Social Housing Mass Customization: Description of a system for real-time cost and spatial generation

Alexander Lopes de A. Brasil[1], Andressa Carmo Pena Martinez[2]

[1] Universidade Federal de Viçosa, Viçosa, Brazil
alexander.brasil@ufv.br
[2] Judson University, Elgin, United Stated of America
andressamartinez@gmail.com

Abstract: This study explores mass customization as an alternative strategy for social housing provision. The paper aims to demonstrate the implementation of an integrated system based on the connection between Building Information Modeling and algorithmic-parametric modeling technologies, seeking to design variability with real-time cost and time data control of single-family housing units. We developed the study according to five phases: (1) context analysis and design language definition; (2) rule-based design system definition; (3) cost and execution time estimation; (4) computer system based on the specified technologies definition; (5) quantitative evaluation and qualitative evaluation of the system. The experiment demonstrates that with the aid of algorithmic-parametric modeling, building information manipulation and visualization can be responsive enough to meet mass demands.

Keywords: Data analytics, Mass customization, Social Housing, BIM, Cost control

1 Introduction

This paper explores the theme of mass customization (MC) for social housing provision as an alternative strategy to standardized mass production. MC promotes value to a product by matching the end-users demands with the maintenance of production costs close to standardized mass production. For this, according to Piller (2019), operational (design, manufacturing, and assembly) and logistic (supply and transportation) processes must be flexible yet stable. According to Kolarevic and Duarte (2019), the technological means for this are already available in the design field. Previous studies have been successful in implementing different levels of automation of the design process, such as the integrated system of Benros and Duarte (2009), the system of customization of apartment plants of Veloso, Celani, and Scheeren (2018), among other examples.

As a next step, it is important to define systems that, in addition to design variability, assist in the visualization and manipulation of building data responsible for controlling execution costs of the generated solutions. This control becomes even more critical in projects targeting socioeconomically vulnerable populations, where resources are generally scarce.

Thus, this work's goal is to demonstrate the implementation of a computational system for MC of single-family housing, target to designers as users, based on the communication between Building Information Modeling (BIM) and algorithmic-parametric modeling (APM), capable of generating topological and dimensional variations with control and estimation of execution cost and time. For this study, we chose as a specific context of application the case of involuntary resettlements in the city of Teresina, Piauí.

1.1 The case of Residential Park Brazil

To avoid generic solutions, we chose a real scenario, the case of the Residential Park Brazil housing complex in Teresina, Piauí – Brazil, where we extracted context information to define a specific design language. The execution of this complex was a City Hall action to relocate families whose residences were affected by the North Lake Urban Program, carried out to promote interventions in the environmentally and socially vulnerable northern region of the city. Hence, this complex has 1022 residential units, which justifies the application of an MC strategy.

In the initial research, we carried out a survey on the houses in the affected region before their demolition, using images captured by Google Maps and technical reports from the City Hall. We noticed that most houses were based on self-constructed ceramic brick masonry and covered with ceramic tiles supported by a wooden structure.

2 Methodology

For the development of the system, we accomplished the following phases: (1) context analysis and definition of the design language; (2) definition of a rule-based design system; (3) definition of cost and execution time estimation; (4) definition of the computer system based on the specified technologies; (5) quantitative evaluation and qualitative evaluation of the system.

The first phase consisted of (1) preliminary research to collect contextual data such as the profile of the affected properties and families, local cultural and geographical aspects, and local building code rules. The work focused on the formal and spatial aspects of the housing units; thus, we adopted the existing land division, with lots of approximately 10x25m. After gathering the information, we developed the design language based on several manually developed solutions, namely the language corpus.

Based on the language corpus, we started defining the (2) design rules, targeted to be manipulated by qualified architects, who are responsible for interpreting the needs of the end-users and evaluating the quality of the generated results. Therefore, we opted for a design logic that allows greater design freedom instead of automatic solution control. In this design logic, the rules obey a hierarchical system where the designer defines a formal-spatial relationship, from which he/she can freely assign room functions to the generated spaces. However, we opened an exception to pre-define a social bathroom. It aims to encourage the grouping of wet areas, as this is a recommended strategy to facilitate plumbing execution and future expansions in a coordinated manner (Brandão, 2011).

The (3) execution cost calculation method is twofold: we used the Basic Unit Cost per square meter (cub/m²) and the estimation by the references of the National Cost and Index Research System (SINAPI). Cub/m² is a reference index that is popular but low accurate compared to SINAPI. Thus, we use the SINAPI as an official value and cub/m² as the maximum reference value.

The cub/m² uses a standard reference value per meter according to construction classes, calculated and released monthly by the National Construction Industry Unions according to the criteria stipulated by Brazilian Standard NBR 12.721. As it does not consider the values of foundations and building installations, we decided to use the cost factors constants of these stages (Fn) in Table 1. For precision of the roof cost, we deducted from the cub/m² a factor equivalent to the roof cost (fC) and then added the SINAPI value-based method (C3) available in Table 2. We did this change because the roof area can be larger than the house area, so considering them equal could distort the final cost.

$$\text{Cost} = ((\text{cub} \times A) \times (F1 + F2 + F3 - fC)) + C3 \qquad (1)$$

Table 1. Cost factors of the stages of the work

Symbol	Factors	Value
F1	Foundation cost factor	4.1
F2	Electrical installations Cost factor	4.8
F3	Plumbing installations cost factor	12.7
fC	Roof cost factor	15

Source: Mattos, 2006.

The SINAPI references are reports of inputs (materials, workforce, and equipment) and compositions according to each Federation Unit. We present the calculation methods based on the values and compositions of SINAPI in Table 2.

Table 2: Method for estimated cost calculation based on the values collected from the SINAPI references.

Symbol	Execution phase	Formulas
C1	Wall	area * cost per m²
C2	Waterproofing of walls	(area *2) * cost per m²
C3	Roof	(area * slope factor) * cost per m²
C4	Concrete slab cast in situ	slab volume * concreting volume cost slab volume * armor rate) * cost per kg of the frame slab cost = concreting + frame
C5	Prefabricated slab	area * cost per m²
C6	Superstructure	weight of beams * cost per kg weight of the columns * cost per kg superstructure cost = beams + columns
C7	Doors	number of doors * unit cost
C8	Windows	window span area * m² cost
C9	**Total cost**	**C1+C2+C3+C4+C6+C7+C8**
C10	Foundation	total cost * f1
C11	Electrical installations	total cost * f2
C12	Plumbing installations	total cost * f3
C13	**Unit final cost**	**C9+C10+C11+C12**

Source: Authors, 2022.

To estimate the execution time, we extracted the value of the involved professionals' working hours and the associated cost per square meter of the constructive components of the analytical composition cost references of SINAPI. In cases where there is more than one professional involved, we consider the highest time value and, depending on the construction component, instead of the area, we used the volume or mass of the component. Based on these numbers, the total execution time required (T) is calculated based on the product of area (A) for the required time per m² (t/m²):

$$T = (A \times t/m^2) \qquad (2)$$

Next, we calculate the cost of the professional per m² (c) by multiplying the value of the professional's hour (p) by the total time required per m², then the value of all professionals involved in the execution of the component is added:

$$c = (p1 \times t1/m^2) + (pn \times tn/m^2) \qquad (3)$$

Last, we can estimate the total execution cost by multiplying the values of (T) and (c).

In the next phase, we based the (4) definition of the computer system on the communication between the APM Grasshopper environment, which runs inside the CAD software Rhinoceros 3D, and the BIM platform Autodesk Revit. We connected the platforms using the Rhino inside Revit plugin, based on a bidirectional information transmission protocol (Iasbik, Martinez, & Gazel, 2020). We selected these tools as some tests have demonstrated that Grasshopper has a processing performance advantage compared with Dynamo (Brito, Silva, & Checcucci, 2020). Also, because of the range of plugins available for the Grasshopper environment, such as the external plugin HUMAN UI, used to develop the user interface. Finally, Revit was connected to the Twinmotion virtual reality environment using the Datasmith export plugin.

Finally, (5) evaluation of the system's results was twofold. First quantitatively, calculating the combinatorial cardinalities (number of elements of a set) of all the design parameters. Second, qualitatively, by developing five different solutions to meet the same housing program requirements within a specific cost range between R$75.000,00 ($13945,96) and R$80.000,00 ($14.875,70) per unit, approximately 20% lower than the average value per unit of the existing residential complex.

3 Results

3.1 Design language

We chose a roof system made of corrugated fiber cement panels suspended and supported by a lightweight steel frame to provide an open shading area with air circulation above the house. Windows and doors are lightweight, easy-to-install aluminum panels that can be easily removed and reinstalled. The complementary steel frame structure provides support for coverage in unbuilt areas and maintains the stability of the roof's rectangular format, regardless of the shape of the housing. The masonry is executed with ceramic bricks, seeking to respect local constructive traditions, low cost, and ease of access to material and labor. The bricks of the external walls have a structural function. The foundation slabs are reinforced concrete cast in situ, while the ceiling slabs system are prefabricated lattice joists with insulation of ceramic blocks. Figure 1 shows an instance of the established design language.

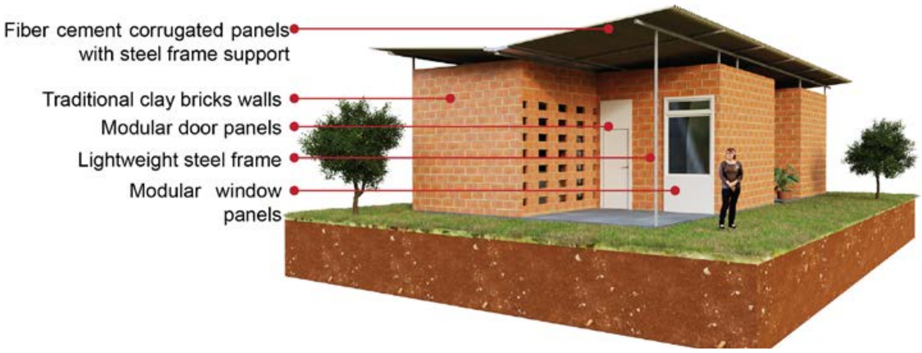

Figure 1: Instance of the universe of possible solutions generated by the developed system and its main constructive characteristics. Source: Authors, 2022.

3.2 Rule-based design system

Next, we describe the rule-based design system focusing on the logic behind the functional groups at each design stage rather than detailing the specific rules. Figure 2 illustrates the branching of design steps.

The first stage defines a mesh made of eight parametric modules, distributed in pairs (AB, CD, EF, GH), represented in Figure 4, which define the formal-spatial boundaries of the building. The longitudinal configuration of the modules seeks to optimize the occupation of the existing lots and establish a clear sense of expansion.

Four functional groups define the modules manipulation rules: (a) changing dimensional parameters; (b) addition or subtraction of modules, which generates opened functional covered areas within the lot; (c) connection between adjacent modules for expansion and reduction, or full integration between them; (d) opening of external spaces between modules for the creation of external circulation in the lot.

We based the wet areas definition phase on four functional groups: (a) subdivision of modules, (b) change of dimensional parameters, (c) exclusion of modules, and (d) positioning of the water tank. The system applies the subdivision rules according to the module that allocates the bathroom, the attached wet areas, and the hydraulic shaft direction defined by the designer. Dimensional constraints certify that the subdivision has the minimum functional and circulation area and does not exceed the module's dimensions. Exclusion rules will ensure that there will always be a ventilation outlet in wet areas.

Finally, the housing water tank's position will always be above the wet area's core.

In the roof definition stage, restrictions guarantee that its rectangular shape will always cover the entire perimeter of the building. This restriction aims to create functional covered external areas, facilitate execution, and lower the final cost. The functional groups define the (a) roof type based on the number and direction of slopes and (b) dimensional parameters that control the inclination, eaves size, and distance between supports.

The last step defines the location and insertion points of doors and windows based on two functional groups: (a) subdivision of the mesh curves to define the vertices that allocate the openings in the center and end-points of the curves, and (b) identification of vertices according to the x and y coordinates.

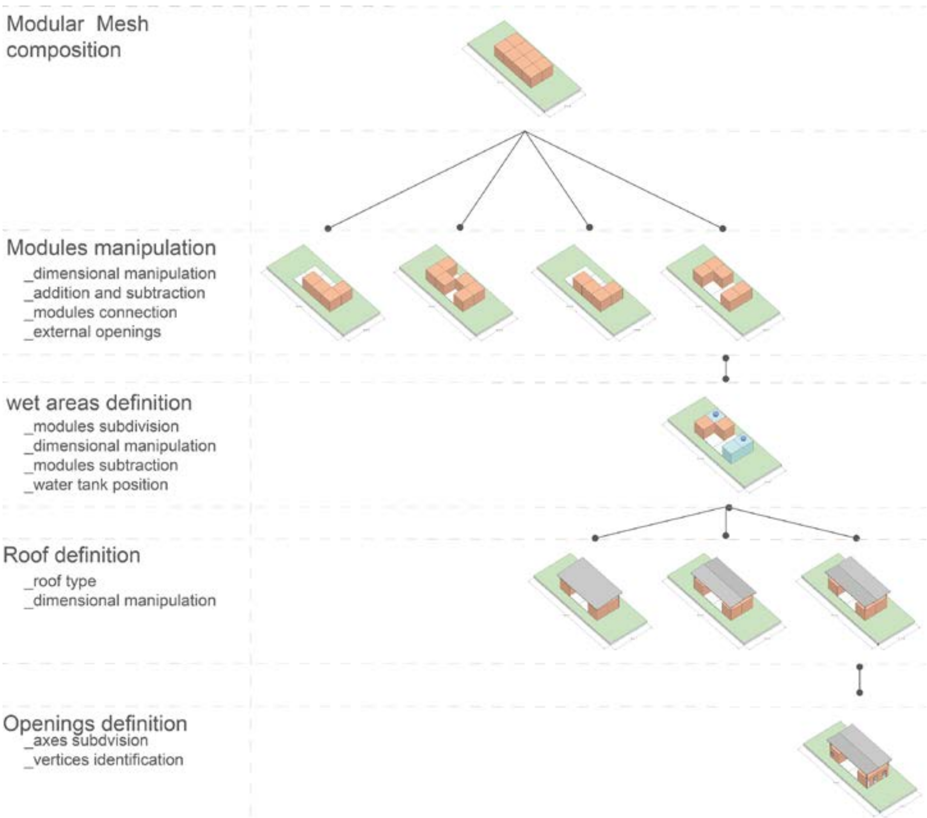

Figure 2: House evolution based on the design language developed. Source: Authors, 2022.

3.3 Computer system

Figure 3: Presentation of the computer system: a) BIM model updated in real-time as the designer manipulates the user interface; b) 2D and 3D representation of the solution inside Rhino 3D; c) interface for parameter settings and building data visualization; virtual reality model loaded inside Twinmotion. Source: Authors, 2022.

The implementation of the computer system is responsible for automating the design process and the construction data manipulation for ease of visualization of solutions and decision-making. Figure 3 shows the system's interface.

The system works based on three groups of parameters: (1) design parameters, (2) building components data parameters, and (3) model display parameters. The design parameters activate the functional groups responsible for triggering the design rules to generate the reference geometry for positioning the building components created within Revit. These BIM components feds the second parameter group, where the designer chooses the component type. These components' information will input data to develop the CAD model within Rhino 3D and the central BIM model within Revit and feed the costing and time calculation routines to generate real-time estimations. The last parameter group allows the system's user to view or hide the 3D models, change the level of detail of the CAD model, and display auxiliary information for a better understanding of the design logic. Figure 5 represents this workflow.

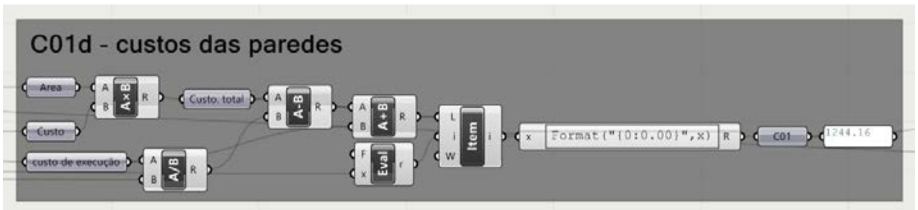

Figure 4: Routine definition example of wall execution cost calculation. Source: Authors, 2022.

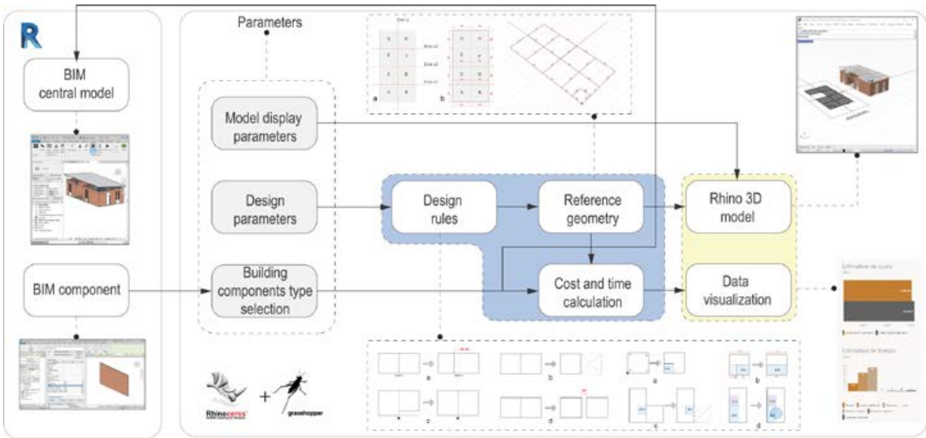

Figure 5: A computer system diagram for housing generation and data visualization. Source: Authors, 2022.

The user interface aims to make parameter manipulation and visualization of building data more fluid and user-friendly by compiling all the necessary information in one dropdown menu to make decision-making easier. Finally, we used the Datasmith plugin to transfer the BIM model to a virtual reality environment with one click.

Figure 6: User interface. a) display parameters; b) design parameters; c) building component parameters; d) building and roof area information; e) execution cost information based on the SINAPI method (orange) and cub/m² method (gray); f) execution time by construction phase. Source: Authors, 2022.

3.4 System's evaluation

Next, we present the combinatorial calculus of spatial arrangements, disregarding dimensional parameters.

Table 3: Method for estimated cost calculation based on the values collected from the SINAPI references.

Combinatorial calculation considering possible spatial arrangements:
Total = (4)14 x (2)22 x (6)2 x 8 x 7 x 3
Total = 6.809.442.636.584.189.952

Source: Authors, 2022

Figure 7: Results generated using the developed platform. A = constructed area of projects in m²; C = construction cost estimate, based on SINAPI references in BRL currency. Source: Authors, 2022.

In the qualitative evaluation, we developed five house options for a family of a young couple with two children, with the need for a room for manual work with independent access to receive clients. The five solutions were developed and documented in approximately 3 hours, respecting the pre-established cost and room areas.

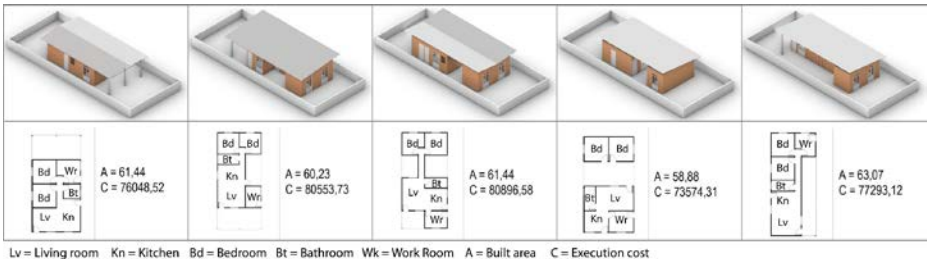

Figure 8: Results from the cost control exercise. A = constructed area of projects in m²; C = construction cost estimated, based on SINAPI references in BRL currency. Source: Authors, 2022.

4 Discussion

This paper aimed to describe the process behind the computational implementation of a rule-based design system with execution cost and time control of mass customized social single-family housing units, based on the communication between APM and BIM technologies.

The experiment demonstrates that the aid of APM provides elasticity and agility for manipulating and visualizing building data to meet mass demands. Therefore, we were able to verify that the transfer of data from the BIM platform to a design script has the potential to assist the implementation of MC as a strategy for social housing provision.

For example, a simple one-click action changed the specification of all walls of a design option from 14x19x29 to 9x19x29 ceramic blocks, making it possible to realize the impact of reducing the total execution cost by $ 601,17 in less than 1 second. In another example, it was possible to quickly identify that the increase in the steel frame weight has a significant impact on the construction costs, allowing us to evaluate with precision and agility the cost-benefit relations of the building solutions of the design language. It is also noteworthy that considering local constructive cultural characteristics in the design language suggests that the use of programming routines for developing houses is not necessarily associated with generalist solutions.

However, there are limitations and improvements to consider. The code does not count some items, such as kitchen finishes, sanitary parts, and other detail items. Also, we highlight that we still did not develop a qualitative evaluation system of the results. We implemented some restrictions, such as minimum circulation width and control of openings to open spaces in the lot. However, as the algorithm allows a high number of formal variations, the architect remains the mediator in the decision-making process, both during the initial configuration of the unit and future changes, by anticipating possible modifications throughout the time, based on the family's profile. Furthermore, the system still needs to be tested by architects to evaluate its usability. Furthermore, the system still needs to be tested by architects to evaluate its usability.

For future development, we plan to insert new building elements in the cost calculation estimation, define and implement new quality control restriction rules, and create an objective performance evaluation subsystem to assist the system's users, as well as perform tests on its usability.

Acknowledgements. We thank Coordenação de Aperfeiçoamento de Pessoal de Nivel Superior (CAPES, Brazil) for funding this research. And the Graduate Program in Architecture and Urbanism at the Federal University of Viçosa (PPG.au/UFV) for supporting the publication of this work.

References

Benros, D., & Duarte, J. P. (2009). An integrated system for providing mass customized housing. Automation in Construction, 18, 310-320.

Brandão, D. Q. (2011). Disposições técnicas e diretrizes para projeto de habitações sociais evolutivas. Ambiente Construído, 11(2), 73-96.

Brito, B. L., Silva, F. T., & Checcucci, É. d. (2020). Estudo Comparativo entre ferramentas de projeto paramétrico. XVIII Encontro Nacional de Tecnologia do Ambiente Construído ENTAC 2020. Porto Alegre: ANTAC.

Iasbik, M. P., Martinez, A. C., & Gazel, J. L. (2020). Integration of BIM and Algorithmic Design logics through data exchange between Grasshopper plugin and Revit and Archicad software. 24th Conference of The Iberoamerican Society of Digital Graphics (pp. 470-477). Medelín: The Iberoamerican Society of Digital Graphics (SIGraDi).

Kolarevic, B., & DUARTE, J. P. (2019). From massive to mass customization and design democratization. Em B. Kolarevic, & J. P. Duarte, Mass customization and design democratization (pp. 1-12). Abington: Routledge.

Mattos, A. D. (2006). Como preparar orçamentos de obras: Dicas para orçamentistas, estudos de caso, exemplos. São Paulo: Editora Pini.

Piller, F. T. (2019). Creating a sustainable mass customization business model. Em B. Kolarevic, & J. P. Duarte Mass customization and design democratization (pp. 30 - 40). Abington: Routledge.

Veloso, P., Celani, G., & Scheeren, R. (2018). From the generation of layouts to the production of construction documents: An application in the customization of apartment plans. Automation in Construction (96), 224-235.