evaluation function serves to assign quality measures to genotypes, thus seeking to evaluate how the system's predefined preferences have been met. It is composed of a set of quality measures in the phenotype space and in its inverse representation.

There are three methods for evaluating individual units: automated, manual, and hybrid. The automated method evaluates the population by a set of fitness functions, which are embedded in the algorithm and referred to as a weighted sum. It applies a weighted linear combination to individuals over the course of their evaluation, wherein the total fitness value is equal to the total weighted sum of the partial fitness value, and parents for each offspring are selected according to ranking.

Manual evaluation, conversely, enacts something of an eyeball test, wherein a user must rank phenotypes manually as they are displayed on a screen, selecting for the fittest. This concept introduces the idea of evaluating phenotypes not only according to fitness, but also to artistry. However, automated selection can result in some identical solutions, making it important to first sort and then select individuals without duplication.

Finally, a hybrid fitness evaluation engages the user in the selection of the fittest individuals on a secondary level, with an automated process that performs the initial screening. To this end, a program selects and presents only a cluster of the fittest individuals to the user, who then evaluates and selects from this limited group.

4.6.1.3 Genetic operators

Genetic operators that are applied to the parents' genotype tend to combine the genetic material of the fitted solutions, with the aim of producing better-fitted outcomes. These genetic operations are divided into three main functions:

- *Selection*: This operator evaluates phenotypes according to a fitness function, which measures the degree to which a unit meets its predefined criteria. Subsequently, a number of surviving phenotypes, along with their corresponding genotypes, survive to the next generation.
- *Crossover*: This operator selects two phenotype parents from the entire population, based on their fitness value, and then creates an offspring genotype by combining the genetic materials of their parents. The foremost reason to perform a crossover operation is to acquire genetic material from the previous generation for the benefit of the next one.
- *Mutation*: This operator introduces further changes into the resulting genotype by stochastically changing one or more of its characters. The rate of this change, however, must be kept to a minimum in order to avoid unfortunate results.

These three operators are repeatedly applied to a population of genotypes and their mutual phenotypes over the course of the algorithmic process, so as to form new populations during every round. The new generation of genotypes is formed from the fittest genotype of the previous series, ensuring that genes keep surviving from one generation to another. Random mutations enrich the process by adding a degree of innovation in the emergence of new features (Eiben & Smith, 2003). Figure 4.6 illustrates the mechanism of genetic operators.

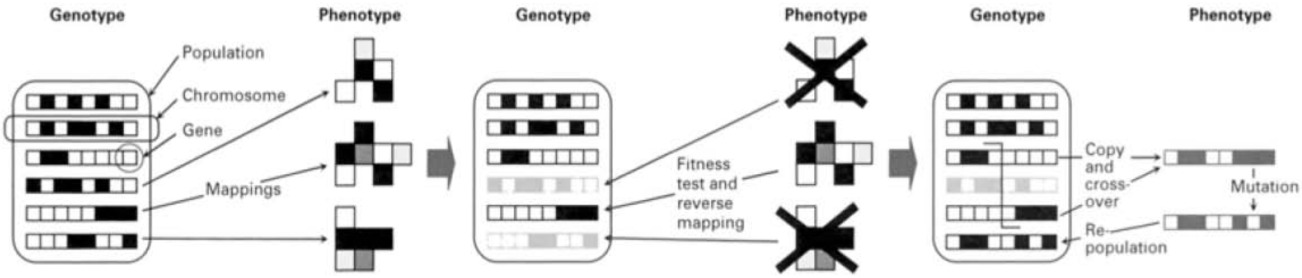


Figure 4.6: Different operators of Genetic Algorithms (Source: Kalay, 2004).

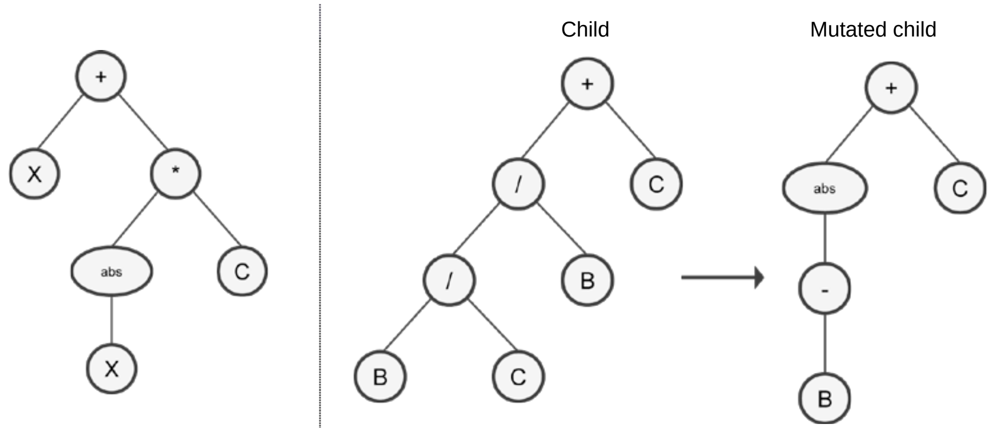
4.6.2 Genetic programming

Genetic Programming was developed by John Koza (1992), in an attempt to make computers program themselves, and thereby evolve through automatic self-programming. According to Bently (1999), genetic programming is considered to be a special type of genetic algorithm whose individuals are programs and whose genetic operations are modified versions of what was originally implemented by genetic algorithms. Populations of individuals, randomly initialized, are maintained and then evaluated. Subsequently, high-fitness parents are selected for the next generation. Crossover and mutation operators are employed to generate offspring which then replace their parents in the population. Individuals are evaluated and parents are selected for reproduction (Koza, 1992). The pseudo-code of genetic programming is as follows:

Create an initial population of randomly generated programs
REPEAT
Execute each program in the population and evaluate its fitness
Create a new population of programs by:
- *Reproduction*
- *Crossover and/or*
- *Mutation*

UNTIL the termination condition is satisfied.

Genetic programming employs syntax trees or binary trees instead of lines, as an abstract representation of the source code in the form of a programming language (Figure 4.7). Each node of the tree indicates a construct occurring in the source code, either as a terminal or a function. In a program, terminals are variables or constants, while non-terminals include arithmetic, Boolean operators, mathematical functions, conditionals, and iterative operators predefined by the program designer.



Simple program by Genetic Programming's heirarchical representation	The behaviour of Genetic Programming mutation operator

Figure 4.7: The representation of genetic programming (Source: Eiben & Smith, 2003).

The initial population consists of the random generation of symbols. These create a programming tree, but they do not possess conventional meaning in and of themselves. The combination of symbols and data types, however, is nevertheless always legal. Despite initial similarities, significant differences distinguish genetic algorithms from genetic programming. Firstly, genetic programming does not discriminate between the search and the solution space. To the program, genotypes are the same as phenotypes- it does not manipulate coded versions of the solution, but rather it manipulates the solutions themselves. In other words, genetic programming considers the search and solution space as one space, presenting solutions in a definite, hierarchical manner

(Bently, 1999). Secondly, the mutation operator in genetic programming functions in an altered way, selecting a random point in a tree, deleting everything below it, and then replacing it with a randomly generated sub-tree. In this schema, mutation is usually considered unnecessary because the crossover operator can perform this task. Finally, the evaluation of solutions in genetic programming is very different than in genetic algorithms. As mentioned earlier, this form of programming evolves phenotypes directly, while bypassing the mapping process. The fitness of solutions is calculated according to how closely the actual output values match the desired values for each input. When a solution evolves with satisfactory fitness values, genetic programming then terminates the evolution process.

Nevertheless, the selection of an algorithm to solve a particular problem, be it through genetic algorithms or genetic programming, depends mainly on the objective of the research and thus on the nature of the problem. Genetic algorithms are more likely to be implemented in clearly-defined single case problems, wherein the required result is the final value of the variable. On the other hand, when the input that defines a problem is ambiguous, genetic programming can offer a series of instructions, which can usually find a solution in a more ideal manner.

4.6.3 Applications in architecture

Scholary interest in genetic algorithms stems from their ability to address problems by offering a diversity of possible solutions. Within the field of architectural design, efforts to employ these innovative models have met with some success. These attempts range from the distribution of architectural programs to the generation of floor plans, and even to design optimization. In some cases, multiple-constraint algorithms were used to control the generation process itself. Other applications, like plan generation, tended to combine genetic algorithms and shape grammars, the former being the control mechanism of the latter. There were also other methods, which focused on combining these algorithms with a case-based reasoning system that used genetic algorithms as a search medium, which finds solutions by randomly sampling within a solution space.

The work of John Frazer (1995) is one of the first and most notable examples of the application of evolutionary computation to architectural design. His projects encompassed geometric transformations and the evolution of designs, and demonstrated the potential of such systems through the novelty of the resulting designs. Frazer (1995) described how the synthesis of architectural design can be performed through two different methodologies. The first starts with specified architectural components, such as rooms, walls, or columns. It then assembles these components according to criterion such as form, function, and context. This approach is common to a computational system that employs structured procedures for the generation of design. The second methodology, which is often followed by architects, consists of creating the whole structure and then identifying components and assemblies within this totality. As the design process unfolds in both methodologies, some novel architectural elements showing potential for creative design may emerge (Frazer, 1995).

In one of his projects, Frazer and his students at the Architecture Association in London sought to combine three-dimensional cellular automata with genetic algorithms. Cellular Automata (CA) were developed in the late 1940s by John Von Neumann as an abstract model for self-reproduction. They consist of discrete models containing an array of cells, each of which exists in one of a finite number of possible states, arrayed on specified, gridded shape. The resulting evolution process was controlled by data, which was collected through an array of inputs from sound and light sensors, infra-red motion detectors, and touch-sensitive body suits. The goal of this project was to measure the impact of such collected data on the changing environment of a spherical surface.

Numerous other research efforts have followed. Gero (1996, 2006) proposed different methodologies to employ evolutionary algorithms in space layout planning, initially based on genetic algorithms and subsequently upon genetic programming. Caldas (2001) employed genetic algorithms towards the optimization of size and positioning of window openings in a facade, in addition to the size of the overhangs that provide shading for windows. Terzidis (2007) explored how a genetic algorithm could offer an effective solution to a design problem by allowing the competition of multiple constraints within an evolving system. In sum, the application of evolutionary algorithms is widely regarded as something of an open-ended area of research, due to the latter's abilities to address architectural problems on multiple levels and to various ends.

4.7 Implementation: Coding and Programming

As mentioned earlier, algorithms are realized as programs, and are implemented using a precise programming language. Architects and designers tend to think algorithmically, and internalize a programming language in order to accomplish design work. Algorithms may be said to have the following qualities:

- Algorithms can be written and implemented in many ways.
- An algorithm requires assumptions.
- An algorithm includes decisions.
- Complex algorithms must be broken down into modules.

In many ways, programming may be considered to be algorithmic thinking in action. It involves the transformation of a concept into a series of steps in the form of commands to be executed by a computer. Programming is diverse, moreover. Two programs may express an identical algorithm, but in fundamentally different ways (Reas & McWilliams, 2010).

One of the important components that allow programmers to organize data is that of *data structures*[3]. Once constructed, data structures can be employed several times to execute multiple tasks. They are easy to use, have a large number of operations and functions, and can also attain values. Their efficiency, however, has come into question in some cases, and they are typically hard to debug (Woodbury, 2010).

Complex programs are usually built in *modules*[4]. Such new modules are required if a system does not support a particular design task. This process, calling upon a programmer to abstract a program to its lowest level, can be difficult. In programming, a code or source code is used to translate a design into a program, which takes the abstract idea of a design and turns it into a set of precise instructions in a particular programming language. It is used to control the operations of a computer: an algorithm written in a programming language. There are thousands of programming languages, all with their own syntax and grammar, and more entries are developed every year. Consequently, a programmer must select a programming language based on their estimated budget, operating system, and aesthetics (Reas & McWilliams,

[3] A data structure is comprised of types, functions, and methods, all of which perform coherent operations on objects of the types. This consists of key abstraction techniques in programming (Bently, 1999).

[4] In computation, a module is a collection of data structures that implement a coherent and consistent behaviour. Creating a module requires that one design, code, debug, refine and maintain data structures and the suite of its functions over that structure's aesthetics (Reas & McWilliams, 2010).

2010). According to Coates (2010), designing code consists of breaking down a problem into its component parts, devising a data structures and algorithms for these parts, and arranging these parts together into a complete program design. In some cases, coding and design can go together, particularly in the conceptual stages.

Prior to starting the coding process, designers tend to write the program in a pseudo-code: an informal description of the operating principles of the algorithm. This uses the structural convention of a programming language, but is directed for human rather than computer reading. It allows ideas to be easily connected and mapped, thus facilitating the coding process (Reas & McWilliams, 2010).

Many of the end-user CAD programs offer programming or scripting environments. This has become a prevalent activity for architects; instead of direct programming, design intentions are codified using a scripting language, which is embedded in 3-D packages to modify or explore design in a more advanced method. Scripting offers designers the ability to manipulate a design by controlling it algorithmically. In such cases, the computer becomes an integral part of decision-making in the design process.

4.8 Reflections

In contrast to other applications, architectural design problems are notably complex and non-linear, wherein decision-making can be manipulated by numerous factors that diverge from one project to the next. In most cases, the design problem slowly becomes more understandable over the course of the design process. Thus, constructing a generative system for a design problem requires a clear definition of the problem from the start, so as to avoid these time-consuming processes.

The selection of the generative systems analyzed in this chapter is based on the review of research efforts in the field of architectural computation, with a focus on systems that enable mass customization in the housing industry. Different approaches were proposed, offering alternative structures of generative systems and solution spaces. These were derived from a critical analysis of the problem of mass customization in housing and its targets. In other words, the proposed generative systems were specifically designed for a particular housing prototype and production system. However, these systems focused on exploring the nature of the generative design techniques, rather than on formalizing methods flexible enough to handle the complexities associated with mass customization such as marketing, design, and production strategies.

It would be highly impractical to value one specific generative design model to the exclusion of all others, as many varied research efforts have demonstrated success with regard to the examined problem. Consequently, the selection of a generative design model would ideally emerge from a clear understanding of the nature of each specific problem; level of customization, integration scheme, design logic, architect's intention, and the company's technological capacities. Additionally, exploring the structure of the design system tends to define the system's automation level, operator, and intended solution spaces, all of which would direct the selection process. Once defined, the role that the design system can perform in the customization process can be devised.

The study in this chapter lays the base for the forthcoming chapters, specifically the design system framework, as well as for the simulation. Nevertheless, it has to be understood that technological applications in design and production are not the sole factors upon which the implementation of customization strategies in housing relies, especially due to their continuously changing nature. However, is it also important to develop a comprehensive approach for orchestrating the relationships between various systems and subsystems. Consequently, the issue of how to develop a design system for the mass customization of housing is the ultimate goal of this research. In its aim to develop a process, rather than a tool, this thesis thus seeks to avoid the inevitable obsolescence of fixed technologies.

Part III:
A Proposed Digital Platform

5.0:

The prefabricated housing industry in Quebec

5.1 Introduction

The Canadian prefabricated housing industry plays an important role in supplying the housing market with diverse products, ranging from single-family homes to prefabricated building components, such as trusses, walls, and panels. In addition to international exports, the industry distributes its products to many external sectors. Its diverse business practices evidence several on-going concerns: targeting affordability, responding to environmental challenges, and contributing to innovation in the homebuilding sector.

This chapter explores the scope of the prefabricated housing industry in the province of Quebec, using interviews and field visits to provide a broad study of this sector and a detailed analysis of industry operations. This chapter focuses on technological applications in sales, design and production that respond to and realize homebuyers' needs and demands. To that end, a survey was conducted to investigate how companies build relationships with customers, create profiles of their needs and habits, and subsequently produce customized products. The data obtained from this study is used to reflect on the development of the design system framework proposed earlier in this thesis. Figure 5.1 illustrates the structure of this chapter within the macro organization of the thesis.

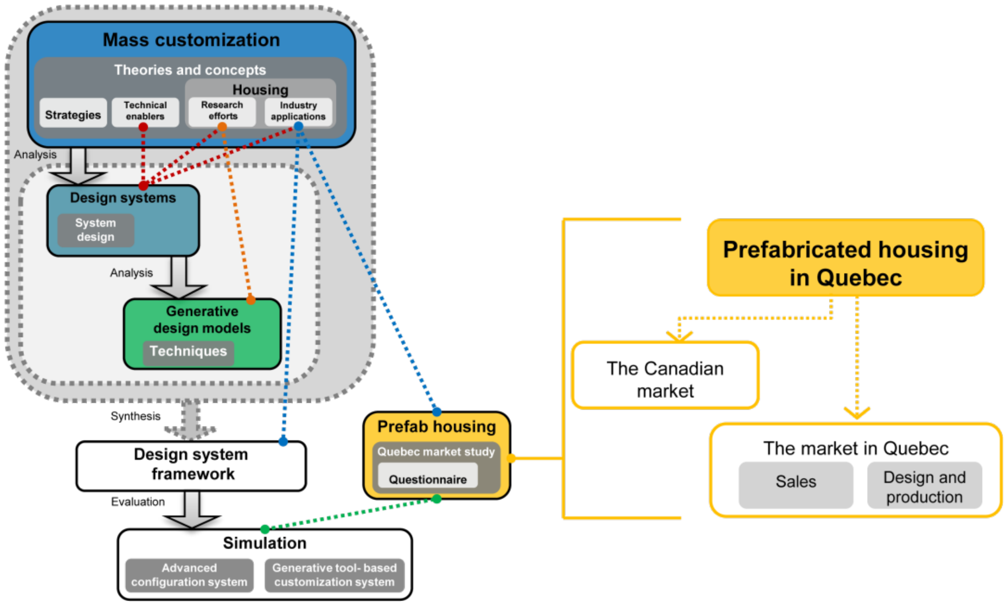


Figure 5.1: Diagrammatic representation of the chapter's outline, in relationship to research structure.

5.2 The Canadian Market

Despite its relatively small size, the prefabricated housing industry in Canada has a long history, which dates back to the production of ready-made wood housing in Nova Scotia in the early 1890s. These units served the housing markets of remote settlements, and were even exported to other isolated locations, such as the Caribbean. Since the Second World War, however, the industry has played a more central (and local) role in the homebuilding sector. It has pioneered labour-saving processes and materials in the manufacturing of the average home by introducing greater amounts of prefabricated components to the production process. As a result, the market shares of total single-family factory-built housing construction rose from about 7% in the late 1940s to 12% by the early 1970s. However, this trend was reversed through the 1980s and 1990s as the industry suffered from a significant gap between the new market demand for more tailored products and the limited accommodations that factory production could deliver. Accordingly, by the mid-1990s, the industry had shifted its focus towards modular production, resulting in more tailored product development and lifestyle marketing (Clayton Research, 2006).

Following from this shift in focus, within the past decade the industry has largely overcome its previous challenges through an emphasis on higher-quality structural materials and by technological advances in design and production. Modular homes are widely considered to be more appealing and of higher-quality than previous factory-builds, placing them advantageously within the prefabricated housing market. This resulted in a notable increase in modular home delivery. According to Clayton research (2006), around 40% of the market's total delivered prefabricated housing in 2005 were modular homes, showing an increase of 13% over the amount of total production in 1993 (Figure 5.2).

Statistics from the most recent report by the Canadian Manufactured Housing Institute (CMHI, 2011) support this trend. In 2011, the industry produced approximately 14,427 factory-built homes, accounting for a 12.5% share of all single-family homes starts. This represented a sharp improvement over the 9.5% share the previous year, and accords with the upward trend established over the past several years (Figure 5.3).

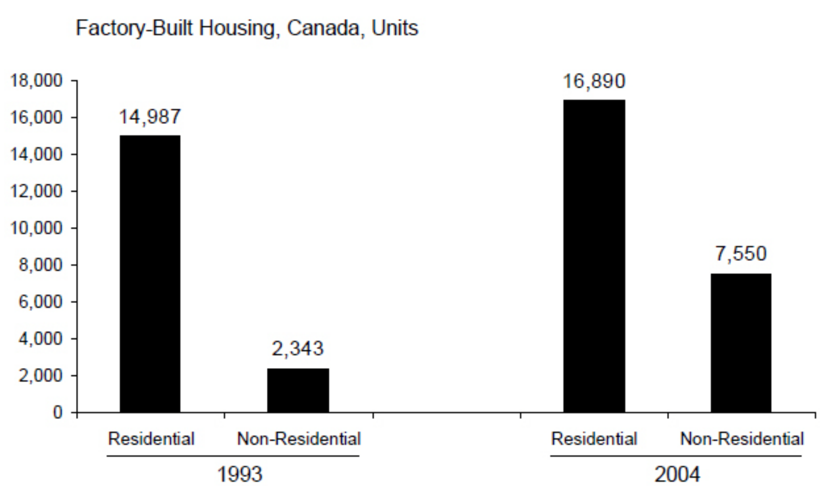


Figure 5.2: Factory- built housing in Canada 1993-2004 (Source: Clayton Research, 2006).

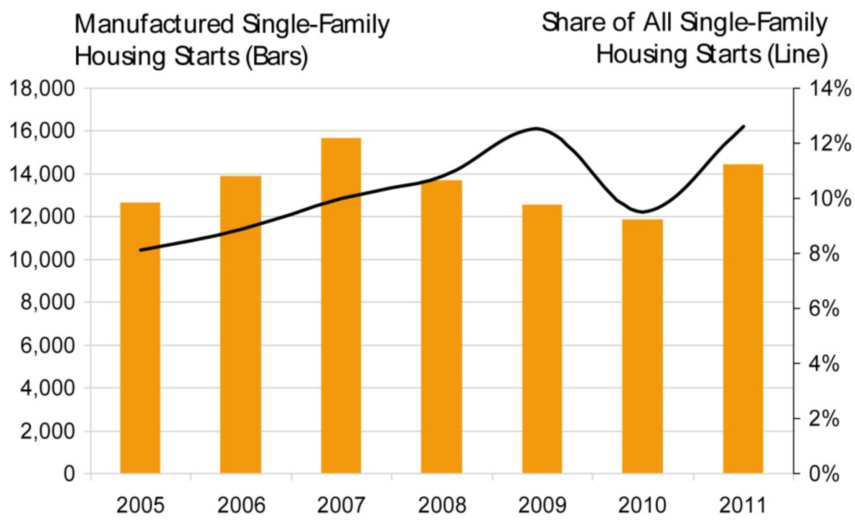


Figure 5.3: Prefabricated residential building starts in Canada, 2005-2011 (Source: CMHI, 2011).

Based on a detailed study of the industry, Clayton Research (2006) stated that the majority of modular-home-manufacturing prefabricated housing companies in Canada focused predominantly on custom-built homes. In this model, such companies respond flexibly to sales and production trends by accommodating almost any design a customer can bring to them.

Contemporary assessments of the prefabricated industry remark on its potential to significantly innovate modern homebuilding, thus creating opportunities to respond to environmental challenges and to greatly expand housing exports (Clayton Research, 2006). These prospects, however, depend on the drivers of traditional housing markets, such as population growth, household formation and demand for single-family housing. Added to this calculation are also the existing factors that make prefaricated housing unique, including issues of affordability, level of customization, and quality.

The industry currently distributes its products through the following channels (Figure 5.4):

- *Factory-Direct Sales*: Most producers in Canada sell their products directly to customers, as this allows them to retain better control of the customer service relationship. The cost of this model, however, is an estimated 7- 10% of their gross revenues for sales and marketing.
- *Retailer Networks*: Many companies depend on dealer networks to market products on their behalf.
- *Community Developers*: Some developers, usually independents, will develop a community or sub-division and then sell finished houses directly to consumers.
- *Export Channel*: Most Canadian modular home producers export at least some of their products to the United States. Overseas exports are also not uncommon, reaching regions such as South America, Europe, and Asia (Clayton Research, 2006), and (CMHI, 2011).

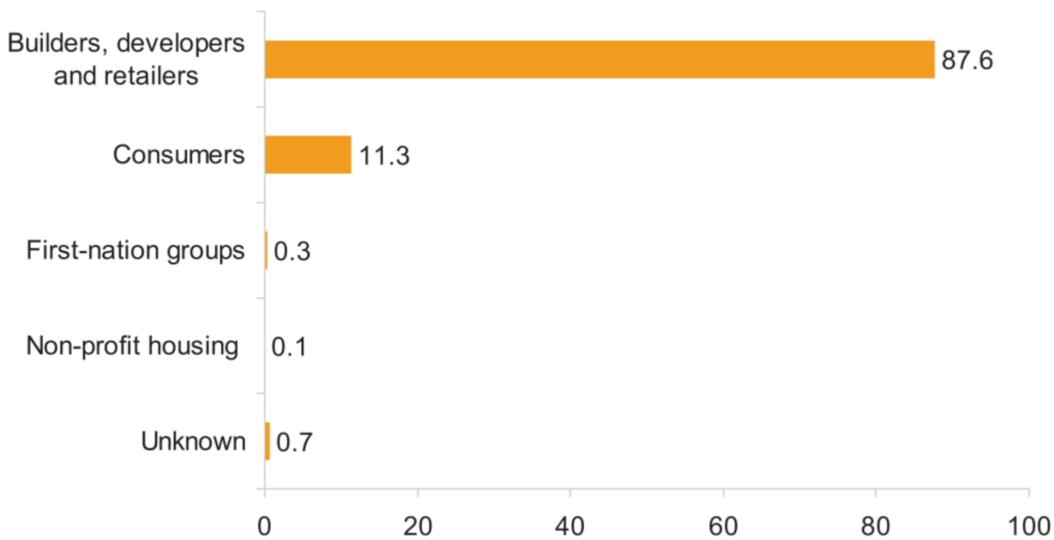


Figure 5.4: Distribution of manufactured single-family homes, 2011 (Source: CMHI, 2011).

5.3 The Market in Quebec

According to the *Société québécoise des manufacturiers d'habitation* (SQMH, 2010), there are approximately 42 prefabricated housing companies sharing the market in Quebec, accounting for roughly 26% of all such establishments in Canada. These companies have a large impact on the market, producing modular, panelized, and kit houses and delivering a total of 18% of the single-family housing market. To expand their market share, some companies also participate in the multi-family housing market, as well as in the production of various building components to be used in many kinds of construction, such as roof trusses, walls, and panels.

This chapter details a survey undertaken to explore the state of technology use throughout the process of collecting and fulfilling customers' housing requirements. A questionnaire was prepared and distributed to five companies, complementing interviews with managers and technicians. These companies were selected based on their market share, applied technologies, and business practices. The questionnaire focused primarily on the sales and design phases, and examined the various marketing strategies employed for the goal of building relationships with customers. Attention was also given to the levels of choices offered to clients throughout the buying process, and the technologies subsequently applied to realize these choices. Overall, this survey examined contemporary industry attitudes towards degrees of customization and its associated technological strategies. Table 5.1 provides basic information about the selected companies, while Figure 5.5 demonstrates the average number of produced units per year among the surveyed firms.

Company	Year of establishment	Number of employees	Main markets	Range of distribution
Alouette Homes	1971	100	Quebec, Ontario, New England, UK, Chile	Global
Enovo	2008	30	Quebec	Eastern Canada
Demtec	1986	70	Quebec	Global
Modulex International	1964	115	Quebec, Ontario	Europe, Asia, Africa, South America
Bone Structure	2005	22	Eastern Canada,	Eastern Canada Western Canada,

Table 5.1: The companies participating in the survey.

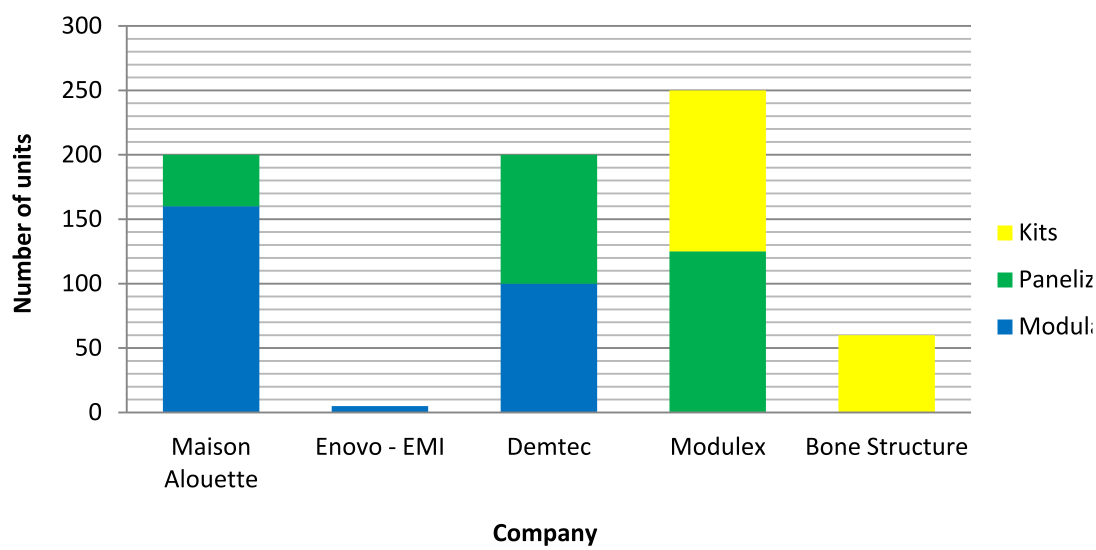


Figure5.5: Average number of produced housing units per year for each company.

5.3.1 Sales and design processes

The prefabricated housing industry has always stood to benefit from the advantages of the ongoing developments in digital design and manufacturing technologies, especially given its ever-important role in facilitating data transfer to engender a more efficient production process. By adopting such technologies, companies aim to deliver high-quality products, and thus expand their shares in the competitive housing market. The results of the survey revealed that prefabricated housing companies employ these communication, design and production technologies in different aspects of their businesses. The following section presents the outcome of the questionnaire, with regard to the use of technologies in sales and design.

5.3.1.1 Sales

The companies analyzed in this survey employ printed and electronic catalogues to market their products. Conventionally, these catalogues are comprised of the range of standard housing prototypes that the company offers, presenting clients with a variety of models to choose from, and an understanding of the quality that the company could offer. Additionally, these companies also tend to build demonstration models adjacent to their sales offices, allowing customers to better envision both the spaces and the different finishing elements by physically visiting the realized house.

The divergences between standardized and custom housing models are fluid, appearing at multiple points in the design process. Most companies depend on the standardization of design drawings, details, and production processes as a cost saving strategy built into their design approach. According to the companies surveyed, even minor modifications in a standard model may require rigorous manipulation of drawings due to technical variances, the outcome of which sometimes results in an entirely new model. This partially explains why there is a higher %age of custom-built homes than standard ones (Figure 5.6). Companies may also receive clients' custom orders in various ways, ranging from full sets of architectural drawings to rough sketches. These drawings are then either used to provide potential homebuyers with a price estimate or, in the case of sketches, are developed into more detailed drawings for estimation. The following figure shows the percentage of custom-built homes to standard ones within the conducted survey.

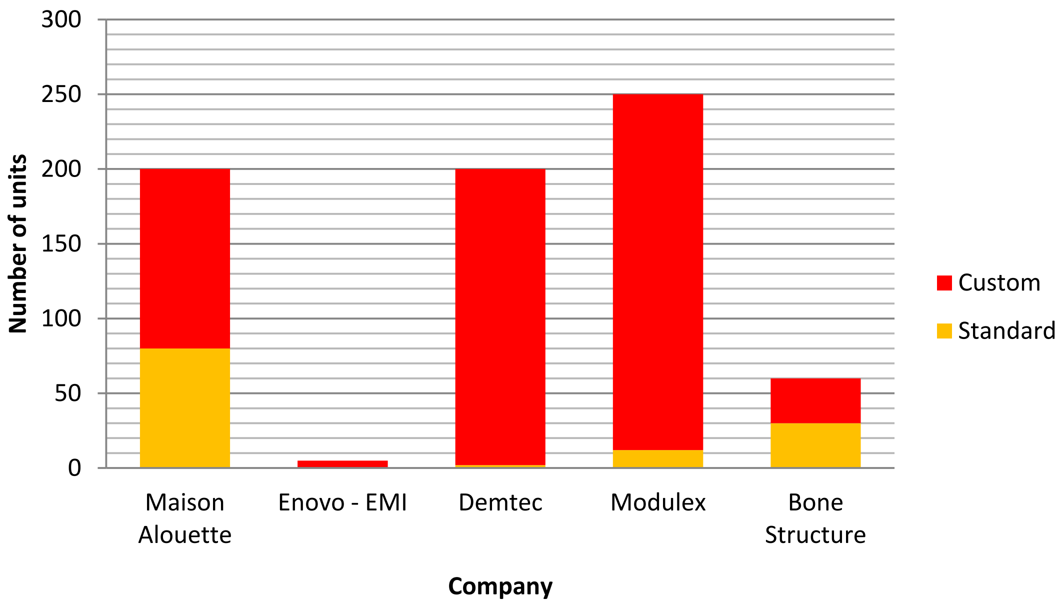


Figure 5.6: Number of custom- built houses vs. standard catalogue ones, with regard to total annual production.

Salespersons play an important role in the home buying process, supporting customers in finding a match between the cost, area, layout, and architectural style of their desired home and those of the standard models offered by a company. In many cases, a salesperson may aid a client in adjusting the plan of a house by adding modifications, finishes and systems to the design of the standard model. Usually, this process takes one to two weeks, as the resulting design must be validated and finalized. Once all customer choices are recorded, the salesperson delivers a quick price estimate and a delivery schedule on the basis of the drawing. According to all the manufacturers in the survey, this phase plays a very important role in the “deal closing” process. To complete this step, the companies employ advanced design and engineering software, which usually includes a pricing module. However, the calculations of this software are not always adequately precise, owing to limitations such as ongoing changes in the cost of materials and the resulting need for a direct connection to suppliers' data on component pricing. Accordingly, the sales process can take between one and two weeks until the "deal is closed" and the production phase can begin. Figure 5.7 illustrates the buying process with the options of a modified standard model or a custom design.

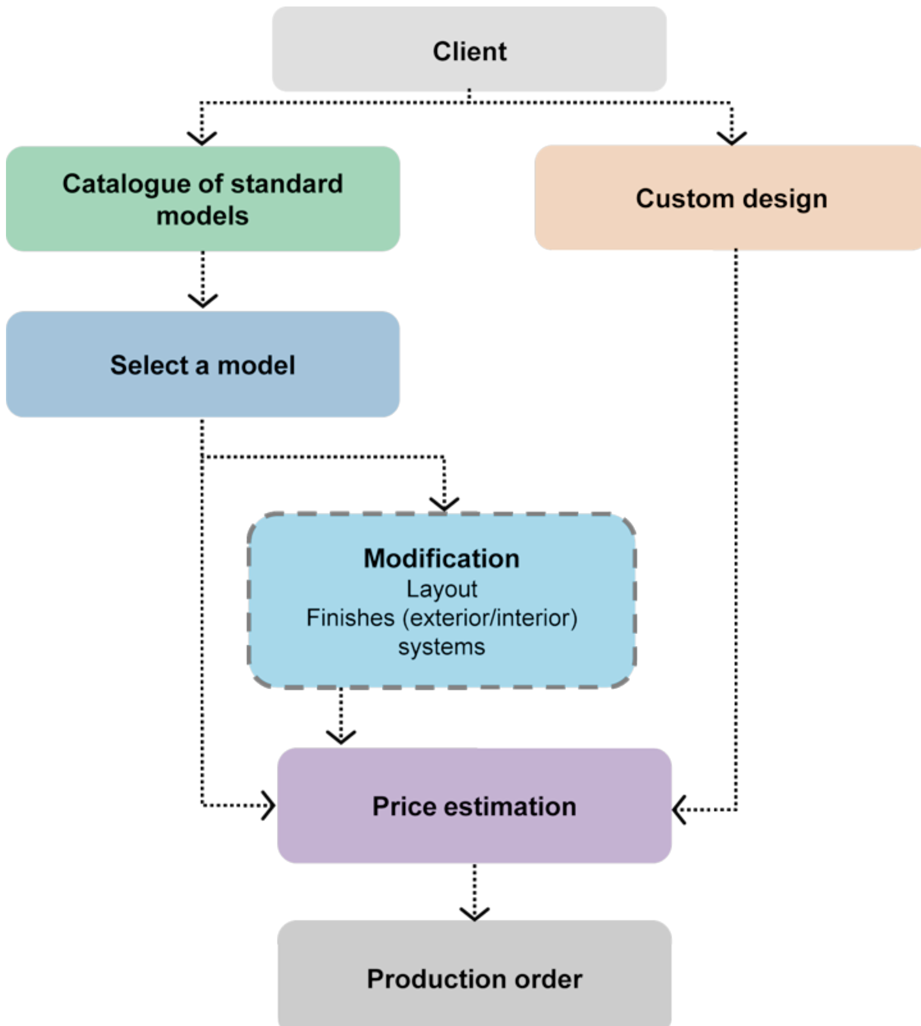


Figure 5.7: Diagrammatic representation of the typical buying process.

5.3.1.2 Design and production

Prefabricated housing companies often develop housing catalogues comprising a wide range of standard models, including bungalows, two-storey houses and cottages. Within the catalogues, models are demonstrated through plans and three-dimensional renderings. The number of models varies from one company to the next, depending on the company's market share and sales strategies. It was observed that, in most cases, such housing models do not emerge from a comprehensive design scheme. Only one company among the manufacturers surveyed developed a modular design system flexible enough to accommodate variations. Figure 5.8 is a sample page from one of the catalogues by the company Modulex.

Figure 5.8: A sample page from Modulex catalogue.

Housing catalogues are developed with the goal of providing a degree of system standardization within the design and production processes, thereby streamlining production and reducing cost. However, this is only feasible if the company reaches a significant level of sales, so as to recover overhead costs. Nevertheless, the survey demonstrated a high market demand for customized housing that necessitates flexibility within design and production, in order to tailor products according to homebuyers' preferences. Accordingly, companies are obliged to offer clients many options with regard to the customization of standard models. The price of a home reflects these modifications, not only because of the material cost of additional features, but also because of the extra time spent on accommodating modifications and producing a set of technical drawings. Figure 5.9 illustrates a conventional sequence of the process from sales to production.

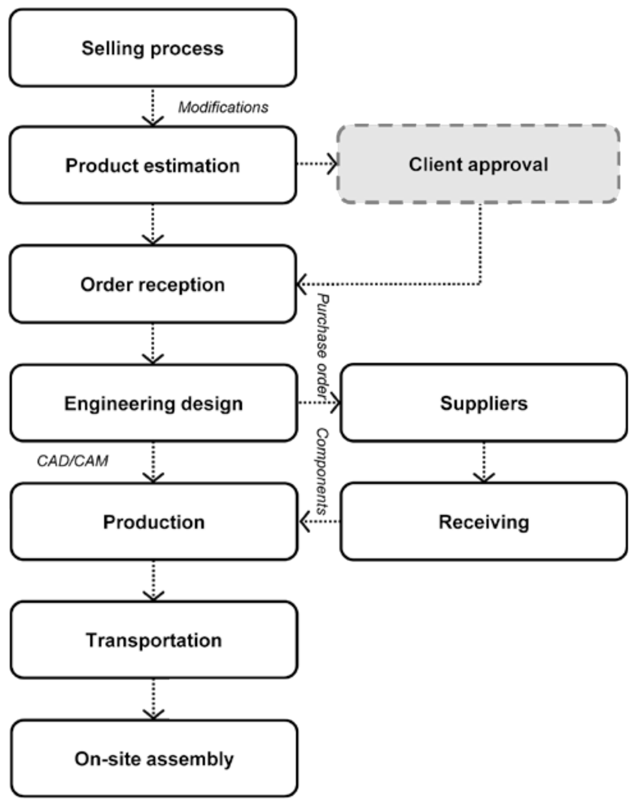


Figure 5.9: Conventional process flow and entity company-client relationships in prefabricated housing companies.

Many technological adaptations facilitate this process. The application of these technologies can vary from one company to another, depending on the level at which it is the most practical. The operational software platform of a company is also a factor. Recent and remarkable developments in digital design technologies have resulted in the availability of more software tools to assist companies with the creation of design and production drawings. Computer-Aided Architectural Design (CAAD) systems are among the most common of such tools and are widely utilized for design and production drawings. Additionally, some companies have started to utilize BIM tools, with the aim of saving time and costs. The application of such tools, however, is not yet efficiently realized in the industry.

Encouraging evidence of the potential of such applications exist in the integration of CAD/CAM systems into the design and production stages, within certain companies. This has occurred in different production streams, including floors, walls and roof systems. By automating fabrication, the production process stands to be greatly optimized, thus minimizing cost. Such applications are not without expensive complexities, however. The investment cost for integrative systems is high and requires extensive linkage to suppliers and manufacture's databases in order to be efficient. It also requires a specific set of hardware and software to effectively implement data sharing and interoperability. Tables 5.2 and 5.3 show these applied technologies within various stages from sales, design, production, and automated components.

	CAD	CAE	BIM
Maison Alouette	Applicable		Applicable
Enovo	Applicable		
Demtec	Applicable		
Modulex	Applicable		
Bone Structure	Applicable	Applicable	Applicable

Table 5.2: Applied technologies within sales, design, and production.

	Walls	Floors	Roofs
Maison Alouette	50 %	--	--
Enovo	50 %	--	--
Demtec	100 %	--	--
Modulex	50 %	50 %	100 %
Bone Structure	100 %	100 %	100 %

Table 5.3: Automated components within production.

5.4 Reflections

Based on the review of the current state of the prefabricated housing industry in Quebec, and preceding studies (Beauregard, Lapointe, & D'amour, 2006), I argue that a large sector of the market follows an *Engineer-to-order* trend: an approach wherein products are scheduled and built in response to a confirmed order received from a homebuyer. Such a trend offers personalized products, yet creates an obstacle to an industry looking to serve a mass market. In order to transition to a system of mass customization, the prefabricated housing industry needs to involve itself in a technological dialogue to resolve various issues with regard to sales, design and production. For example, despite its additional advanced applications, almost all of the companies surveyed in this research employ CAD software merely for drafting, but fail to apply it expansively in other stages of production. Furthermore, only two companies out of all those surveyed employ BIM, an essential element for enabling mass customization.

With regard to production processes, for the most part, the technology deployed by the factory-built housing sector is often not that different from the tools employed by site-built home construction. Some pre-fabrication manufacturers, however, do capitalize on the unique advantages of factory technologies, integrating sophisticated machines such as automated and computerized framing jigs, saws, nailing bridges, and overhead cranes and scaffolds into the off-site production of their housing products.

This chapter's study aims to deduce a theoretical basis with which to develop a design system framework by investigating the limitations facing the adoption of mass customization in the prefabricated housing industry in Quebec. Accordingly, this study identified a technological gap between the current state of research on mass customization and its industry applications. The proposed design system framework in the following chapter tackles this gap through a computational-based approach, which is developed through a sequential configuration from macro to micro components. Each component is denoted with a specific level of interaction between the homebuyer, architect, and manufacturer.

6.0:

A design system for mass customization

6.1 Introduction

While there is tremendous capacity for variation within housing design, the final product is bounded by constraints ranging from client needs to the site and building code regulations. Addressing all possible variables and parameters with predesigned prototypes would be impractical. Consequently, the rational solution is to offer homebuyers products that are tailored to their needs by involving them at an early stage of the design process.

The previous chapters explored the basic concepts and approaches that underlie mass customization, as well as the methods and components required to construct a design system, and to enable its application in the housing industry. This chapter proposes a framework for the development of design systems for the mass customization of housing. It is aimed at conceptualizing a process, rather than a computational tool. This method can be pursued in order to develop a design system that would allow future homebuyers' participation in the design of their homes. This framework would seek to overcome limitations to customization in the housing industry by employing digital design and manufacturing techniques. Figure 6.1 illustrates the structure of this chapter within the macro organization of the thesis.

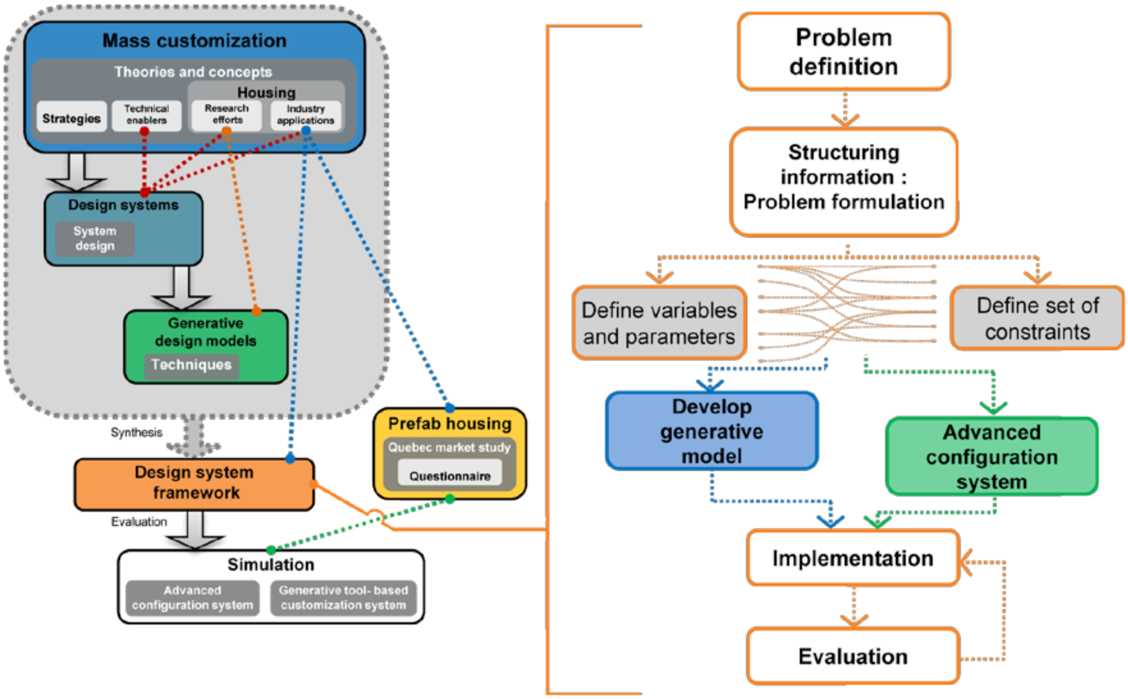


Figure 6.1: Diagrammatic representation of the chapter's outline, in relationship to research structure.

6.2 The Design System Framework

Developing a system for the mass customization of housing is a multi-disciplinary process that requires different levels of expertise, and involves handling a large amount of information. The homebuyer, architect, and manufacturer are the three main participants active in the customization process. As mentioned in previous chapters, the success of a mass customization system hinges upon utilizing an efficient means of communication and data transfer within the design and production processes, so as to engage homebuyers and manufacturers in a comprehensive dialogue.

The design system framework emerges as the logical consequence of a critical analysis of approaches to mass customization, prefabricated housing systems, computational design systems, and any extant efforts towards the application of mass customization in the housing industry

(Figure 6.2). Moreover, the framework derives its procedures from the major milestones in design process research. These emphasize information and data transfer, management aspects of the design process, and the achievement of conceptual integrity between various participants in the process. Such a framework promises to be a flexible, comprehensive approach to a mass customization system that would support homebuyers' participation the design of their homes. It represents an algorithmic approach towards the implementation of a design system for the mass customization of housing.

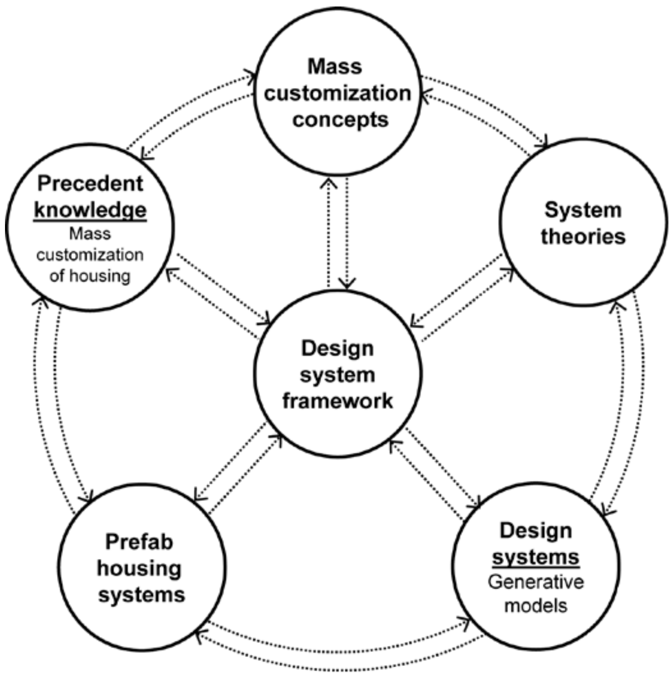


Figure 6.2: A multi-disciplinary approach to design system development.

The framework is structured based on three main stages:

- *Stage I*: Aimed at clarifying the process by which the design system might be structured by identifying the various levels and activities that would constitute the mass customization of housing. This stage focuses on the strategy and process of customization to be implemented by the manufacturer. Accordingly, a comprehensive array of information is gathered, in order to establish a clear definition of the processes required for handling the problem. At this stage, the problem is well-formulated and functions can be defined.

- *Stage II:* Explores the process of selecting a methodology to devise a solution to the formulated problem. Based on the company's production capabilities, applied technologies, and available means of communication with architects and clients, the design system will be modeled in the form of interacting components to perform a specific design task. At this stage, the focus is directed towards users, and based on the identification of a specific customization approach.
- *Stage III:* Concerned with implementing the design system and verifying its capability to generate housing solutions, based on the requirements defined in the preceding stages. Implementation will follow once the system is clearly articulated and understood, and once the specific generative tool has been elaborated and verified. At this point, the system operator and degree of automation can be defined. Developing a design system for the mass customization of housing, and allowing homebuyers' participation in the early design stages, is a complex process that requires managing large amounts of information. Accordingly, the design of a system capable of guiding homebuyers through all levels of customization requires a concentrated and interdisciplinary collaboration between experts.

Figure 6.3 illustrates the different levels of this framework, and represents the concepts required to build the design system. A comprehensive list of disciplines and data sets should be established at each level of development. While each step can be explored independently, there are several points of interaction within the framework according to technological applications.

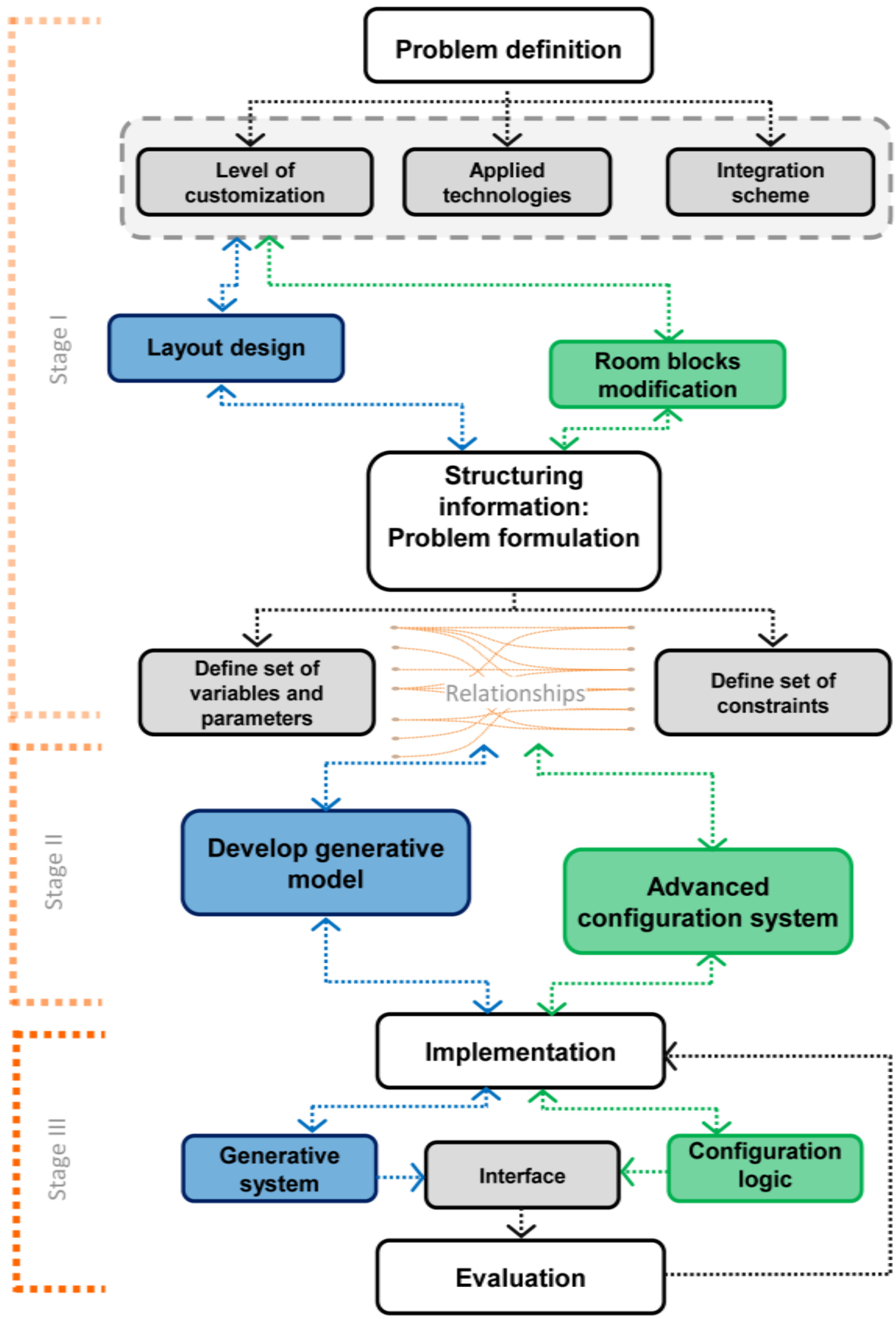


Figure 6.3: A diagrammatic representation of the design system framework demonstrating the various phases: problem definition, formulation, design generation/configuration method, implementation, and evaluation.

6.2.1 Problem definition

The first step towards solving a problem is clearly defining the nature of the problem. This is best accomplished by specifying a detailed description of the required object. Within this research, the design system constitutes the desired object. Accordingly, the problem here is complex, where the framework seeks to provide a model for developing design systems, which themselves seek to solve an architectural design problem. The design system is aimed at redefining the relationship between the homebuyer, architect, and manufacturer, and creating an effective model of information transfer between these various participants in the process.

As mentioned in previous chapters, the necessary starting point for customization is to define the level of customer intervention in the value chain process. Determining the level of customization depends on an analysis of the external and internal aspects of a mass customization approach. External aspects can be classified as market conditions, economic attributes, and customer demand for customization. Conversely, internal aspects are determined by the manufacturer's readiness to adopt a mass customization system; a decision frequently based on the degree of applied technologies in the design, production and organizational structure. The focus of this research is on the internal aspects of the customization process.

Friedman (2011) proposed a project-based decision-making model that would assist designers and builders in housing to define the degree of flexibility in a design with regard to project type (Figure 6.4). The model addresses the issue of flexible implementation in design by developing a decision-making tool. This would better guide builders in the selection and implementation of resilient design strategies, so as to fit their users' needs and maintain their market approach. Accordingly, the type of flexibility selected is based on the definition of the socio-economic backgrounds of users. Employing diverse criteria to identify the level of flexibility and design alternatives to be offered, including cost estimation, regulations, and execution time, the model established a process for making choices from a range of flexible alternatives.

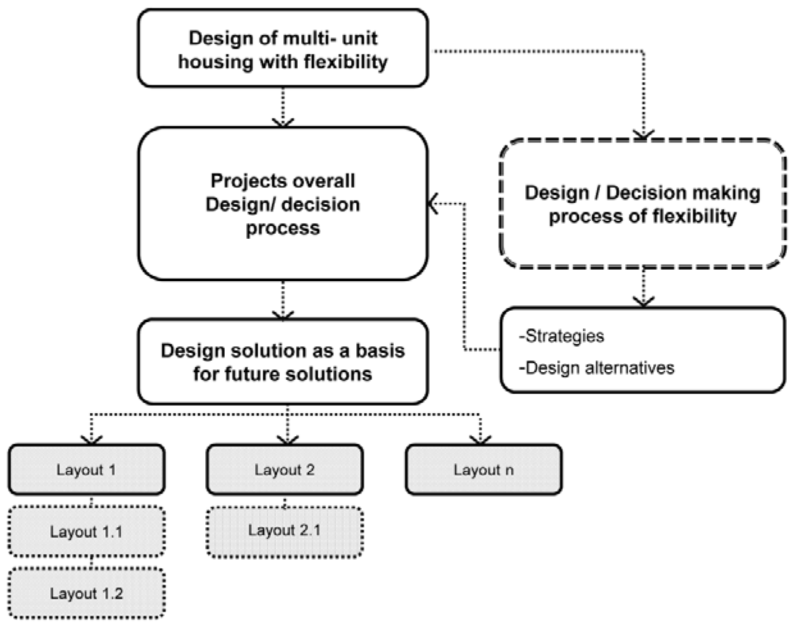


Figure 6.4: Diagrammatic representation of design process with flexibility loop (Source: Friedman, 2011).

Customization of housing can be structured on different levels (Figure 6.5). The common application of customization covers the mid-level in the hierarchy chart (layout selection, internal and external appearance of the housing unit). However, the proposed framework attempts to push boundaries further so as to enable homebuyer’s participation at the level of layout design. The framework tackles the internal capabilities of the manufacturer to implement a mass customization system through the application of computational design and manufacturing techniques.

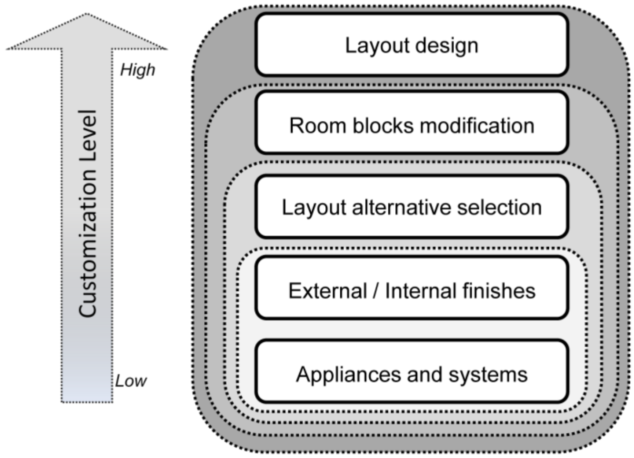


Figure 6.5: Levels of customization in housing organized sequentially from high to low, as a series of decisions that homebuyers make.

There are a series of elements a system designer has to examine in order to define the nature of the problem:

a. Problem statement

This is established by defining various conditions that must be met, tools and operations that are available to be employed, and limits on resources. This requires breaking down the problem into smaller levels and sub-problems, in order to offer a better understanding of the problem domain.

In the case of customizing housing at an early stage, the design problem can be described as a space layout planning challenge that requires employing a computer-based generative model aimed at generating housing layouts in response to homebuyers' profiles. At a high degree of customization, the system must go beyond solving an architectural problem, relying on individual identity to define the design problem. Conversely, a lower level of customization is commonly regarded as being a less complex process, simply requiring a database of options, catalogue of choices, and the means to navigate through these options.

At each level of customization, direct means of communication must be established between homebuyer, and manufacturer.

b. Goals

This is aimed at defining primary goals to be achieved. The main goal of the customization process is to understand and respond to the needs of homebuyers while following a builder's specific production method. The ultimate goal of the design system framework is to establish a methodology capable of effectively implementing mass customization in order to respond to homebuyer's demographic and psychographic qualities.

c. Desiderata

Brooks (2010) mentioned that, associated with the definition of a primary objective, is a series of desiderata, or set of clearly defined secondary objectives. The notion of customizing housing goes beyond the simply realizing homebuyers' needs, to efficiently accommodating those needs within the constraints of technical limitations while cost. Accordingly, one of the design system objectives would be the preservation of technical integrity between design and production components while realizing the requirements of homebuyers.

d. Appropriateness of the problem for being solved through computation methods

Commonly, a designer is required to find a design problem representation of sufficient computational efficiency so as to allow the problem to be solved within practical time and resource limits. Once the level of customization is defined, the application mode of a computational system can be determined. At each level of customization, an appropriate approach can be selected for application. Higher levels of customization would require a more complex system than that required for lower levels.

As mentioned previously, the highest levels of customization relate to a space layout-planning problem. This involves creating a plan for a house that reflects the assignment of relationships to a group of functions, and also provides a clear geometry for defining these functions. The plan has to fulfill some specific criteria, including adjacency between different functions, minimum circulation distance, area and volume efficiency, geometric composition, environmental performance, and economic values. Automated layout planning is concerned with the application of CAD techniques towards devising solutions to architectural design problems, and more specifically, for space planning.

There are two primary approaches to space layout planning: aggregating spaces and subdividing spaces. Aggregating spaces builds a layout through which various pre-defined spaces are connected into one layout, based on adjacency requirements. Conversely, subdividing spaces starts with a predefined layout, which is then subdivided in accordance with predefined spatial typologies. These subdivisions are assigned tasks according to programmatic requirements. Both approaches can be implemented through generative algorithms, and thus the design system will have to embody specific design logic.

e. Integration scheme

One of the critical issues when implementing a mass customization system is the establishment of a model for efficient information transfer between the participants and activities involved in the customization process. This thesis proposes that the relationship between homebuyers and manufacturers can be established using a web-based open computing environment. This process would allow homebuyers to input their profiles, describe their needs and requirements, make design decisions, manipulate the designs and visualize data. Accordingly, there are a sequence of steps that describe the communication between homebuyer and manufacturer (Figure 6.6). These steps can be pursued at any level of customization, along with the application of information technology, for a deeper integration of activities inside and outside the production chain, as well as for managing the communication process between companies, homebuyers, and suppliers.

The most important element at this stage is the user-profiling model, which is tasked with the definition of customer requirements. At each customization level, the amount of customer requirements will range in complexity. In addition to identifying requirements, customers will need to prioritize them in accordance to perceived importance. This process would begin by identifying requirements, followed by analysis and prioritization before finally translating requirements into a design brief.

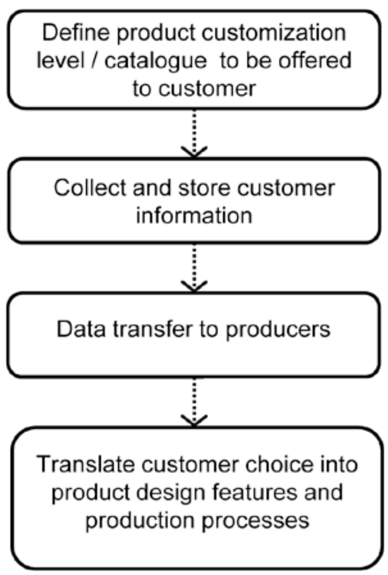


Figure 6.6: Information transfer in mass customization.

6.2.1.1 Problem definition framework

In summary, problem definition breaks down the problem of mass customization into sub-components, and arranges them within a tree in order to devise a separate solution for each component. Solutions are then synthesized into one comprehensive system (Figure 6.7). By the end of this phase, the system designer should be able to define the level of customization, the technologies required to implement the system, and an integration scheme. However the level of possible customization will necessarily be derived from the company's readiness for customization, marketing strategies, and the design and building system.

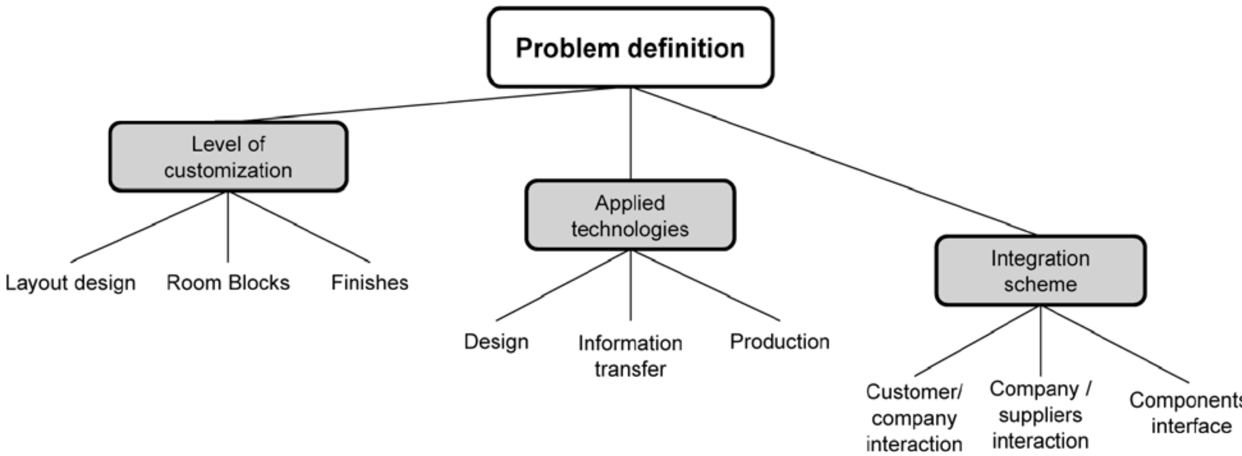


Figure 6.7: Process of defining the problem, based on breaking it into sub-problems and components .

6.2.2 Structuring information: problem formulation

The outcome of the problem definition stage is an array of precise information regarding different levels of the problem. Collected information has to be structured in a hierarchical order, so as to formalize a design brief for developing the design system. The notion of structuring information was proposed in Alexander's seminal book *Notes on the Synthesis of Form* (1964), where a *set theory* was developed. The concepts of the set theory are based on identifying a group of sets, each of which comprises a collection of unique elements that represent requirements. Sets can be linked, grouped, or intersected depending on the relation between elements (Figure 6.8). The power of set theory as an analytical tool is that elements can be as diverse as needed, and do not have to be restricted to requirements expressed in quantifiable form.

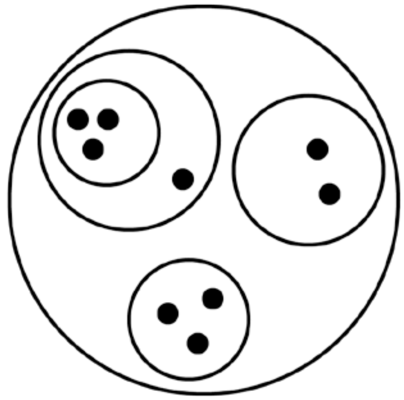


Figure 6.8: Structuring a complex entity through hierarchically nesting sets within sets (Source: Alexander, 1964).

As mentioned previously, mass customization requires the capacity to handle large volumes of information. The process produces a design that reflects the profile of individual homebuyers, while also following a manufacturer's precise design and construction system. A system for mass customization will comprise a set of analysis and design activities with high complexity levels. This system cannot be easily managed unless it is arranged hierarchically. A design system for customizing housing will therefore be required to integrate data from each information stream, including the homebuyer, design, and production, into one comprehensive array.

The information collected from the problem definition phase must be structured hierarchically, in order to understand the horizontal and vertical correlation between various elements of the problem. Once defined clearly, these elements can be connected, creating a network of modules capable of managing the complexities associated with the design process. Each module will be assigned to a particular level in the customization process, with a specific function to perform. This reforms the relationship between various elements into a coherent representation to direct the design process towards an understandable series of steps. Additionally, this method is aimed at formalizing a clear structure of the design system, in order to integrate various system designers and other members that would contribute to the process.

Figure 6.9 represents a holistic perspective of the structuring information phase, where all systems, subsystems, and components are linked. The diagram illustrates that focusing on the highest level of customization layout design results in a generative system statement. This must then be linked to subsystems and components in the applied technologies and integration scheme level. Because layout design has the highest complexity of customization, it also requires a high degree of applied technologies as well as integration between various participants and activities (Figure 6.10). However, analyzing each level separately might change the relationship between sets, causing one to become integrated within another main set and creating a more dependent relationship.

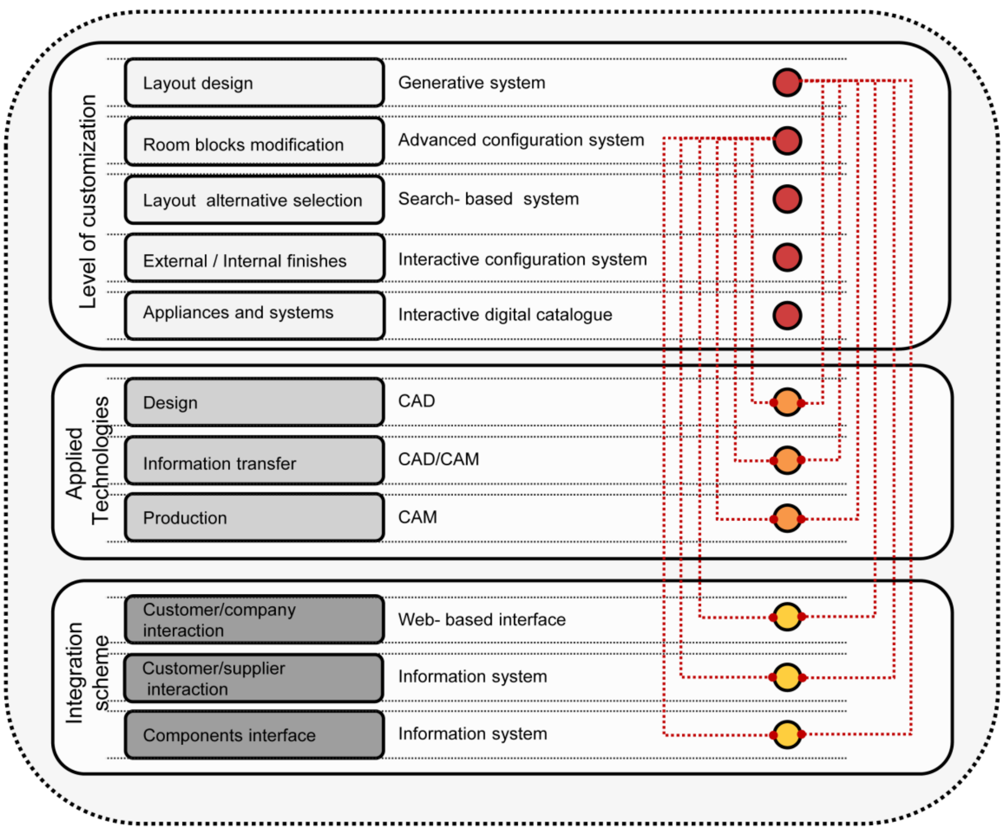


Figure 6.9: A schematic representation of the structuring information phase, through creating horizontal and vertical connections between various elements and components.

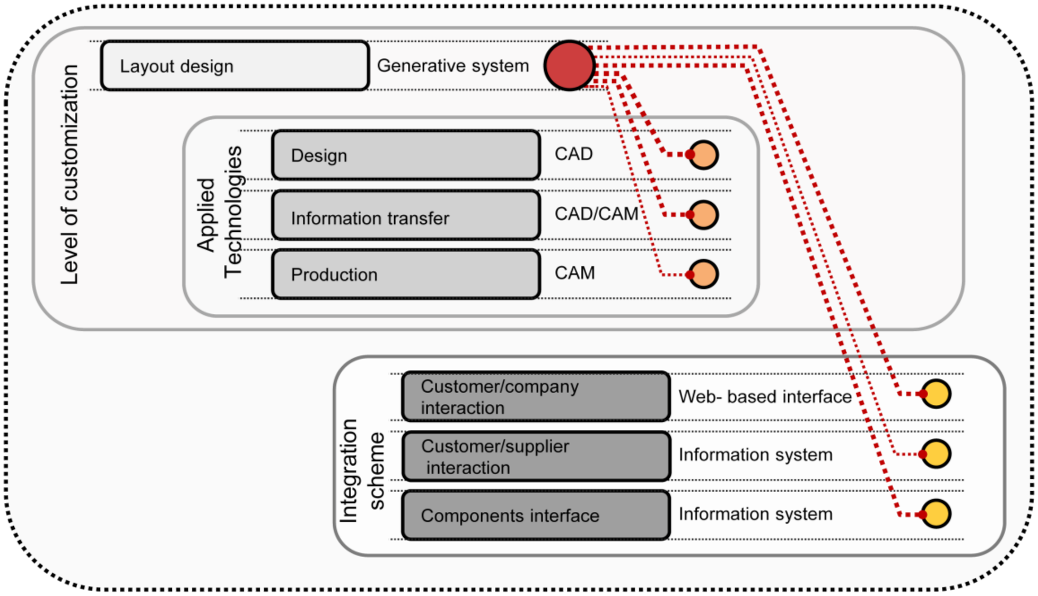


Figure 6.10: Relationship between layout design as the highest customization level and other components and sub-components. The relationship between the level of customization and components can be described with different magnitudes, representing the dependencies.

Within this framework it is necessary to explore variables, parameters, and constraints that should be involved in the activities of the design system, proceeding to the designation of the generative model, and the implementation, as it controls the following phases of the design system framework.

6.2.2.1 Define set of variables and parameters

Variables allow design to be expressed as a collection of values. It is important that each variable be clear and specific, so it can be employed properly by the design system. Woodbury (2010) argued that a dynamic variable, one that exists in a constant state of change, is easier to account for than a static variable. Once a set of variables is defined, a coherent relationship between these components can be established and the links associated with them can be defined. A parameter is a special type of variable used in a subroutine, and related to one of the sets of data provided as input to the subroutine. Parameters are typically static, and sometimes can be changed into variables in order to increase the design space.

Customization of housing requires the translation of homebuyers' profiles, socio-cultural backgrounds, budgets, and desired spaces and activities into a set of precise programmatic requirements, in order to structure a design brief for any given case. The design system is tasked with generating housing solutions in conjunction with the housing brief, while taking into account the ability of the building system to accommodate these variations. In other words, the process of generating design solutions is closely constrained by a building system that has its own discrete characteristics, including economic limitations, technical requirements of production and transportation, and environmental performance. Accordingly, once the level of customization is defined, a company can initiate a data-driven understanding of users' needs and preferences, as well as the available production systems, in order to identify a set of variables and parameters that would feed the design system.

The process of generating and maintaining homebuyers' profiles is therefore a crucial issue for customization. Within the configuration system approach, there have been valuable research efforts on recommender agents, which utilize user profile data and information filtering techniques to generate and maintain a user profile. Montaner et al. (2003) presented a taxonomy of techniques for profile generation and maintenance, as well as profile exploitation. They proposed five dimensions the system would require: a method for profile representation, the generation of an initial profile, a source of relevant feedback, a profile learning technique, and a profile adaptation technique. One of the more interesting representation methods, the vector space model, utilizes vectors to represent items by associating them with a value, which can be recorded as a *Boolean*[1] or a real number.

Profile exploitation is aimed at filtering information, in order to make recommendations. Three main dimensions are defined to provide accurate data through information filtering: content-based filtering, collaborative-based filtering, and a hybrid approach that merges both. While content-based filtering uses a detailed description of products, normally in the form of vectors or item matrices, collaborative-based filtering relies more on matching users with similar interests, and then makes recommendations on this basis. Finally, the hybrid approach merges features of content-based and collaborative-based, as they prove to be complementary (Montaner el al., 2003) (Larson, 2011).

A hybrid approach can be employed towards collecting data and creating a user profile that would assist in generating and matching solutions for housing customization. Such an approach would target collecting demographic and psychographic qualities, along with household activities. The importance of each activity should be represented as a vector of values, acting as inputs to drive the process of design. Users may also differentiate between the relative levels of importance of each requirement. However, there remains a set of requirements that would usually be present in any housing design problem, regardless of user customization.

Computer-based design systems are only able to deal with quantifiable variables in the form of numerical data. Quantifiable variables (e.g. family structure, budget, desired area) are easy to define, as they rely on specific criteria of selection. Non-quantifiable variables (i.e. lifestyle,

[1] In computation, a Boolean is a data type that has two possible values: true and false (Reas & McWilliams, 2010).

activities) are difficult to process through a design system. Here they represent design qualities that can become very complex, especially in the case of housing, and due to the high diversity amongst the socio-cultural backgrounds of homebuyers. There is a tendency for people to transform spaces in their environment, in order to host their activities and needs. This transformation cannot be considered to be merely a random aggregation of enclosed spaces, but rather as responding to certain generative rules that vary among different societies and cultures.

Hiller and Hanson (1984) attempted to decode the quantitative attributes of a building's inner structure with regard to the social processes that manipulate their form and order. The authors proposed that the relationships in the physical configuration of space could describe its social meaning. One of the objectives was to isolate the rules of construction that would produce the resulting spatial configuration. These rules were concerned with the combination of elementary generators into a more general set of rules, which constitute the building's genotype; a container of characteristics.

In addition to mathematical equations, variables and parameters are employed to map the user profiles and building system onto a set of numerical data that can be translated into a design (Figure 6.11). The quantity and nature of variables and parameters emerge from a comprehensive analysis of the logic of customization, based on a definition of the level of customization. Commonly, a high level of customization involves a significant number of variables, which represent detailed information pertaining to the profile of homebuyers. These variables can be structured as primary or secondary variables. Primary variables would represent basic information, such as family structure, budget, and number of floors, while secondary variables represent additional options to refine the search space. Once the design is generated and approved by the homebuyer, a new set of variables might emerge, representing an advanced selection platform

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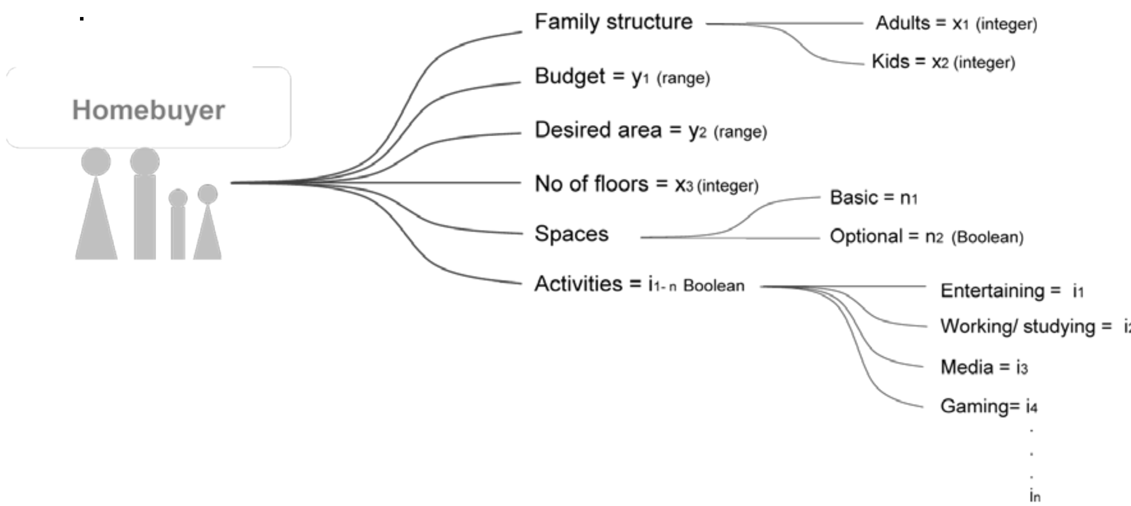

Figure 6.11: Variables representing homebuyer's profile.

6.2.2.2 Define Set of Constraints

Constraints are employed within a design process to refine the search space and to facilitate the isolation of appropriate designs. Constraints help direct the search process towards the suitable candidates by providing checkpoints. Each constraint is a definite statement of characteristics within which the solution must remain in compliance. Constraints can be grouped into larger classes, each related to a precise feature of the project.

Constraints can be classified into three types: quantitative constraints, qualitative constraints, and hybrid constraints that combine elements of both. Both quantitative and qualitative constraints have to be expressed numerically. Typically, the design of a building is required to comply with a set of design and legislation constraints. Subsequently, these two main categories can be further subdivided into geometrical constraints, structural constraints, economic constraints, and environmental constraints, in addition to technical requirements, as well as the programmatic regulations that follow from the briefs of homebuyers (Kumar, 1992).

Achieving mass customization therefore requires the definition of a set of constraints to guide the design system towards generating housing solutions that fulfil the requirements of both the user profile and the building system (Figure 6.12).

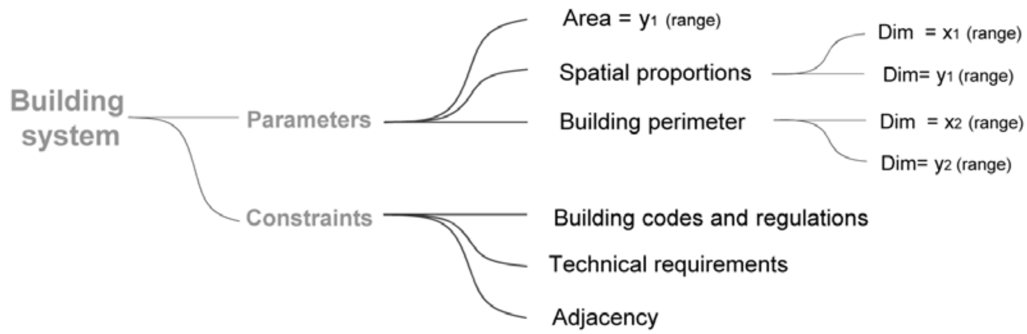

Figure 6.12: The list of parameters and constraints as an expected outcome of analyzing the building system.

6.2.2.3 Relationships

Once a list of variables and constraints related to the building system is developed, it must be linked to the variables that emerge from data regarding user profile generation methodology, thus creating a comprehensive platform that promotes interaction between system components (Figure 6.13). Both sets have to be linked in order to build a coherent relationship between system components. Such a relationship must be flexible, as individual homebuyers have different priorities with regard to the specifics of their budgetary requirements, and the areas and spaces necessary for their activities. Accordingly, the definition of variables and constraints, taking into account the capacities of the builder, would be directed towards the selection of an appropriate generative model or method of interaction between homebuyer and builder, depending on the level of customization.

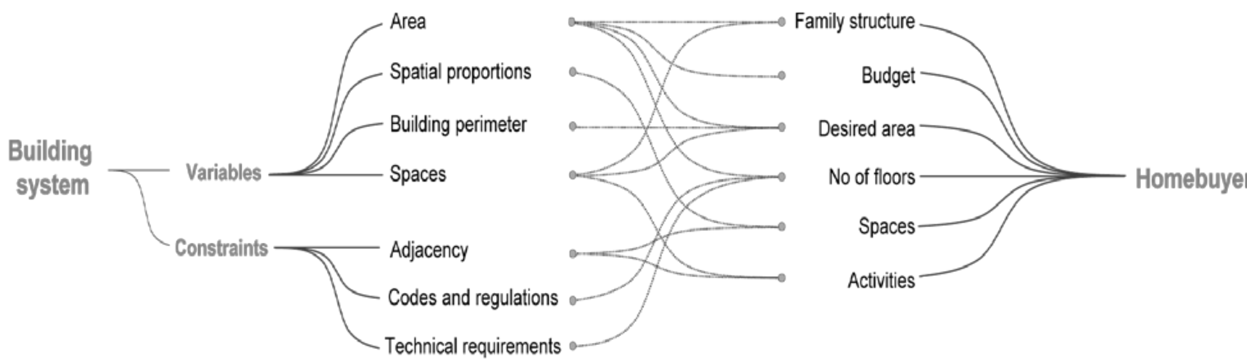

Figure 6.13: An abstract relationship between homebuyers' variables and the building system variables and constraints. Such a relationship has to be transformed into a numerical relationship, to feed the generative model, thus regulating the design generation process.

6.2.3 Developing the generative model

Generative models, also commonly known as generative systems, tend to model a specific design method for generating designs, based on a set of input specifications. Various models have been presented, including evolutionary systems, shape grammars, and parametric methods. Each model has its capabilities and methods of implementation. However, it must be understood that a generative model would only be implemented in cases where the highest level of customization is required.

Typically, a generative system has the capability to develop designs. These must comply with inputs describing the design, the generative rules of the algorithm, and the specific set of constraints built into the representation formalism. The process follows a cycle of problem specification, design generation, and then design evaluation. While evolutionary systems create design by iterating through this cycle multiple times, shape grammars might be applied either once or more, depending on the nature of the problem. Therefore, it can be argued that the design of a generative system is a discrete process within the process of developing the design system.

The behaviour of design generation can be controlled interactively by the system designer through the specification of design relationships in the form of desirable qualities, rules and a set of well-defined constraints. Each of these qualities has a different impact on the process, either by directing the design generation process towards a specific search space or by narrowing it. However, one of the main challenges when building a generative system is the method by which designs would be evaluated.

The selection of a generative system is influenced mainly by the manufacturer's design approach and design objectives. In other words, the selection would be an outcome of the problem breakdown and formulation explored in earlier stages. The design approach would be expressed in the number of variables, parameters and their types. In contrast, design rules and objectives functions would relate more to the nature of constraints. Additionally, the selection process is dependent on the builder's capability to adopt such a system, as the effectiveness of an algorithm is influenced by both the underlying theory and its implementation.

The generative system has to be constructed from a set of modules, each of which are assigned a specific function. Modules for data storage, variables and constraints can also be included. Koza (1992) argued that in order to implement a computer-based system for solving specific problems, the structure of the computer program is crucial. Such a structure can have these qualities:

- Perform operations in a hierarchical way;
- Perform alternative computations, depending on the outcome of intermediate calculations;
- Perform iterations and recursions;
- Perform computations on variables of many various types;

- Define intermediate values and subprograms, which can be subsequently employed.

As mentioned in the problem definition phase, if a manufacturer decides to adopt the highest level of customization, thus allowing homebuyers into the early stage of design, the problem becomes a space-layout problem. This then requires a system to support the automatic creation of floor layouts, based on user needs and requirements, while respecting the capacities of the building system. When implementing a generative system for customization, the first thing to decide is whether the computer system would assist the architect in creating custom housing, or if it would operate under the control of the homebuyer to generate housing solutions. Consequently, the two crucial factors that need to be defined are the degree of system automation and the system's operator. These two issues are more closely related to the implementation phases, which will be discussed later in this chapter.

A variety of generative models have been proposed to address the problem of space layout in architecture, a list that includes a number of the systems already explained in previous chapters, such as evolutionary systems, shape grammars, and parametric systems, in addition to other systems such as physically-based modelling.

Genetic algorithms have the ability to search a population of points in parallel using probabilistic transition rules, and are thus capable of operating in various forms of application. However, formalizing an evolutionary system for space planning such a complex process requires a high degree of computational expertise, as well as the capacity to determine feasible generation and production methods. Coates (2010) defined two main factors that restrict the application of evolutionary algorithms in design. Firstly, determining the dimensionality of the search space by the number of parameters to the problem, and secondly by the direction taken within those dimensions by the fitness function. Additionally, much like other heuristic algorithms, genetic algorithms have no clear termination criteria and, in some cases, do not guarantee an optimum solution.

Shape grammars necessitate the presence of a robust design approach, in the form of rules that would be utilized as the criteria through which designs are generated. The complexity of the process increases as more rules are required, which would prove necessary in the case of customization in order to offer variation. An analysis of prefabricated housing catalogues revealed that, in most cases, housing prototypes are not derived from a clear design scheme. Accordingly, no design shapes or rules can be extracted from the housing prototypes, indicating the application of a generative system other than shape grammar.

Parametric systems offer a representation of the design in the form of parameters and relationships, and would thus be capable of facilitating variation. Most generative models can be implemented in a parametric manner, rendering the design generation process more efficient. Generative systems should encode design and production knowledge with performance feedback, in order to create an integrated design system.

It is impractical to define an optimum generative system for space layout planning while also providing an appropriate degree of customization. Each system displays pros and cons with regard to a specific aspect of specific design, yet there is no evidence for a single comprehensive approach. As mentioned earlier, in addition to a housing manufacturers' design approach, there are several factors that would influence the selection of the generative technique (Figure 6.14), depending on applied design and production technologies, the degree of automation, the system operator, as well as representation techniques.

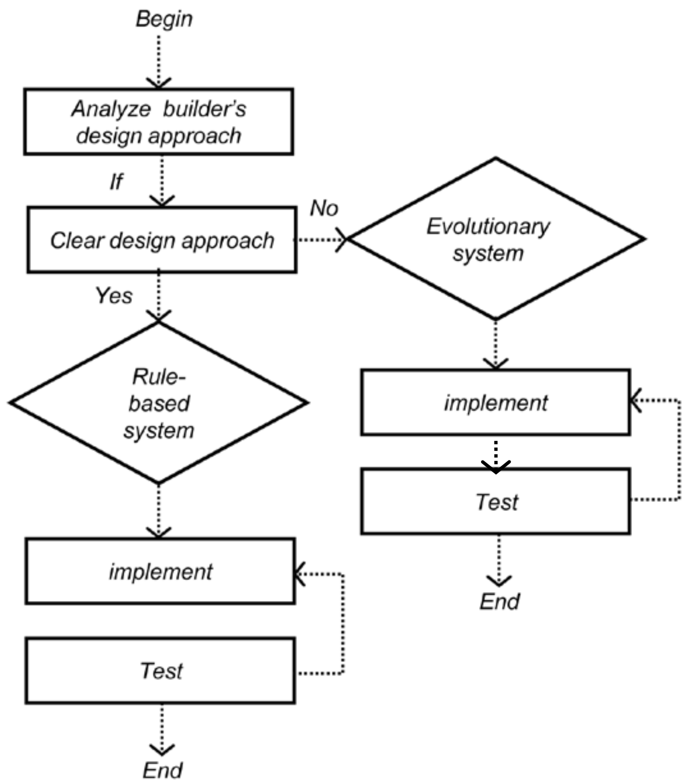

Figure 6.14: An abstract representation of the thinking process while selecting a generative system. In a more advanced approach, both systems can be combined to increase the generation process creativity. Also, both systems can be parameterized.

6.2.4 Implementation

The implementation stage is comprised of the development of a prototype model of the design system, and its subsystems, interfaces, modules, and generative algorithms within a functional computer program. This then tests the design system's capacity to reliably enable users to participate in the design of their homes. The process requires the collaboration of experts from different fields, who code the knowledge gained in previous stages and design system procedures into one comprehensive system.

Within this section, core elements of the design system are described, including its interface and generative model, in addition to supporting systems that are intended to improve the effectiveness of the proposed design system framework, such as advanced implementation through programming and BIM.

6.2.4.1 System architecture

Since the design of the system is a crucial phase in the system development process, the starting point for the implementation phase is the development of system *architecture*[2]. The system architecture acts as an action plan for the implementation of the system, and comprises the design of the necessary data structures, databases, knowledge-bases, and interaction schemes. Also, it involves a clear understanding of the system domain, as well as of the applications of pertinent computational and technical knowledge.

6.2.4.2 The interface

The term "interface" can be used to describe the interaction between components within a software or hardware system. A more specific subset of the term is the *user interface*[3], which is the focus of this section. Such an interface is aimed at allowing homebuyers to exert control over operations and processes through their interactions with the machine.

User interface design is a key element in system development, and ensures the program will suit the diverse need and perceptions of a wide

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[2] System architecture is defined as the scheme for the process of constructing a system by putting various subsystems and components into perspective, specifying system functionalities, and defining dynamic interactions among various system components (Aguilar, 1973).

[3] User interface is the medium at which interaction between human and machine occurs (Aguilar, 1973).

variety of users. It requires a clear representational structure in order to allow both unskilled users and experts to use it to engage in the design process. This can alter the design process fundamentally, and might require integrating a finer granularity of information (e.g. advanced visualization, prototype specifications). Therefore, with regard to customization, it is important to clearly identify the system operator and the degree of system automation.

While the notion of employing web-based configuration systems has been implemented by a number of prefabricated housing companies in North America (*LivingHomes*, *bluHomes*, and *ConnectHomes*), introducing homebuyers to the higher level of customization can be difficult. The process entails the possibility of manipulating the spatial layout of their future dwellings, thus making more complex decisions that go beyond the simple selection of dwelling appearance. In that sense, the interface has to be designed in a manner that enriches the customization process, supported by a high degree of visualization and a set of information to assist homebuyers in their decision-making process.

Since many homebuyers might find the customization process exhaustive, a decision support system, also called an advisory system, would be devised to operate in an interactive manner, so as to guide homebuyers in their decision-making, according to their profiles and need during the customization process. The classification of decision support systems would be based on the recommender agents, or information filtering techniques, which were discussed earlier. Blecker et al. (2005) defined a set of requirements that would need to be met in order to efficiently implement an online advisory through which to derive objective needs:

- *Interactivity*: The dialogue must run interactively, following a flexible approach. The system must also be designed to take into consideration a user's preferences and knowledge.
- *Dialogue sequence*: The sequence of the dialogue has to be determined in a logical way for users to understand.
- *Presentation of the results*: The system should present a clear rationale for why certain product variants are offered and others are not. Additionally, the user must be able to evaluate the quality of recommendations.

The proposed system will be tasked with providing homebuyers with additional information periodically at various nodes of interaction, leading to the generation of housing variants, which fulfill homebuyers' needs. It would also aid in organizing information, thoughts, and managing data. There is, however, a level of complexity that can arise when the automated dialogues between the manufacturer and homebuyers become composite. Additionally, the system will greatly emphasize visualization of the dialogue, since many homebuyers might lack the experience needed to properly envisage architectural drawings.

The structure of the decision support system can be devised on different levels, offering assistance to homebuyers at each stage of the customization process:

- *Define preferences*: Family profile, budget, desired area, space, and activities.
- *Define spatial requirements*: Layout planning or modification, based on user preferences and data collected at the first stage, supported by high-quality visualization.
- *Define interior/exterior appearance*: Fittings and finish selection according to user attributes, supported by high-quality visualization.

- *Define technical systems*: heating, cooling, ventilation, and automation systems, to be added or eliminated, according to a homebuyer's budget.

In order to implement a decision support system effectively, a manufacturer must conduct a deep analysis regarding the pattern of modifications that homebuyers normally request. Advisory experts would graphically model process flow by specifying a tree of advisory steps, which identify and create different nodes of interaction. Figure 6.15 proposes a structure for the interface, with focus on the interaction nodes between homebuyer and the customization system.

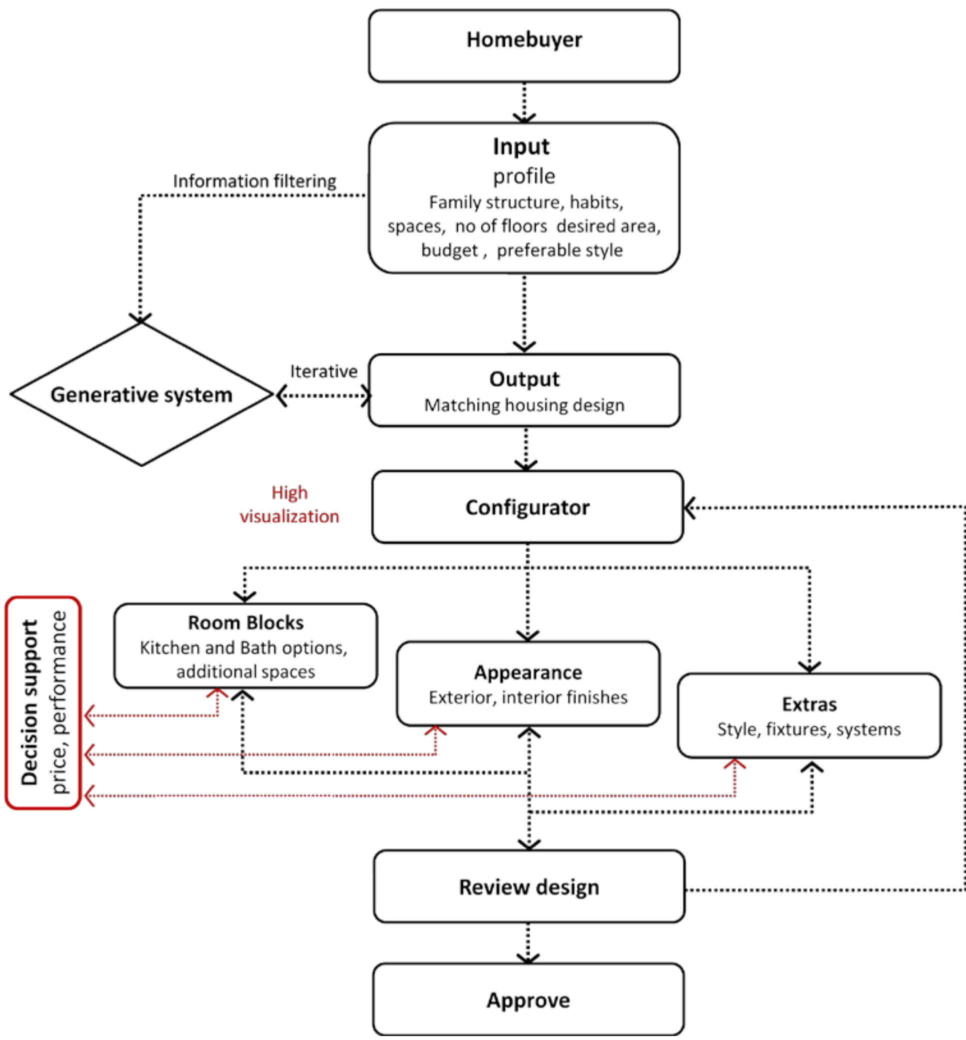

Figure 6.15: The structure of the user- interface, following a sequence to support the interaction between homebuyer and customization system.

6.2.4.3 The generative system

Generative systems are employed with the aim of assisting designers, and architects in the problem-solving process. In the case of a computer-design system for mass customization, the process involved is particularly complex in its application. In such a case, the generative system would be employed to produce the design of a customized house, which responds on a case-by-case basis to the homebuyer's profile.

There are two possible approaches to implementing a generative system for design synthesis. Firstly, building a system from scratch; a process that would involve encoding variables, parameters, constraints, functions, as well as a systematized approach to design, into a computational program with the ability to generate design solutions. The tool would be implemented using a programming or scripting language (e.g. Java, C++, VBScript, MEL) or any other syntax that supports algorithmic operations. Commonly, programming languages are used for problem-solving, modeling data, and accurate simulation through the use of a logical structure. To facilitate ease of development, there are some open-source libraries that would facilitate the implementation process. The second approach would be via implementing software plug-ins included within parametric CAD packages. Recently, various CAD software platforms have developed advanced plug-in systems to extend their software abilities beyond modeling. While the use of a plug-in for implementing a generative system would be simpler than programming from the ground up, such an approach has its limitations. It offers less flexibility in implementation strategies and user interface, as well as a lesser degree of control over design approach and representation.

Commonly, the first step towards solving any problem with the aid of a computer is to properly translate the problem into a form the computer is able to interpret and process. Typically this involves transforming the problem into a numerical model, logically divided into one or more groups, and able to address the physical properties of the problem. Described in terms of numerical values, spaces and spatial relationships are defined within a formal language that describes the internal structures and operations of the model.

One of the most common and effective concepts in implementing complex algorithms is *Object-Oriented Programming (OOP)*[4]*,* a protocol that enables software designers to construct reliable, user-friendly, easily maintained, well-documented, and reusable software systems that fulfill the requirements of their users. It provides an approach to computation that views the computer system as an inter-dependent group of objects that cooperate by exchanging information between them, in order to solve a problem (Reas & McWilliams, 2010).

The main components in OOP are objects and classes. A class is a shared definition for a given collection of objects, acting as a template that defines their parameters, what functions they can perform, and the internal logic for the construction of an object within the class. The objects that constitute classes are bundles of variables and associated operations. When referring to a particular object, it is sometimes referred to as an 'instance'. Eck (2005) defined three principles for OOP:

- *Abstraction:* In computing, this refers to the mechanism by which details are factored out to focus on a specific, yet broadly defined topic.

[4] Object Oriented Programming (OOP) is a process where a system is broken down into objects, based on data communication and requirements. It represents an attempt to make programs model the way people think and solve problems. In such a case, a programmer considers creating objects in memory; this involves self-contained data boxes that can be used in a normal linear programming style (Reas & McWilliams, 2010).

- *Modularization:* Breaking a program into individual modules that constitute components existing within a larger system operating independently from other components. A program's modularity is the degree to which it can be subdivided into these independent components.
- *Information hiding:* The separation of information from functions. Maintaining operational distance between the components of the program that are expected to change and those that are expected to remain static, in order to prevent an alteration in one area of the program from altering the program elsewhere. This provides a stable interface, which shields the remainder of the program from changes in implementation.

A programming project goes through a number of phases, beginning with the definition of the problem to be solved, and followed by an analysis of the problem and then by designing a program to solve it. Coding follows this, wherein the program's design is expressed within the programming language. Finally, there is the testing and debugging of the program. Complex programming projects are generally considered to be more likely to succeed if a systematic programming approach is employed from the outset.

6.2.4.4 BIM

Tools, platforms, and environments constitute the three levels of BIM applications. While BIM tools are task-specific applications that produce a specific outcome, including model generation, drawing production, scheduling, and cost estimation, BIM platforms are design applications that offer data to multiple users. They provide primary data-models that manage the information on the platform. Finally, BIM environments allow for the management of one or more data streams that integrate BIM tools and platforms within an organization. They support interoperability within a system, or the development of an efficient workflow through the exchange of data between applications, thus facilitating its automation. It eliminates the duplication of structural, electrical, and mechanical data previously generated by other applications. However, the main challenge of interoperability exists across platforms such as the ArchiCAD, Revit, and Digital Project and fabrication model platforms, as it requires the incorporation of specific rules in order to maintain project integrity (Eastman, InterScience, Sacks, & Liston, 2008).

Within the proposed framework, there are three important capabilities of BIM platforms and environments that would support the mass customization of housing. Firstly, there is the ease of creating BIM parametric and customizable product families that can be shared between the manufacturer and other components' producers in the production process. The goal would be to standardize the structure of object information beyond geometry, so as to include specifications for selection and use in analyses, along with material properties. Second is extensibility, which is how the BIM platform supports a scripting interface; an interactive language that customizes the platform's capabilities. Finally, the capacity to establish a multiuser environment which enables efficient collaboration and data exchange within the design and production team. This includes the ability to export data in suitable forms for automation of the fabrication tasks using CNC machinery, based on manufacturer's capabilities, thus reducing the time required to generate technical drawings.

For a higher level of integration, prefabricated housing companies are encouraged to develop an Integrated Project Delivery (IPD) strategy. This is a single collaborative assembly that connects the homebuyer, designers, manufacturer, and components producers, creating a comprehensive team that is based on common interests, and shares the technical and social means to communicate and collaborate (Figure 6.16). It is an approach that redefines the relationships and interests between various participants in the project realization process (Smith, 2010) (Eastman, InterScience, Sacks, & Liston, 2008).

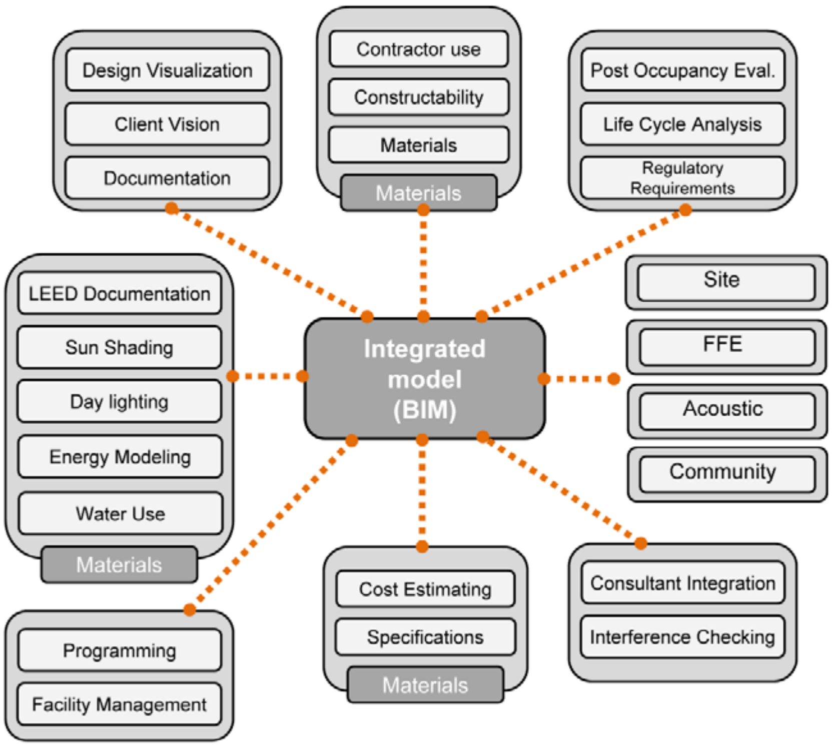

Figure 6.16: Integrated project delivery through BIM environment (Source: Eastman, InterScience, Sacks, & Liston, 2008).

6.2.5 Evaluation

Once a design system is constructed and implemented, it is necessary to carry out a few experiments in order to evaluate the system performance. These will test its capabilities to generate valid design solutions that comply with both the building system and user profile input. The evaluation phase is not intended to validate the system as a whole, but rather is meant to verify the functioning of some of the system components and decisions, such as the type of variables, system constraints, and structure of the objective functions.

The results of evaluation should be interpreted and appraised based on the goals and objectives of the system framework, in the context of the requirements that were defined at the early stages of the process. The system development process is an open-ended process, where the exploration of new design and production technologies can enhance the system performance in later stages.

Nunamker et al. (2001) proposed a series of steps for the evaluation of a system, within system development research:

- Observe the use of the system by case studies and filed studies.
- Develop new methodologies, based on the observation and experimentation of the system usage.
- Consolidate experiences learned.

Evaluating a design system for mass customization goes beyond the validation of a generated design, and extends to the appraisal of each module and subsystem, rather than only the system as a whole. To make the evaluation process accurate, it is necessary to gather as much information as possible, drawing on the success of user-system interaction, design space exploration, and the link between design and production. It is therefore required to set specific criteria for the evaluation of the system, based on the level of customization and the objectives of the design system. Each objective must be assessed and stated quantitatively, and ranked by assigning relative weightings. Finally, a performance parameter would be established to appraise the implementation of the design system. At this point, the system architect may call for the review of some of the modules and system components, with the intent of enhancing system performance.

6.3 Collaboration

Swiftly becoming a typical practice for the design and production of modern products, the purpose of collaboration between different participants in the development process is to gather expertise from different fields into one team, towards the achievement of a specific goal.

Commonly, the main driver towards collaborative design is to tackle the sophisticated nature of engineering systems, the design of which requires a multi-disciplinary approach executed by specialists operating within their field of expertise. Fischer and Herr (2001) have noted that the implementation of a generative system necessarily requires interdisciplinary skills. Good designers are not always good programmers, and good programmers cannot replace the interpretive skills of the designers.

Since implementing mass customization involves the integration of expertise from different participants in the process, the challenge becomes how to achieve and maintain conceptual integrity while performing as a team. Design coherence benefits ease of use (Brooks, 2010). Achieving integrity in collaborative design environments requires appropriate management of multiple activities, and effective knowledge transfer between individual specialists. The ideal outcome is to gain all of the advantages of a broad knowledge base in order to reflect on the required design and production activities.

6.3.1 The design system team

The design of complex systems surpasses the capabilities of any single human designer, necessitating the collaboration of specialists from different fields in a multi-disciplinary approach. In order to ensure conceptual integrity in a team design, it is important to empower a system architect, who would be competent in the relevant technologies and experienced in the type of system to be designed, while having a clear vision of the end product of the system (Brooks, 2010). Figure 6.16 proposes how a design system team involved in the mass customization process might be structured.

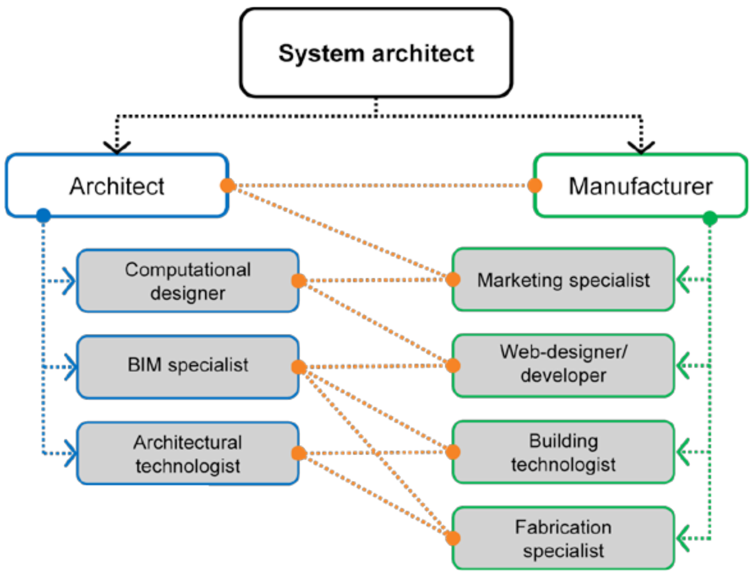

Figure 6.17: The system architect and other specialists might be involved in the process of developing a design system for mass customization. An information platform connects specialists directly throughout the process. In some cases, the architect could play the role of the system architect.

The system architect would have two primary functions within the design team. Firstly, the architect would supervise and maintain the relationships between various team members. Secondly, the architect would perform system design and integration by defining subsystems and system components, thus establishing the method of interactions between required modules. The system architect should possess adequate knowledge to comprehend the system design and its environment, from its highest to its lowest level. Concomitantly, in order to ensure effective communication between the system architect and design specialists when defining technical challenges, there should be significant overlap in knowledge-base.

6.4 Reflections

As previously mentioned, the main goal of this chapter is to present a framework for the development of a design system for the mass customization of housing, rather than a specific computational design tool. Drawing upon various research directions, this framework follows a systematic approach, informed by the analysis of the theories and concepts underlying mass customization and system design approaches, so as to enable the application of these practices within the housing industry.

Any design problem-solving process typically begins with a clear definition of the problem to be solved. In the case of the mass customization of housing, the problem definition phase focuses on defining the level of customization required, as determined by the point at which homebuyers would become involved in the design process of their homes. Such a definition relates primarily to two aspects: market conditions and applied technologies.

Because one of the main objects of mass customization is cost control, the selection and design of a design system will be primarily determined by the degree of customization, production technologies, and housing type that can be accommodated by the chosen business model. Accordingly, this will dictate whether the system implemented will operate through a search-based process, which will select from a given range of alternatives, or through a creative problem-solving approach with the capacity to generate entirely new designs and prototypes.

Selecting, and thus designing, a system for the mass customization of housing depends mainly on the business model; codifying the level of customization, housing type, design and production technologies, and marketing strategies. This requires either the implementation of a system based on a search process from a set of alternatives, or a creative problem-solving approach that has the capability to generate new designs and prototypes. However, as one of the main objectives of mass customization is cost control, the implemented design system must be sensitive in this regard, in addition to being efficient in design production.

Perhaps one of the most significant issues when developing a computer-based design system is to identify which activities can be automated, and how it can be achieved effectively. Accordingly, a theoretical understanding is required in order to develop a reliable model of what classes can be automated.

Following the definition of design system components, implementation involves processing data types and information into a functional customization model. This requires establishing a definition of the method of interaction through which to design the user interface and decision support system. By developing a BIM integrated process, a comprehensive set of capacities to increase design and production quality can be leveraged during the implementation process.

Developing and implementing a mass customization system is a multi-disciplinary process involving the integration of expertise from a broad range of fields. Mass customization is a production strategy that requires the deployment of cutting-edge technological tools in response to extensive market studies. This requires a team of experts from different domains, led by the system architect, with the aim of structuring a coherent design system that can produce a comprehensive mass customization model.

Part IV: Simulation and Conclusion

7.0: Simulation

7.1 Introduction

Over the past few decades, a spirit of exploration and experimentation has characterized the prefabricated housing industry. While various researchers studied the application of prefabrication concepts to mass production systems, the success of these efforts has been compromised by multiple challenges regarding design and production. One of the major limitations of the current systems of the mass production of dwellings is the lack of robust customization options for the industry's clients. Contemporary advancements in design and fabrication technologies, however, now make the idea of customization more feasible.

This chapter simulates the proposed design system framework to the profile of *Alouette Homes*[1], a prefabricated housing company operating in the Quebec market. The applicability and flexibility of the proposed design system framework is tested in the face of two different levels of customization, based on data obtained from Alouette Homes' company profile. The first experiment explores the implementation of an advanced configurations system, while the second demonstrates the application of generative systems to facilitate the highest levels of customization.

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[1] Alouette Homes, located in Granby, Quebec, is a leading builder of energy-efficient, factory-built homes. The company employs one hundred and twenty employees, and builds an average of two hundred and fifty units per year. The company was established in 1971, and since then has built over twenty thousand wood-frame homes for customers around the world.

7.2 Case 1- Simulating an Advanced Configuration System

As mentioned earlier, configuration systems are information tools that automate the order-taking process, capturing customers' requirements without the need of external human intermediaries. A configuration system's main component is a knowledge base, which is further divided into two subcomponents: the database and the configuration logic. While the database comprises the whole set of component types and their instances, the configuration logic identifies the existing constraints between different components, to ensure valid product variants. The proposed system is the outcome of the analysis of both relevant research in mass customization, and of a detailed study of the prefabricated housing industry in the Quebec region.

7.2.1 System overview – problem definition

7.2.1.1 Level of customization

The company studied in this simulation developed a prior housing catalogue, comprised of a set of pre-designed housing prototypes. This catalogue offered a variety of two to three bedroom houses and one to two storey single-family housing units. This catalogue aimed to cover a wide range of the housing market, as a result of continuous studies of homebuyers' demands. By standardizing the design and production processes, Alouette Homes also sought to minimize cost and resultantly lower their product pricing.

When selecting a standard model, homebuyers are graphically introduced to their prospective home through an existing plan and a 3-D rendering (Figure 7.1). By meeting with a salesperson, a customer can then customize and select doors, windows, shingles, siding, and a range of interior finishing materials in an assortment of colours. Additionally, homebuyers can also request certain modifications be made to their home's layout, though this must be approved by the engineering department. This process commonly incurs extra fees, as seemingly simple modifications can snowball in both complexity and time requirements over the course of manipulating the technical drawings.

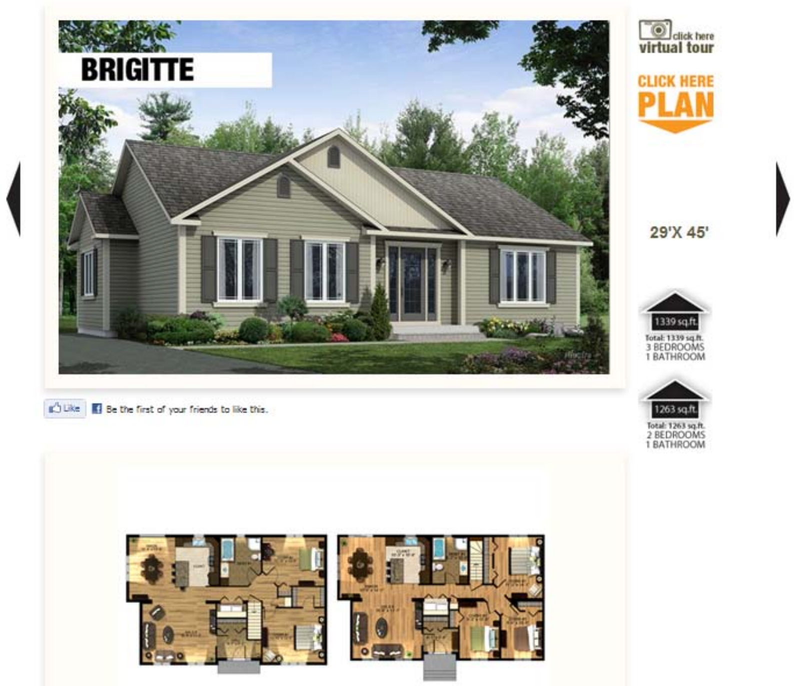


Figure 7.1: A screen shot of the housing model data-page from Maison Alouette's website.

Following the company's marketing, design, and production approaches, and in conjunction with the goal of gaining leads in the market by delivering high-quality products, a more advanced and rigorous level of customization has been proposed by company executives (Figure 7.2). This tool aimed to offer homebuyers greater flexibility with regard to the decision-making process. To that end, the proposed configuration system goes beyond the mere selection of predetermined finishes, to a more personalized approach that involves discovering the most appropriate housing prototype based on an information filtering approach. Consequently, room block modifications can be added to the customization process.

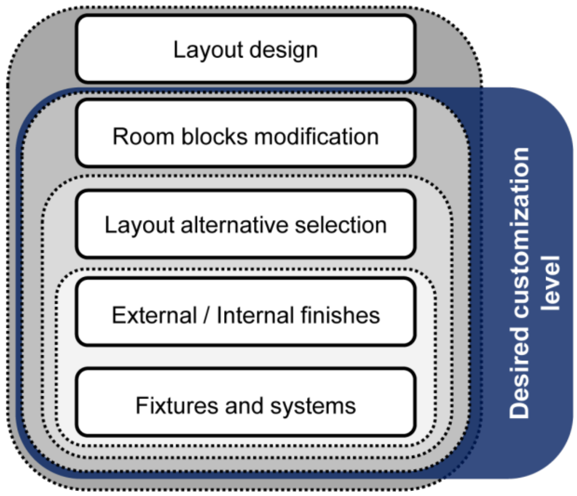


Figure 7.2: Desired level of customization.

7.2.1.2 Applied technologies

The previous chapter's design system framework proposed the study of three different levels of technological applications to enable customization: design, information transfer, and production. The aim of these applications is accommodating variations in costs and materials. The use of CAD tools to this end is crucial- it enables housing prototypes and corresponding technical documentation to be designed and developed in a systematic and responsive manner. Commonly, when homebuyers request modifications, an extra "administrative fee" is charged: this fee represents the overhead costs for the time invested by engineers to accommodate a client's modifications. This cost increase could be avoided by the implementation of a flexible design and pricing system, which could instantly accommodate these variations. Such a system would support greater interoperability- a characteristic of BIM tools.

Information transfer, a key aspect of this process, occurs on two levels: firstly between designers, and secondly between the engineering team and the producers. Communication at the first level can be optimized through the intensive use of BIM tools, while the nature of information transfer at the second level calls for advanced CAD/CAM applications. Advances at these two levels strongly correlate to increased levels of customization: the greater the degree of customization offered, the more sophisticated information transfer techniques are required to be.

7.2.1.3 Integration scheme

Integration schemes are methods to create coherent data management processes between various participants in the customization process: the homebuyers, the manufacturer, the architect, the engineering team, and the producers of building components. This thesis is particularly attentive to the means by which homebuyers are linked to builders, as it is at this link in the chain that homebuyers make choices to customize a housing unit. The results of this critical, early step are later felt in the links between design and production.

In order to efficiently communicate with homebuyers, Alouette Homes developed a website that includes a set of housing prototypes seeking to capture a large sector of the market. However, no customization options are offered online. If an advanced configuration system were to be implemented, however, the company's communication model could be developed to facilitate more interactivity on the part of the consumer, thereby enhancing homebuyers' experience throughout the configuration process.

An inventory of existing integration tools reveals clear room for improvement in the industry. Prior to this simulation's analysis of technological applications within the company, it was noted that Alouette Homes already utilizes a basic BIM tool to produce sets of architectural and technical drawings. In regard to the larger links between design and production, however, this tool appears to be underutilized. Moreover, the company employs many digital production tools, such as CAD/CAM software and hsbCAD to facilitate automation processes. However, BIM, advanced CAD/CAM applications, and digital fabrication tools are required to support the proposed outcomes of a mass customization process. Figure 7.3 represents a summary of the problem definition phases, showing various system objectives on different levels.

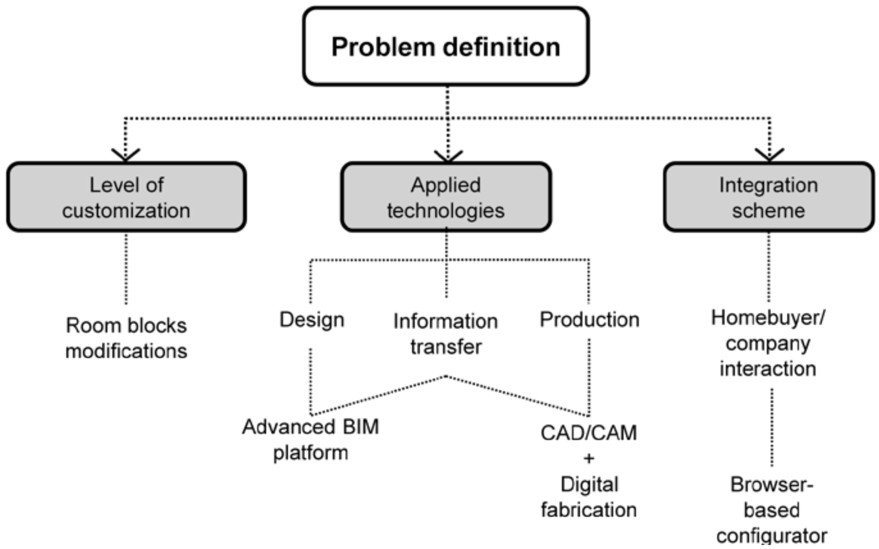


Figure 7.3: Problem definition framework, illustrating different levels of objectives.

7.2.2 Structuring information: problem formulation

One of the main components of a targeted configuration system is that of a database, comprised of a set of housing prototypes and a catalogue of variant spaces. Such a system is a requirement of a methodology to classify these prototypes and match them with consumers based on relevant information filtered from a homebuyers' profile. This would lead to the creation of a matrix of data, representing relationships between various data streams. Figure 7.4 represents the logic that structures various levels of system objectives and connects these levels together to define relationships.

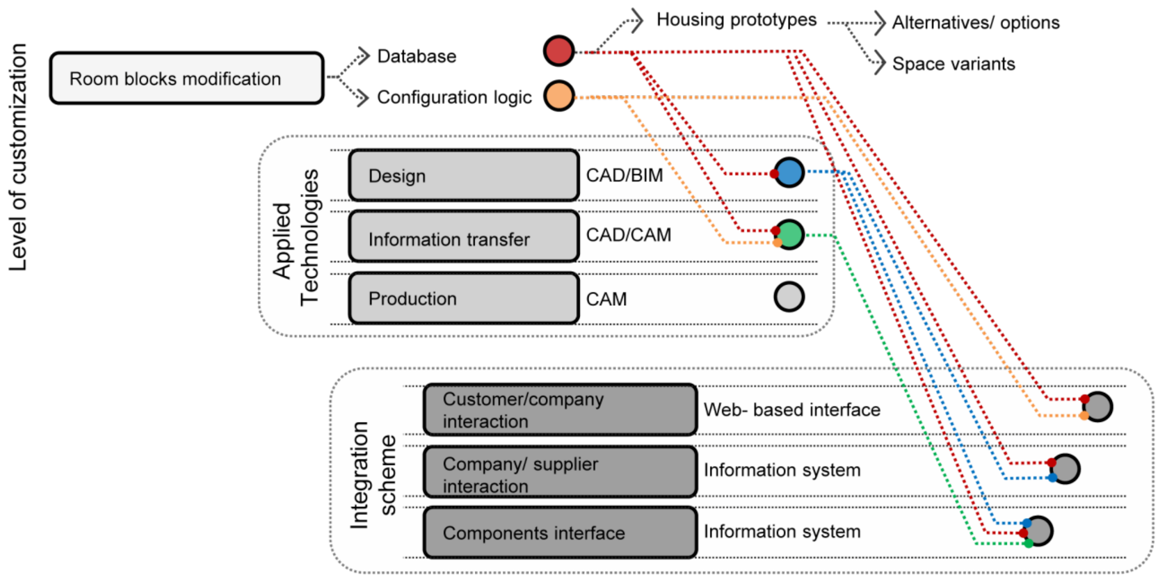


Figure 7.4: The process of structuring information involves defining various levels of information and then creating links between them. These links represent an abstract connection and would be elaborated more within the process of developing the configuration logic.

The problem formulation phase aims to structure the collected data on different levels, and subsequently creates a multi-levelled link between them. It specifically targets the definition of data types required to feed the configuration processes, in addition to the outputs that feed the production process.

7.2.2.1 Define sets of variables: user, and solution profiling

The set of variables within an advanced configuration system is the outcome of an analysis of certain cues within homebuyers' profiles, which direct the search to recommend suitable housing units. This section details the necessary creation of a user profile filtering process, and proposes a method to match user profiles with design profiles.

In such a process, elements from a user profile would be represented as vector values and then linked to a housing prototypes' classification breakdown, thus directing the recommendation process towards suitable solutions. Additionally, some housing prototypes would also be described in a vector of values that demonstrates unique features. Figure 7.5 represents a taxonomy of homebuyer's profile variables and its relationship to housing prototypes classification. Such variables and classifications represent some of the most common qualities a company might offer, though they can be adjusted to suit the needs of each individual manufacturer.

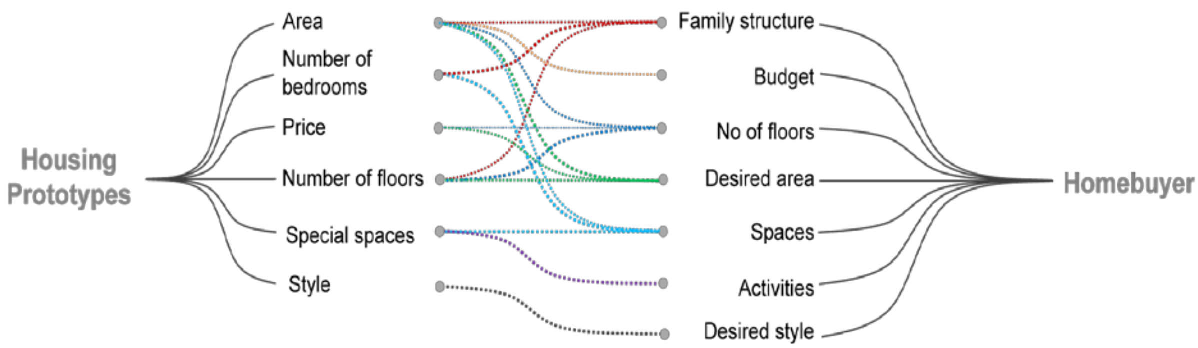


Figure 7.5: The classification of housing prototypes would follow specific criteria, corresponding to the breakdown of homebuyers' profiles, with the aim of facilitating the matching process.

Following this model, greater amounts of data gathered in a homebuyer's profile result in a more refined search process. Consequently, an extra element was added to further enhance sensible customization- that of "activities" which reflect a homebuyer's lifestyle and social values.

7.2.3 Develop configuration logic

Based on the level of customization, the configuration concept, and the related components that constitute a configuration system, two primary functions are embedded within the configuration logic. Firstly, a recommendation agent seeks the most suitable housing models that correspond to a homebuyers' profiling outcome. Secondly, a hierarchically structured product configurator allows homebuyers to modify their selected housing unit. Figure 7.6 illustrates the structure of the configuration system, detailing the procedures of each phase.

The recommendation agent derives its logic from an interactive inquisition process, structured to engage users in a dialogue to discover their requirements and values. The collected information relates to different activities, with their corresponding spaces within a home, in addition to demographic and psychographic qualities. The analyzed data feeds the recommendation agent, thus revealing the most suitable alternatives from the database. Selected homes are then displayed to the homebuyer through a set of understandable architectural drawings, plans, and 3-D photorealistic renderings. Once the homebuyer selects a model from the recommended design alternatives, the configuration process is initiated.

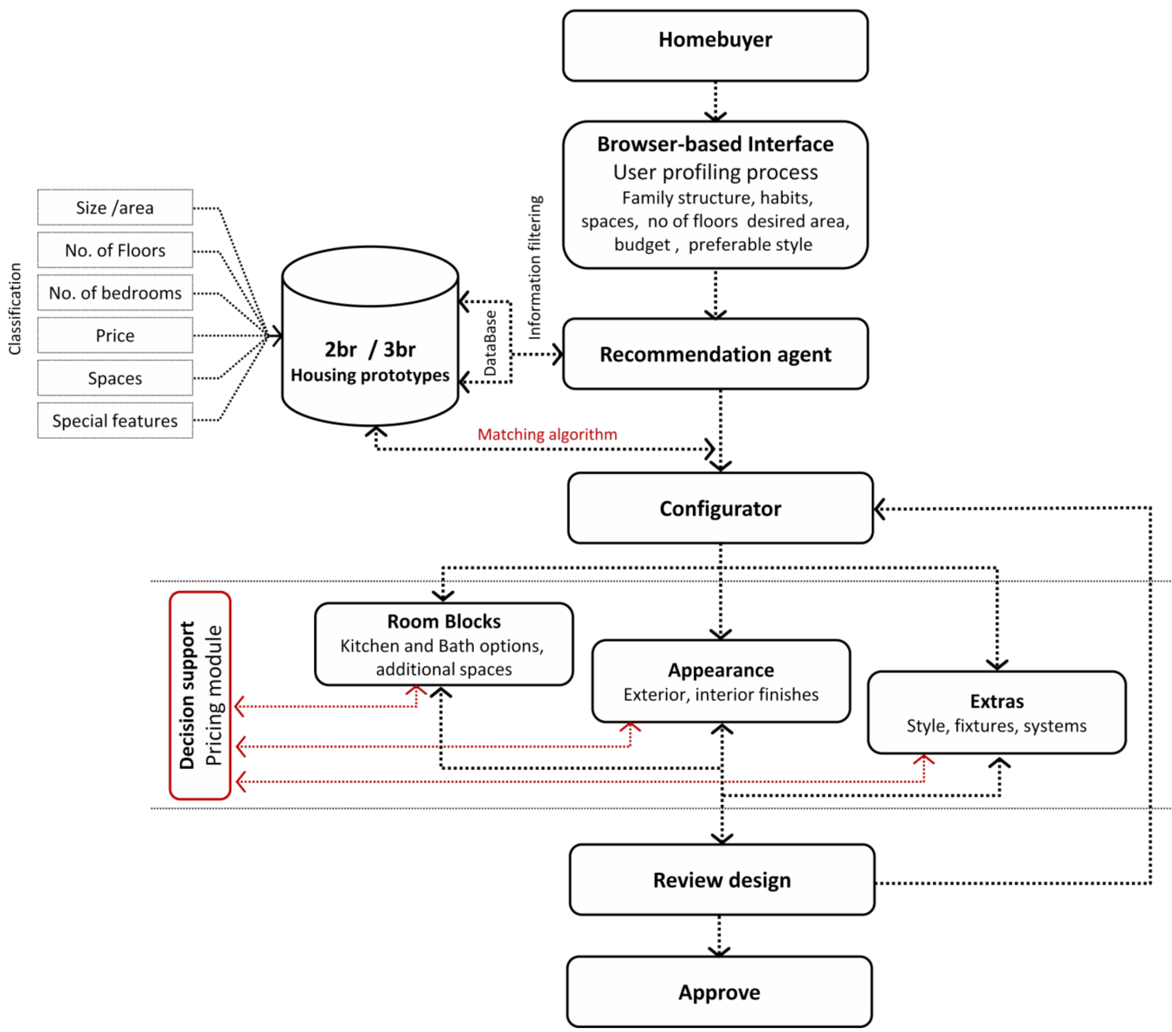


Figure 7.6: A diagrammatic representation of the configuration system outline.

7.2.3.1 The recommendation agent

The main function embedded within the recommendation agent is that of its *matching algorithm,* which matches a user's profile to a set of housing alternatives that have already been saved to the database. This process can be described as the synthesis phase of the problem formulation elements. The algorithm derives its mechanism from conditional programming in the form of IF/THEN/ELSE structures- basic constructs of an expert system. The algorithm matches related attributes and isolates irrelevant housing profiles. Figure 7.7 explains the logic behind the recommendation agent. A simple pseudocode example of the matching algorithm is as follows:

Start
Get household variables (i.e.: family structure, area, number of floors)
IF household variable is less than or equal to three
THEN eliminate three-bedroom houses
or ELSE keep list
IF budget variable is less than or equal to xxx
THEN eliminate models with area greater than xxx
IF number of floors variable is equal to one
THEN eliminate two floor models
Display remaining models
Repeat until a model is selected
End

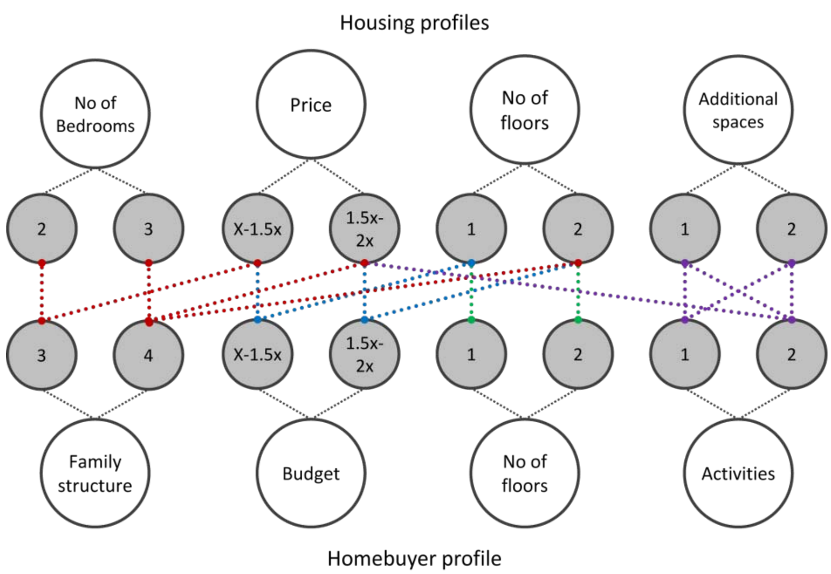


Figure 7.7: An abstract representation of the relationship between homebuyer profiling and housing profiles. The dotted lines represent relationships between profile elements.

Within the matching process, some relationships are simple and direct, while others may attain great levels of complexity. Consequently, in order for the recommendation agent to perform efficiently, user and solution profiles must deconstruct into sublevels, with a matching method instituted between them. In some cases, homebuyers can prioritize certain requirements, assisting in narrowing their choices by eliminating redundant prototypes. This process is regulated through a relationship matrix that translates various connections into a vector of values. Figure 7.8 illustrates this matrix relationship between a user profile and a housing profile by defining primary and secondary relationships.

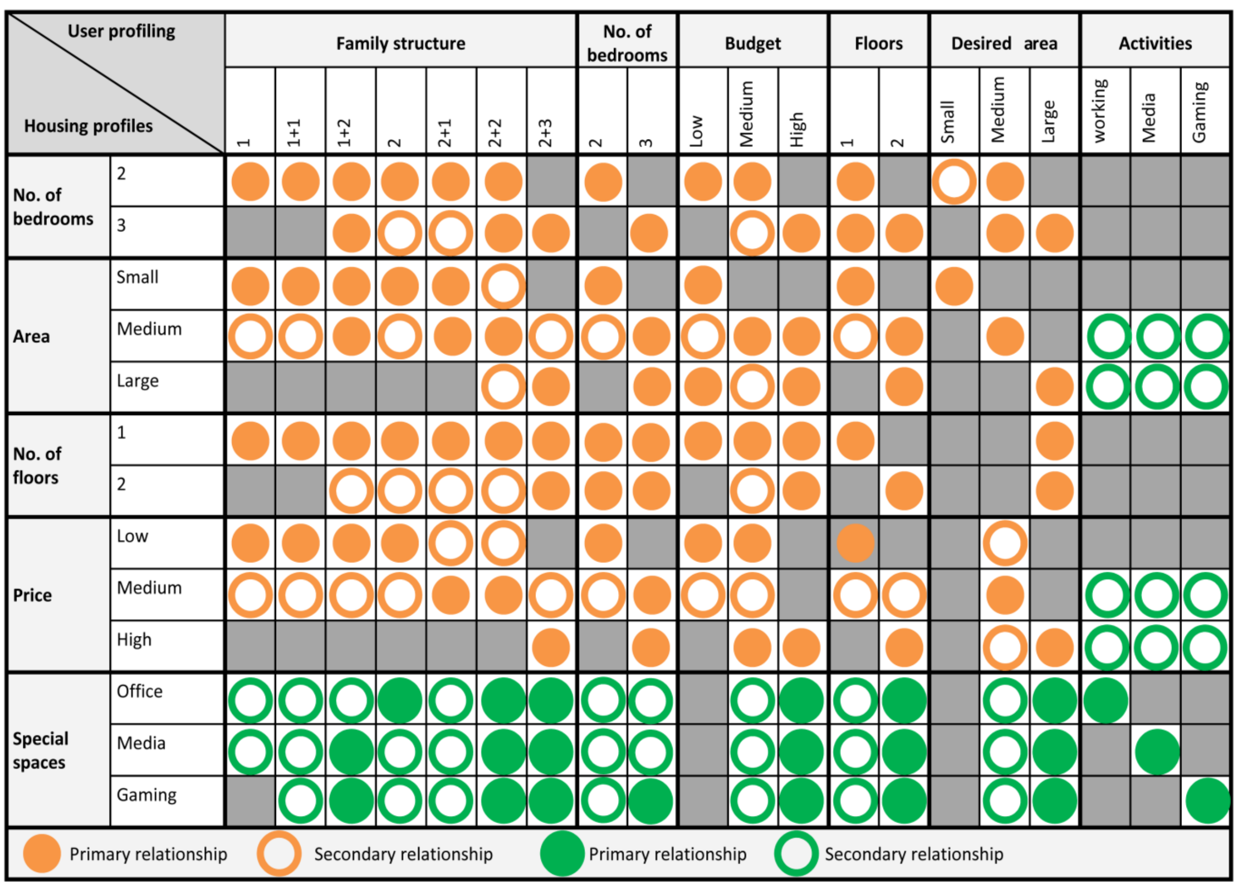


Figure 7.8: A matrix representation of the relationship between homebuyer profiling and housing profiles based on the configuration system outline.

7.2.3.2 The configurator

A browser-based configuration tool would allow the functionality of a multi-level interactive process, offering homebuyers a procedure to add or modify design elements according to the user's preferences, once a design prototype has been selected. This process is broken down into three consecutive levels:

- *Room block modifications:* Configures room blocks, particularly those of the kitchen and bathroom.
- *Appearance:* Configures surface materials, colour, and texture selections of exterior and interior components.
- *Appliances/systems:* Configures kitchen appliances, laundry, air conditioning, and heating/cooling systems.

a. Space layout and design

Given the configuration process' goal of a highly interactive consumer experience, two or three alternatives of a housing prototype are offered to a homebuyer after an initial selection is made. Within the algorithmic system of this tool, these alternatives branch from the prototype proposed by the recommendation agent. Any variation between the possible layouts is considered in light of space allocation, in order to fit a variety of needs. Once a layout is chosen, then the process advances to room block modification, where three different kitchen and bathroom layouts are presented consecutively. Using the user's profile data, these components would aim to reflect the homebuyer's presumed preferences and lifestyle. Acting as a decision support medium, a pricing module implemented within the system would provide a constant update of the total price, arising from the decision-making process.

One of the main ideas informing the development of such a tool is the desire to standardize housing components as much as possible within certain units, thus promoting the inter-changeability of common architectural and structural features, and resulting in a reduction of production costs. Figure 7.9 represent a tree of housing prototypes and different variants.

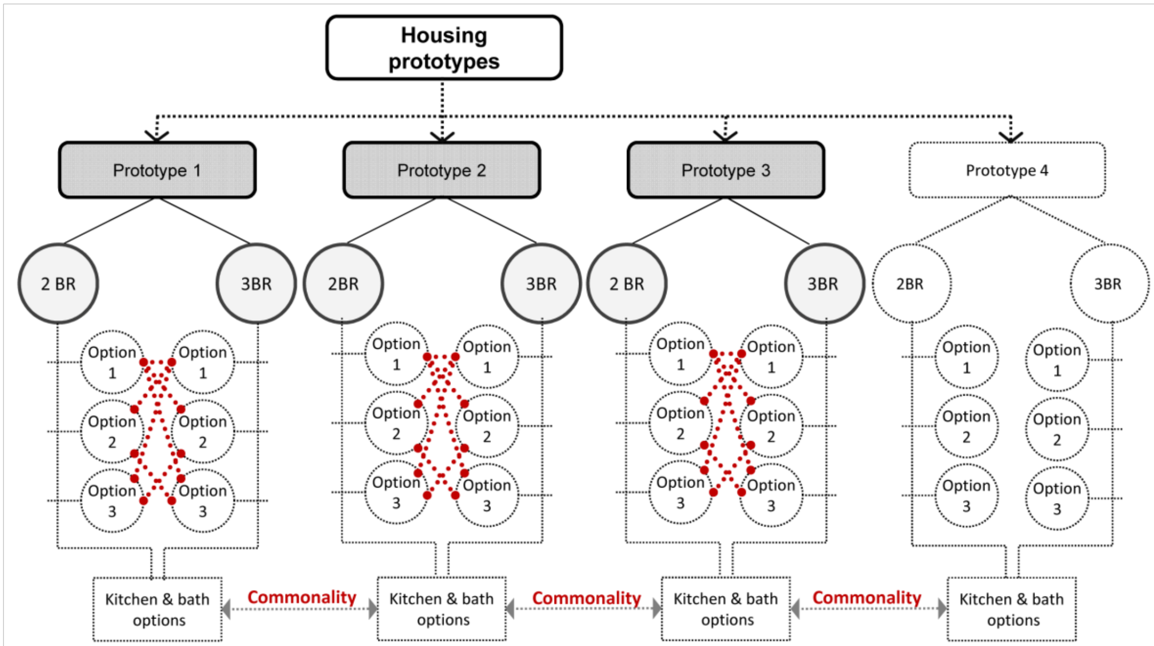


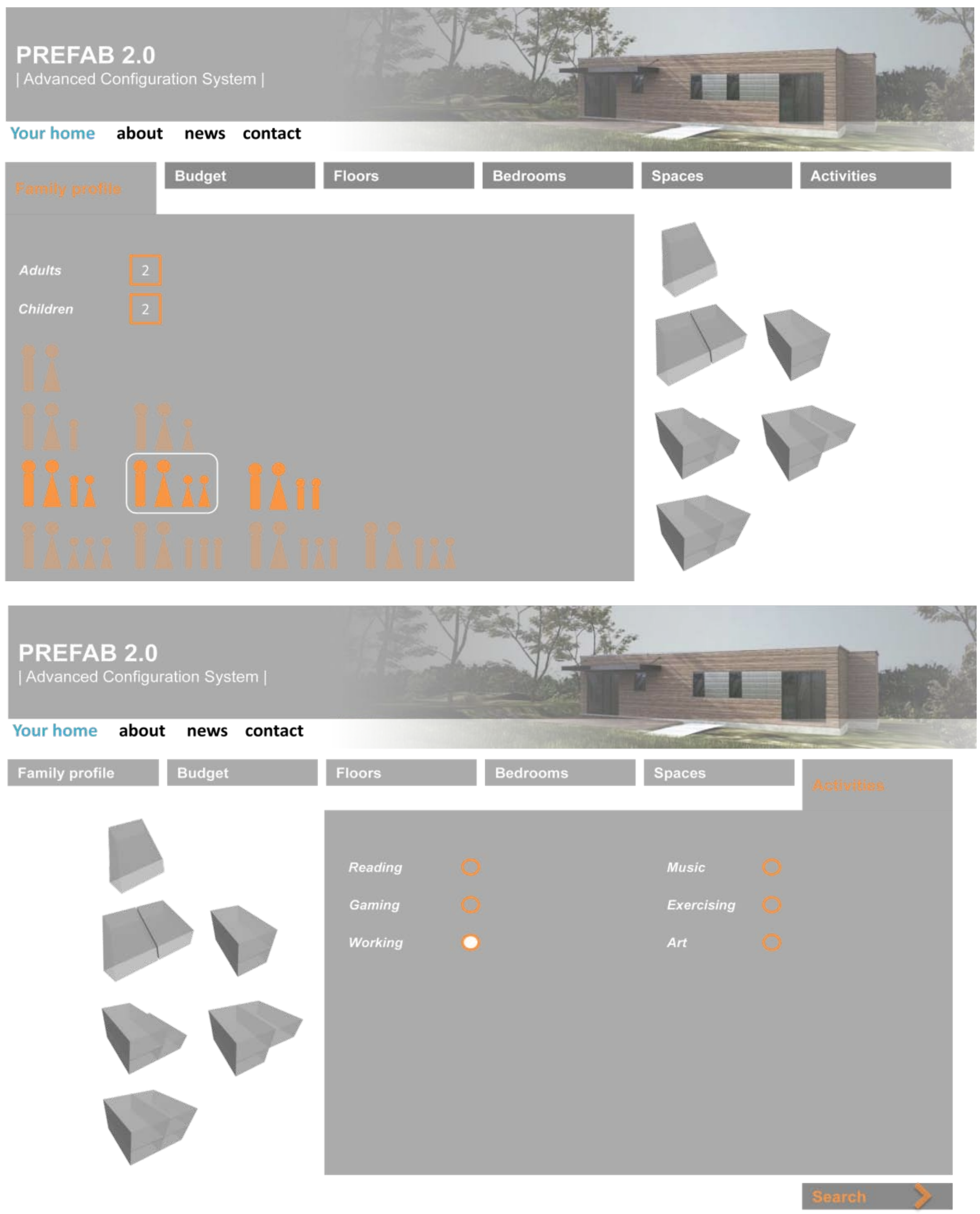
Figure 7.9: A representation of the housing prototypes data tree. Commonality represents components that are shared between various prototypes.

b. Finishes and appliances

Once the layout alternative, space adjacencies, and room blocks have been decided, the rest of the customization process concerns the building's appearance: the finishes, appliances and systems. This concept of customized building components, selected via a browser-based, interactive interface, has formed something of a fashionable trend in recent years. This movement has been implemented by several modular prefab housing manufacturers, using various techniques for 2-D and 3-D navigation, based on WebGL and video gaming technologies, resulting in a real-time configuration process. The details of such a process will be further elaborated in the subsequent section.

7.2.4 The interface

The design of the browser-based interface structure creates design continuities with the company's website, while introducing additional features to support the customization process. These features are connected with the data structure within the website and an accompanying information bar, which aims to facilitate the customization sequence based on the configuration logic. Figure 7.10 illustrates the sequence for the proposed user-interface.



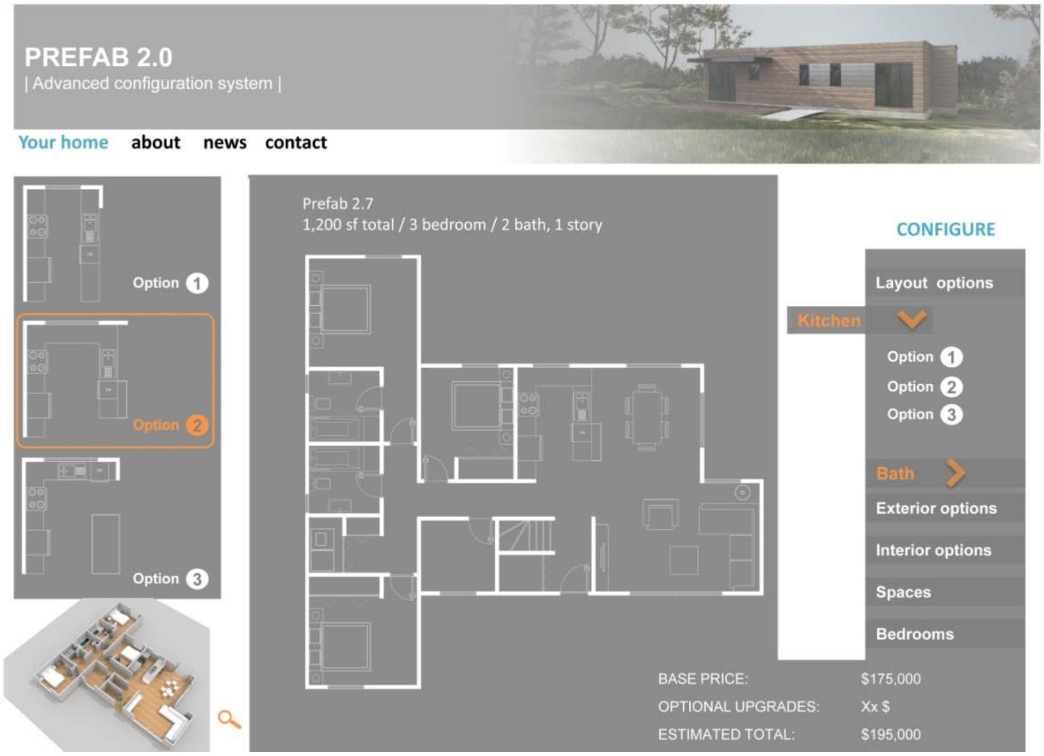


Figure 7.10: The interface prototype of first and last steps in the user profiling process, in addition to a sample step in the configuration process.

The browser-based prototype model combines the data collection of the homebuyers' profiles and requirements with a design configuration system. As such, the user interface creates a real-time simulation of the interaction that otherwise only takes place between a homebuyer and an architect. The first series of questions asked of a user aims to identifying a household profile, which can direct the system's matching algorithm towards an appropriate housing model category. The second series of questions seeks to minimize the system's search pool by collecting more information about homebuyers' lifestyles and spatial needs. For instance, if a client needed to work at home, the system would consider the potential need for a home office. This phase culminates in a set of housing models that correspond to a homebuyer's entered data. Once the homebuyer selects a model, two further options are presented: the homebuyer may either purchase the standard unit or proceed to further layout configuration, followed by the customization of finishes and systems.

7.2.5 Implementation

While the processes of implementing the proposed customization system can be devised on various levels and phases, a collaborative approach is necessary. These levels would address each of the configuration system components, with the aim of creating a coherent mechanism for implementing the configuration system, as shown in Figure 7.11. The goals of this process and the research that informs its objectives is as follows:

- *Develop a comprehensive product platform*: The study of prefabricated companies in Quebec, particularly that of Alouette Homes, demonstrated that, in most cases, there is a set of “successful models”, comprised of the units that are most commonly sold in the market. A critical analysis of these housing prototypes reveals that they lack a robust and shared design theme, which would otherwise engender the interchangeability of design features and components across units. As one of the fundamental aspects of implementing mass customization is the development of a product platform to provide the necessary taxonomy for positioning different products and structuring their interrelationships, this absence poses a challenge for further innovation. Moreover, further advances in mass customization processes require the improved functional and technical variety of products within the platform. Such diversification would bring new product functionalities, in addition to diverse technologies, design methods, manufacturing processes, components and assemblies. While greater functional variety corresponds with greater customer satisfaction, greater technical variety may affect manufacturability and costs.

One of the main challenges within this simulation was the development of a product family (i.e. a housing catalogue) for the studied company. In order to examine this concept, the author developed different alternatives for four housing prototypes recommended by the company as “successful models”. A product family tree was developed, offering various alternatives for each prototype, while supporting the concept of commonality, especially within bathrooms and kitchen spaces. Such an approach is aimed at enhancing functional and technical variety. This product family could be further branched out into to a wider tree of products if adapted to the general housing market.

- *Develop parametric, three-dimensional BIM models for the housing prototypes*: Parametric modeling, in addition to BIM, creates the means by which architects, engineers, planners, manufacturers and components fabricators can communicate together in a fully integrated environment. BIM forms the basis for design, and contains all the information required for the fabrication and assembly of a housing unit. Such integration would produce multiple advantages, including efficient structural and technical coordination, maintenance of information and design model integrity, collaboration in design and production through the better management of parts schedules of procurement, an understandable approach to sequence of assembly, and greater control over fabrication, assembly, and construction.
- *Develop an appropriate method of representation:* In most cases, homebuyers lack the experience and training to fully interpret architectural drawings and technical features in a house’s design. Traditionally, a salesperson would assist homebuyers in overcoming any difficulties or confusion. In the case of a browser-based configuration process, the salesperson is generally absent. Consequently, the techniques the system employs to visualize the

home become ever more important. The configuration system would present homebuyers with 2-D drawings that represent housing plans, augmented by 3-D images that offer multiple angle views of the virtualized dwelling. Additionally, dynamic, real-time configurations would be represented in these image previews. Finally, a pricing module would be implemented to reflect the effects of each selection on the total cost of the housing unit.

- *The matching algorithm:* Implementing a search algorithm is considered to be an easy programming exercise. The challenging part would be to efficiently translate the relationship between the homebuyer's profile and housing prototypes classification. The system proposes a matching methodology based on an expert system construct.
- *Develop a browser-based interface*: Given that the configuration process would operate online through the company's website, the quality, structure, and design of the interface plays an important role in the process, as it represents the medium of a virtual dialogue between homebuyer and designer. Signifying the company's brand and the homebuyer's aspirations, the interface must offer visual cues for quality and success.
- *Establish a design/production link*: Alouette Homes already employed CAD/CAM software and hsbCAD to interlink design and production processes in the automated production of walls. Further possibilities for the automation of other building components have been previously realized elsewhere in the market. This thesis, however, focuses primarily on the link to production facilitated by the application of BIM tools. While this research does not provide a clear method for implementing BIM, it raises the possibility of testing the application of an Integrated Project Delivery (IPD) approach to prefabricated housing companies in Quebec.

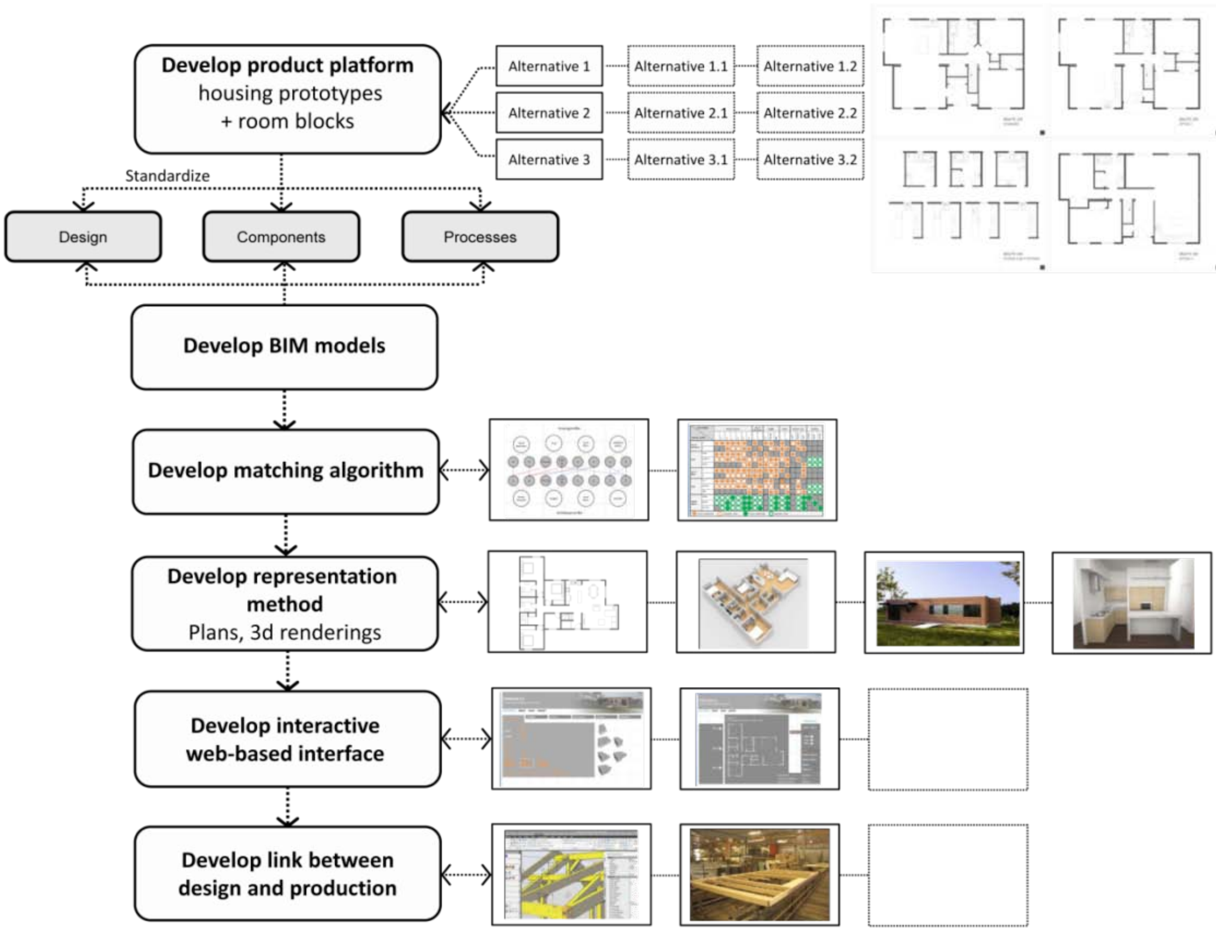


Figure 7.11: A diagrammatic representation of the implementation mechanism.

The implementation of a configuration system should be a multi-disciplinary process, aimed at engaging various forms of expertise from different fields, in order to deliver high-quality, customizable prefabricated housing prototypes that are fundamentally responsive to market demand.

7.3 Case 2- Simulating a Generative Tool-Based Customization System

The previous scenario simulated an advanced configuration system based on a search engine that revealed the most fitting housing prototypes in response to homebuyer's preferences. However, the present case-study seeks to move beyond configuration to a complex system that employs a generative tool to create housing solutions, based on the analysis of a homebuyer's profile.

This analysis draws upon the application of computation techniques throughout different phases of the design process, with the aim of enabling customization in the housing industry, as explored in previous chapters. The focus of many of these applications lay in developing methodologies to automate the process of generating solutions for space planning problems, thus supporting customization in the early stages. These applications employed various computational approaches and techniques, focusing on the fulfilment of diverse programmatic, spatial, and environmental design requirements.

7.3.1 System overview – problem definition

7.3.1.1 Level of customization

This simulation aims to tackle the highest level of customization alongside layout design (Figure 7.12). Commonly, when a homebuyer is not able to find a housing prototype that satisfies their needs, they require a custom built house, the specifications of which are outside that of the builder's catalogue. This design can either be developed by the company's architect or purchased from an external, ready-to-build online housing catalogue.

In order to respond to this specific market sector, Alouette Homes decided to explore the possibility of implementing a system that would allow for the highest level of customization. These process features aim to deliver custom housing units, tailored to homebuyers' preferences at the level of layout design. In that sense, the problem required a computational approach to space layout planning, involving the automation of the process of generating spatial layouts for housing units. The proposed system was intended to produce novel designs while respecting existing prefabricated housing design and production requirements and constraints.

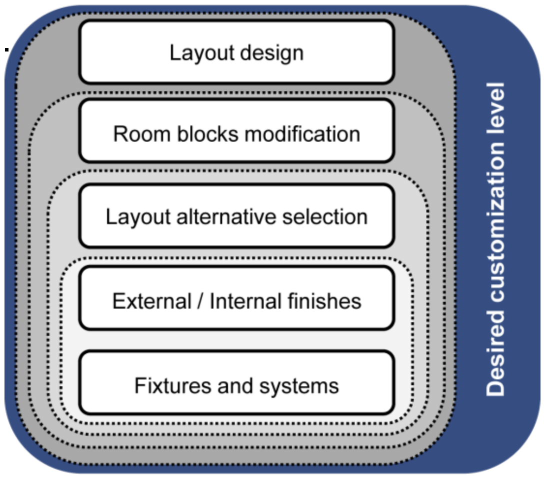


Figure 7.12 : Desired level of customization; the highest level denoted with space layout design.

As mentioned previously, space layout planning can be a complex architectural design problem, to be resolved through a computational approach. Since the development of CAD technologies in the 1960s, many researchers have explored its potential in the field of space planning, resulting in diverse techniques and methods. One such approach relating to the aims of this thesis is that of Schnarsky (1971). Concerned with the lack of choices in industrialized housing, he developed a concept based on employing a computer system that could generate house designs, in response to a detailed questionnaire that captures users' requirements. The questionnaire measured the number of users, their interactions, budget and priorities. The data extracted from the questionnaire was then used to direct Schnarsky's system to select from a predetermined array of parts. The proposed system then systematically combined mass-produced modules based on rules of assemblage. The end product of this process would be industrialized, responsive housing production capitalizing on factory robotics.

While these ideas were proposed over forty years ago, the practice of the design and production of prefabricated housing failed to benefit from such efforts. Recently, with the development of heightened computer abilities and augmented applications of problem-solving algorithms, it may now be possible to realize the potential of this model with only minor human intervention.

7.3.1.2 Applied technologies

There is a direct relationship between the degree of customization and the degree of required technologies in this system. A higher level of the former requires advances in the latter. Technological applications support customization by transforming homebuyers' preferences and requirements into buildable housing designs. Consequently, these applications must draw upon the logic of the generative algorithms that were explored and analyzed in chapter three.

A generative-based customization approach requires advanced processes in data management to optimize and safeguard information transfer. Unlike the previous case study, the outcomes of the generative tool are ambiguous, and yet accord with a set of pre-defined constraints. All modified designs, unlike that of standard housing models, must undergo various phases of validation. In the prior system, even while a set of constraints is made to control the design-generation process, the validation process of any customization measure inevitably requires interference from the engineering team, in addition to various producers of components and materials. Accordingly, real-time validations only address design issues, leaving technical concerns to external actors. A careful balance is resultantly required to minimize inconsistencies that may arise between a system's pre-defined components and the interjection of novel design. While there are various tools and software plug-ins for constraint-checking, along with concurrent research efforts, fully automating this process has nevertheless currently proven infeasible, as it involves complex computational techniques. This raises questions as to the level of automation of the proposed system, to be explored later in the implementation section.

7.3.1.3 Integration scheme

The level of customization in a system directly reflects on its levels and processes of integration. Given that the proposed system is an autonomous, generative tool that creates custom designs of modular houses, it is essential to explore the means by which homebuyers could efficiently participate in the design process. Similarly, it is also important to study the system operator, whether that consists of the homebuyer, a salesperson, or an assisted-participatory process that draws upon collaboration between the two.

In a similar approach, homebuyers could also be linked to the manufacturer via an interactive, web-based interface. As a result, this process would require a larger amount of more detailed information about the homebuyer to feed its generative tool. While the configuration system displays pre-designed housing prototypes, the generative tool would create housing designs through the aggregation of pre-defined spaces. In this way, rather than selecting pre-designed models, the design system instead recommends a set of domestic spaces to be connected together to build a housing unit. Figure 7.13 represents a summary of the problem definition phases, showing various system objectives on different levels.

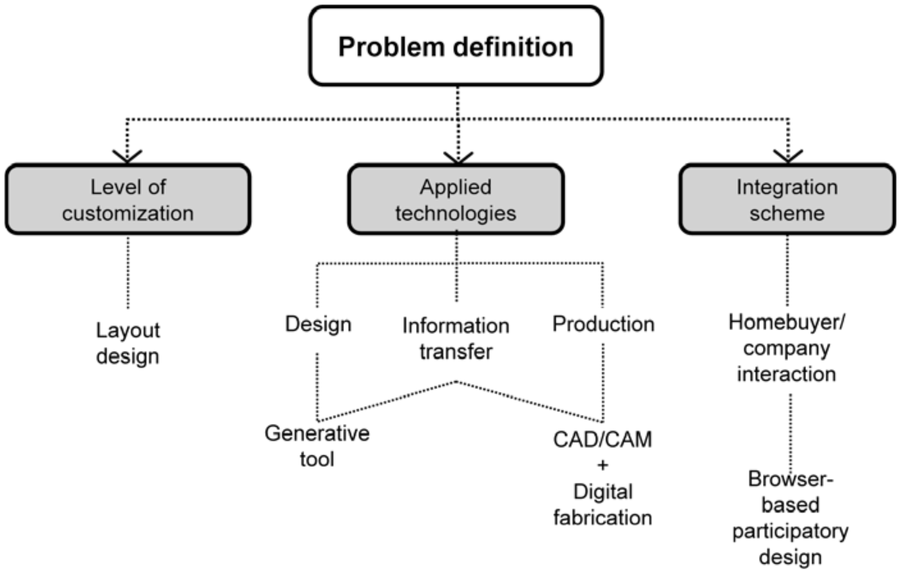


Figure 7.13: Problem definition framework, illustrating different levels of objectives.

7.3.2 Structuring information: problem formulation

Once the level of customization is defined, a subsequent phase structures the gathered information and develops an efficient link between various data types to serve the needs of the customization system. This section conceptualizes a methodology for managing various types of data, given that the intended level of customization involves an ever-changing flow of information. These data types include the homebuyer's profile and correspondent design profile, which then branch into variables, parameters, and a set of constraints. Following from this framework, one of the main challenges to formalizing this design system is the creation of a method for evaluating the magnitude of each data stream, as well as the subsequent means by which various data types will be integrated into a comprehensive scheme. Accordingly, the outcome of this formulation phase would be the definition of the generative tool's inputs, in addition to an outline of a functional rationale with which the output must comply. Figure 7.14 represents the horizontal and vertical relationships between levels of customization and their corresponding technological applications. The vertical connections define the relationships between sub-components, thereby defining various objectives.

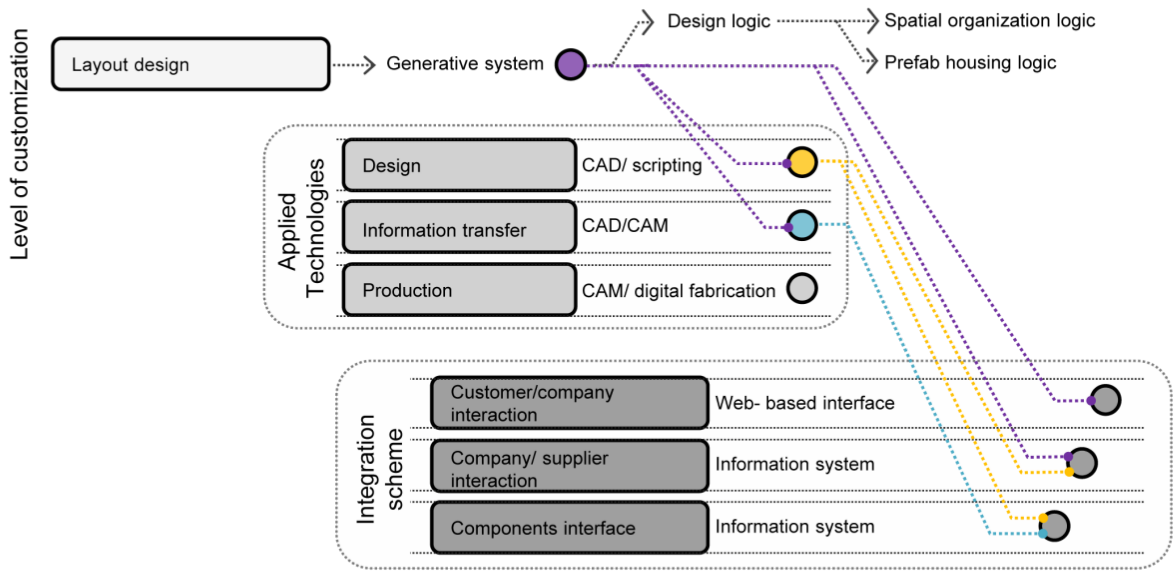


Figure 7.14: A diagrammatic representation of the initial and abstract levels of structuring information.

7.3.2.1 Define sets of variables and parameters: user and design profiling

In the case of a generative tool, a more detailed approach to the user and design profiling process is required. Accordingly, the system represents elements from the user profile in the form of integers, ranges, and Boolean values, all of which refer to the demographic and psychographic qualities of a homebuyer. Elements from design logic are similarly represented, and refer to spatial organization logic, typological characteristics based on predefined classification, the number of floors, and building style (Figure 7.5). The interconnections between these variables can change once the system's generative technique has been selected, based on the nature of its generation logic.

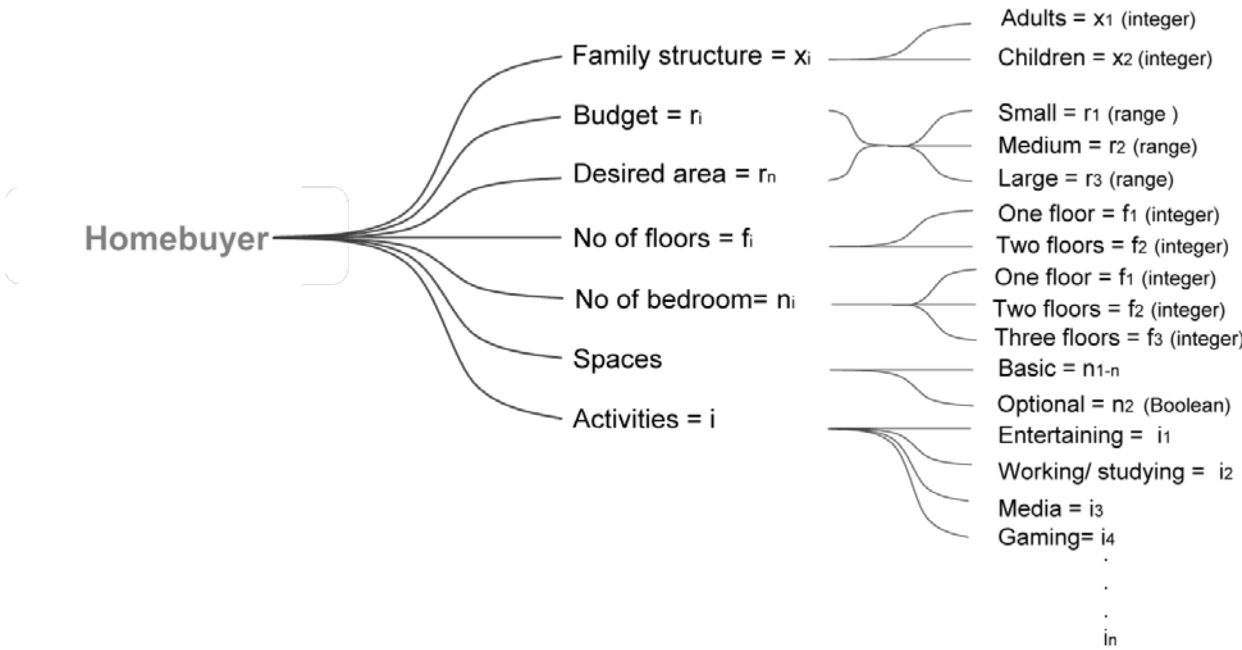


Figure 7.15: The classification of the homebuyer's profile and according extraction of variables. A detailed formulation of these variables is required to feed the generative tool.

Concurrent with the homebuyer's profile, a set of building parameters interrelates with the existing data (Figure 7.16). These parameters represent the whole building system, based on a specific classification of modular components representing a house, and sub-components representing an array of spaces. As previously mentioned, these parameters tend to be more static. They are initiated in response to variables extracted from the analysis of a homebuyer's profile, in addition to the study of building systems and a possible matching process. Both data types are then defined and coded as inputs to the generative tool.

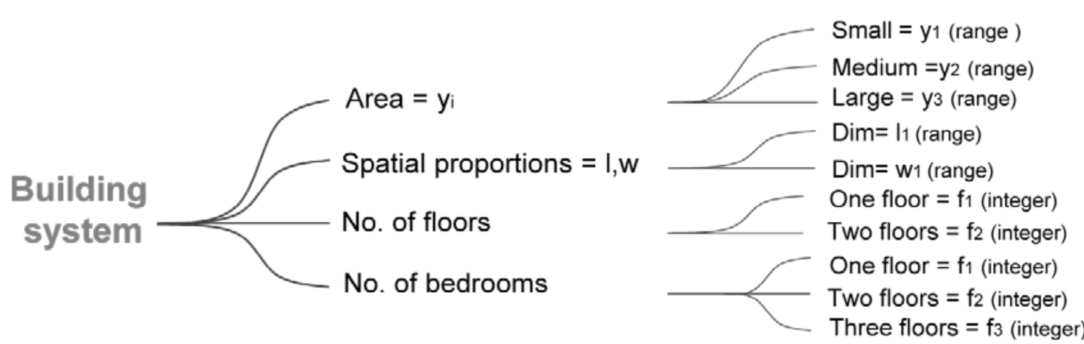


Figure 7.16: The classification of the building system's parameters.

Once both variables and parameters are defined, a link representing dependency would connect these elements (Figure 7.17). At this stage, a clear design logic has not yet been implemented. Accordingly, the process of structuring variables, parameters, and inter-linkages remains flexible, based on the selection of the design logic. Fundamentally, however, the connection between user profile and building system feeds the logic of the matching algorithm.

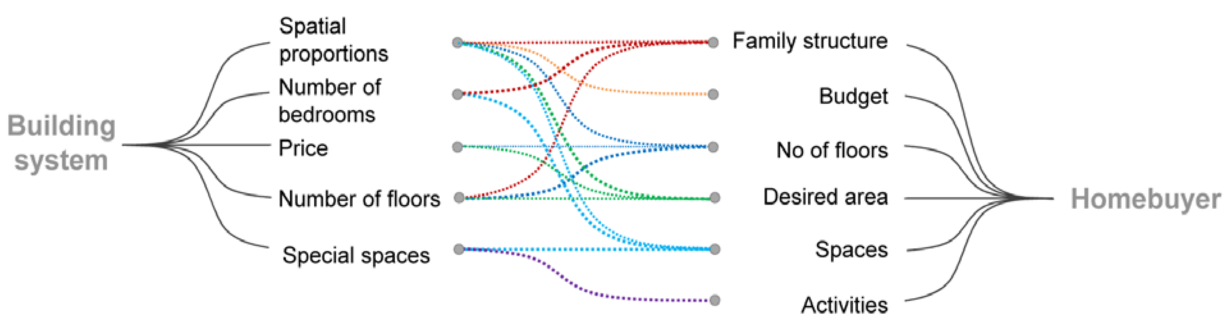


Figure 7.17: The logic of linking homebuyers' profile variables to building system parameters.

7.3.2.2 Define sets of constraints

While the prefabricated housing industry greatly benefits from constructing its modules within an indoor, controlled environment, design and production in this industry is still controlled by various factors. Technical issues result in maximum and minimum module sizes, structural constraints controlling opening sizes and locations, and the legality of transporting components are all regulated by provincial codes. Consequently, the consideration of this diverse range of constraints within a computer-based design system is no small task. Accordingly, these factors are summarized in Figure 7.18.

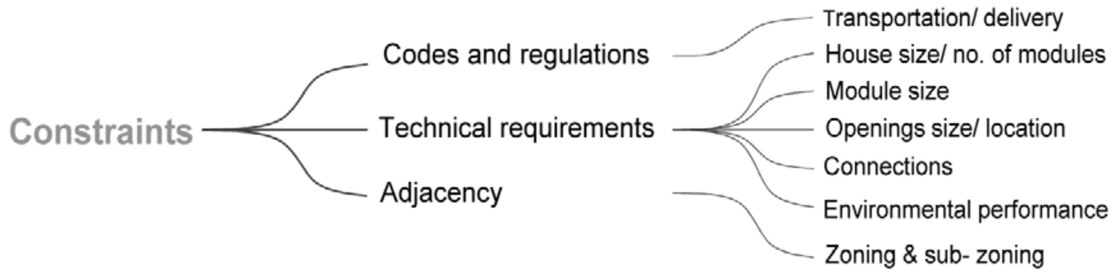


Figure 7.18: Representation of building constraints. These constraints are derived from the analysis of prefabricated housing system.

7.3.3 The generative model

Before the generative tool can be explored, a design logic must first be defined, as it influences the tool's ensuing selections and implementation. Figure 7.19 illustrates a comprehensive approach to the design of this generative, tool-based design system.

Within this thesis, there are two approaches for implementing the generative tool capable of providing layout-planning solutions. The first is based on a user-operated design system, while the second represents an approach to layout planning using evolutionary computation. The two approaches tackle various aspects with regard to layout design, design system operators, design evaluation, and implementation techniques. These aspects will be explored in more detail in the next sections.

Based on an analysis of prior approaches to space layout planning and the prefabricated housing industry, a design logic is proposed to control the process of generating solutions. As mentioned earlier, there are two methodologies for space layout planning: aggregation of spaces, or spatial subdivision. Each of the presented generative tools in this research engages with one of these methodologies.

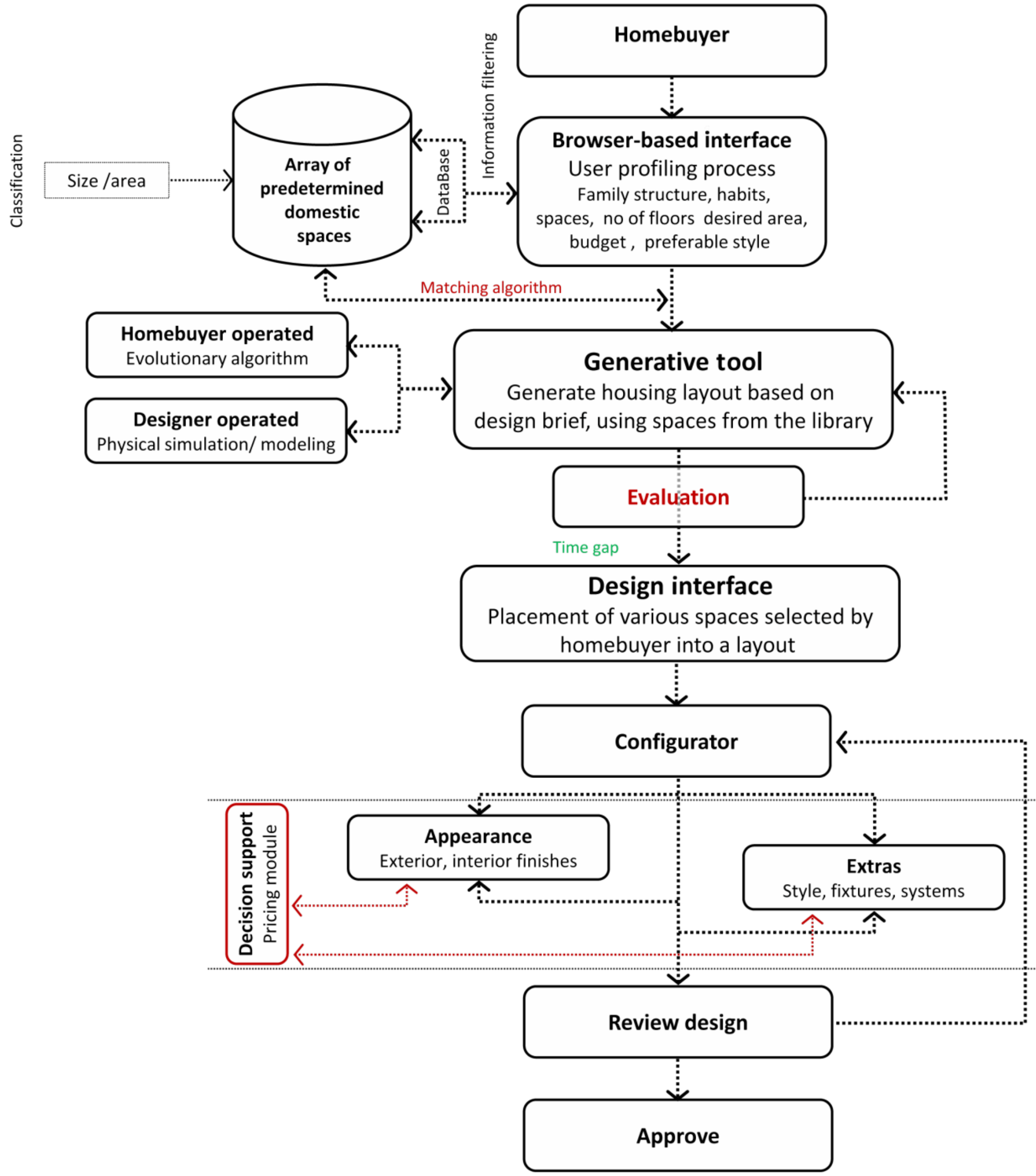


Figure 7.19: A diagrammatic representation of the structure and sequence of the generative tool-based customization process.

7.3.3.1 Problem statement

Space layout planning is one of the most challenging phases of customization. Grouping together a set of spaces according to various relationships and diverse criteria, such as the ever-important issues of aesthetics, this problem presents complex objectives for both human and computer-based systems. Lobos and Donath (2010) stated that the problem of space layout planning is often ill-defined, necessitating a search through a set of both geometrical and topological design constraints that must be successively satisfied. Accordingly, the optimum solution to such a problem is difficult to find.

The generative model is a core component emerging from a branch of the larger design system. Selecting and then developing this model therefore requires a discrete problem definition process. While its larger structure provides a generic framework for the design of a customization system, the proposed generative models tackle the method by which layout design can be achieved. Due to the high complexity associated with the development of a generative model that would serve the absolute customization system, this thesis proposes a generative logic rather than a tool.

a. Spaces

The spaces used in this application represent a set of basic activities that, when combined, will form a two-bedroom single-family house. The topological properties of these spaces were derived from a critical analysis of Alouette Homes' housing models. The listed spaces are categorized according to name (EN, LR, KT, DR, BA, LA, BR, MBR), and dimensionally coordinated (i.e. their size is based on a common basic unit of 2'x2'). Table 7.1 represents these spaces, assigning each function with a colour code.

Space1	Entrance	**EN (5,4)**
Space **2**	Living room	**LV (8,6)**
Space **3**	Kitchen	**KT (4,6)**
Space **4**	Dining room	**DN (5,6)**
Space **5**	Bathroom	**BA (4,5) – possible L+1 increment**
Space 6	Laundry	**LA (2,3)**
Space **7**	Bedroom	**BR (5,6) – possible L+1 increment**
Space **8**	Master Bedroom	**MBR (8,6)**
Space 9	Corridor	**CR (2,6) – possible L+1 increment**

Table 7.1: Definition of spaces.

b. Module

A module is a rectangular, 3-Dimensional component that could contain a housing unit or be assembled with other modules so as to form a larger house. It has a maximum virtual perimeter of 16’x 60’ (4.8m x 14.2m), based on transportation regulations. A module is built by connecting a set of space-representing functions, arranged according to adjacency regulations (Figure 7.20).

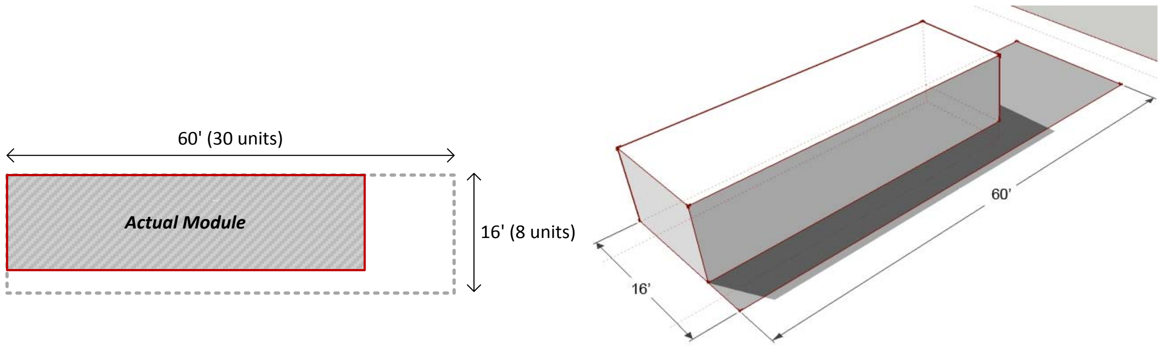


Figure 7.20: Definition of maximum and actual module.

c. Modular house

A house is built by combining two or three modules that may vary in size, depending on the desired area. To minimize design complexity, modules have to be arranged within the maximum perimeter of the house, which is 60++ * 60++ (30++units * 30 units). The resulting house must be comprised of all the listed spaces, and it is identified by the configuration of modules (Figure 7.21).

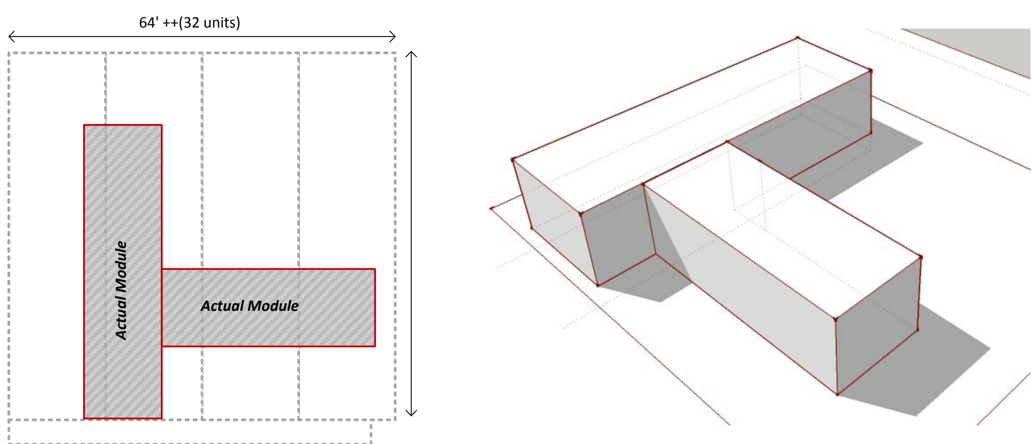


Figure 7.21: Definition of maximum perimeter and actual house.

7.3.3.2 Approach 1: evolutionary algorithm

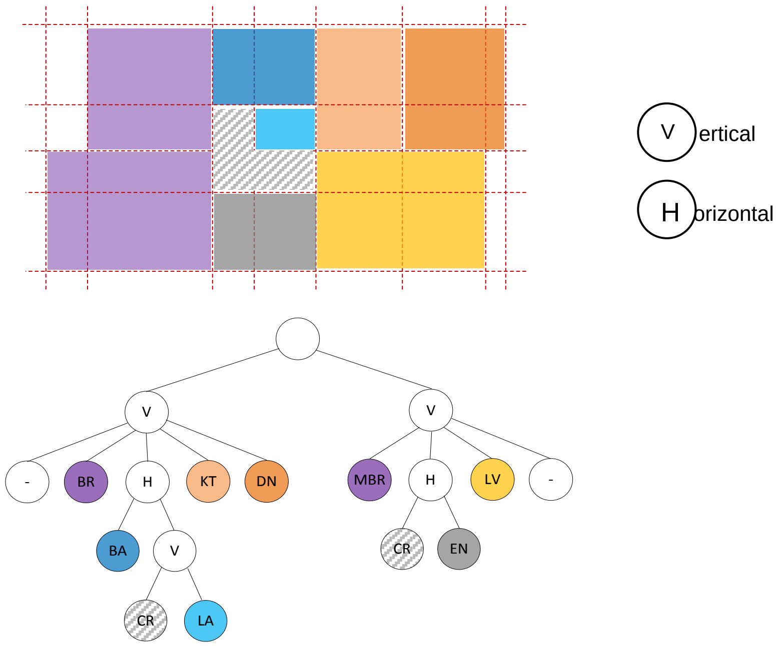
Genetic algorithms (GAs) are creative tools branching from evolutionary methods, with the ability to generate novel solutions to search and optimization problems. They express a technique inspired by evolution in nature and have been previously applied successfully to solve space layout planning problems.

The proposed model in this section is aimed at devising solutions that would largely satisfy adjacency requirements and reflect topological and dimensional constraints. In order to keep the simulation uncomplicated, the end-configuration of a house is intended to reflect a modular, two bedroom housing scheme, being composed of either two to three modules that must fit within a maximum allowable size.

a. Genetic representation and phenomic mapping

The employed genetic algorithm in this problem has the unique quality of using syntax trees, instead of lines of code, as an abstract representation of its source code in the form of a programming language (Figure 7.22). Each node of the tree indicates a construct occurring in the source code; either a terminal or a function. In a program, terminals are variable or constant, while non-terminals include arithmetic, Boolean operators, mathematical functions, conditionals, and iterative operators predefined by the program designer.

The program's initial population would derive from a random generation of symbols, which create a tree that does not have any conventional meaning, yet whose combination of symbols and data types are nonetheless legal. The appropriateness of using a syntax tree to derive a number of house designs, using the available spaces represented through a tree structure, tested this representation technique.



H(V(-,BR,H(BA,V(CR,LA),KT,DN),V(MBR,H(CR,EN),LV,-))

Figure 7.22: Applicability of syntax trees for sub-division of spaces.

b. Population initialization

Initialization seeks to generate random units which will later be evaluated for their fitness with algorithmic criteria. During the initialization stage, a population of genotype strings is generated by randomly seeding the genotype, where each genotype represents a potential solution. The process starts by creating an initial rectangle, representing a house perimeter that would be recursively subdivided until it achieves a certain depth. All spaces would then be stored within a vector (Figure 7.23). The spaces that are produced from the subdivision represent the initial configuration of the layout.

Generate_House
*Step 1: set house_perimeter   W <=21, >=12 , L <=22, >=21   (>= 12*21, <= 22*22)*
Step 2: select a random starting space
Step 3: place initial space at corner of house (0,0)
Step 4: select random space
Step 5: locate space adjacent to initial space
Step 6: if house_area equal area of space1+ space2+ space i…
Step 7: then output
Step 8: else, go to step 4
Step 9: repeat until population count #

Set house_perimeter width W range 12 - 22
Set house_perimeter length L range 21 -22
X equal random length W
Y equal random Width L
For house_perimeter rect (0,0, X, Y) // house perimeter
Select Random Space_1
Locate space_1 at (0,0)
*Calculate tot_area equal Wspace_i *Lspace_i*
Select random space_2
Locate random space_2 at (xspace1, yspace1)
*Calculate tot_area equal Wspace_2*Lspace_2*
Calculate house_area equal area of(space_1+space_2+space_i…)
If house_area equal to tot_area
print output
Else repeat until tot_area equal house_area
End if

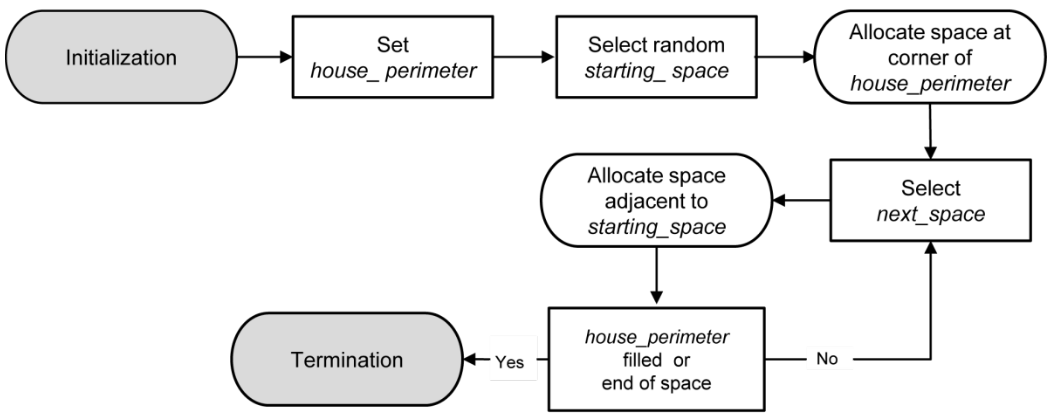


Figure 7.23: The initialization algorithm.

c. Fitness evaluation

The role of the fitness evaluation function is to assign quality measures to genotypes, thereby seeking to evaluate the degree and methods with which predefined preferences have been met. It is composed of a set of quality measures in both the phenotype space and in the inverse representation. Once the assignment process is terminated, the final evaluation procedure of the layout is initialized.

c.1 Fitness terms

The research proposes a set of fitness terms, by which a modular house design can be evaluated. These terms can vary depending on the desired output.

- *Adjacency Fitness:* The house is divided into three main zones: (1) Public Zone: EN (Entrance), LV (Living Room), Kitchen (KT), Dining Room (DN); (2) Private Zone: Bedroom (BR), Master-Bedroom (MBR); and (3) Intermediate Zone: Entrance (EN), Bathroom (BA), Laundry (LA). Adjacency terms evaluate the design according to the following adjacency matrix, which is subsequently illustrated in Table 7.2:

  (N - min)/(Max - min)
  N: actual adjacency, min: 0(best) , max = 46
  Range [0,1], where 0 is the best
  (N -0 / 46)

	EN	LV	KT	DN	BA	LA	BR	MBR
EN								
LV	0							
KT	1	0						
DN	1	0	0					
BA	2	1	0	2				
LA	3	3	1	3	0			
BR	2	2	3	3	1	2		
MBR	2	2	3	3	1	2	0	
Total	11	8	9	1	2	4	0	46

Matrix scale 0-3 (0 = strongest adjacency)

Table 7.2: Adjacency matrix.

- *Area Fitness:* The area of the house is the sum of the area of all its spaces, including its corridor. This term evaluates the total area of the house when modules are connected, and gives lower fitness values to houses with smaller areas. While the area of spaces within this simulation is as fixed to their dimensions, the area of the resulting corridor controls for the variation of house area.

  (N - min)/(max - min)
  N: actual area, min = 252 unit^2, max =321 unit^2
  Range [0, 1], where 0 is best.
  (N - 252 / 69)

- *Number of Modules Fitness term:* This term insures that the size of the house will not exceed the maximum number of allowed modules.

  (N - Min)/(Max - Min)
  N: actual no. of module, min = 2, max = 3
  Range [0,1], where 0 is best.
  (N -2 / 1)

While more sophisticated criteria for fitness evaluation can be added to allow the genetic algorithm to optimize solutions in multiple directions, including viewshed, windows, and lighting, the process here was simplified to minimize the system's complexity level.

c.2 Hybrid evaluation

As customization focuses on user participation in the design process, the notion of employing hybrid fitness evaluation in this application seeks to engage users in the selection of the fittest units. Hybrid evaluation combines automated and manual evaluations (Figure 7.24). Consequently, this process flows from an automated evaluation to manual selections on the part of homebuyers. A cluster of fittest individuals would be displayed to a user, who would be able to either select individuals and thereby terminate the process, or decide to re-generate another set of individuals in the case of inadequate selections.

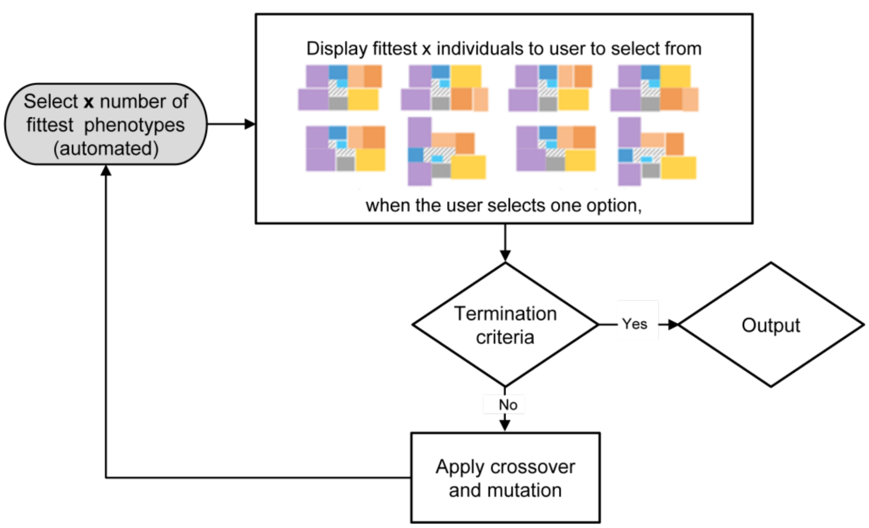


Figure 7.24: The process of hybrid evaluation.

d. Diversification

d.1 Parent selection

Once the individuals are evaluated by hybrid evaluation, the fittest individuals are sorted, from the best fit to the worst fit. As a result, probability selection defines the parents for the next generation of individuals, according to the ranking of the solutions.

d.2 Offspring generation

Genetic operators applied over the parents' genotype seek to combine the genetic material of two fit parents, in order to produce better–fitted results. These genetic operations are divided into two sub-functions: Crossover and Mutation:

- *Crossover*: During the crossover function, a random break-point is selected in each tree-structure, concerning a random number of nodes from two parents' genotype. These branches are subsequently swapped. The outcome is then measured with regard to adjacency fitness and used to define parents for the next generation (Figure 7.25).

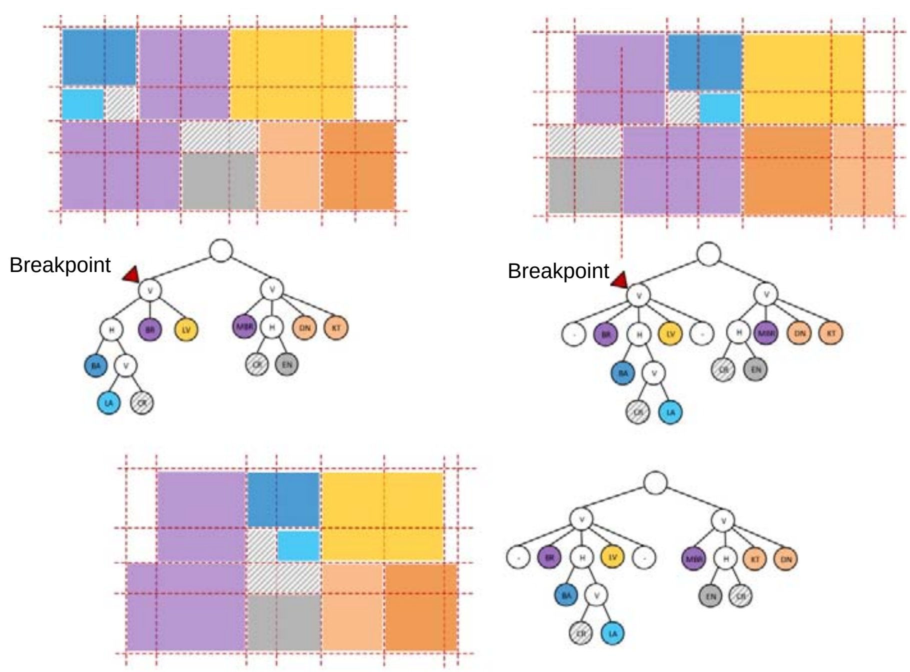


Figure 7.25: Crossover genetic operator.

- *Mutation*: Mutations are applied with a low probability over the offspring genotype resulting from the crossover function. Mutation randomly selects a node on the tree-structure of the genotype, and replaces the sub-tree with a randomly generated one. Any given operation might be to replace, reorder, delete, add, rotate, or randomize.

7.4.3.3 Approach 2: physical simulation/modeling

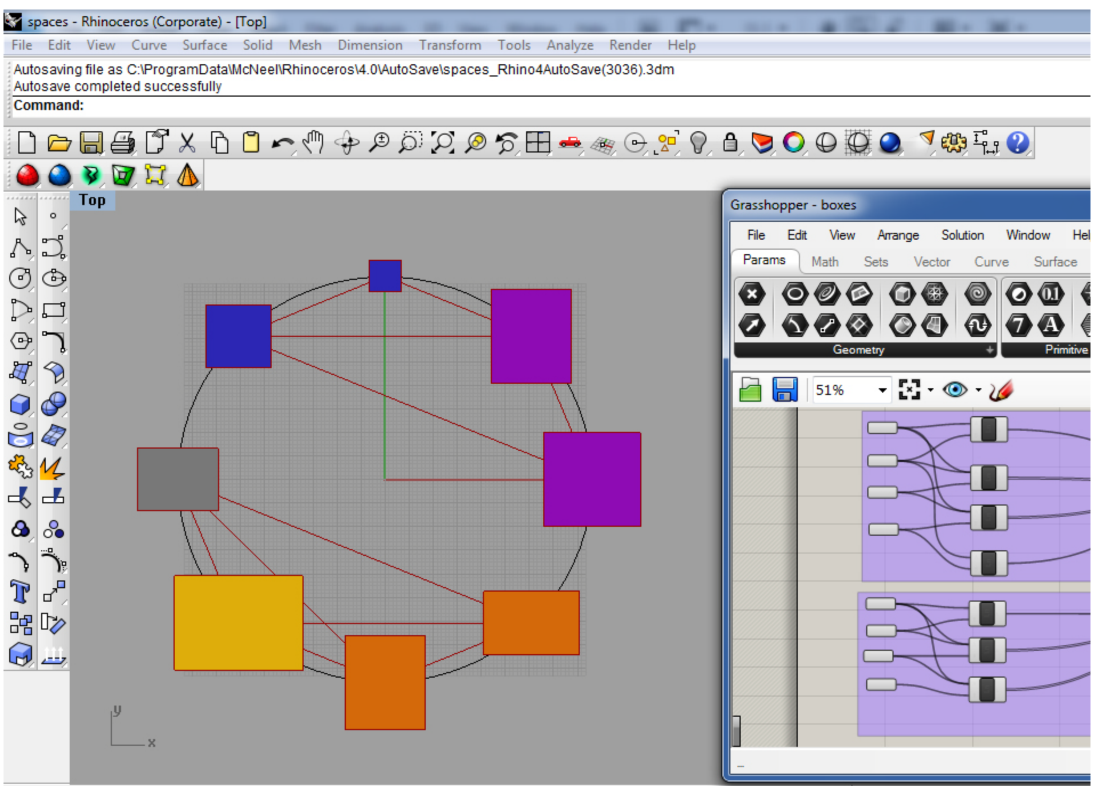
The application of cutting-edge software add-ons has shifted the way architects and designers tackle design problems, offering them greater power over the design process, from conceptual design and development to production documents.

The methodology proposed by this research is based on a robust approach to problem solving, based on dynamic physical simulation, a concept developed by Arvin and House in 1999. The physical modeling technique derives its structure from the application of force and tension to space layout. Architects define programmatic objectives in the usual manner, and represent proximity through a 'spring connection'. This transforms the movement of space within a design via the compression or expansion of forces. Spaces and walls are modeled as physical objects and masses, while objectives specified in the architectural plans are translated into forces and applied to the masses in a dynamic physical simulation.

The implementation of such a process follows a series of phases that, while they differ from one software platform to another, are connected by a unified concept. In general, topological objectives apply forces to the center of spaces, in the form of a spring dynamics, which are the primary component of physical modeling. These forces symbolize primary and secondary adjacency requirements, operating in 3-D environments.

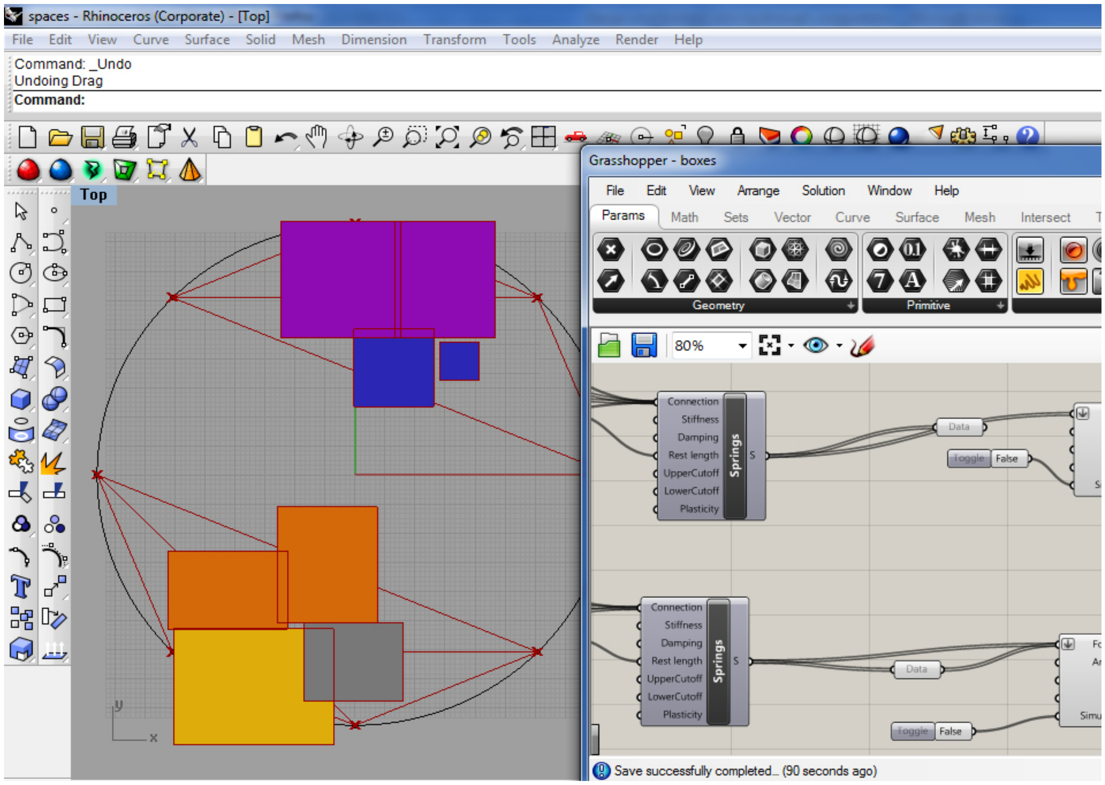
Once the forces are applied, geometric objectives assign volumes to specific points. The resultant volumes represent various domestic spaces, as derived from the basic program requirements.

In order to avoid the overlapping of volumes, constraining the length of the spring force to a specific range controls collision. This also maintains a precise distance between spaces, and ensures adjacency. Once the geometrical simulations have reached equilibrium, the designer can add a set of anchor points to suggest specific relationships to site conditions, thus making minute adjustments to the outcome by manipulating the solution components, in order to respond to additional design criteria other than adjacency. Figure 7.26 represents the outcome of applying the physical simulation approach to previously defined spaces.

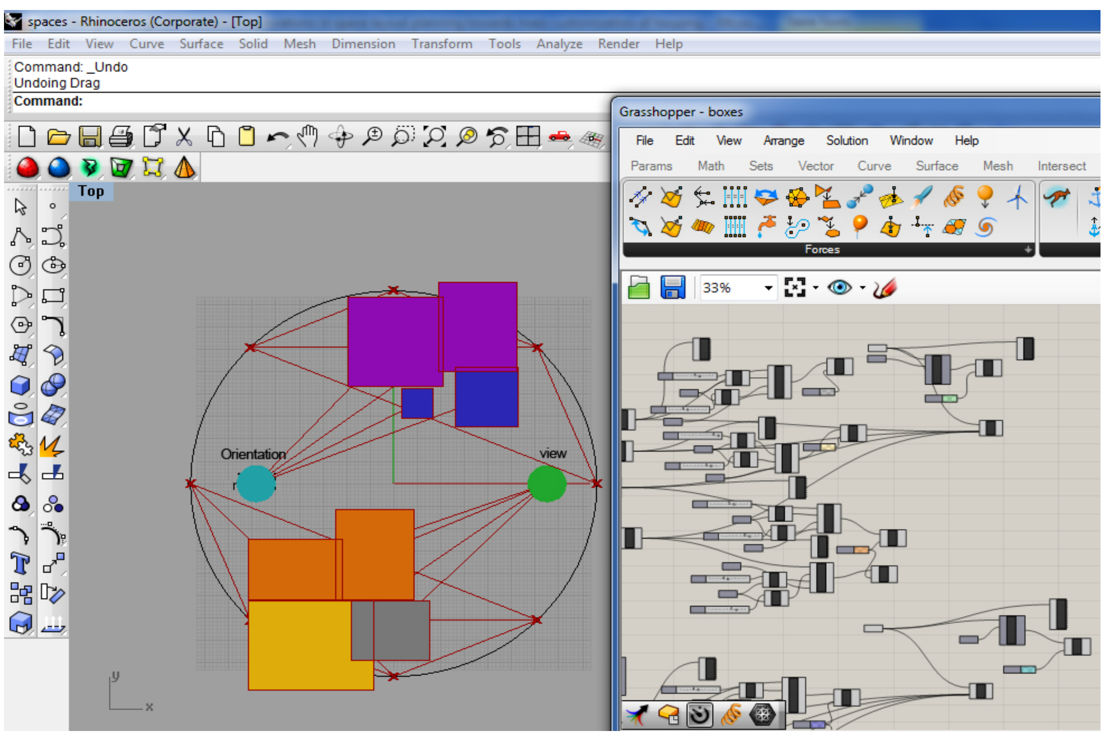


Phase 1: Defining a set of points, and then assigning geometrical objectives to these points, which represent various spaces in 3-D format.

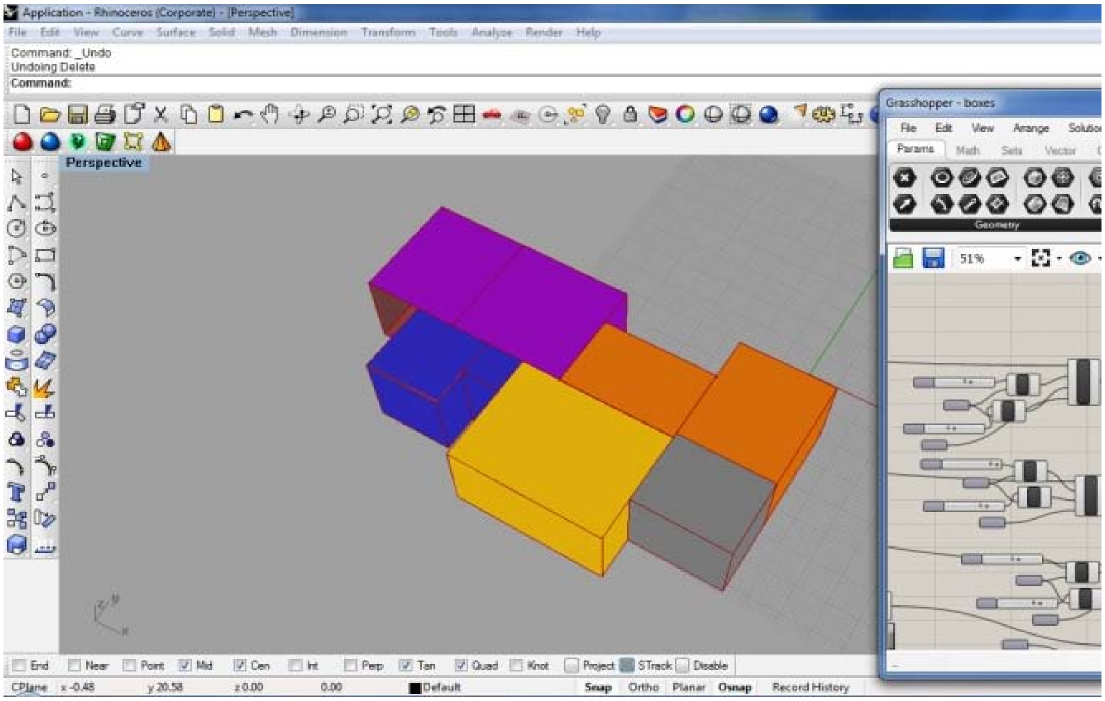
Phase 2: Applying spring force between spaces, simulating proximity requirements.



Phase 3: The dynamic simulation starts running, thus transforming spaces along spring force connections, based on proximity objective. This creates a zoning definition.



Phase 4: Creating an additional set of anchor points that represents additional organizational criteria related to the site, or to performance of the housing unit, to refine the location of different elements.



Refining the relationship between elements in order to reach a layout that would fulfill design requirements, with regard to spatial organization as well as other criteria added by the designer.

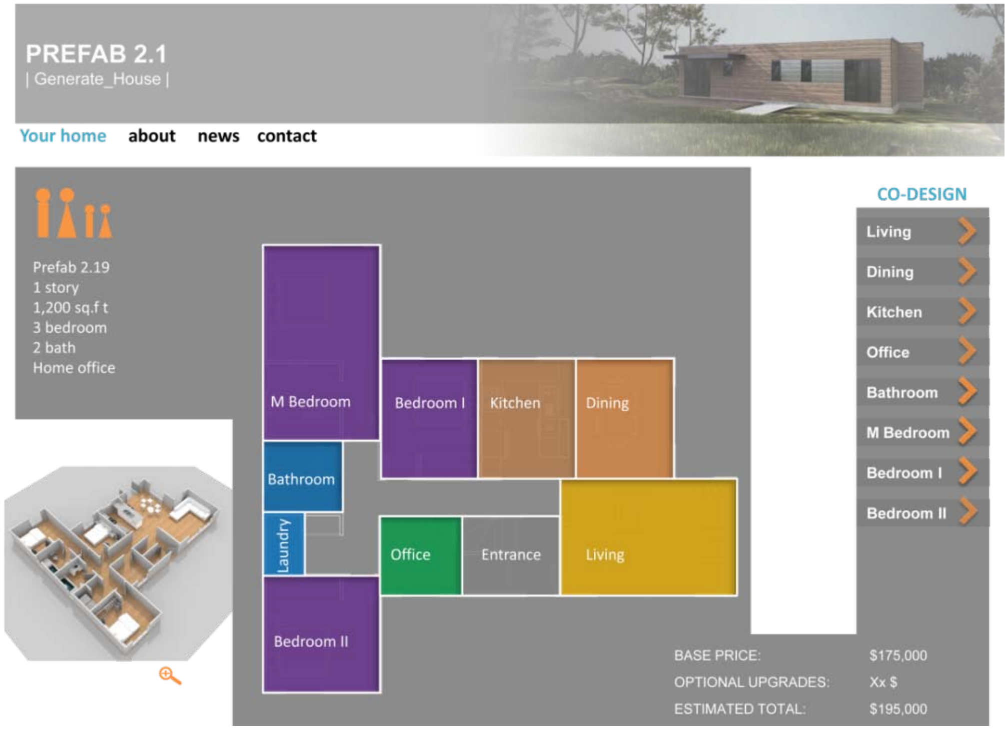
Figure 7.26: The process of the physical simulation-based generative model.

Further elements, such as site conditions, could be added to refine the design generation process, and to account for orientation, views, and accessibility. Each of these elements can be translated into an anchor point, which would utilize a spring connection to generate forces from specific spaces, in accordance with defined requirements, such as the orientation of all bedrooms towards the north-east, as preferred by the homebuyer. Such an approach to design systems has proven successful, and offers great flexibility based on the employed software platform.

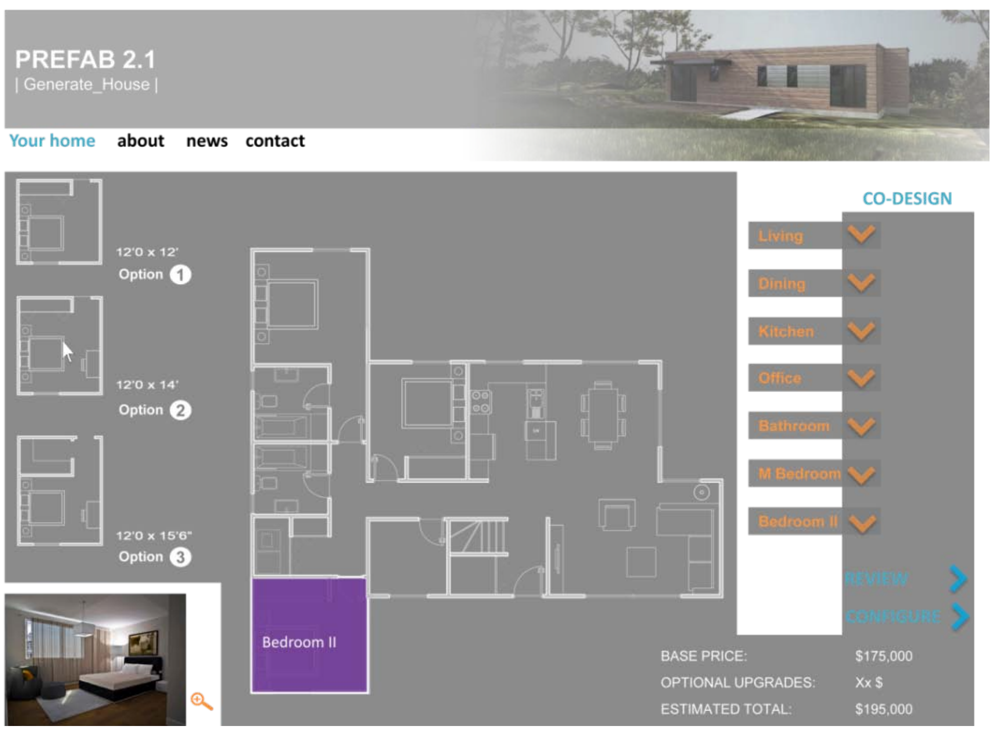
7.3.4 The interface

In a manner similar to the aforementioned case, the structure of the first section of the interface is dedicated to extracting the demographic and psychographic qualities of homebuyers by utilizing a profiling agent. Once required data is entered and analyzed, design generation may commence. The generative tool performs as mentioned in the previous section, and is operated either by the homebuyer or the company's designer. At this point, there would be a data-gap between the output of the generative tool and the visuals to be displayed to the client: the outcome of the generative tool would be shaped as a schematic layout rather than a detailed design. As the intention is to offer homebuyers with readily comprehensible visuals, such a schematic would require further development, and be supported with additional, detailed 2-D and 3-D visuals, to assist in the decision-making process. As developing a generative tool to produce detailed design is an unfeasible and exhaustive process, this methodology proposes the insertion of a gap between the automated design generation and the detailed design. This gap would operate as a phrase for design development.

The homebuyer must first approve a housing layout, both as an early output of the generative tool and designer's later revision. The next step is the initiation of a process of detailed space selection. In addition to the homebuyer profiling agent and the generative tool, there is another component that plays a vital role within this customization process; an interactive selection process that aims to transform the schematic layout into a more detailed one. While within the previous case, fully detailed housing prototypes are predesigned and supported with various alternatives; the current case instead employs predesigned spaces as a basic design component, combinations of which may be used in the construction of a whole house. The process allows homebuyers to decide on each functional zone, choosing from an array of three alternatives. The system ultimately outputs a detailed plan that is constructed through the aggregation of spaces selected by the homebuyer. At this point, the user would be offered to either review the plan, or proceed with a detailed configuration process. Figure 7.27 illustrates the interface prototype.



The outcome of the generative tool would be a diagrammatic layout of the house. Once approved, homebuyers are allowed to co-design the house.



A detailed selection of spaces is initiated. Once a space is selected, it appears to fill the gap in the plan.

Figure 7.27: The interface prototype for the co-design process.

7.3.5 Implementation

The implementation of the proposed customization system is a sophisticated process that involves the manipulation and management of a large amount of data, and the application of advanced software platforms. The process requires a collaborative approach, engaging expertise from broad spectrum of fields. The structure of the proposed system will employ the following features:

- *Analyze existing housing prototypes:* The housing catalogue offered by the prefabricated housing company will be comprised of housing models that vary in size and layout. The analysis of these housing models is aimed at understanding the underlying design scheme by which special configuration and proportions are determined. Accordingly, all of the single storey, two-bedrooms units were analyzed. It was found that the design of the prototypes does not emerge from a clear design scheme. Such an analysis lays the base for the generative system logic, in support of clearly defined objectives and limitations.
- *Develop an array of domestic spaces:* The analysis of housing prototypes indicated that, in order to achieve the goal of the proposed design system, it would be necessary to develop an array of interchangeable, modular spaces that represent various spatial functions. These spaces are classified according to typology, area and size, and proportions. A matching algorithm is employed to match the homebuyers profile to the space category within the array that most accurately reflects their preferences. In order to maintain technical efficiency, each category will be modular and coordinated by overall standards, to facilitate the formation of micro-assemblages into modules as well as assemble modules on the macro-scale to form a house. BIM models of the spaces would be built to generate production details and order materials.

- *Develop assemblies variations:* Developing variations on assemblies allows already designed modular spaces to be evaluated for their potential to construct modular housing prototypes. Since these spaces act as the basic components for the generative process, the purpose is to simulate the logic of the generative tool, thus understanding the pattern by which spaces may be aggregated to form a modular house. Assemblies were successful, resulting in a variety of housing prototypes, revealing the potential of such an array of spaces. Figure 7.28 illustrates the first phases of the implementation process.

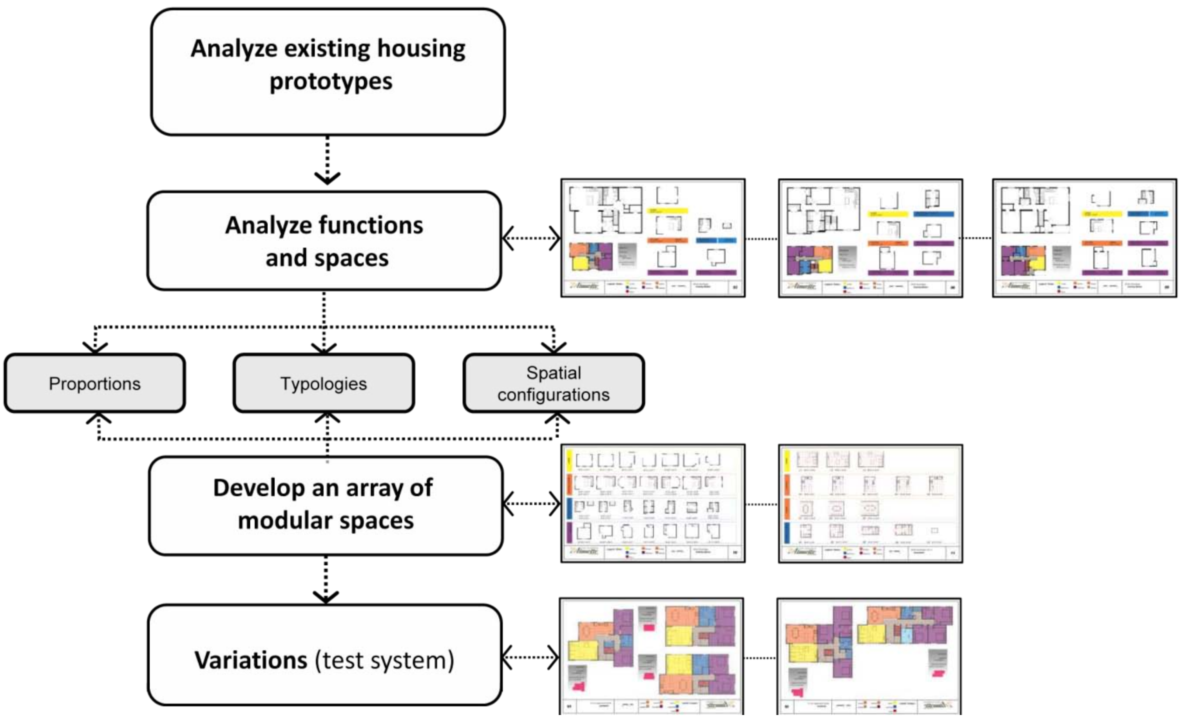


Figure 7.28: Implementation process.

- *Develop and implement the generative* tool: Developing the generative tool is concerned with the logic of generation systems, while the implementation is focused on coding the logic into an operable program. Within this research, two generational logics are proposed; the first requires sophisticated coding knowledge, while the second could be implemented via a software plug-in. On the one hand, plug-ins demonstrate great potential, as their ability to connect to other software platforms results in the development of a comprehensive, computational–based design environment. On the other hand, the genetic algorithm described in this research can be coded on any programming platform. One of the possibilities is *processing*, a simple programming language that supports developing ideas and offers a high degree of visualization. One of the advantages of such a language is that the program can be implemented as an applet within a browser-based interface, supporting its desired implementation as an online generative tool. In order to fully benefit from such a system, the algorithm must be exploited to include more spaces. As such, the generative tool will be a part of a multi-level design system, accompanied by a matching algorithm that searches for an appropriate space category to match the homebuyer's profile and needs.

- *Develop the web-based interface*: The interface prototype simulates the co-design customization process. While the structure of the interface is partially similar to the one described in Case 1, the major difference lies in the proposed generative tool. Accordingly, various functions are to be utilized, including a profiling agent, generative tool, and space-selection mechanism. Each of these elements comprises sub-components that directly affect the overall logic of the interface.

7.4 Reflections

This chapter represents the process of simulating the proposed design system framework for an existing prefabricated housing company operating in the Quebec market. This simulation is aimed at exploring the potential of implementing a comprehensive mass customization system within an existing manufacturing structure. The methodology employed focuses on achieving a high degree of customization, in accordance with the classification presented in the previous chapters.

Two levels of customization have been simulated; room-blocks modification level and space layout design. This has resulted in an advanced configuration system and a generative tool-based system. The advanced configuration system is based primarily on first building and then manipulating a database. It is accompanied by a matching algorithm that filters homebuyer profiles for necessary information, in order to match them with appropriate housing profiles from the database.

The author proposes a more advanced method to achieve the highest degree of customization, in the form of a generative-tool based system that shifts the user’s involvement in customization to an earlier point in the design process. The core component of the system is a generative model that would be able to transform homebuyer’s profile into a housing solution. A secondary component is comprised of an array of modular spaces that represent various housing functions, derived from a critical analysis of the company’s housing prototypes.

The system tackled the system operator and degree of automation as two crucial aspects of implementation. Accordingly, two generative approaches were proposed. First, an evolutionary algorithm operated by the user, and second, a physical simulation approach operated by the company designer. The process utilizes computational tools to bring a homebuyer’s profile together with a logic of construction and design, and to ultimately generate a housing design. Two different generative models have been proposed; evolutionary algorithm and physical simulation, with the aim of tackling the system’s level of automation, and its operator. Furthermore, an advanced development would ultimately combine them together into one generative approach system, taking advantage of the generative and optimization power of both systems. However, the proposed framework raises various questions about the efficiency of the machine's role in the customization process, rather than offering an optimum solution for the application of generative design system.

In both cases, the customization process would take place over a browser-based interface, allowing potential homebuyers to navigate through the different housing prototypes, generated as an outcome of the search process, and then select a model to configure according to their unique needs and requirements. An interface prototype has therefore been proposed to simulate the configuration process.

Given the industry conditions, with regard to market shares, design and representation approaches, the advanced configuration is more likely to be implemented in the near future. However, the implementation of a generative tool-based system is still questionable. The simulation of such a system proposed both a fully, and a semi-automated process for generating housing solutions, based on two implementation approaches. It can be argued that because it involves the designer as system operator, the semi-automated generative system is more feasible, allowing for more control over the quality of the system's design solution output.

8.0: Discussion and conclusion

8.1 Thesis Summary

In this thesis, the author investigated theories and concepts of mass customization, in addition to various research endeavours for the implementation of mass customization in the housing industry. The author also explored current prefabricated housing market practices in North America, with a detailed focus on the Canadian and Quebec markets. The aim of this study was to survey various industry approaches, and subsequently propose a comprehensive scheme for the mass customization of prefabricated housing that would bridge the gap between research and its industrial applications.

8.1.1 Mass customization

Mass customization, as defined by Pine (1993), is the production of individually customized goods and services. In this method, customized products or services are provided through flexible processes in high volumes and at reasonably low costs. The process of customization is multi-faceted, requiring a focus on diverse aspects, both managerial and technical.

Companies adopt various mass customization strategies based on two main characteristics: the point of customer involvement in the design process and the type of modularity. Identifying these aspects is key to defining the configuration of processes and technologies necessary to produce a mass-customized product.

8.1.1.1 Mass customization of housing

Mass customization of housing has taken place in two different areas: that of research efforts and that of industry applications. On the one hand, researchers have explored the application of digital tools and computer-based design systems to enable customization of dwellings on various levels, ranging from direct participation in unit layout to selecting finishing materials. On the other hand, prefabricated housing companies tend to provide homebuyers with different alternatives regarding layout, finishing and systems. This approach has been defined in research as "multiple choice housing", and takes the form of either traditional printed catalogues or more recent and interactive electronic catalogues. The latter typically takes the form of browser-based interfaces, offering homebuyers the ability to navigate, and then modify, the design of a housing unit online. This trend, however, is inefficient, as the architect is required to design all possible alternatives in advance.

8.1.2 Design systems

The application of computer-based systems in design began in the 1960s, along with the development of systems theory in computation. Researchers explored the use of computer-based design systems to solve architectural problems, with the purpose of partially or fully automating the design process, thus assisting in both the analysis and synthesis phases of design. These early applications employed accessible programming techniques, focusing on fulfilling diverse design requirements.

Recently, computers are becoming increasingly integral to the design process, offering intelligent knowledge-based processing of architectural information. Coates (2010), however, argued that these recent applications of computational techniques in architecture differ greatly from the ones developed in the late 1960s. In fact, this study illustrates that ideas between these periods are conceptually very analogous, yet differ significantly in regard to their implementation models, coding, and visualization. This is an outcome of significant advancements in software platforms, offering designers a new perspective in solving problems.

Pertaining to the customization of housing, computer-based design systems demonstrated great potential, offering a practical platform to directly link architects, homebuyers and manufacturers. The core element of such a platform is the design system, which serves to offer homebuyers a solution space to navigate product variants. In this sense, the core element of this design system is its generative model.

8.1.3 Generative design systems

The goal of constructing, then operating a generative system, is the production of a variety of potential solutions to a specific problem. Within the realm of architecture, a generative system could be defined as an approach to developing applications that can generate, evolve, or design objects, architectural structures, or spaces more or less autonomously.

The application of generative design systems to enable the customization of housing has been explored as a core component within a design system, with the aim of generating design solutions based on the homebuyer's profiling process. Four types of generative systems can be identified and evaluated as follows:

- *Shape Grammars*: Classified as a rule-based formalism that facilitates the process of generating design by firstly structuring and then applying a set of rules. However, implementing such a system on the computer is time-consuming, as it requires the defining of shapes and rules and their subsequent encoding. Additionally, the application is further limited to designs with a robust approach to spatial organization.

- *Evolutionary systems*: Considered highly creative, they can be employed in various phases of architectural design. Introducing constraints to the generation process can enhance their performance. Unfortunately, formalizing an evolutionary generative system requires considerable computing expertise, in addition to competence in feasible form generation and production methods. Finally, the discourse about how to encode forms and manipulate the resulting data may be considered more philosophical than technical in nature.
- *Parametric systems*: Classified as a specific case of an algorithmic system, these processes were developed to handle variations within various design and production environments. They are based on the notion of associativity, wherein object properties branch from relationships or inheritances. While any design system can be parameterized, the process significantly increases the complexity of both designer tasks and interfaces, because designers must model the structure through which variation is controlled, in addition to the artefact being designed.
- *Combinational systems*: Relying on the combinatory logic of two or more systems, these processes depend on the nature of the problem and its level of complexity. Various hybrids of combinational systems and other algorithms have been proposed, such as combining shape grammars with evolutionary algorithms, and parametric systems with other rule-based systems. Such a task would involve a combination of the power of knowledge-based and rule-based systems, perhaps even increasing exponentially.

8.1.4 The prefabricated housing in Quebec

The prefabricated housing industry in Canada plays an important role in supplying the housing market with diverse products, ranging from single-family homes, to prefabricated building components such as trusses, walls, and panels. With regard to the province of Quebec, which is the focus of this research, there are roughly 42 prefabricated housing companies sharing the provincial market, accounting for some 26% of all such establishments in Canada.

A survey was conducted in order to explore the application of technology within sales, design, and production processes, in regards to extant degrees of customization. A questionnaire was prepared and distributed to five companies during an interview with managers and technicians. The companies were selected according to their market share, applied technologies, and business practices.

The survey revealed that there is limited use of design and production technologies in the industry. CAD is only used for the production of drawings and only two companies employed automated production units. With regard to BIM, it was found that only one company has implemented such a platform for the ease of design and fabrication of components. Accordingly, the survey led to the identification of a technological gap between the current state of research on mass customization and its present industry applications.

8.1.5 The design system framework

The proposed design 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.

Based on manufacturer's capabilities, applied technologies, and the means of communication between architects and clients, the design system will be modeled in the form of interacting components, each of which perform a specific design task. In order to implement this system, a clear concept of its generative model must be elaborated and verified before coding can begin. Thus, the system accommodates varying degrees of automation and system operators. This framework relies on the following procedures:

- *Problem definition*: This procedure comprises various processes, with the aim of breaking down the problem of mass customization into sub-components, including the level of customization, applied technologies, and integration scheme, in order to devise a solution for each component separately. Solutions are then synthesized into one comprehensive system. By the end of this phase, the system designer should be able to define the level of customization, the integration scheme, and the technology required to adapt the system.
- *Structuring information-problem formulation*: This procedure devises a coherent structure for the collected information in a hierarchical manner. The process in turn relies on:
  - *Define set of variables and parameters*: This sub-procedure aims to translate user profiles and preferences into the numeric data required for the design. Variables may include desired area, rooms that correspond to family structure, and choices related to layout perimeter. Parameters are used to represent this building data.
  - *Define set of constraints*: This sub-procedure is derived from a critical analysis of the following: functional requirements, spatial adjacency, spatial proportions, and orientation, building codes and regulations, and environmental consideration. Additional

constraints may be added according to the requirements of the construction system.

- *Relationships*: This sub-procedure develops dependencies that link various sets of information, in order to a build a coherent relationship between system components. Such a relationship must be formed in an adaptable manner, as different homebuyers have different priorities with regard to budget, area, spaces, and activities.

- *Develop generative model*: This procedure decodes design thinking to express a robust design method. Based on a clear understanding of the nature of the problem, level of customization, integration scheme, design logic, and architect's intention, a generative model could be selected, thus leading to a holistic definition of the design system.
- *Implementation*: This procedure is structured on three levels. The first concerns the development of system architecture, and thereby the creation of a clear process for constructing a system. This occurs by contextualizing various subsystems and components, specifying system functionalities, and defining relationships and dynamic interactions among various system components. The second level concerns the interface, which regulates the medium at which the interaction between humans and the customization process occurs. Finally, the third level concerns the coding of the generative model, which involves translating a design into a program by taking the abstract idea of a design and turning it into a set of precise instructions in a particular programming language.
- *Evaluation:* This procedure validates the system performance and tests its capabilities to generate valid design solutions, which generally comply with building systems and user profile inputs. The evaluation phase is not intended to validate the system as a whole, but rather to ensure that key system components and decisions,

such as type of variables, system constraints, and structures of the objective, are functional.

8.2 Thesis Contributions

Some of the concepts introduced in this thesis are not new, and yet they represent a different perspective from which to view the process of the mass customization of housing. These concepts are the outcome of exploring the precedents set by previous research efforts and computational design tools, which were developed in pursuit of a comprehensive model for mass customization of housing, and more specifically, a design system framework. The following section describes these concepts in detail.

8.2.1 A model to redefine the role of the architect, and customization team

One of the important observations while conducting the industry survey was that there is only one company that employs an architect to design housing prototypes or accommodate homebuyer's modifications. Instead, it is almost always the responsibility of a salesperson, who then transfers the homebuyer's requirements to a technician. In order to overcome such an issue, this research tends to redefine the relationship between the homebuyer, architect, and manufacturer by repositioning the role of the architect within the customization process. Instead of designing housing models, the architect would design a system of coherent, modular, and partially interchangeable housing prototypes. Additionally, the architect would also be responsible for the configuration logic of the customization system. In this way, all modifications follow a pre-conceived scenario, overcoming any potential design or technical challenges.

8.2.2 A comprehensive model for mass customization of housing

This thesis is primarily an elaboration on a comprehensive model for the mass customization of prefabricated housing. There are two main driving forces behind proposing such a model. First, while analysing research efforts to enable mass customization in the housing industry, it was observed that most studies approach the problem from a computational perspective. In other words, the focus has almost always been on either the development of generative tools as enablers for mass customization, or an exploration of the potential of digital fabrication. Second, the study of prefabricated housing in the Quebec region demonstrated the limited involvement of architects in the design of housing prototypes. Companies generally purchase pre-designed, ready-to-build prototypes from online resources such as Drummond House Plans, including them in catalogues after minor modifications. Additionally, when homebuyers demand modifications, changes are always accommodated by architectural technicians, and added to the cost of the house.

In this research, mass customization is approached from a broader perspective, based on a rigorous study of the theoretical background that underlies mass customization as a concept. The reason for this is that mass customization must be classified as a model for business, management, and production, rather than being solely technological. Design, production, and communication technologies are essential enablers for the implementation of mass customization in any industry, including prefabricated housing. However, the process requires a holistic approach that begins with a clear definition of the level of customer involvement in the process, before moving on to corresponding technological applications.

The model presented in this research proposes an information system, design system, a computer system, and an integration system. Each is composed of subsystems stemming from an investigation of strategies to link mass customization theories to prefabricated housing practices. The aim here is to bridge the gap between theories, research efforts in the area, and real-world industry applications.

8.2.3 An advanced configuration system

Configuration systems are information tools through which the order-taking process is automated, capturing customer requirements without human intermediaries. Several prefabricated housing companies have taken the initiative to build web-based interfaces, so as to assist homebuyers in the buying process by offering them choices online.

The proposed configuration system within this research draws on diverse research efforts regarding mass customization theories, specifically in the area of configuration systems, as well as on a critical investigation of the prefabricated housing industry in the Quebec market. Furthermore, the author has also examined a number of systems already in implementation by various companies in North America, with the aim of developing an understanding of their structures, customization levels, and methods of interaction.

A number of concepts have been proposed within this system that go beyond existing industry applications. First, developing a configuration logic that aims for a high level of customization in the form of room blocks modification. Second, proposing an information model for the homebuyers' profiling process; a crucial step in the initiation of the customization process. Third, proposing a logic structure for the sorting algorithm that matches homebuyers' profiles to housing profiles. Finally, developing a user-interface prototype that simulates the traditional interaction between a homebuyer and a designer/salesperson within the purchasing process of a prefabricated housing unit. The supporting data for such a configuration system has the potential to impact how the prefabricated housing company would operate in the future.

8.2.4 The design system framework

As mentioned previously, the described framework in this thesis presents a process for a design system, rather than a single computational tool. The framework emerges as the logical outcome of a diverse body of research on mass customization, design methods, system theories, generative algorithms, the prefabricated housing industry, and previous efforts to implement mass customization in the housing industry.

The ultimate goal is to provide a framework that would offer a systematic approach to assist prefabricated housing companies in implementing mass customization effectively. It must also go beyond the limitations and difficulties that are typically entailed by the customization of housing. This framework aims to respond to market demands for high quality customized housing, while maintaining a robust information transfer and data management system for housing companies.

Within this framework, the levels of customization and corresponding essential technologies can be clearly identified. Additionally, the structure of the framework provides a methodology for establishing a link between the profiling processes for the house and homebuyer. This connection can be used by computational tools, programmed with the appropriate design logic, to generate a housing design.

8.2.5 A computational approach to design systems

One of the important contributions of this design system framework is the proposal of two different methodologies for a generative model that can be operated by either a homebuyer or a company designer. As discussed earlier, the issue of the design system's level of automation has been always an area of confusion in mass customization research. The proposed framework offers a degree of flexibility, based on a company's available technological applications, as demonstrated in the simulations. Furthermore, it offers flexibility with regard to the generative technique, where it could accommodate a number of approaches to generative systems. Overall, the model can adapt to change, due to its flexible nature.

The design system framework was simulated through both an evolutionary algorithm and physical simulation algorithms. Both techniques have been employed before, and simulations demonstrated their effectiveness. A focus on prefabricated housing and an array of spaces representing domestic functions suggests the techniques' potential real-world application.

8.2.6 Advancing the prefabricated housing industry: Quality, and affordability

The prefabricated housing industry has great potential to reposition itself in the housing market, through a focus on the application of available design and production. The proposed digital platform for mass customization is intended to remodel the role of technology in the design and delivery of prefabricated housing, thus opening new opportunities to overcome current industry challenges.

In addition to the advantage of building in a controlled environment, the application of cutting-edge design and manufacturing technologies in the form of parametric design, BIM, CAD/CAM allows for a high level of precision in the production of housing units. This would greatly improve the quality of housing, overcoming one of oft-repeated concerns about prefabricated housing; lack of quality. The use of modeling and simulation software can also lead to better environmental performance and improved operating costs. Additionally, offering homebuyers choices can increase affordability, giving consumers the opportunity to select only the elements and components that comply with their needs. A high degree of customization, allowing room blocks modifications, and a diverse range of space variants, can also contribute to affordability, as homebuyers would be permitted to manipulate the layout and area of spaces within the floorplan, impacting the total price of the buyable unit.

8.3 Limitations and Challenges

Although the design system framework demonstrates potential, there are still several challenges that need to be overcome in order for full implementation within the prefabricated housing company. The adoption of a mass customization strategy within a company requires the approval and support of executives to shift production towards mass customization. One of the major challenges that faced the author during the simulation phase was to fully integrate the customization system within the company under experimentation in this research. This is due to economic and market limitations, which influenced the company's decision to postpone a full implementation of the system until market conditions stabilize. However, the structures of both proposed customization systems were simulated and approved for implementation.

8.3.2 Site considerations

One of the main difficulties that faced the researcher while developing the design system framework, specifically the user-profiling process, were site considerations within the two customization levels that have been simulated in this research. When questioning the five previously-listed prefabricated housing companies in Quebec, almost all mentioned that in most cases, homebuyers do not own a site. It was common then for the company to offer homebuyers the opportunity to purchase a site owned by the company along with a modular house.

While such a difficulty can be overcome at an early stage of the homebuyer profiling process, it would dramatically increase the complexity of the system. Site considerations can have a notable impact on the design of the house, due to the orientation of the sun, desirable views, and accessibility. However, this issue can be resolved after homebuyers have made all the necessary decisions with regard to layout and appearance, at which point a company designer would be involved in site implementation.

8.3.2 Design representation

The representation of the housing design through a web-based interface has always been an area of exploration, using HTML5, gaming technologies, and other techniques to offer homebuyers photo-realistic images and real-time manipulation of design appearance. Yet, one of the main challenges is the presentation of plans.

Implementing a generative system that would produce detailed plans would be an exhaustive process. Within this thesis, the author proposed a time gap between schematic and detailed plans, supported by 3D views of the layout. This might help in overcoming such a problem. Ultimately, it will be necessary to develop new visualization techniques to assist homebuyers as well as companies.

8.3.3 The generative model

Coding and scripting have been emerging as a powerful trend in the realm of architecture, with many architects using these methods to extend software capabilities. Since a full implementation of the proposed evolutionary algorithm is time consuming, and requires significant programming knowledge, the thesis proposes an applicable methodology, supported by a tested initialization phase, rather than a complete implementation.

8.3.4 Levels of customization

While the thesis proposes a method to structure different levels of customization, some issues remain ambiguous. For instance, the building appearance is comprised of several elements, such as cladding, openings, trims, and even style. While it might be simple to customize window sizes, colors, and materials, this must be limited, to prevent the system from becoming excessively complicated. Many components will still be necessarily standardized in order to minimize these complexities.

8.3.5 Technology applications in the prefabricated housing industry

One of the major difficulties that face prefabricated housing companies, especially in Quebec, is the lack of competition with regard to technological application. Within the survey that the author carried out, only two out of five companies employed advanced design software platforms and automated production. When proposing the implementation of a customization system, companies tend to be reluctant, lacking vision in the absence of any external drive to overcome the complexity associated with implementing advanced systems. Accordingly, it was very challenging to get involved in a dialogue with them about the benefits such a process would bring to technologies in design and fabrication.

8.4 Future Work

The thesis represents a remarkable step towards the development of a comprehensive system to achieve a high level of customization in the prefabricated housing industry. Areas for future work are twofold. The first is improvement to current research, while the second is dedicated to other supporting areas. The following list represents various avenues for further developments:

- *Develop the computer implementation*: While there are different available methods through which to implement the proposed generative model, further exploration is required to determine which would be the most efficient and applicable approach. While space layout planning is an architectural problem, solving such a problem through computation requires expertise from within computation research, which may involve the collaboration of computational designers to envisage different approaches to a solution.
- *Explore site consideration*: This is a crucial area that requires further exploration in order to enrich the customization process.
- *Level of automation*: While two different levels of system automation have been proposed within this research, it is difficult at present to determine which one could be carried out more efficiently in the housing market. Studies will have to be carried out to identify which approach would be most suitable.
- *Explore the power of BIM*: While BIM has been proposed as a solution it remains to be fully tested. Building BIM models of housing prototypes could assist the development of a product family, and once created, the process of customization would be supported by an efficient system for data management and transfer.
- *Develop open source architecture*: This would include spaces and a variety of other modular components that could be installed into a single scheme from which to build a house.

- *Explore the notion of introducing cultural values within the homebuyers profiling process*: One of the important issues to tackle while creating an interactive customization process, is to reflect homebuyers lifestyle. Mentioned earlier, is that transforming qualitative data, into quantitative one to be evaluated by a computer-based system, is considered as a challenging process. in that sense, future research would have to focus on expanding the data types included in user profiling phase, to capture sufficient information that would reflect cultural values of homebuyers.

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Appendix I

Industry Questionnaire

Prefabricated Housing in Quebec

Questionnaire

Date:

Time:

COMPANY PROFILE

Company:

……………………………………………………………………………………………………
…………………………

Address:
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Mr/Ms : ………………………………………………………………………

Position in the company: ……………………………………………

Year of establishment: ……………………………………………….

Number of Employees: ……………………………………………….

Management: ………………………………………………..

Office : ………………………………………………………...

Marketing : ………………………………………………..

Sales: ……………………………………………………….

Technicians : ………………………………………………..

Production : ………………………………………………..

Main Markets:

Quebec/ Region : ………………………………………………….

Eastern Canada / Region:……………………………………………

US: ………………………………………………………………………..

Range of Distribution :

……………………………………………………………………………………………………
……………………………………………………………………………………………………

1. **What type of production system the company produces?**

Type	Sales %
Modular	
Panelized	
Kits	

2. **Who are the company's clientele?**

Type	Sales %
Developers	
Builders	
Self-builders	
Individuals	

3. **How many residential units are produced/ sold yearly?**

- o 200
- o 200 - 250
- o 250 - 300
- o 300 - 350
- o More than 350
- o Other ……….

SALES

4. **What marketing strategies the company is following to attract clients?**

- o Printed Catalogue
- o Electronic Catalogue (Internet website)
- o Demonstration unit on company's site

5. **Do catalogues (Printed / electronic) comprise all the models the company offers?**

- o yes
- o No

6. **What role Electronic catalogue plays in the sales process?**

   ………………………………………………………………………………………………
   ………………………………………………………………………………………………
   ………………………………………………………………………………………………

7. **Do catalogues (Printed / electronic) offer prices for the models?**

   - o yes
   - o No

8. **If yes, which catalogue offers prices?**

   - o Printed Catalogue
   - o Electronic Catalogue (Internet website)
   - o Both

9. **Do the catalogues offer options to select from, with regard to layout, exterior/interior finishing materials for any of the models?**

   - o yes
   - o No

10. **If yes, what are the available options for clients to choose from?**

    ………………………………………………………………………………………………
    ………………………………………………………………………………………………
    ………………………………………………………………………………………………

11. **How does modification/variation by clients affect the cost ?**

    ………………………………………………………………………………………………
    ………………………………………………………………………………………………
    ………………………………………………………………………………………………

12. **Do clients fill any forms mentioning their needs and requirements when they walk in to the company?**

    - o yes
    - o No

13. **If yes, what type of information is included in the form?**

- o Client profile
- o House type and model
- o Budget

………………………………………………………………………………………………
………………………………………………………………………………………………
……………………………………………………………………………………

14. **How important is the pricing in the sales process ?**

- o Very Important
- o Important
- o Not important

15. **What responsibilities are carried on by a salesperson ?**

- o Welcoming clients
- o Meeting with clients and demonstrating various models
- o Modifications of models, if any required
- o Process clients drawings into price estimates and delivery schedule

Sales Process :
………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………

16. **How much time is spent with clients on adaptation?**

- o 15 – 30 minutes
- o 30 – 45 minutes
- o 45 – 60 minutes
- o More than 60 minutes

17. **Does a salesperson need to have architectural training?**

- o yes
- o No

18. How long does the process take from pricing/contract until the issuance of construction drawings?

- 1 – 7 days
- 8 – 14 days
- 14 - 21 days
- 1 month
- More than a month

DESIGN AND PRODUCTION

19. What types of houses the company offers?

Type	demand %
Standard	
Custom	

20. What are the types of standard models the company offers?

Type	demand %
Bungalow (2 bedrooms)	
Bungalow (3 bedrooms)	
Two - storey	
Cottages (2 bedrooms)	
Cottages (3 bedrooms)	

21. How often a new standard model is developed?

- Three to six months
- Six to nine Months
- Once a year
- Depends on market condition

22. When a new model of standard homes is developed, how is it advertized?

- Paper catalogue
- Electronic catalogue
- Housing exhibitions

23. How many standard models the company offers clients to select from?

- Bungalow (2 bedrooms)
  5 – 10 10 – 15 15 – 20 more than 20

- Bungalow (3 bedrooms)
  5 – 10 10 – 15 15 – 20 more than 20

- Two – storey
  5 – 10 10 – 15 15 – 20 more than 20

- Cottages (2 bedrooms)
  5 – 10 10 – 15 15 – 20 more than 20

- Cottages (3 bedrooms)
  5 – 10 10 – 15 15 – 20 more than 20

24. In the case of standard homes, does the company offer clients personalization /choices?

- Yes
- No

25. If yes, what is the level of personalization/selection?

- Layout / Plan modifications
- Exterior Finishing
- Interior finishing
- Exterior Openings (Doors/Windows)
- Kitchen cabinets and accessories
- Bathroom Fixtures
- Wall cabinet
- Others

……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

26. How the personalization / selection process is achieved?

- o Using catalogues
- o Clients meet with a salesperson
- o Samples room
- o Physical model

……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

27. Once the customers made their decisions / Choices, is the outcome displayed visually?

- o Yes
- o No

28. If yes, what visualization technique is used?

……………………………………………………………………………………
……………………………………………………………………………………
……………………………………………………………………………………

29. How long does it take to implement modifications and selection made by clients and turns it into construction drawings?

- o Less than Five Days
- o A week
- o More than a week

30. How personalization/selection reflect on the price of the house?

cost	%
Increase	
Reduce	
Depends on the clients' selection, possibility to increase or reduce	

31. Are clients willing to pay for changes?

- o Yes
- o No

32. If yes, at what percentage of cost increase?

- o 1- 2.5 %
- o 2.5 – 5 %
- o More than 5

33. What technologies are used to facilitate data transfer from sales to design, then from design to production?

- o CADD (Computer Aided Design &Drafting)
- o CAE (Computer Aided Engineering)
- o BIM (Building Information Modeling)
- o PDM (Product Data Management)
- o CAM (Computer Aided Manufacturing)

34. At which stage these technologies are applied most?

- o Sales
- o Design
- o Production
- o Planning

35. Is the production automated?

- o Yes
- o No

36. If yes, at which level the production is automated most?

- o walls
- o floors
- o roofs
- o Assembly

37. How long is the process from design approval to delivery?

…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

38. Who is responsible for getting the construction permit?

- o Client
- o Company

…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

39. Will you provide the customer with working drawings if he decides to only buy the design?

- o Yes
- o No

40. To the best of your knowledge, how does your cost compare to traditional construction technique?

…………………………………………………………………………………………
…………………………………………………………………………………………
…………………………………………………………………………………………

Appendix II

Spaces Library - Assemblies

LES MAISONS Alouette HOMES

MASS CUSTOMIZATION

Série Avantage

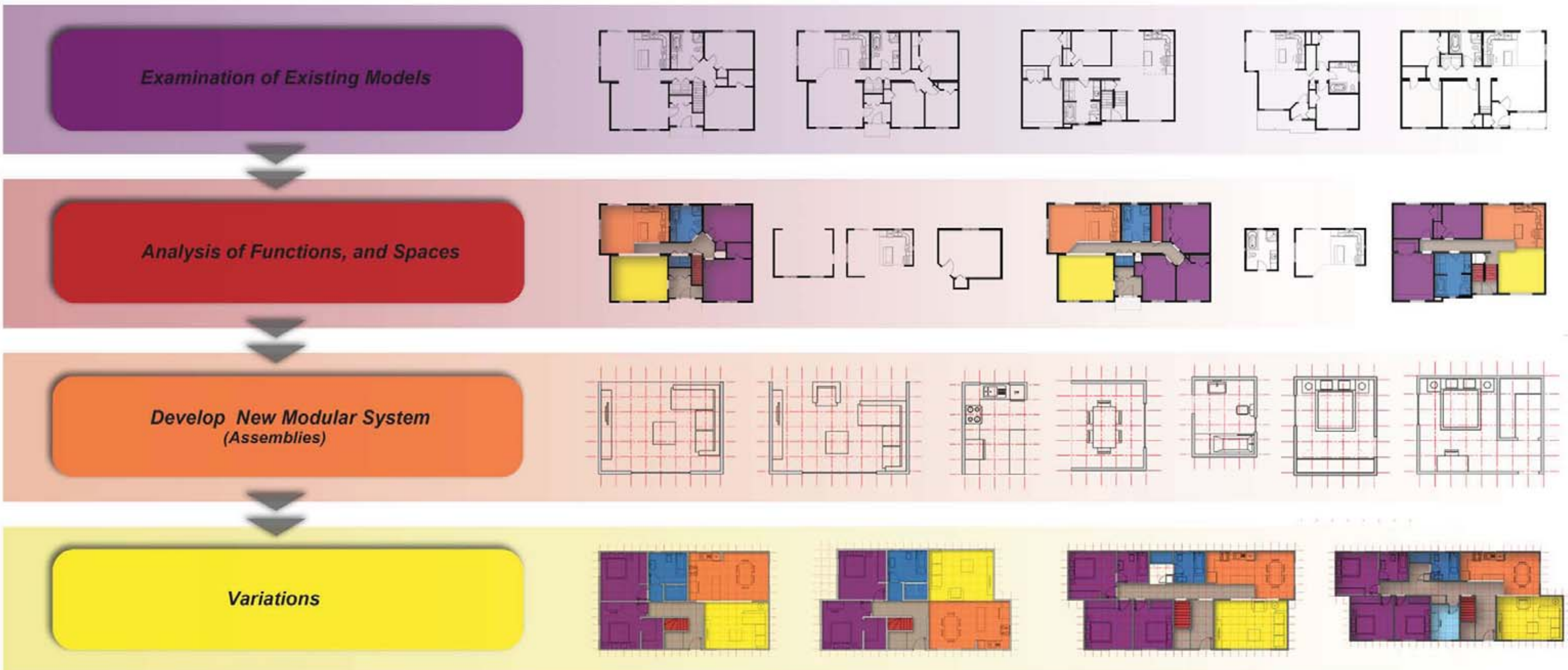
RESEARCH / DESIGN

AVI FRIEDMAN, Ph.D.
BASEM.M. EID

LES MAISONS Alouette HOMES

Série Avantage : Existing Models

LES MAISONS Alouette HOMES	Legend / Notes :		Process Summary	01

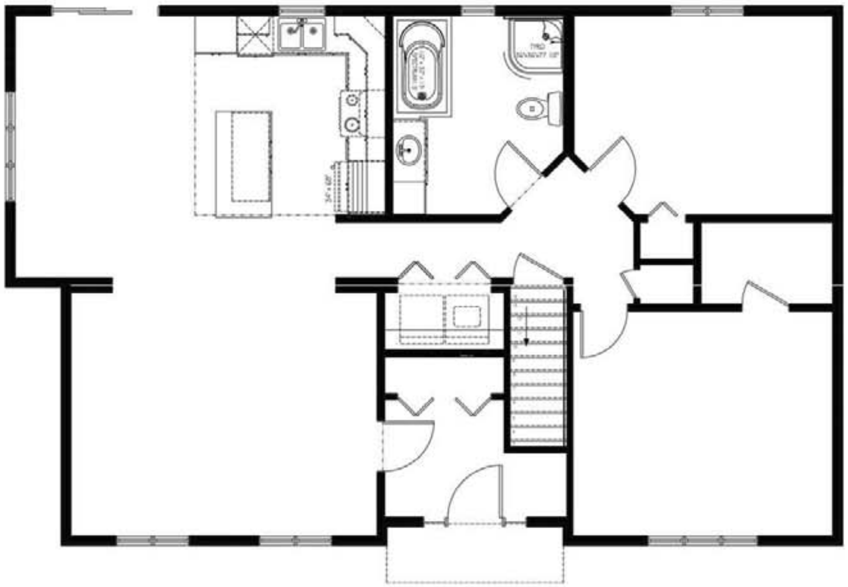


LES MAISONS Alouette HOMES

Legend / Notes :

Process Towards Customization

02



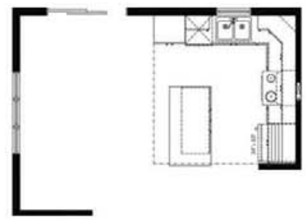
BRIGITTE

2 Bedrooms

Total Area
1175.15 sq. ft

Horizontal Circulation
86.45 sq. ft (7 %)

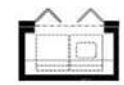
LIVING
16'-6" x 13'-1"



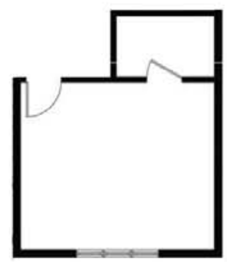
KITCHEN **10'-8" x 10'-3"**

DINING **14'-1" x 9'-7"**

BATHROOM **10'-8" x 9'-3"**

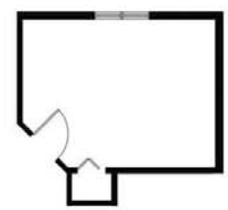


LAUNDRY **6'-5" x 3'-1"**



BEDROOM I **13'-10" x 12'-1"**

CLOSET **7'-1" x 4'-4"**



BEDROOM II **13'-10" x 10'-8"**

CLOSET **2'-10" x 2'-0"**

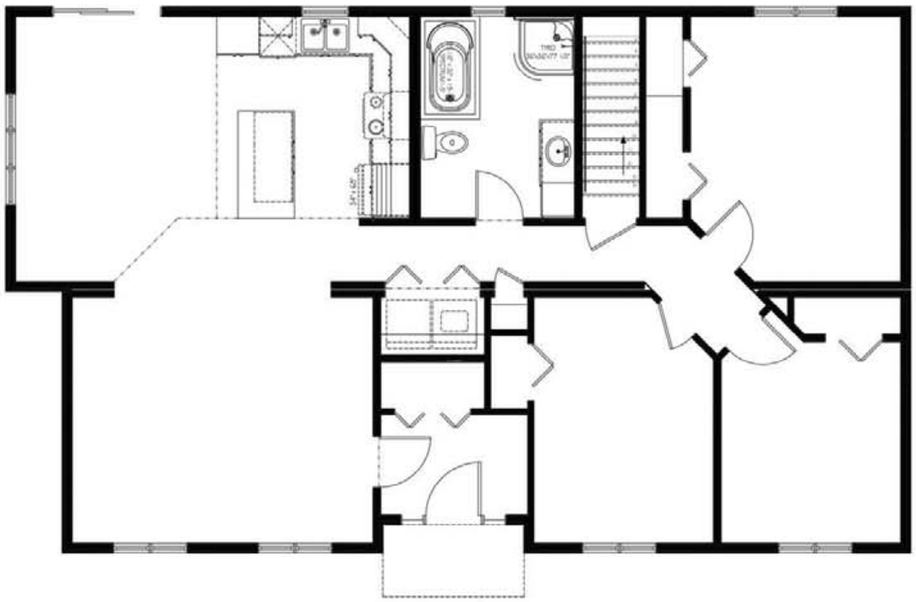
LES MAISONS Alouette HOMES

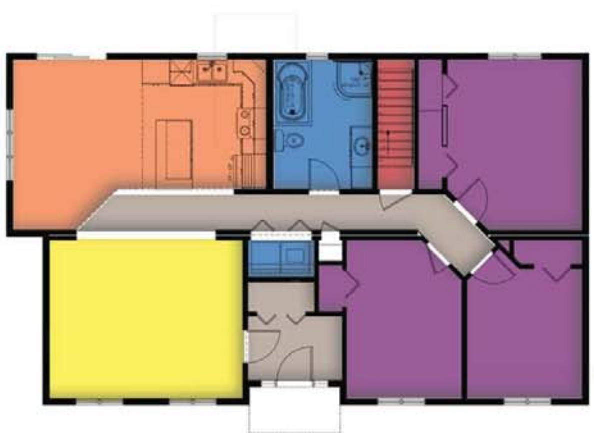
Legend / Notes : Living, Bathroom, Stairs, Kitchen, Bedroom, Dining, Hallway

0 2 4 8 ft.

Série Avantage
Existing Models

03





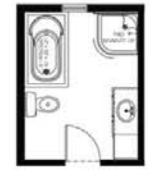
BRIGITTE

3 Bedrooms

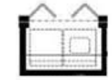
Total Area :
1259.15 sq. ft

Horizontal Circulation:
100.05 sq. ft (8 %)

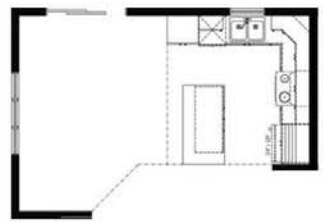
LIVING
15'-11" x 13'-1"



BATHROOM
10'-8" x 8'-2"

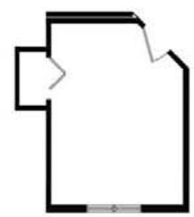


LAUNDRY
5'-6" x 3'-1"

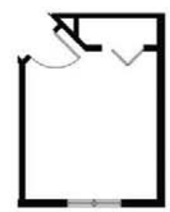


KITCHEN 10'-8" x 10'-3"
DINING 14'-0" x 10'-7"

BATHROOM III 10'-8" x 9'-3"
CLOSET 6'-5" x 3'-1"



BEDROOM I 13'-0" x 9'-7"
CLOSET 3'-1" x 2'-0"



BEDROOM II 13'-1" x 9'-6"

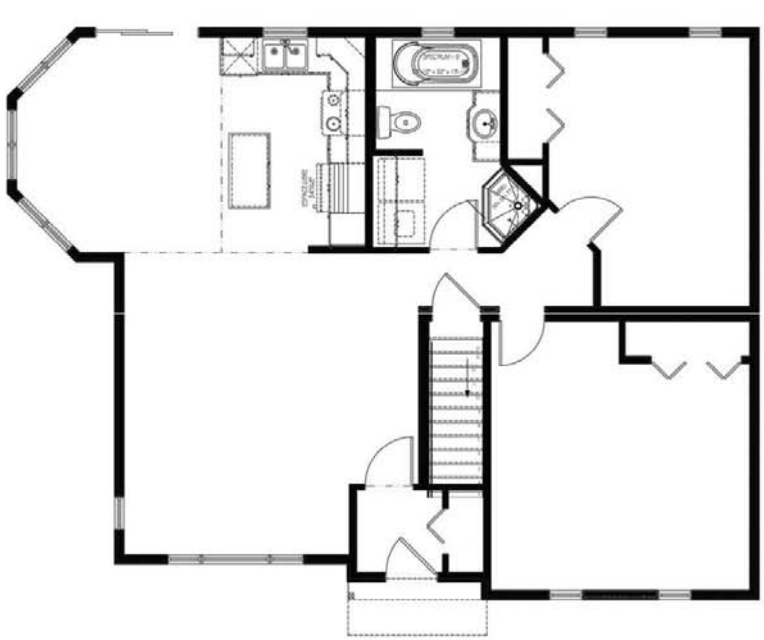
LES MAISONS Alouette HOMES

Legend / Notes : Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

0 2 4 8 ft.

Série Avantage
Existing Models

04

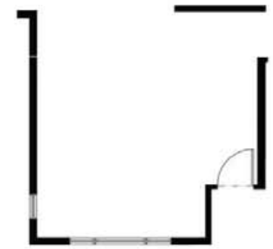


CLEMENCE

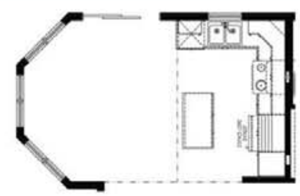
3 Bedrooms

Total Area : 1101.15 sq. ft

Horizontal Circulation: 75.05 sq. ft (7 %)

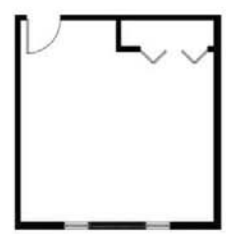


LIVING
16'-3" x 13'-1"

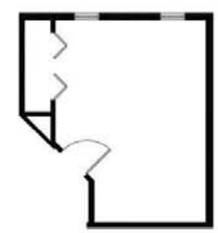


KITCHEN 12'-1" x 8'-1" — **DINING** 11'-0" x 11'-7"

BATHROOM & LAUNDRY
11'-8" x 7'-0"



BEDROOM I
15'-0" x 14'-6



BEDROOM II
15'-1" x 12'-6"

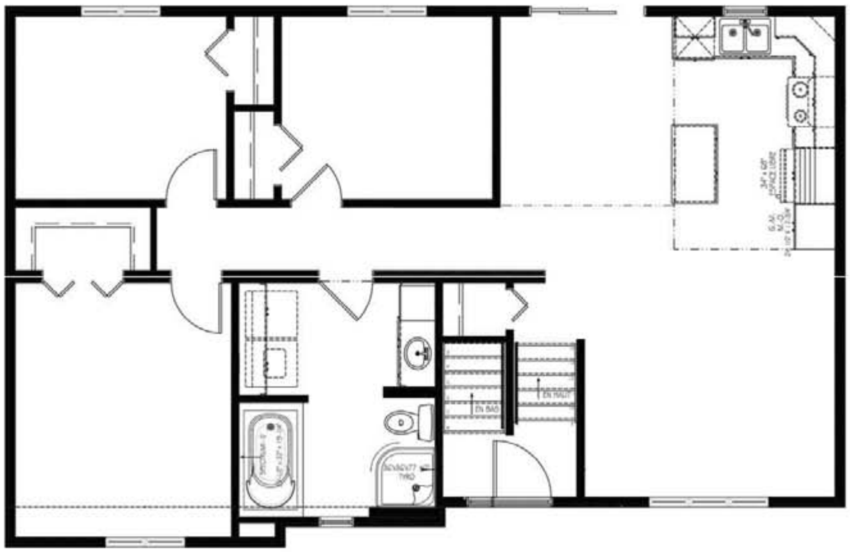
LES MAISONS Alouette HOMES

Legend / Notes : Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

0 2 4 8 ft.

Série Avantage
Existing Models

05

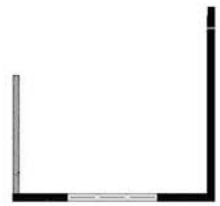


RICHELIEU

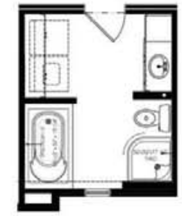
3 Bedrooms

Total Area :
1196.15 sq. ft

Horizontal Circulation:
100.05 sq. ft (8 %)

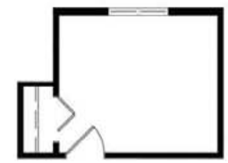


LIVING
12'-3" x 12'-1"

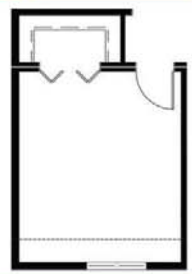


BATHROOM & LAUNDRY
11'-6" x 9'-9"

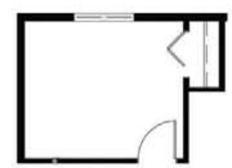
KITCHEN 11'-5" x 7'-11"
DINING 9'-4" x 8'-7"



BEDROOM II 10'-6" x 9'-0"
CLOSET 4'-4" x 2'-0"



BEDROOM I 12'-6" x 10'-9"
CLOSET 6'-8" x 3'-1"



BEDROOM II 10'-6" x 9'-0"
CLOSET 4'-4" x 2'-0"

LES MAISONS Alouette HOMES

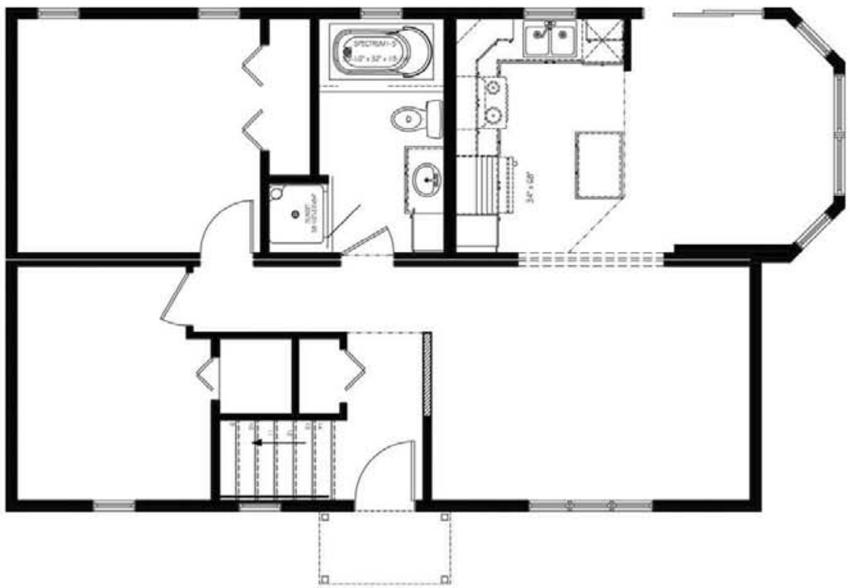
Legend / Notes :

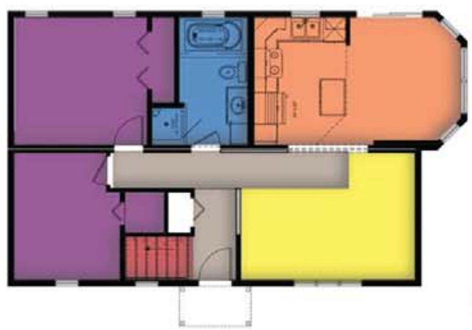
- Living
- Kitchen
- Dining
- Bathroom
- Bedroom
- Hallway
- Stairs

0 2 4 8 ft.

Série Avantage
Existing Models

06





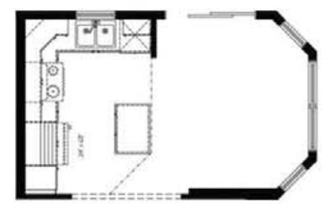
SHEFFORD

2 Bedrooms

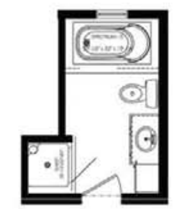
Total Area : 834.90 sq. ft

Horizontal Circulation: 56.75 sq. ft (8 %)

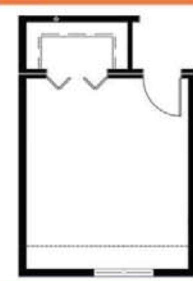
LIVING
15'-02" x 12'-1"



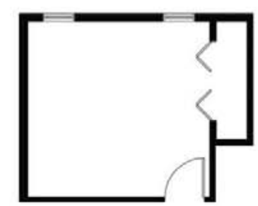
KITCHEN 11'-2" x 8'-1" — **DINING** 11'-2" x 10'-0"



BATHROOM &
11'-2" x 5'-11"



BEDROOM I 12'-6" x 10'-9" — **CLOSET** 6'-8" x 3'-1"



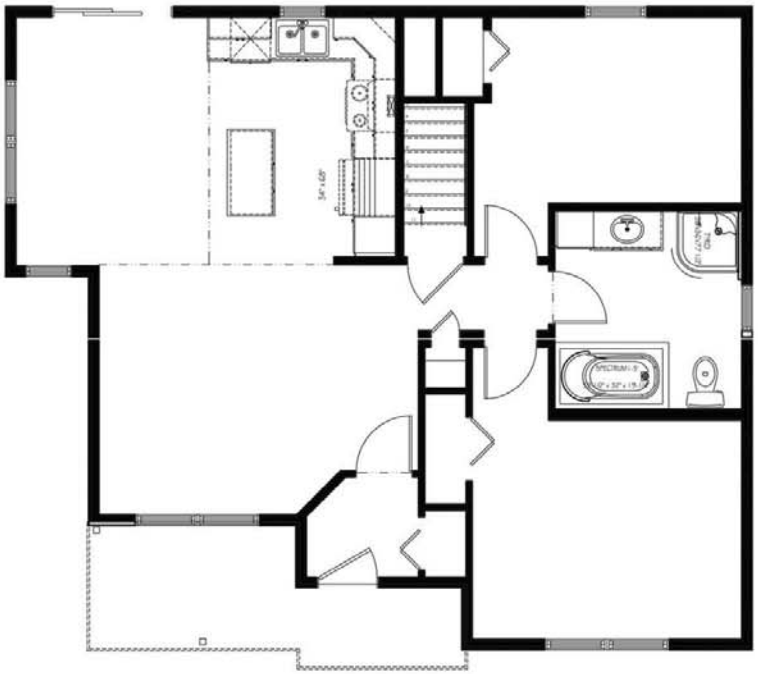
BEDROOM II 11'-6" x 11'-1" — **CLOSET** 7'-5" x 2'-0"

LES MAISONS Alouette HOMES

Legend / Notes : Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

0 2 4 8 ft.

Série Avantage
Existing Models

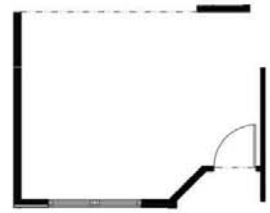


SOPHIA

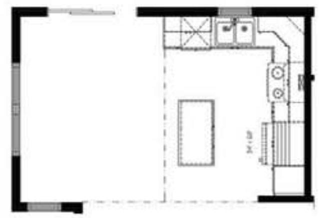
2 Bedrooms

Total Area : 891.90 sq. ft

Horizontal Circulation: 50.75 sq. ft (7 %)

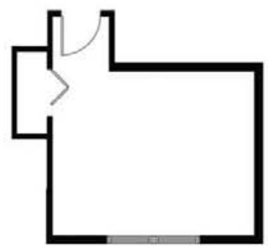


LIVING
15'-06" x 12'-0"

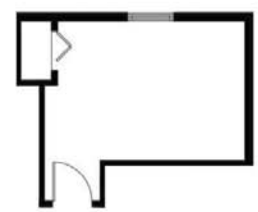


KITCHEN 11'-10" x 9'-0" — **DINING** 11'-10" x 9-03"

BATHROOM
9'-06" x 9'-0"



BEDROOM I 12'-10" x 10'-6" — **CLOSET** 5'-3" x 2'-0"

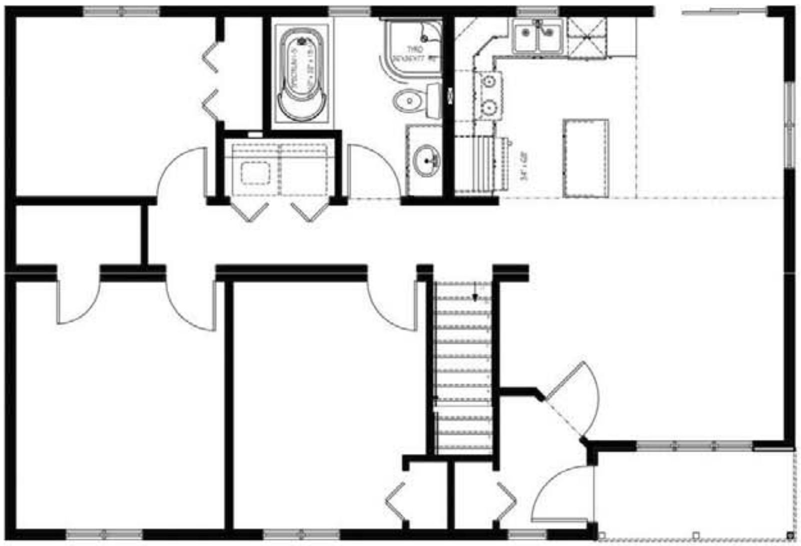


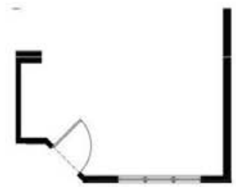
BEDROOM II 12'-10" x 8'-11" — **CLOSET** 3'-9" x 2'-0"

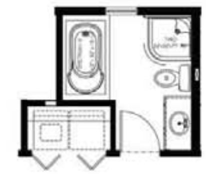
LES MAISONS Alouette HOMES

Legend / Notes : Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

Série Avantage
Existing Models



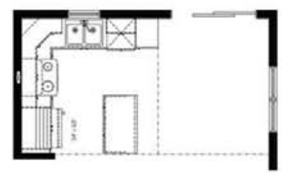


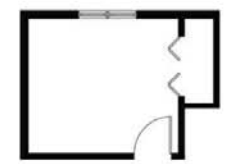


LIVING
15'-06" x 12'-0"

BATHROOM
9'-2" x 8'-0"

LAUNDRY
5'-07" x 3'-0"





KITCHEN
9'-6" x 9'-3"

DINING
9'-6" x 7'-6"

BEDROOM III
10'-2" x 9'-2"

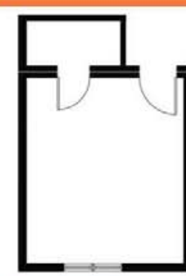
CLOSET
6'-6" x 2'-0"

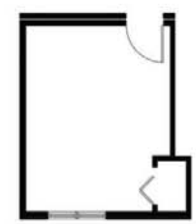
YAMASKA

3 Bedrooms

Total Area :
961.60 sq. ft

Horizontal Circulation:
100.75 sq. ft (7 %)





BEDROOM I
12'-7" x 10'-7"

CLOSET
6'-4" x 3'-0"

BEDROOM II
12'-07" x 9'-8"

CLOSET
3'-6" x 2'-0"

LES MAISONS Alouette HOMES

Legend / Notes :

Living
Kitchen
Dining
Bathroom
Bedroom
Hallway
Stairs

0 2 4 8 ft.

Série Avantage
Existing Models

LIVING

16'-6" x 13'-1" | 15'-11" x 13'-1" | 16'-3" x 13'-1" | 12'-3" x 12'-1" | 15'-02" x 12'-1" | 15'-02" x 12'-1" | 15'-06" x 12'-0"

KITCHEN & DINING

10'-8" x 10'-3"
14'-1" x 9'-7"

10'-8" x 10'-3"
14'-0" x 10'-7"

12'-1" x 8'-1"
11'-0" x 11'-7"

11'-5" x 7'-11"
9'-4" x 8'-7"

11'-2" x 8'-1"
11'-2" x 10'-0"

11'-10" x 9'-0"
11'-10" x 9-03"

9'-6" x 8'-4"
9'-6" x 7'-6"

BATHROOM & LAUNDRY

10'-8" x 9'-3"
6'-5" x 3'-1"

10'-8" x 8'-2"
5'-6" x 3'-1"

11'-8" x 7'-0"

11'-6" x 9'-9"

11'-2" x 5'-11"

9'-06" x 9'-0"

9'-2" x 8'-0"
5'-07" x 3'-0"

BEDROOM

13'-10" x 12'-1" | 13'-10" x 10'-8" | 13'-0" x 9'-7" | 13'-1" x 9'-6" | 10'-8" x 9'-3" | 15'-0" x 14'-6 | 15'-1" x 12'-6"

LES MAISONS Alouette HOMES

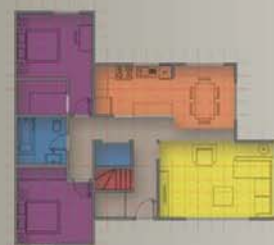
Legend / Notes :

- Living
- Kitchen
- Dining
- Bathroom
- Bedroom
- Hallway
- Stairs

0 2 4 8 ft.

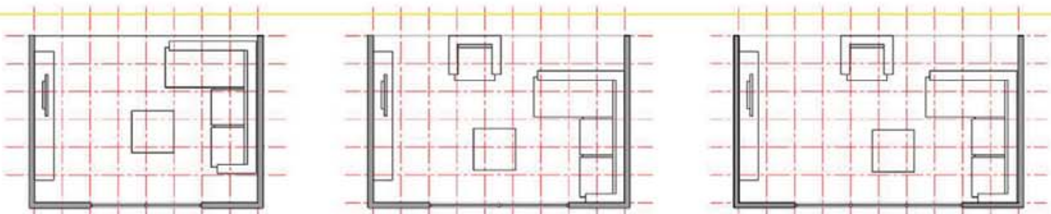
Série Avantage
Existing Spaces

LES MAISONS Alouette HOMES



Série Avantage : VOL. II

LIVING



L1 16'-0" x 12'-0"

L2 18'-0" x 12'-0"

L3 20'-0" x 12'-0"

KITCHEN

K1 12'-0" x 8'-0"

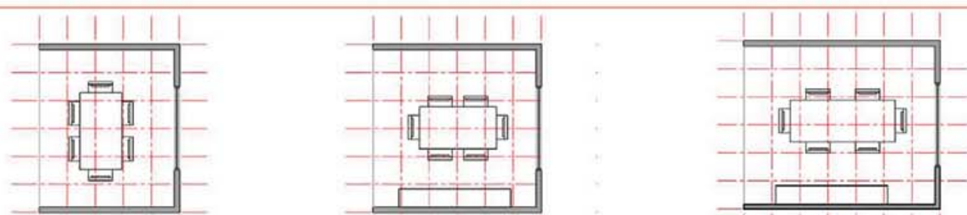
K2 12'-0" x 8'-0"

K3 12'-0" x 8'-0"

K4 12'-0" x 8'-0"

K5 12'-0" x 8'-0"

DINING

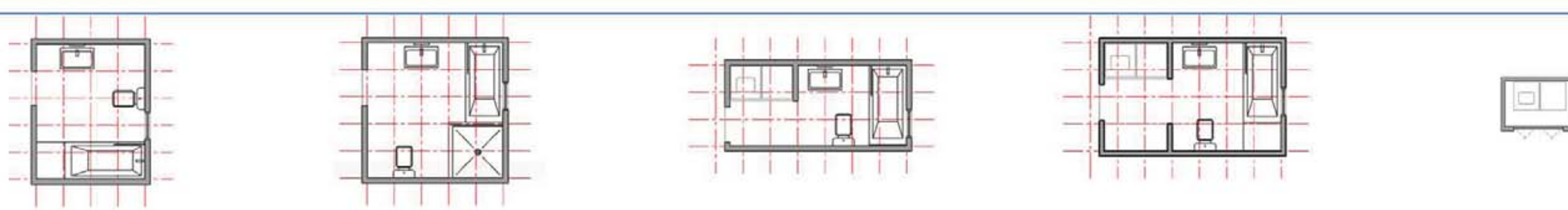


D1 12'-0" x 10'-0"

D2 12'-0" x 12'-0"

D3 14'-0" x 12'-0"

BATHROOM & LAUNDRY



B1 10'-0" x 8'-0"

B2 10'-0" x 10'-0"

B3 12'-6" x 6'-0"

B4 12'-6" x 8'-0"

LA 6'-0" x 4'-0"

LES MAISONS Alouette HOMES

Legend / Notes :

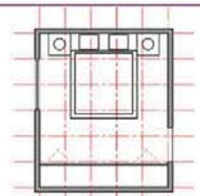
Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

0 2 4 8 ft.

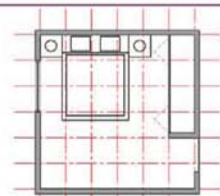
Série Avantage vol. II

Assemblies

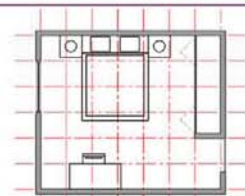
BEDROOM



BR1 12'-0" x 10'-0"

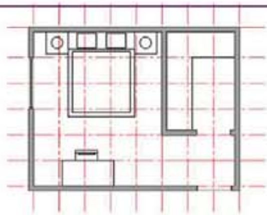


BR2 12'-0" x 12'-0"

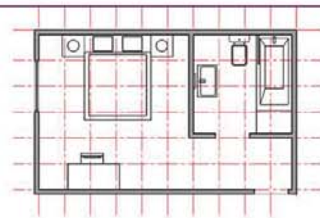


BR3 14'-0" x 12'-0"

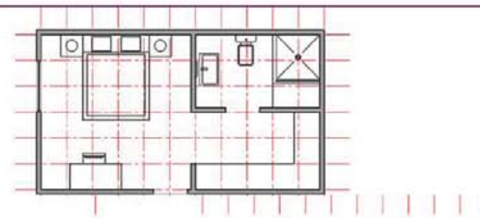
MASTER BEDROOM



MBR1 16'-0" x 12'-0"

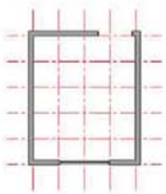


MBR2 20'-0" x 12'-0"

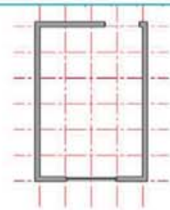


MBR3 22'-0" x 12'-0"

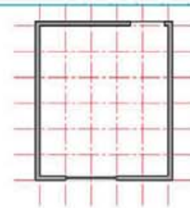
HOME OFFICE



O1 10'-0" x 8'-0"

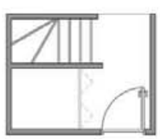


O2 12'-0" x 8'-0"



O3 12'-0" x 10'-0"

ENTRANCE



LES MAISONS Alouette HOMES

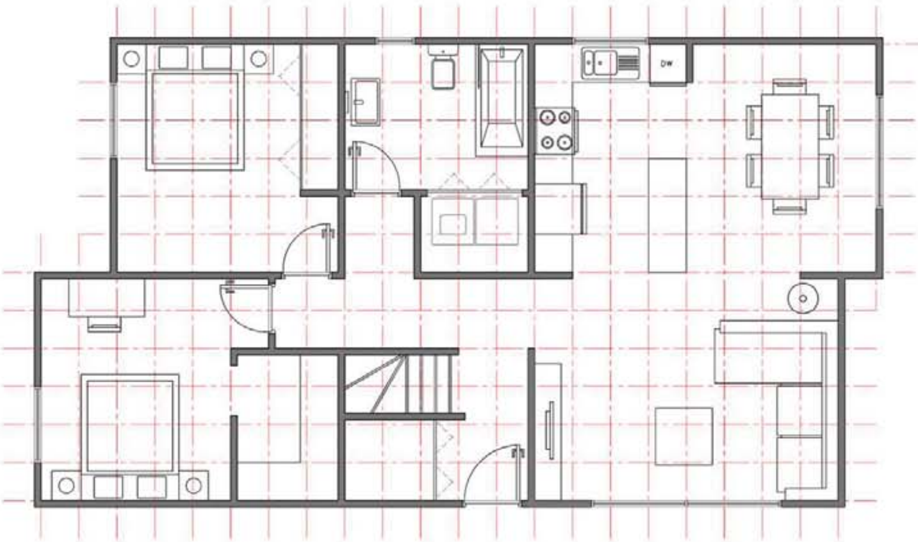
Legend / Notes :

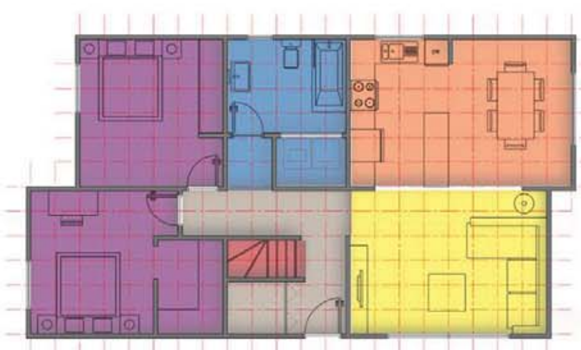
Living
Bathroom
Stairs
Kitchen
Bedroom
Dining
Hallway

0 2 4 8 ft.

Série Avantage vol. II

Assemblies

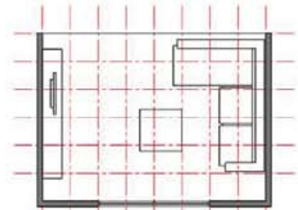




2 Bedrooms

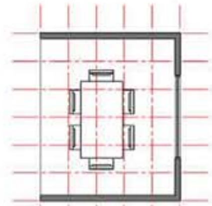
Total Area
982.65 sq. ft

Horizontal Circulation
50.10 sq. ft (5 %)

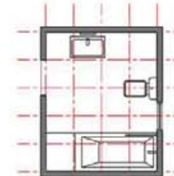


L1 16'-0" x 12'-0"

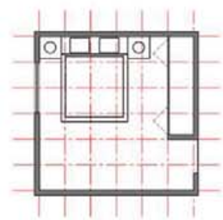
K1 12'-0" x 8'-0"



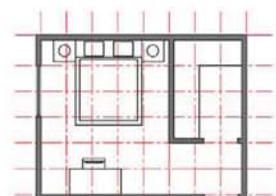
D1 12'-0" x 10'-0"



B1 10'-0" x 8'-0"



BR2 12'-0" x 12'-0"



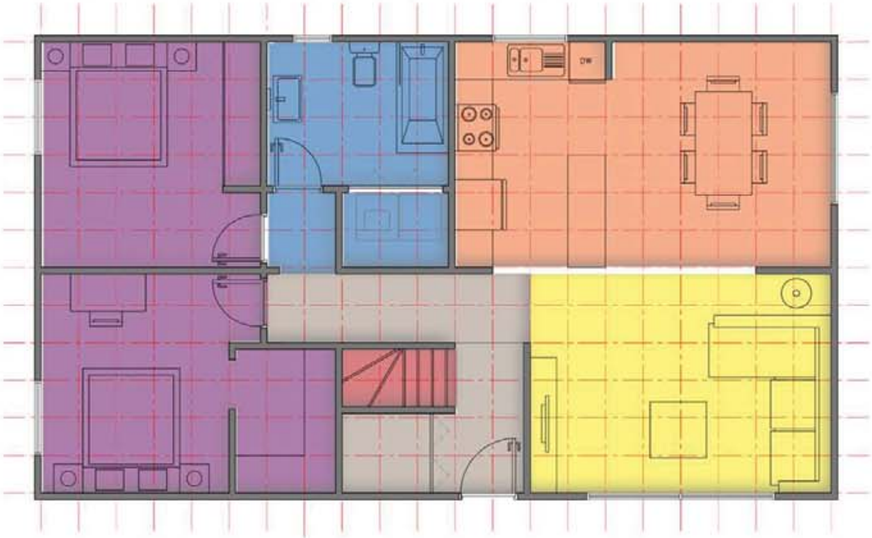
MBR1 16'-0" x 12'-0"

LES MAISONS Alouette HOMES

Legend / Notes :

- Living
- Kitchen
- Dining
- Bathroom
- Bedroom
- Hallway
- Stairs

Série Avantage vol. II
Variations



2 Bedrooms

Total Area
1008.00 sq. ft

Horizontal Circulation
50.10 sq. ft (5 %)

2 Bedrooms

Total Area
995.30 sq. ft

Horizontal Circulation
49.05 sq. ft (5 %)

2 Bedrooms

Total Area
1015.20 sq. ft

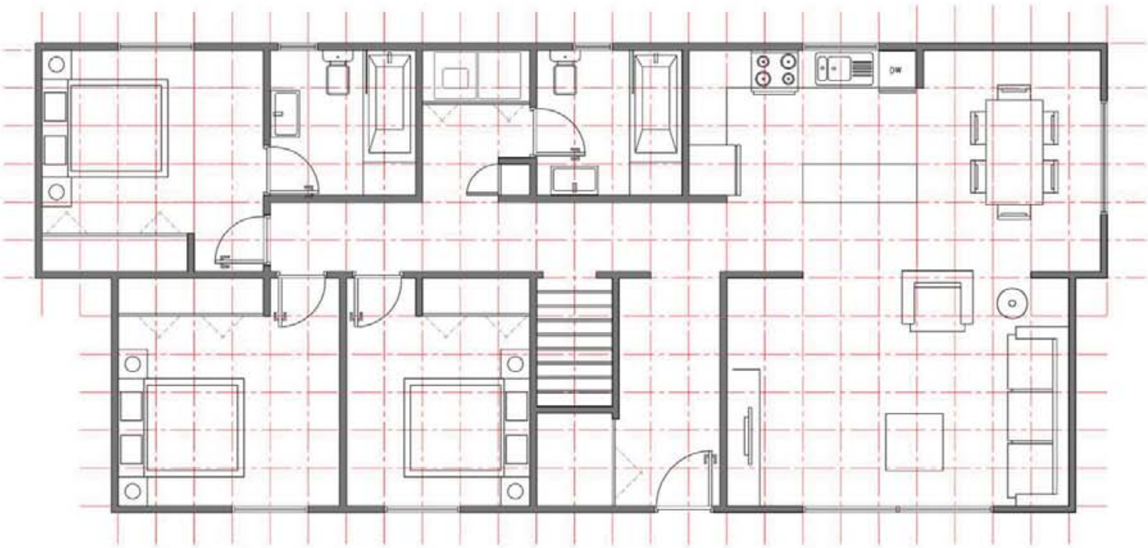
Horizontal Circulation
100.05 sq. ft (9%)

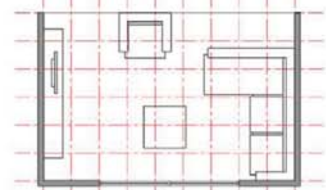
LES MAISONS Alouette HOMES

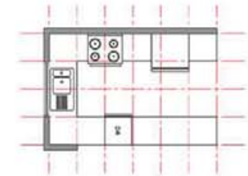
Legend / Notes : Living, Kitchen, Dining, Bathroom, Bedroom, Hallway, Stairs

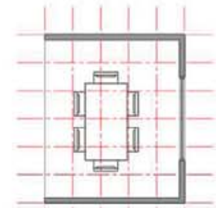
0 2 4 8 ft.

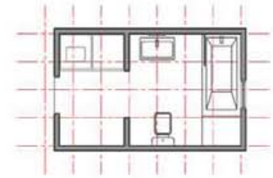
Série Avantage vol. II
Variations

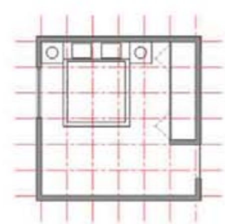


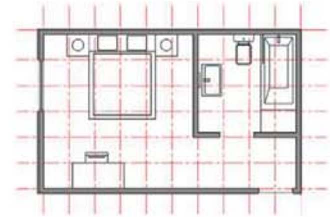

L2 18'-0" x 12'-0"

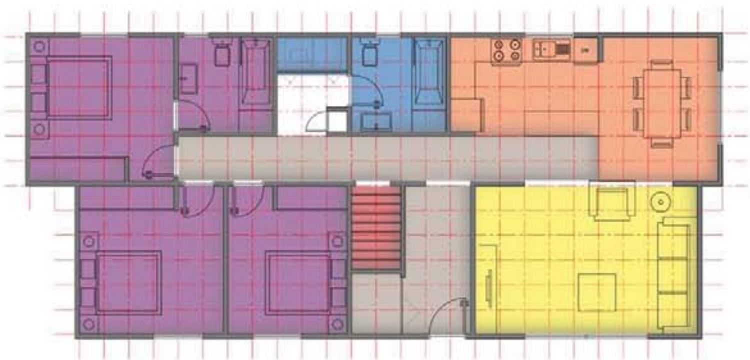

K1 12'-0" x 8'-0"


D1 12'-0" x 10'-0"


B1 10'-0" x 8'-0"


BR2 12'-0" x 12'-0"


MBR2 20'-0" x 12'-0"



3 Bedrooms

Total Area
1265.10 sq. ft

Horizontal Circulation
120.10 sq. ft (9 %)

LES MAISONS Alouette HOMES

Legend / Notes :

- Living
- Kitchen
- Dining
- Bathroom
- Bedroom
- Hallway
- Stairs

Série Avantage vol. II
Variations

3 Bedrooms

Total Area
1362.65 sq. ft

Horizontal Circulation
130.10 sq. ft (10 %)

3 Bedrooms

Total Area
1225.25 sq. ft

Horizontal Circulation
102.10 sq. ft (8 %)

LES MAISONS Alouette HOMES

Legend / Notes :

Living · Kitchen · Dining · Bathroom · Bedroom · Hallway · Stairs

Série Avantage vol. II
Variations