A mass-customized housing shape grammar application – The Orange County Sustainability Decathlon experience

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Abstract. Prompted by an international competition, a multinational team developed a sustainable, affordable housing solution to be built in California. The Orange County Sustainability Decathlon proposed a platform to test the system's viability. The generative system created encompasses a design system, a structural strategy, and an infill/cladding process. The method chosen was a descriptive shape grammar, a system that uses a finite number of graphical rules, and parametric schemata to produce a family of solutions, based on an offsite volumetric pod. The grammar allows basic design rules each one targeted at the combination of adjacent spaces: a bathroom, a kitchen, an entrance space, a living area, a sleeping area and additional accommodation. The spatial variations allow for several parametric solutions. Once the spaces are associated, they are constructed using light structural framing systems. The experiment has proved to be operational and could be scaled up for commercial applications.

Keywords: Housing mass-customization, housing shape grammar, affordable housing.

1 Introduction

Tongji University and the University of East London teamed up to develop a sustainable, affordable housing solution to be built in Orange County USA in October 2023. The current work describes the generative system developed, whose methodology could be replicated and marketed post-competition. The project was named ‘Elemental House’ as it is composed of different articulated elements which are key for a successful house excluding any redundant spaces. The design was co-designed along eighteen months of design meetings, two international workshops hosted by both universities, one directed to student design solutions and the second aimed at robotic construction and the use of graphical scripting and one physical meeting.

The current house market is often divided into onsite construction, (linked to increased costs, morosity, lack of sustainable solutions and the production of waste); or offsite (linked to inflexible housing, unimaginative layouts, and repetitive solutions). Previous work proposed mass-customized offsite with a degree of success but without the production of either a prototype or built solutions (Benros & Duarte, 2009). Previous solutions focused on either descriptive grammar (Duarte, 2003) or parametric rule-based systems (Benros et al., 2007).

Shape grammar faced criticism in the past concerning the lack of real-life application and is usually tested only in academic environments. This constitutes one of the first known real-life applications of shape grammar to achieve a design concept and a multitude of different solutions applied to mass-housing customization. Which is believed to be linked to affordability, personalization and more refined end-result quality.

Some commercial sponsors have shown interest both in Asia and in North America proving the proposal's merit.

2 Methodology

The selected methodology is threefold: Firstly, the development of a generative system, secondly the development of an efficient constructive method offsite to build the solutions tested through real scale mock-ups and lastly the construction and assemblage on site of the final selected solution.

2.1 Generative system – Shape grammar

The shape grammar formalism selected uses a rule system based on the Kindergarten grammar (Stiny, 1980). This is a typical additive grammar where each space is added in sequence to a previously assigned space. A grammar typically uses a graphical procedure that describes a geometric operation (Stiny, 2006), in this case, the Prairie Houses grammar was also influential on its formulation (Koning & Eizenberg, 1981). Is composed of an initial state, a transformation and an end state. In this 'Elemental house grammar', the first rule proposes the entrance porch, followed by the inclusion of the living-dining social space illustrated in Figure 1. Typically, this is located towards the West with glazing at one end. The slope of the roof is orientated towards the South, and its slope is parametrically angled according to the daylight angle, optimizing the positioning of solar panels. The living/dining is limited by the placement of the kitchen unit that faces the space. The kitchen unit placement refers to stage 3 of the grammar procedure. Two possible layouts are allowed: one immediately bordering the living space and a lateral option against the pod wall. Stage 4 allows for the positioning of the bathroom pod. This enables two possible layouts, a one-story layout and a bathroom and loft configuration for additional maisonette sleeping arrangements.

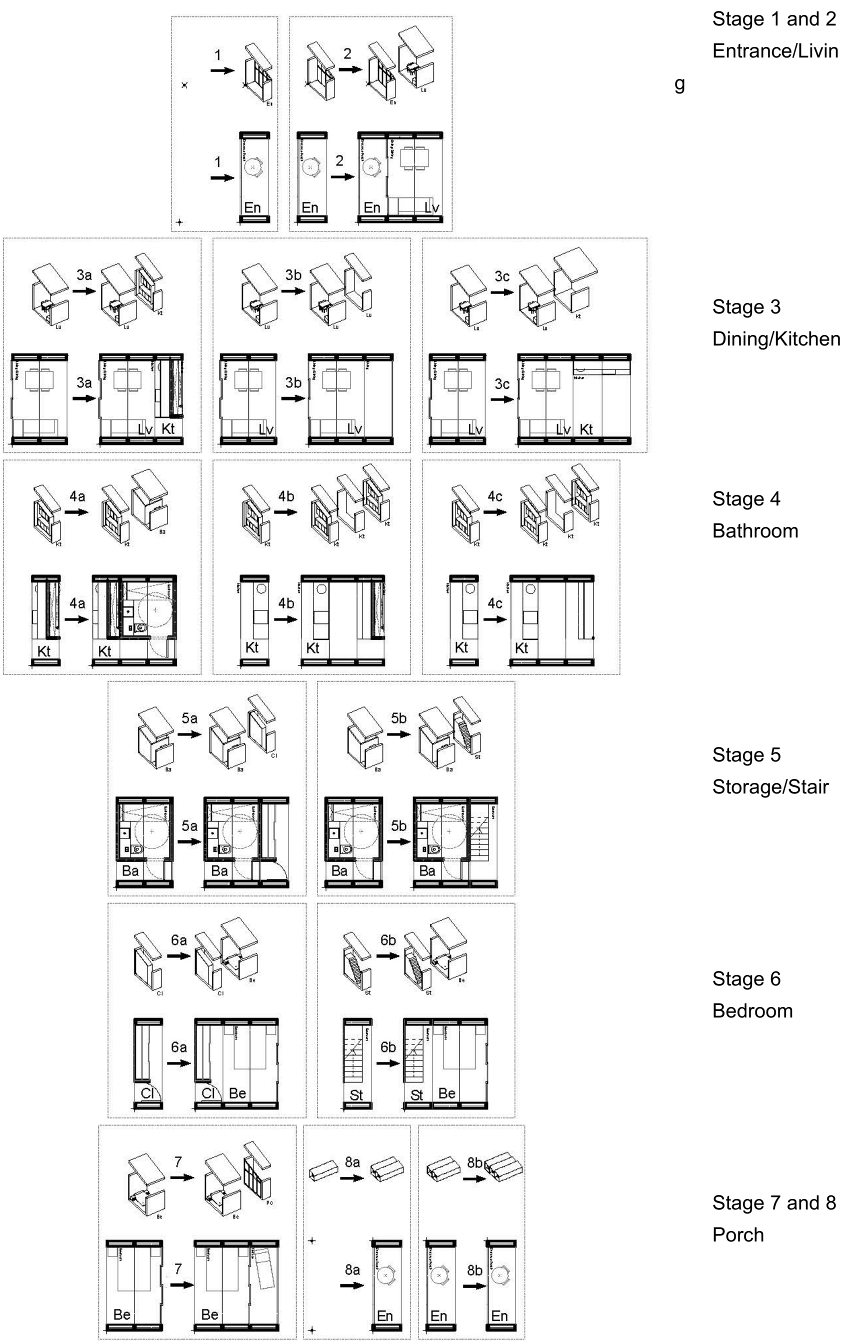

Figure 1. Elemental House Grammar rule system. Source: D. Benros et al.

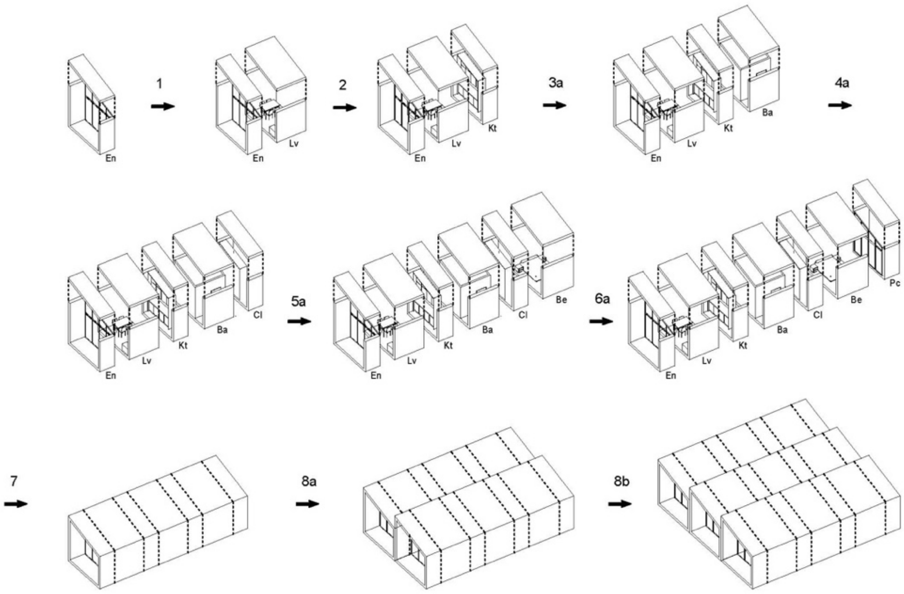

Figure 2. Elemental House Shape Grammar derivation showcasing rule application system. Source: D. Benros et al, 2023.

Associated with the bathroom positioning is the storage unit which is typically placed straight against it. The storage unit, similar to Actar's ABC System (Gausa & Salazar, 2003), could be a self-contained prefab pod allowing easy placement. This constitutes Stage 5 and is often associated with Stage 6 or the bedroom placement. The bedroom usually faces East and is ideally placed opposite the main access to the housing unit for effective privacy and ideal morning daytime (North hemisphere).

The grammar allows for an all-inclusive constructive system where structure, envelope and infill are accounted for. The grammar is proposed as a parametric system that allows for overall dimensions and proportions to be altered to suit different scenarios and specifications. The rule application system is better illustrated by applying the rules recursively as described in Figure 2 where a selected elemental house generation is described. The whole system and its possibilities are well shown in the grammar tree diagram (Figure 3) which illustrates the bottom-up approach of the system and five possible solutions.

The grammar also allows different types of structural solutions depending on local material availability and suitability, from all timber solutions to metallic structures. This will have an impact on the overall language and configuration of the cladding adding to the versatility of the system. Both angular and curvilinear configurations are allowed as shown in Figure 4.

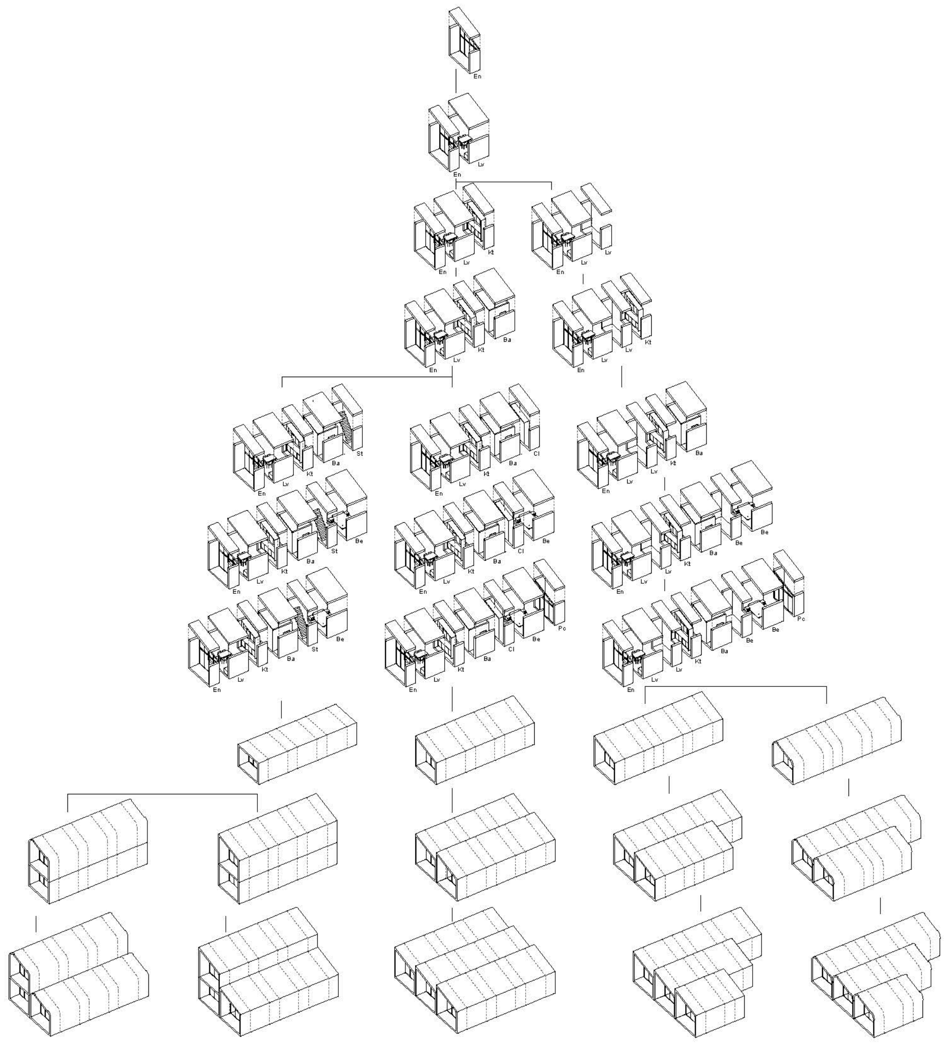

Figure 3. Elemental House Shape Grammar Tree diagram using a bottom-up approach for additive grammar and showcasing five possible design solutions. Source: D. Benros et al, 2023.

2.2 Offsite – Constructive system

The system developed is based on a parametric shape grammar. Although the system is parametric, is based on a modular matrix of 1.2x1.2 m resembling the system described in the 'Design of supports' (Habraken, 1976). The modularity allows for further subdivision of 0.6x0.6m typically used in cabinetry or more generous multiple modules of 2.4x2.4m which can create offsite modules for on-site assemblage.

The proposed offsite solution to be built in OC is prefabricated in one volume of 12 x 3.9 x 4 m totalling an internal area of 32 sqm. The proposed house unit will be built overseas, offsite, shipped and transported over a short distance using a lorry. However, a more compact solution can be proposed to fit a typical shipping container with a maximum size of 9 x 2.4 x 2.9 m which is more affordable. The system allows for each prefab unit to be assembled adjacent to one another creating more generous housing solutions of two, three or more-bedroom housing offerings as shown in Figures 3 and 4. The prefab unit maximum solution is ruled by highway codes and maximum vehicular circulation which varies from country to country.

The structural solutions allowed by the grammar vary with the location, site, daylight exposure, availability of materials and specificities of the project.

The elemental house was developed as a net-zero sustainable solution targeting flexibility, personalization, and affordability. The system enables two distinct structural solutions: a timber portal frame structure and an ultra-light steel solution as Figure 5 illustrates. The floorplan is shown in Figure 6.

The first option is a net-zero solution using engineered timber arches. These engineered timber arches have a 4m span, spaced every 2,4m. The resulting housing elements can be modules of 2,4m spacings. The structural elements and infill can be digitally manufactured using CNC routing. This is illustrated in the prototype pictures (Figure 7).

A second option allows for a series of ultra-light steel gauge trusses. This solution is more suitable for earthquake-prone areas or where wildfires are a real concern such as California. The competition entry is being erected using this strategy. These trusses are 300mm deep, span the same 4m and are built using 1,2m modules. This will allow prefabrication, ease of transportation and enough robustness for craning/lifting. Each truss is composed of standard light steel gauges cut in standard dimensions and mechanically fixed. Together they form non-standard solutions and uneven arches using the scheme of a 'Meccano' toy. The use of minimal components in a truss-like structure reduces the amount of steel used and once the house is decommissioned this can be dissembled and reused (Figure 8).

The cladding can also be selected according to the availability/suitability of local materials which include: timber cladding in slats or engineered panels, metallic panelling, or even more sustainable materials such as cork, hemp or 'sugarcrete-bagasse' (a bi-product of the sugar industry). These above-mentioned materials would be suitable for the opaque vault/slope cladding whilst the East and West façade would allow for glazing with adapted ventilation, access and shading devices.

The system could be upgraded to respond to ‘Passivhaus’ standards by increasing the airtightness and amount of insulation within the external wall.

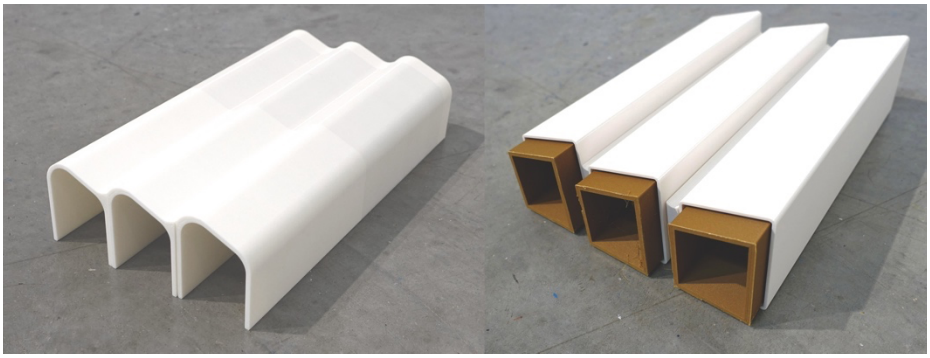

Figure 4. Elemental House design exploration options allow different structural systems. 3D Printed physical models. Source: D. Benros et al, 2023.

Figure 5. Elemental House design exploration options allow different structural systems. 3D Printed physical models. Source: D. Benros et al, 2023.

2.3 Selected solution and assemblage

The selected design solution encompasses a sloped roof-orientated South allowing for daylight optimization to feed the roof-mounted solar panels totalling an area of 22 sqm. Considering the site, the proposed structural solution is robust against earthquakes whilst also using non-combustible materials. During the project development, a mockup was developed to illustrate the challenges, interfaces, and spatiality. The mock-up was erected in the University of East London's 'Makers space' from December to January using the timber structural solution. Portal frames spaced every 2.4m spanning 4m were manufactured using assembled plywood elements by a group of students from the Master of Architecture and Design Technology (Figure 7). Originally only a portion of the roof structure and cladding was supposed to be constructed, but soon the ambition of erecting walls and floors was considered. The idea was to place the prototype house on the exterior and test its thermal performance using data loggers. For the competition entry, an ultra-light steel gauge frame was selected to address a multitude of issues such as ease of assemblage/demountability, future reuse of components, recyclability, robustness against wildfires and earthquakes, ease of transportation and craning. The house prototype will be fully constructed offsite, shipped and transported via vehicular transportation for the last stretch of the route. It will be installed on the Orange County designated exhibition site where the fabricating and designer team will come together to successfully erect the building. Final touches such as craning. placement, landscaping, decking, internal dressing and furnishing will take 10 days. The prototype will then be exhibited for 10 days where transeunt visitors, industry representatives and governmental institutions will visit the event and review the solutions prepared by this and the other 17 teams.

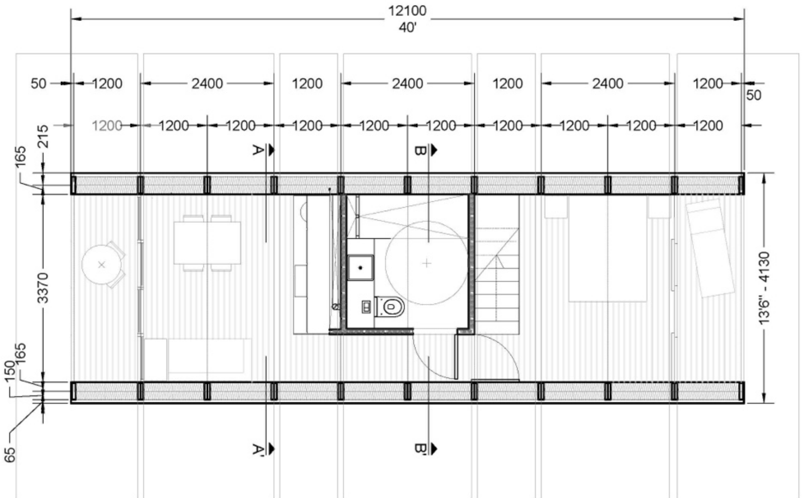

Figure 6. Elemental House plan designed solution. Source: D. Benros et al, 2023.

Figure 7. Elemental House real-scale prototype being built in the makers' space by a group of students. Source: N Healy, 2023.

3 Results

The presented project is part of ongoing research on affordable sustainable housing. With the described project, other spin-offs will take place including the use of robotic construction to expedite building technology. This wider reflection on housing using a multidisciplinary and multinational team focuses on novel methods to address the current housing crisis both in the Western world and for housing relief faced through catastrophic climate events.

As described, this project aims at a competition to be held on October 2023 in OC and the design will be judged against its competitors involving multi-criteria which include, design, energy consumption, construction and innovation. This was the product of collaborative design amongst international teams that have cooperated for over a year.

Soon the team realized that there was a market for rethinking conventional offsite techniques improving their outcomes and their carbon footprint. Therefore, two constructive techniques were selected, a whole timber solution and when not available a more efficient ultra-light steel frame that can be repurposed and reused. Also, key was the idea of a highly adaptive solution that could be deployed in a multitude of geographical locations. The geometry and parametric nature of the solution can adapt allowing compatibility with the surroundings, which can be fine-tuned by the choice of structural solution and cladding materials.

Whilst the competition is forthcoming and its result unknown, the success of the system will be measured by addressing three main aspects:

1. The generative system used to generate the solutions
2. The system's ability to be customizable and flexible
3. The quality and performance of the final prototype

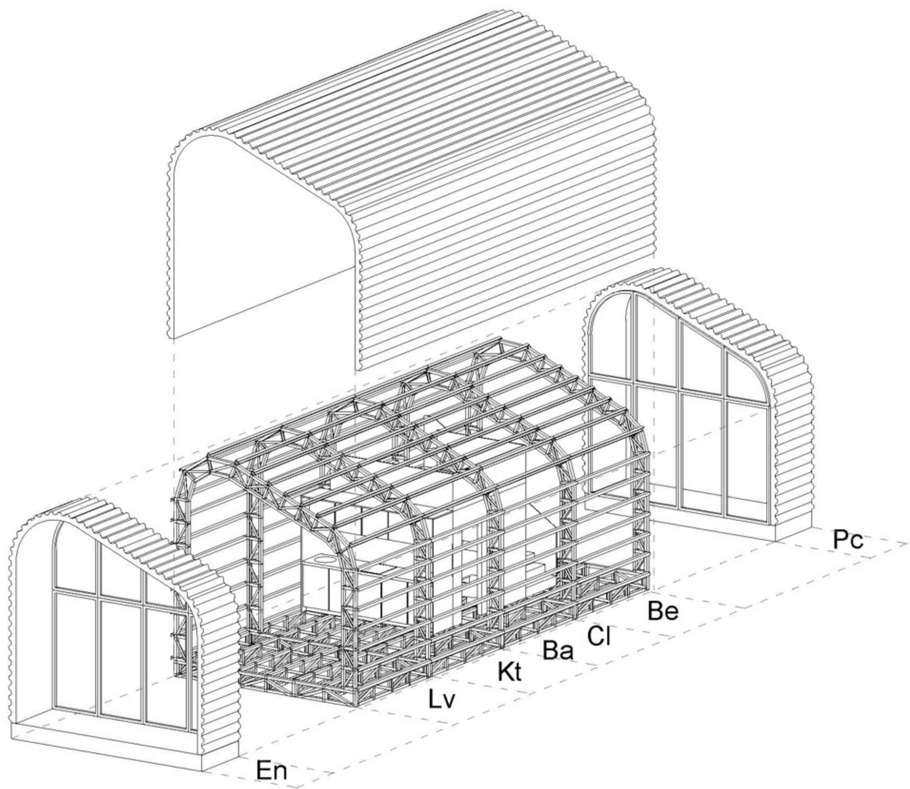

Figure 8. Elemental House real-scale prototype being built in the makers' space by a group of students. Source: N Healy, 2023.

4 Discussion

The contribution of the ‘Elemental House’ project is threefold:

4.1 Generative system – housing shape grammar

Shape grammars as introduced by Stiny, are generative systems that allow the recreation of a family of designs (Stiny, 2006). They are efficient systems to articulate a rule-based system that encapsulates a design language. Often, they are used to describe an existing style. Most of the criticism has focused on how very little novel design they have generated. This project uses grammar formulation to address that shortfall and generate consistent designs that follow the design criteria. The ‘Elemental house grammar’ uses a set of graphical rules that not only describe the system but cater for multiple parametric combinations. This system has not yet been implemented on a computer tool but that is the short-term ambition.

4.2 Customization of housing

Previous research focused on the problem of customization. Housing is the item most associated with debt and its cost has made it unaffordable for most families and individuals to attain. Offsite offers a great opportunity for optimal and affordable housing. However, is also associated with repetition and poor quality. It is well proven that offsite can produce high-quality affordable solutions, but rarely associated with personalization or variations. The issue of mass customization is not new but seldomly you see real options in the housing market. This project offers a real alternative where with the use of modularity and a generative system, customization is accessible. The computer platform would allow ease of manufacturing without increased cost.

4.3 Commercialization

During the extent of this project, several manufacturers were approached, and their feedback was addressed. Two companies one in the USA and one in China championing offsite steel solutions were either visited or participated in regular workshops. This insight of industry partners allowed the design team to address the manufacturers' concerns, capabilities and suggestions. The industry understands the need for novel, expedited and affordable solutions both for the typical housing market and for the extreme climate events relief. Despite proposing all timber net-zero solutions the system looks at how to address change within already commercially viable steel solutions.

The project could be the first application of shape grammar and a generative system for architectural design exploration to be commercially viable.

4.4 Conclusion

This paper describes a work in progress that aims at affordable, mass-customized housing units to assess energy performances and indoor environmental quality of the prototype/house during winter and summer by installing data loggers. This is part of ongoing research on housing that will conclude within the following 18 months with the construction of two real-size prototypes. The project implements a real application of shape grammar in design which is thought to be the first pushing boundaries in the generative systems field.

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References

Benros, D., Duarte, J., & Branco, F. (2007). A System for Providing Customized Housing. Proceedings of the 12th International Conference on Computer Aided Architectural Design Futures, 153–166.

Benros, D., & Duarte, J. P. (2009). An integrated system for providing mass-customized housing. Automation in Construction, 18(3), 310–320. https://doi.org/10.1016/j.autcon.2008.09.006

Duarte, J. (2003). A Discursive Grammar for Customizing Mass Housing—The case of Siza's houses at Malagueira

Gausa, M., & Salazar, J. (2003). Housing + Singular Housing (Spanish ed. edition). Actar Inc.)

Habraken, N. J. (1976). Variations: The Systematic Design of Supports (New edition edition). MIT Press

Koning, H., & Eizenberg, J. (1981). The language of the prairie: Frank Lloyd Wright's prairie houses. Environment and Planning B: Planning and Design, 8(3), 295–323. https://doi.org/10.1068/b080295.

Stiny, G. (1980). Kindergarten grammars: Designing with Froebel's building gifts. Environment and Planning B: Planning and Design, 7(4), 409–462. https://doi.org/10.1068/b070409

Stiny, G. (2006). Shape: Talking About Seeing And Doing. MIT Press.