A Grammar for Shelters

An exploration of rule-based designs in prefabricated and modular shelters.

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This work explores the possible use of the shape grammar formalism in generating small/medium sized dwellings or shelters as a possible and effective solution for shelter shortages that usually follows in the wake of a natural disaster. The shelters are generated using a set of pre-fabricated elements that add up to form a coherent and functional dwelling. The grammar exemplified here, being a shape grammar, deals specially with generating the underlying functional diagram and the floor plan of one possible solution based on a set of typologies design a priori.

Keywords: *Shape Grammars, Modular Architecture, Emergency Architecture*

INTRODUCTION

For the past few decades we have witnessed drastic changes in the Earth's climate, often manifested as natural catastrophes that leave countless people shelterless in their wake. According to the Centre for Research on the Epidemiology of Disasters (2013), it is estimated that, in 2012, 357 natural disasters were triggered, affecting 124.5 million of people worldwide. The reality of these devastating events calls for a dire need for architects and other built-environment specialist, who have the tools, background and knowledge, to come forth with clever and creative solutions to the problematic housing shortages that follows these disastrous events. With this motivation, the work in progress here presented explores an attempt at using computational methods, namely shape grammars, as a viable approach to quickly and intuitively generate possible designs of shelters.

EVOLUTION OF MODULAR PREFABRICATED CONSTRUCTION

During the 20th century several models for family houses were proposed and developed based on the concept of modular and prefabricated architecture. As examples we have the Maison Dom-ino (1914) by Le Corbusier, the "American System-Built Houses" (1911) of Frank Lloyd Wright, Buckminster Fuller's "Dymaxion" (1927) and "Wishita Houses" (1944-46), the "Package House" (1941-52) develop by Walter Gropius and the "Plas-2-Point" house designed by Marcel Breuer in 1943. After the 2nd World War we witness a renewed interest for prefabricated construction in order to address the destruction that followed those tumultuous years. In France, Jean Prouvé studies several house models that were mindful of the environment and could be easily shipped and transported to the location. The "Maison Tropical" (1949) is one such example. Contemporary to

Prouvé's work are the "Loustron Houses" (1948) manufactured by the Lustron Corporation in the USA.

In Northern Europe, Scandinavian countries were exploring modular and prefabricated architecture with a predominant use of timber. One of the best examples is perhaps the "Moduli 225" (1969-71) by Finnish architects Kristian Gullichsen and Juhani Pallasmaa. The construction of this modular system is based on a cubic 225 cm structural module composed of timber pillars and beams to which modular panels are connected. The panel system was programmed with different variants in mind for the walls, floors and ceilings and the different possible combinations of panels allowed for several configurations and typologies within this 225 cm grid. For its structural system, versatility, ease of transport and on-site assembly the construction system used in this shape grammar is heavily influenced on the Moduli system.

During the last decades there have also been many interesting examples worth mentioning that show a more ecological concern and seek to answer the new paradigms in the way we inhabit spaces and buildings. A notable example is the "System 3" house presented in MoMA's 2008 exhibition entitled "Home Delivery: Fabricating the Modern Dwelling". The System 3 was a prototype that showcased a more rigorous design and the potential of new fabrication methods. It was composed of two main modules - a functional module with a kitchen, a bathroom and technical/storage area and a living module. These modules were fabricated separately and easily transported and assembled together on site.

Previous to the "System 3" house, Shigeru Ban designed the first of three "Furniture Houses" (1995). This house combines the concerns of earthquakes with the possibilities of open space, thus resulting in a construction system where vertical furniture assumes the role of structural elements. The furniture units - cabinets, closets and bookshelves - act as spatial dividers. This house proved to be a creative and effective way of building cost-efficient houses with considerable reduction of produced waste and construction time.

In Portugal, there have also been a few examples like the "Modular System" (2003-07) by Arquiporto and the "Treehouse" (2005-2008) by Appleton & Domingos. Both are based on a modular system which coordinates different multi-functional modules that can be added or removed based on the client's desire.

THE SHELTERS - COMPONENTS, ASSEMBLY AND TYPOLOGIES

Like the Moduli 225 construction system mentioned in the previous section, the shelters here proposed are based on a modular system composed of a timber portico structure to which panels can be easily added or removed. All components are treated as individual and prefabricated elements that can be easily packed, shipped and assembled. The intention was to design a flexible and functional program based on the "do it yourself" model.

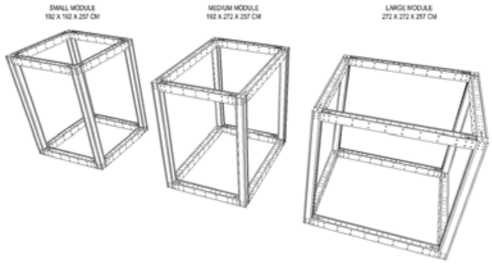

Figure 1
The three possible modules

The portal frame results from the modular coordination between beams and pillars, (both with a 16x16 cm section), designed to form a modular structure with a minimum and maximum span of 192 cm and 272 cm respectively. Hence, the structural beams have two dimensions that limit the size of the modular system. The beams connect to the pillars through means of concealed fittings that are of easy access to allow the structure and modules to be changed at any give time. The combination of these elements it is possible to obtain three different structural modules of 192x192x257 cm, 192x272x257 cm and 272x272x257 cm, from hereafter addressed as "small", "medium" and "large" modules respectively (figure 1).

The vertical and horizontal panels don't serve a structural purpose and as such can be placed and removed easily at any given time depending on the user's desire and needs. The vertical panels are grouped in different categories depending on what function they serve in the system. There are exterior and interior opaque panels, doors and windows panels and lattice panels, some of them with different variations. The combination of these elements also allows several different facades and inner space configurations. The horizontal panels are grouped in floor panels, with two variants, and ceiling panels.

The sloped roof is seen as an individual element mounted over the main structure. Although a separate structure, the roof is still dependent on the primary modular system. Its structure is based on the principles of traditional construction and materialized through prefabricated modular structural struts and stubs that rest directly on top pf the pillars..

The possibility to change the structure and modules was a determinant premise to this project since it is predictable that in some cases these shelters, which are thought to act as immediate and temporary dwellings , may in time acquire a more permanent nature if the occupants decided they wish to turn these shelters into a permanent home. In that case, additional modules can be added to enhance the basic shelter and increase it's comfort and space.

Assembly

The whole assembly process starts with building the skeletal portico frame structure, which rests directly over the foundations. The concrete foundations are laid on site and need to be carefully planned beforehand to abide by the same grid layout of the shelter. Using the appropriate connectors, the pillars are mounted over the foundations and the bottom beams screwed onto them to form the basic structural frame. At this point, the connectors for the vertical panels can also be placed.

The second stage of assembly is to place and connect the floor and wall panels to the beams in the desired orientation. The connections, although concealed, remain accessible if the user one day wishes to take the structure apart or add more modules or change the existing ones. This is also the stage at which all technical installations are provided so as to make the shelter habitable. Once all the vertical panels are in place and the interiors are terminated then the structure can be completed by placing the top structure, assembled in a similar way as the bottom structure. With the top beams in place the wall panels are locked in place.

The modules are topped with the roof to provide sunlight protection and make the whole structure weatherproof. The roof structure is composed of wood stubs, fixed on top of the pillars, roof struts that join together by means of lap joints and OSB (Oriented Strand Board) roof panels that receive a coating membrane.The assembly process and corresponding numbers can be seen in figure 2.

Shelter Typologies

For this grammar one basic typology of shelter was designed that serves as starting point for the generation procedure that allows the grammar to form more elaborate typologies. Having into account the possible number of inhabitants for these shelters, this basic typology is intended for one person or possibly a couple, and represents what is considered the most basic and compact solution while still maintaining a favorable level of comfort, living space and functionality. This basic T_0 typology (figure 3) is composed of a multi-purpose living area that can also serve as sleeping accommodations, a small kitchen, a small bathroom and a technical/storage area. Because the system is modular and possible to be changed at any given time, it is possible to obtain more complex typologies simply by adding more modules for bedrooms, balconies, porches or patios or by expanding existing ones. There is in fact no restriction of size or number of modules for each functional area although the small module is the most conditioned

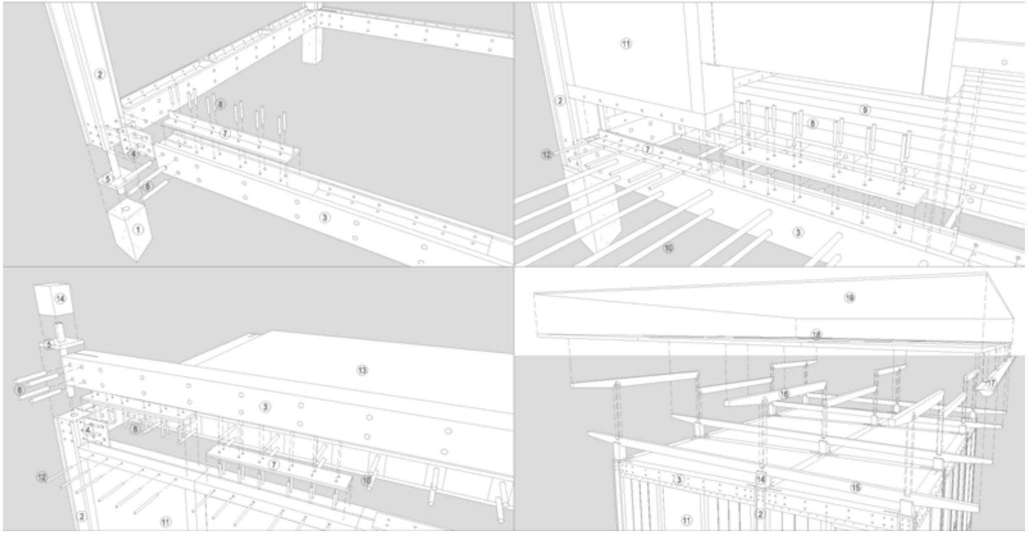

Figure 2
Stages of assembly

in the number of functions it can assume. However, it is still flexible enough to be used for bathrooms, kitchens, storage compartments, corridors, porches or simply as extensions to existing areas.

In order to introduce versatility into the system, several simulations were conducted, each one testing different layout configurations that could be generated from the basic T0 typology and grew in complexity, size and destined number of occupants. From these tests the first set of rules that generate the functional structure, deal with adjacency/connectivity rules, number of cells for each functional zone and location of the components, were extracted.

THE GRAMMAR

The formalism of shape grammars is specified in greater detail in Stiny (1980) but briefly explained it is a way of describing a computational procedure, starting with an initial shape, possibly labelled, to each rules are recursively applied to transform one shape into another. This 4-tuple - set of shapes, labels, rules and initial shape, forms the basic structure of a shape grammar. One useful application of such formalism is the generation of designs, extensively used in architecture to describe forms and the interactions between them in different algebras (Stiny 1989). We can also enhance these devices by attributing

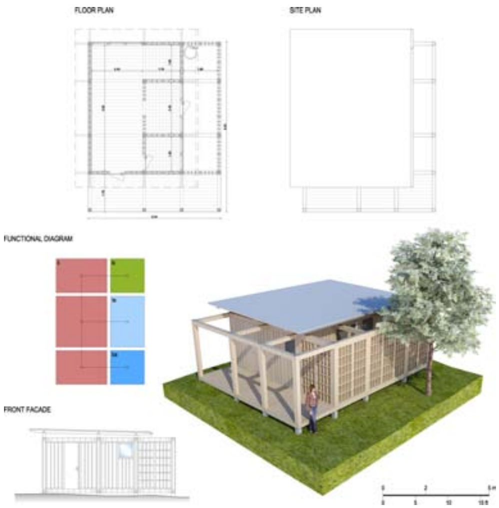

Figure 3
The basic T0 typology

variables to the elements that define them, thus creating parameterized shapes that describe families of shapes. Functions can then apply real values to these variables.

The shape grammar that follows deals with generating floor and site plans of modular shelters. Since it is composed of shapes, labels and weighted lines it works in the algebras U_{22}, V_{22} and W_{22}. The grammar incorporates a system composed of a set of elements that form the vocabulary of shapes to be used, the spatial relations between these elements and the shape rules that act upon the spatial relations and place each element in its correct position. The way it is structured follows the order of assembly of the shelters, that is to say it starts by defining the underlying functional structure with all corresponding adjacency and connectivity rules and then starts placing the elements in the same order they need to be placed on-site to complete the shelter.

A design for a shelter may be generated in the following seven stages:

1. initiation
2. interior layout and functional zones
3. bottom structure and floor
4. wall paneling
5. top structure and ceiling
6. roof
7. termination

Stage 1: Initiation. The initial shape of this grammar is the functional diagram of the basic T_0 (figure 4) from which every designed typology is defined, withe the label **dot-slash-dot** being used to indicate the connectivity between zones and the $\cdot$ indicating the direction in which additional modules can be placed in further stages of this grammar. The labels d and D are used to indicate the length and width of each side since the shared wall of two modules must have the same size.

Stage 2: Interior layout and functional zones. From the initial shape, the rules in this stage (figure 5) progressively add additional modules for the other functional areas, thus defining the desired interior layout. These adjacency rules are determined by the connection between zones and with label **dot-slash-dot**. The rules 1, 2 and 3 deal with expanding the technical zones in order to obtain the expanded version of the basic typology. Again, each space is identified with a color - red- living areas; green - kitchen; blue - bathroom; grey - technical areas; orange - bedrooms; dark grey - porches/balconies; brown - gardens/patios - and a $\cdot$ to indicate the position of adjacent spaces. The instances of the labels D and d again serve to indicate the dimension of each side for later use in the grammar.

In some rules, the $\cdot$ is progressively erased to stop further generation of areas. The last two rules in this stage erases the labels $\cdot$ and **dot-slash-dot** so that no adjacent areas can be added from this point onward. Only after the functional diagram has been generated correctly can these labels be erased.

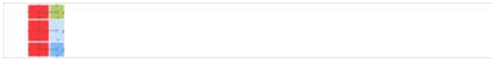

Figure 4
Initial shape

Figure 5
Rules for generating the functional diagram

Stage 3: Bottom structure and flooring. After the functional layout has been generated the next rules add the bottom structure (figure 6), consisting of the foundations, pillars, bottom beams and floors, placed in this order. The first schema (rules 71 to 74) starts adding the foundations at each corner and intersection of the previously drawn rectangles, that define the functional areas, and the pillar connectors on top of them. Placing the pillars comes next and these need to be place straight on top of the foundations (rule 75). The label $|-$ indicates the possible location of the beams which are placed with rules 77 and 78. When a beam is added this label is erased. Any remaining instances of the label are erased with rule 79.

Figure 6
Rules for placing the bottoms structure and floors

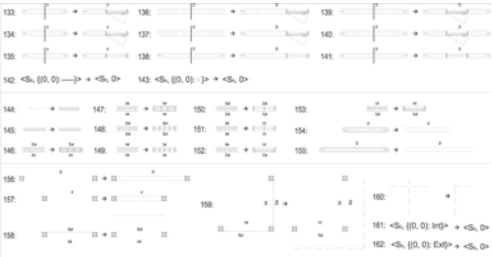

Figure 7
Rules for placing the door and wall panels

To aid the placement of wall panels in upcoming stages, rules 80 to 114 place a label Ext and Int indicating which side of each module is exterior and which is interior. These labels remain in the design for later use. The rule schemata 115 to 129 associate a floor panel for each space. Because each functional area is shaded with a different color the rules associate one of the two possible flooring panels with a specific color - wooden floors for living areas, bedrooms and porches/balconies and tiled floors for all technical areas. For the garden modules, because they don't have a floor or bottom structure, rule 130 merges the sides of these spaces. Only exterior areas shaded brown can have their sides merged. The last two rules eliminate spurious lines that are no longer needed in the design.

Stage 4: Wall panelling. The rules for this stage (figure 7) add the wall panels to fill the spaces in between the pillars. The first panels to be placed are the door panels wherever an instance of the label $-$ intersects the beam's outlines (rules 133 to 141). All other connection labels are then erased so that no more door panels can be placed (rules 142 and 143). The bottom wall connectors are placed afterwards over the beam t-sections (rule 144). The remaining panels come next and although the choice of rules for placing these panels can be somewhat arbitrary they still need to follow certain conditions. For example, the opaque panels with insulation and window panels can only be placed between the exterior and interior zones and lattice panels can only be placed when both sides are interior or exterior. When adjacent spaces share the same function and no panel is to be placed between them, rules 154 and 155 place boards to level the floor and conceal the beam connections.

At this point there is a choice to generate a complete floor plan or to continue applying rules to get a complete site plan. If we desire to get just the floor plan then rules schema 156 to 160 are applied. These rules mark the top beams (rules 156 and 157) and roof line (rules 158 and 159) with dashed lines and also eliminate all spurious geometry and remaining labels so that no other rule can be applied and the design is complete. If, however, we choose to continue with the grammar and carry on generating the site plan then the aforementioned rules are not applied and we move on to the next stage.

Stage 5: Top structure and ceiling. This grammar makes use of weighted lines as indicate which elements are be sectioned by the top horizontal plane. In order for the forthcoming elements to be visible on the ground plan the first rule schema defined in this stage (figure 8) erase this section plane, which translates in changing the representation method of all the elements placed before this stage (rules 163 to 172). Rule 173 then adds the top wall connectors and spurious lines are once again eliminated (rule 174). Afterwards, the next rules add the top beams in the same way the bottom beams were added, once the corresponding pillar connectors have been placed (rules 176). The final part is to add the ceiling panels over the interior zones, covering the floor patterns (rules 184 to 188).

Figure 8
Rules for placing the top structure and ceilings

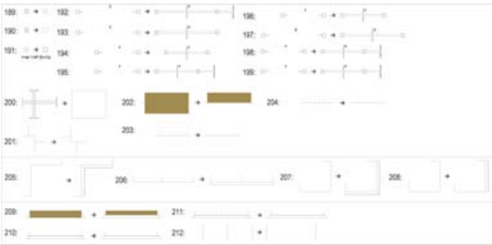

Figure 9
Rules for placing the roof

Figure 10
Termination rules

Stage 6: Roof structure and roof panels. The rules of this stage (figure 9) start placing the connectors on top of the pillars (rules 189 and 190). Placing the supporting stubs come next and because of the roof slope the total height of each stub changes throughout the structure. Resorting to the trigonometric relation between length and height, the formula for calculating this height is:

$$h = \tan 1.40(D + d) \qquad (1)$$

where ΣD is the sum of all D-length sides and Σd is the sum of all d-length sides. The angle 1.40º is the slope angle. Afterwards, rules place the transverse and longitudinal struts for both lengths, in the same order these need to be joined together - transverse struts first and longitudinal next (rules 192 to 199). Here a label $-$ is also placed to define the limits of each roof panel (rule 200). From this top view the roof overlaps with existing geometry so rules 201 to 204 are defined to trim the geometry that is concealed.

The next rules are for placing the rain gutter on the side for which the roof slopes to (rules 205 to 208). The gutter is also defined in modular sections with a predetermined size. The last rules of this stage delete lines and geometry that is once again being concealed or no longer needed in the grammar.

Stage 7: Termination. At this stage the generation of the shelter is terminated, leaving only to erase the remaining labels, D and d. Only shelters that have been correctly generated may have their labels erased. The entire process and result of applying the rules of this grammar to the initial shape can be seen in figures 11 and 12.

FINAL OBSERVATIONS

The paper shows the design and application of a work in progress shape grammar capable of generating modular shelters, based on the manipulation of three different modules and independent elements that are configured in different layouts to form different typologies and spaces. The ultimate intention was to explore how digital tools such as shape grammars could present a viable way to rationalize the design process and quickly generate several solutions based on an initial brief, as well as produce drawing representations of said solutions to be used in later project stages and to aid the manufacturing process. It would be interesting to couple this shape grammar with a descriptive grammar to enhance this user-based rule model. From an initial design brief, a set of heuristics would be used to translate the brief into a design solution (Duarte 2005). Another addition that could help the visualization of the grammar would be

Figure 11
Rule application process

Figure 12
Rule application process (continue)

to explore how these modules and elements relate to each other in the third dimension, possibly by generating isometric models of the shelters.

It is important to note that the scope of focus was both to showcase a modular system for constructing shelters and also to explore the application of shape grammars in rationalizing the design and assembly stages of modular-type dwellings.. For this reason and since this is still a work in progress, the design here presented may not have been described extensively enough and several changes remain to be made and some questions tackled. The dimensions, construction details, materials and typologies here exemplified mean only to provide a base for the shape grammar and the definition of the rules. It was also not possible, due to time restrictions, to include in this grammar furniture and fittings in the grammar, consider possible site restrictions, adaptability to particular building regulations, introduce energy efficient solutions or technical installations and infrastructures .These were nevertheless taken into consideration for defining the dimensions of the modules and guarantee the grammar could not generate spaces that are too small or inappropriate for the functions they serve.

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