Automated design and delivery of relief housing: the case of post-earthquake Haiti

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This paper proposes integrated design and building systems for provision of sustainable customized housing. It advances previous work by applying a methodology to generate these systems from vernacular precedents. The methodology is based on the use of shape grammars to derive and encode a contemporary system from the precedents. The combined set of rules can be applied to generate housing solutions tailored to specific user and site contexts. The provision of housing to shelter the population affected by the 2010 Haiti earthquake illustrates the application of the methodology. A computer implementation is currently under development in C# using the BIM platform provided by Revit. The goal is to use a similar methodology to suit other housing emergencies.

Mass customization, Housing, Building system, Sustainable construction, Life cycle energy consumption, Shape grammar

1. Introduction

As the 21st century unfolds, the world still experiences an increase in population. Estimated to be 6.8 billion people in 2009, the world population is expected to achieve 9.0 billion in 2050 [23]. At the same time, the world experiences an urbanization process. The number of people living in cities, which represented half of the world’s population in 2008, may increase up to 60% in 2030. These phenomena are particularly acute
in developing countries, calling for the development of effective means to solve the housing deficit. There is a need to build in a few decades the same amount of houses built over the past four millennia! The informal response to the problem relies mainly on handcrafted processes, resulting in an increase of urban slums in many of the big cities. These often lack the sanitary and spatial qualities required to provide the population with dignified living conditions. On the other hand, the formal sector has produced monotonous environments based on the idea of mass production that one size fits all. This response fails to meet the individual and cultural needs of the population, even if it provides desirable sanitary conditions. This article follows an alternative approach in which mass customization is used to produce planned environments with some of the qualities found in historical incrementally grown settlements.

Mass customization, a new paradigm emerging due to the technological developments of the last decades, combines the economy of scale of mass production and the aesthetics and functional qualities of customization. When applied to housing, it provides houses that respond to the context in which they are built. This means a response to individual household needs, but also to technological, economic, social, and environmental constraints. In this sense, the term ‘customization’ also means ‘sustainability’. From the environmental viewpoint, the goal is to develop a housing system that requires low energy consumption for its production, for the construction of its buildings, and for the use of such buildings.

The conceptual model for the mass customization of housing used in the study here departs from the idea of a housing type [8] which is the combined result of three systems. The functional and spatial system specifies how spaces should be organized in a house to respond to a particular way of living in a certain culture. The structural and building system determines how houses should be materialized within the technological means available in that culture. The stylistic and decorative system describes how houses can be embellished in response to needs of individual expression, aesthetic pleasure, or spiritual fulfillment.

The conceptual model for the mass customization of housing [6] includes a design, production, and a computer system. The design system uses contextual user and site data and specifies the functional and spatial organization of spaces in the dwelling. The production system permits the effective materialization of the dwelling. Finally, the computer system integrates the two systems to enable the exploration of solutions that match the context and the generation of information for manufacturing.

The conceptual model just described was tested by Benfros and Duarte [2] by developing a computer system for existing design and building systems. The current project develops an original design, building, and computer
system for a particular context. The specific methodology to arrive at new systems is derived from the idea of architectural precedents and archetypes and it will be the subject of a future publication. A brief account of the methodology is provided in Section 2.

The research is mainly focused on developing countries, where quality housing needs are large and there are resources to build at this scale [17]. The methodology is to be tested in a few case studies. For the current study, the selected country was Haiti. The high percentage of slum population – around 2.3 million in 2005, which represented 58% of the urban population and 25% of the total population [24] –, resulting from the explosive relative urban growth of the recent past, shows the housing shortage in the country, making it a suitable case study for the development of a new housing system. The decision to choose Haiti for this study, however, was due to the devastating earthquake that struck this country in 2010 and destroyed its capital city, Port-au-Prince. This natural catastrophe affected the population with human and material losses, leaving a great demand on housing. The experience acquired with this particular research focused on the Caribbean reality can be applied in future massive building efforts in other developing countries. Moreover, the methodology and process rehearsed are suitable to similar housing shortage scenarios in countries with similar climates and latitudes.

The urgent need to build fast in the aftermath of catastrophes quite often overrides any cultural concerns. As a result, the temporary shelters provided in such circumstances are indistinct and impersonal. However, temporary becomes permanent in many cases. In addition, taking cultural aspects into account and incorporating them into the design of houses might lead to a better identification of the population with their new environment, contributing to a faster healing process. As the methodology is based on the idea of architectural precedents, taking existing vernacular housing as a reference permits the incorporation of cultural aspects and facilitates the identification with the new housing. Knight and Sass [14] similarly stress the importance of integrating cultural factors within a generative approach to housing design for developing or post-disaster environments.

For this study, we chose colonial Haitian architecture as precedent because it constituted an important part of the traditional urban fabric destroyed by the earthquake and is adapted to suit the climate and the way of life, despite its European roots. The chosen houses are commonly named “gingerbread houses”. The more famous are the aristocratic types, but there are plenty of humble examples in smaller-sized forms. The main features are the rectangular footprint and orthogonal grid, the inclusion of verandas or porches, the high pitched roofs and the profusion of
decoration, some with utilitarian use, such as the louvered shutters for shading and ventilation and the patterned balustrades. Cross ventilation is a common technique to provide natural cooling and diminish the air dampness, as is the porch buffer area.

A contemporary take inspired by the gingerbread houses was the origin of the proposed design system. The building system was designed to address the orthogonal grid proposed by the design system.

The following Section 2 provides a description of the design methodology. Section 3 describes the design system, focusing on its shape rules. Section 4 addresses the building system, the corresponding grammar rules and the proposed manufacturing process. Section 5 discusses the computer implementation and the systemization of design and building systems. The final Section discusses the obtained results and outlines future work.

2. Methodology

The methodology to devise new integrated design and building systems for customized housing was based on two ideas: precedents and transformations in design.

Studies in cognition and human behavior demonstrated that looking to solutions to known problems is an efficient strategy to solve new problems. In architecture this strategy is mirrored in the use of precedents in design; when confronted with a new design problem, designers look for sources of inspiration. Precedents provide designers with a typical solution for a particular problem, a good departing point for a new design.

Shape grammars are defined by sets of shape transformation rules that apply recursively to derive a design from an initial shape [21],[22]. The universe of designs derived from a rule set define a design language or style. Shape grammars have been developed for a wide range of designs languages including the gingerbread houses or other vernacular languages such as traditional architecture in Japan [12], Taiwan [4], Turkey [3], China [15], and Bosnia [5]. Studies in shape grammars have also shown that the evolution of one style into another can be described as a transformation of the underlying shape grammar [13]. A particular housetype can be encoded by a shape grammar forming a design system [6]. The proposed methodology takes off from these ideas and comprises the following steps [7] [9]:

Selection of precedents: This step is aimed at the selection of one or more precedents from existing housetypes that possess features that are relevant for the current design problem.
Derivation of an archetype: The conception of the system’s archetypical design from the precedent(s), which can be accomplished by the following approaches:

Structured approach: An attempt to formalize the process of creating a new design from existing ones, which requires one to infer the grammar(s) underlying the precedent(s) and then obtain the new grammar by changing, deleting, or adding new rules.

Intuitive approach: In this case, one designs the archetype design considering or not any precedents in a conscious way and following the conventional ‘intuitive’ design approach. Then, one may follow the structured approach to obtain the grammar of the new design system.

Listing of rules: After following any of the procedures above, one ends up with a set of rules. These rules then need to be organized and systematized to facilitate their use.

Derivation of designs: In this step the set of rules in 3 is applied in the generation of new designs to test and fine-tune the grammar.

Cataloguing of solutions: The goal is to give an idea of the universe of design solutions that can be generated by the rule set. This may be accomplished by creating a catalogue of basic solutions that represent the style and illustrating the range of design possibilities.

Derivation of tailored solution: After having the rules, knowing how to apply them and having an idea of the range of possible solutions, the encoded system may be used in the generation of a solution for a particular context, that is, for a particular family on a particular site.

The application of the proposed methodology was tested in the Haiti case as documented.

3. Design System

To tackle the complex problem of mass reconstruction and the provision of emergency dwellings, a time and cost effective approach is proposed. Reconstruction should aim at recreating minimum living conditions for the affected population, but also to increase living quality using the opportunity to enhance the urban environment. Assumptions were taken to create a starting point for house generation. Observation showed common grounds in single family houses whether they were isolated in plots or erected as row houses. Both cases are allowed. Single family houses can be built with one or two storeys. The opportunity for future expansion is addressed and rules were created to show how houses can be incrementally enlarged in time, while respecting the original vision and principles. Incremental rules are crucial for making the project viable by responding to family evolution and better economic scenarios.
The use of shape grammars allows for the manipulation of shapes and functions creating operable design alternatives and adding diversity. It encompasses a set of rules that when applied in a sequential manner allow for the design of a consistent solution. This specific grammar includes 14 sequential stages with 103 different design rules. The rules embed knowledge regarding form and function. The shape nature of each transformation codes the overall shape of the dwelling and the function assigned stipulates the internal spatial distribution. Different levels of intimacy within the indoor space progress from semi-public verandas towards more private sleeping areas.

The graphic definition of rules includes labels that help contextualize and control their application. Slash and dotted lines define symmetry axes placed along central bays. These restrain the application of rules, reducing ambiguity and avoiding its application in bays that are not in the central position. An arrow represents the main entrance, centered and facing the main access street. A vertical border offset line indicates an edge or party wall with a neighboring plot, limiting inclusion of openings such as windows or even the future expansion of the house. Labels ‘S’ and ‘Y’ give orientation hints, standing respectively for Street and Yard. Similarly, ‘E’ and ‘W’ stand for East or West solar exposure and they are present in façade definition stage rules.

The fourteen-stage process is described in the following paragraphs:

Stage 1 is the starting point. It is responsible for the underlying floor plan grid. The optional grids are comprised of orthogonal, parametric rectangular modules that relate directly with the conditions of the structural span. Six different rules determine possible grid sizes ranging from 3x1, 5x1, 3x2, 5x2, 3x3 to 5x3. Parametric variation of the modules rules allow for a measurement of 2.5m, the minimum acceptable size for a living compartment, and 5m, the maximum span supported by the structure. The number of rows varies from 1 (core house) to 3 (enlarged version). The number of columns is always an odd number in order to accommodate and centre the main entrance or access.

Stage 2 resizes the central bay to accommodate the entrance and indoor access. This stage allows for grid manipulation and realignment. Three of the rules allocate the access, a fourth one splits a cell into minor compartments, and the last four rules enable the concatenation of adjacent spaces to create an enlarged living space with a specific layout.

Stage 3 is mandatory for double-storey houses. It positions the staircase to be easily accessible from different parts of the house. Six different rules can be applied provided that these conditions are fulfilled, such as the insertion of the staircase on the central bay whenever it is possible and the connection of the staircase with the main house entrance. Rules such 3.1
and 3.2 apply to one-bay grids, 3.3 and 3.4 to two bays and the following to three bays.

Stage 4 starts detailing the functional areas of the house. This stage is focused mainly on the design of the living space, the most important social room and thus the most spacious. The living room area can range from 1 module up to 3, dependent on the grid dimension of the house. One-bay grids require a mandatory minimum of a 1 module room (rules 4.1 and 4.2), two bays, 2 adjacent modules (rules 4.2 and 4.3) and 3 a minimum of 3 modules (rules 4.4 and 4.5). Another basic requirement is the street connection. The living room, as a centre of social activity, should be the most public space in the house and related with the semi-public porch or veranda. It should be provided with natural ventilation and daylight. The ‘S’ label, denoting Street, limits the application of the rule. Stages 1 to 4 are illustrated in figure 1.

Stage 5 continues detailing the interior of the dwelling by adding the dining room. The inclusion of this as an independent space is not mandatory, as it can be combined with the living room in small sized houses (rule 5.9). This space has to meet two basic requirements: direct access from the living space, and natural ventilation and lighting. The rules at this stage determine possible alignments and layouts.

The first service area is included in Stage 6. The kitchen constitutes an important service point and within the present system it is desirable that it faces the Yard (labeled as ‘Y’). This way, ventilation and natural lighting are guaranteed. In addition, all associated functions such as cooking,
Fig. 2: Rule System, Stages 5 to 7 (Image: Deborah Benrós)

laundry, and pantries are not exposed to the public but enjoy some privacy. In addition, such a location permits access to the yard, which might constitute a suitable outdoor extension for the service area. Another important constraint is the proximity to the dining area.

Stage 6 incorporates 10 different rules that are applicable in different scenarios with various parametric variations. The inclusion of at least one spatial module for the kitchen is mandatory for all housetypes.

Stage 7 determines the design of the ground floor sleeping areas. Sleeping rooms can be designed both on the ground floor and on the upper floor. All bedrooms should provide exterior views either towards the yard or the street side, as determined by rules 7.1 to 7.6. A house can have one or more independent bedrooms according to the grid, area and size. One-bay grids, due to their diminished size, may permit sleeping to be integrated with living space (rule 7.1). Therefore rules allow the design of smaller, studio-like houses, while not restricting the possibility of having independent rooms in larger houses. This stage is mandatory for houses with one floor. Figure 2 contains an illustration of stages 5 to 7.

Stage 8 wraps up the ground floor interior layout with the placement of bathrooms. At least one bathroom has to be integrated on the ground level. Bathroom placement rules anticipate the best location by segregating social from service spaces. Its preferential location is next to private sleeping areas (rules 8.2 to 8.5), or in interior bays (8.7).

Once the ground level is completed, a veranda can be added in Stage 9. As mentioned above, the veranda or porch constitutes an important space in vernacular houses and a feature with great architectural and
environmental potential. It acts like a buffer zone helping to maintain a cool indoor environment, controlling the solar radiance, shading, providing ventilation, and recessing the interior private space. Hence, every design has to include at least one street facing veranda (rule 9.5), but it may include yard facing verandas (9.4), L-shaped (9.3), U-shaped (9.2) or O-shaped verandas (9.1).

Stage 10 addresses the insertion of the house on the plot responding to topography. Rule 10.1 deals with the insertion on a flat terrain while rule 10.2 adapts the solution to sloped scenarios. Both rules are inspired by gingerbread houses precedents. Every house is slightly elevated from the terrain. However, on sloped terrains the house’s ground level is raised from the ground and is accessed by a flight of stairs. This also provides enhancement of passive cooling strategy allowing some room between the terrain and the bottom slab for ventilation. Stage 11 starts once the last level is completed. It is driven by 4 rules that determine how the pyramidal shaped roofs are applied. The design of the roofs stems from vernacular examples but also responds to the intent of expressing on the roof what is encapsulated in the interior. Adjacent modules with similar functions share the same roof. Verandas are covered by either pitched roofs (rule 11.4) or by flat shading screens (11.5).

An important step in the definition of houses is the design of façades. These are relevant for thermal performance and permeability with the outside. Namely, it is important to allow cross ventilation as these houses are located in a tropical humid climate. Therefore, the strategy is to allow natural light but to control excessive radiation that leads to overheating, to promote cross ventilation for passive cooling strategy, and to allocate access to outdoor spaces such as yards and verandas. These rules are included in Stage 12. In brief, the key principles encoded in these rules are: the maximum area allocated for openings on the facade wall is 30% (rule 12.1), the minimum height for door openings is 2.1 m, the ratio for the openings’ length is therefore $21 \times A/10$ (12.2), windows should have similar length as door openings, and full sized shutters or screens should be applied on the East and West façades providing shading to cope with dusk and dawn sun conditions (12.3-5).

The potential of the design system to include incremental housing is described and foreseen in Stage 13. Grid expansion possibilities include the full range of grid types foreseen in the system and proposed in stage 1. This means that one particular grid can only evolve to any larger grid predefined by the system, maintaining design consistency. A smaller grid of 3x1 can grow in rows or columns to become a 5x1 grid (rule 13.1) or a 3x2 grid (rule 13.2), a 5x1 grid can evolve to a 5x2 grid (rule 13.3), a 3x2 grid can increase by one row to become a 3x3 grid (rule 13.5) or by two
columns to become a 5x2 grid (rule 13.4), and a 5x2 grid can add an extra row to become the larger 5x3 grid, (rule 13.6) which cannot extend any further.

The building system is detailed in Stage 14. Nine different rules design the structure, support and infill elements of the envelope. The structural system, described in further detail in Section 3, is a typical beam and column 3D grid made of wood elements. The original grid settled in Stage 1 constitutes the structural axis and in the vertex of each module a column is placed and topped up by a horizontal beam, as described in rules 14.4 and 14.5. Different wall systems address the wall types available. A typical wall will be constructed out of vertical studs adjacent to the columns and spaced by 80 cm (rule 14.1). Whenever an opening punctuates the wall, reinforcement is provided to apertures with edge adjacent studs and local beams as shown in rules 14.2 and 14.3. Exterior facade walls need to deal with possible seismic horizontal movements; for this reason diagonal elements are introduced (rules 14.8-9). Slabs are light-weight and built out of an orthogonal overlapping grid of small wooden beams that will be finished with wooden floor boards as detailed in rule 14.6. Roof trusses to support the roof finish are designed according to rule 14.7.

Stages 8 to 14 are illustrated in figure 3.

The design of a house is completed with the recursive application of rules from the different consecutive stages. The overall application of rules is summarized in the tree diagram (Fig. 4) that shows house derivation obtained through the application of different rules up to stage 8. The top
level of the tree corresponds to the grid layout definition stage and it includes all the six possibilities ranging from 3x1 to 5x3 grids. The levels below correspond to the subsequent stages, from the access definition to interior layout stages. The bottom of the tree shows 20 of the many different possible solutions from a humble studio-like house to a 4-bedroom. This diagram is relevant to give a glimpse of the potential of the system to design many varied house solutions. Figure 5 shows the architectural drawings (plan, front view and section) of another possible solution generated by this system.
4. Building System

In the conceptual model for mass customization of housing defined by Duarte [6] the role of the building system is to materialize the customized architectural design proposals generated by the design system.

The current building system was created bearing in mind three characteristics: modularity, possibility of incremental housing, and seismic resistance.

4.1. Modularity

The level of industrialization of the building system to use in construction of buildings depends on the context of the enterprise, namely on the number of buildings, on the speed of construction and on the available construction technology, which can be a constraint. Therefore, different contexts imply different levels of industrialization. Haiti, in particular Port-au-Prince, is a disaster area as a consequence of the earthquake. This housing emergency requires a high speed of construction and a large number of buildings. These imply the industrialization of the construction process, resorting to prefabrication and to modular construction. The available construction technology can be considered insufficient, only labor is available. Therefore, the building system has to be produced abroad, transported and assembled on site. Modularity is a characteristic which facilitates the last two requirements.

4.2. Possibility of Incremental Housing

Incremental housing is, in fact, a typical construction method in developing countries. According to a family’s financial possibilities, a house is made with the essential features for living. As the family increases in number or the financial situation improves, new spaces are added. Although the design system does not incorporate this feature yet, the building system was created considering a future version of the design system, for which the inclusion of the possibility of incremental housing would be the logical next step.

4.3. Seismic Resistance

Haiti is crossed by a tectonic fault line, which causes occasional earthquakes, like the one occurring on January 12 2010, which partially destroyed its capital city, Port-au-Prince. Given the catastrophic consequences of the earthquake on the structures of Port-au-Prince, it was mandatory to endow the building system with a seismic resistant structural system, in order to prevent similar levels of destruction to the houses built.
4.4. Description of the Building System

The building system is composed of four sub-systems: structural, curtain wall and roofing, foundations, and joints. The structural sub-system is formed by linear elements – columns, beams, braces and roof trusses – and planar elements – slab panels. The inclusion of diagonal braces in the structural sub-system provides this sub-system with seismic resistance. Braces are to be placed between two consecutive columns in each façade. The curtain wall and roofing sub-system are made of planar elements – wall and roof panels. The foundations sub-system is composed of block elements – spread footing blocks. The joints sub-system is also formed by block elements, the connection devices which allow for the joining of the elements of the previous three sub-systems.

The main material is wood, which is used in the linear and planar elements. The joints are made in steel, and the foundations are made in concrete. The main existing types of joints are: column to foundation, column to two beams, column to three beams, column to four beams, column to brace (and n beams) and column to column (and n beams and n braces).

Figure 6 shows a schematic representation of the building system – only the structural and curtain wall and the roofing sub-systems for a generic module of the orthogonal grid. Figure 7 shows a three-dimensional image of a finished house (the house featured in Fig. 5).

The incremental capacity of this building system is granted by the possibility of expanding it both horizontally (in plan) and vertically, by adding new elements of the sub-systems. The column to column joint allows the system to increment the generated houses by adding a second floor to one storey houses. Also the seismic resistance feature of the structural system is maintained when the building is expanded to a second floor, by adding a new set of diagonal braces in a correct position so they function continuously with the braces of the floor below.

Fig. 6: Building System (Image: Deborah Benrós)
Fig. 7: 3D Image of a Single Storey, 5x2 House (Image: Deborah Benrós)
5. Computer System

The conceptual model for housing mass customization defined by Duarte (2008) usually involves a wide range of building design solutions, depending on the complexity of the design system – hence the need for the computer system to speed up the exploration of solutions. In addition, it is useful for materializing a design solution by matching it to elements of the building system and generating information for production. The latter was already explored by Benrós and Duarte (2009), using an existing design system (ABC), conceived by the Spanish architect Manuel Gausa, and a building system created by the British firm Kingspan. The computer system was scripted in AutoLISP using AutoCAD 2006.

In this study, both the design and the building systems are original. The main novelty regarding computer system is the software in which it is being crafted (yet to be concluded). Instead of using traditional computer-aided design software, like AutoCAD, it was decided to develop the computer system using Building Information Modeling (BIM) software – Revit Architecture 2009.

BIM is a growing and innovative field and it represents a significant paradigm shift in the development of computer tools for building design. The use of BIM may provide a significant increase in productivity in both the design and the construction processes, by facilitating coordination and collaboration among the various parties involved in the design phase [19]. BIM uses three-dimensional dynamic modeling and, among other features, encompasses geometry, spatial relationships, geographic information, quantities and physical properties of building components.

The scripting language in Revit is C#, an object-oriented class based programming language developed by Microsoft within the .NET framework.

6. Conclusion and Future Work

Previous work proposed a conceptual framework for mass customization of housing that included design and computer systems that permitted exploration of solutions and generation of information for fabrication [19]. The validity of this framework was later shown by developing a computer system for existing design and construction systems [2]. The current work proposes a combined system developed anew for a specific context, namely, the design of emergency housing for post-earthquake Haiti. The idea is that it can be applied to solve similar problems in other developing countries. The conception of this system followed a specific grammar-based methodology that uses design precedents and transformations to be described in a future publication. This methodology permits the new
system to be grounded in examples taken from vernacular housing. This approach is relevant in emergency situations as it facilitates the identification of people with their new houses, minimizing the rupture caused by the natural catastrophe. It also might help to minimize individual and social disruption in other urbanization scenarios with the need to shelter a large numbers in a relatively short period.

This article describes a new system, focusing mainly on design and building systems. The conception of the design system and setting of shape rules is a time consuming process. Nevertheless, the time invested in its creation can be compensated by the efficiency of the design of bespoke solutions. This is particularly relevant, when the computer implementation facilitates the exploration of solutions and the generation of information to fabricate and assembly houses. The computer implementation described in this paper is currently being developed in C# using Revit’s BIM platform. The use of the BIM platform for these purposes is also new, and the expectation is that it will facilitate integration and the generation of relevant design and building information. The general framework is the design of low cost residential neighborhoods. Mass production often implies a large number of units. Therefore, housing mass customization is specifically intended to build large housing estates. With regard to low cost, energy consumption is a feature closely related. The energy consumption for the production and construction of a building, mainly involving materials, is related to the initial investment cost – and normally low cost refers to this. The energy consumption of a building’s use relates mostly to its energy bills, for lighting, heating and cooling. These two types of energy consumption and cost involve an important trade-off: a reduced demand for energy during the usage phase (achieved by an increased use of energy intensive materials) [18]. As buildings have long life spans, a wrong selection of materials can incur on high energy consumptions. Therefore, low cost will also relate to a life cycle context.

The building system crafted so far is a first draft for the next phases. Next phase will focus on the redesign of the building system in a sustainable manner by minimizing the life cycle energy consumption. The second phase, already under development, will study the use of digital fabrication in the building system production process to reduce the energy consumption by introducing automated techniques. The third phase will address the selection of building materials, supported by a study on the region’s sustainability [1] and by a preliminary energy and economic analysis. The last phase will analyze the energy performance, in a life cycle perspective [10]; [25]. This analysis will determine the group of passive construction solutions that better adjust to the spatial context of the project [16].
References


