http://periodicos.sbu.unicamp.br/ojs/index.php/parc
https://doi.org/10.20396/parc.v14i00.8672170

CLIMATIC CONDITIONS AS A GUIDELINE TO MASS CUSTOMISATION IN BRAZILIAN HOUSING

CONDIÇÕES CLIMÁTICAS COMO DIRETRIZ PARA A CUSTOMIZAÇÃO EM MASSA DE HABITAÇÕES BRASILEIRAS

Larissa Pereira de Souza[1]

Mateus Bavaresco[2]

Matheus Soares Geraldi[3]

Carlos Eduardo Verzola Vaz[4]

Enedir Ghisi[5]

[1] Federal University of Santa Catarina, Florianópolis, SC, Brazil, laripereiradesouza@gmail.com
[2] Federal University of Santa Catarina, Florianópolis, SC, Brazil, bavarescomateus@gmail.com
[3] Federal University of Santa Catarina, Florianópolis, SC, Brazil, matheus.s.geraldi@gmail.com
[4] Federal University of Santa Catarina, Florianópolis, SC, Brazil, carlos.vaz@ufsc.br
[5] Federal University of Santa Catarina, Florianópolis, SC, Brazil, enedir.ghisi@ufsc.br

Authors' contributions:
LPS: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review & editing. **MB**: data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review & editing. **MSG**: data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review & editing. **CEVV**: conceptualization, methodology, writing – review & editing. **EG**: methodology, writing – review & editing.

Funding: Coordination for the Improvement of Higher Education Personnel
Conflict declaration: nothing was declared.
Responsible Editor:
Arthur Santos Silva

Abstract

Reducing the housing deficit is a vital issue to be addressed in developing countries. Although government programmes in Brazil aim to reduce it, there is criticism regarding the housing design, especially about their poor thermal performance. Guaranteeing high levels of thermal performance in affordable housing is expected to improve occupants' satisfaction and reduce energy consumption. Therefore, this article aims to propose a system to develop solutions for designing a housing-unit module that enables adaptation to climate, topography, and site plan, as well as flexibility regarding expansions and changes in the pattern of use. Guidelines were created to develop the adaptable housing unit framework, which was programmed in Grasshopper to allow parametric design. One of the possible compositions was simulated using EnergyPlus and Ladybug Tools to determine suitable envelope characteristics for different climates. This process relied on multi-criteria analyses to determine the best solution considering cooling and heating degree hours. Thermal performance simulation results show that the envelope solution for Florianópolis differs from that for São Joaquim, even with the same shape composition. While Florianópolis has lower wall absorptance and brick walls as the best solution, São Joaquim requires insulated walls and higher wall absorptances. The main conclusion is that such a framework is more feasible than a single solution because the design might be adapted according to problems identified a priori. This outcome is expected to guide practitioners toward sustainable development, considering the vital role that affordable housing plays in Brazil.

Keywords: design process, shape grammar, thermal performance, Grasshopper, simulation.

Resumo

A redução do déficit habitacional é uma questão importante em países em desenvolvimento. Embora os programas governamentais no Brasil visem reduzi-lo, existem diversas críticas ao projeto habitacional, principalmente quanto ao seu baixo desempenho térmico. Espera-se que garantir altos níveis de desempenho térmico melhore a satisfação dos ocupantes, bem como reduza o consumo de energia. Assim, o objetivo deste artigo é propor um sistema para solucionar parâmetros de projeto de um módulo habitacional que possibilite adequação ao clima, topografia, planta do terreno, além de flexibilidade para ampliações e mudanças no padrão de uso. Diretrizes foram criadas para desenvolver a unidade habitacional unifamiliar programada no Grasshopper para permitir o desenho paramétrico. Uma das composições foi simulada no EnergyPlus, utilizando o Ladybug Tools, para determinar características da envoltória adequadas. Este processo contou com análises multicritério para determinar a melhor solução considerando tanto os graus-hora de resfriamento quanto os de aquecimento. Os resultados de simulações termoenergéticas enfatizam que a solução de envoltória para Florianópolis difere da solução para São Joaquim, mesmo que considerando a mesma forma. Para Florianópolis a melhor solução consiste em baixa absortância solar da parede e parede de tijolo, mas São Joaquim necessita de paredes isoladas e com absortância solar alta. A principal conclusão é que tal estrutura de trabalho é mais viável do que uma única solução, pois o projeto pode ser adaptado de acordo com os problemas. Espera-se que este resultado forneça orientações aos profissionais para trilhar o caminho para o desenvolvimento sustentável, considerando o importante papel que a habitação de interesse social desempenha no Brasil.

Palavras-chave: *processo de projeto, gramática da forma, desempenho térmico, Grasshopper, simulação.*

How to cite this article:

SOUZA, L. P.; BAVARESCO, M.; GERALDI, M. S.; VAZ, C. E. V.; GHISI, E. Climatic conditions as a guideline to mass customisation in Brazilian housing. **PARC Pesq. em Arquit. e Constr.**, Campinas, SP, v. 14, p. e023022, 2023. DOI: https://doi.org/10.20396/parc.v14i00.8672170

Submitted 30.01.2023 – Approved 24.07.2023 – Published 09.10.2023

Introduction

The current situation of affordable housing in Brazil reflects its history. Initially, affordable housing occurred in tenements, unhealthy areas with frequent epidemics. Later, industrialisation increased the rural exodus, which led to a housing deficit and a need for more urban planning of cities. Consequently, affordable housing was primarily due to self-construction and irregularity (VILLAÇA, 1986).

Despite the growth in the number of houses and stabilisation in the energy consumption by residential units, affordable houses have presented significant growth in energy consumption per unit since 2010 (Geraldi; Bavaresco; Melo; Lamberts, 2022). Residential buildings should be evaluated regarding income since electricity consumption and performance patterns are different among residential buildings, and it is essential to improve public policies focused on affordable houses (Bavaresco *et al.*, 2022). The Brazilian government invested in the construction sector to improve national infrastructure and promote economic growth (Campos; Guilhoto, 2017). The "My House, My Life" Programme (PMCMV) – launched in 2009 – is an example of investment in this area. It has increased the Brazilian construction sector by maintaining investments in affordable housing for a few years. Gonçalves Junior; Dutra; Lopes and Rodrigues (2014) state that the construction sector positively affects the national economy, especially regarding job creation.

Over the past few years, different aspects of the PMCMV have been studied. Lima; Costa; Rosa and Vallone (2020) analysed the PMCMV implementation at the urban level according to the area's diversity of uses, construction density, and urban services. Santos and Penteado Neto (2020) evaluated the houses' pathologies during operational use, and most of the time, the problems came from concrete structure deformation and water pipe leakage. Buligon *et al.* (2022) also showed that, in residential buildings in general, the conventional walls (such as concrete or ceramic brick) do not minimise moisture and have the potential for mould formation. There is also criticism about the absence of spaces for future expansion (Müller; Lima, 2017), and one may consider this need when designing new housing units.

Regarding climate, Morais and Labaki (2017) pointed out that the construction sector replicates the same basic PMCMV in different climates, resulting in poor thermal performance and poor thermal comfort conditions for users. Invidiata *et al.* (2016) carried out computer simulations for the prototype of a PMCMV dwelling with different envelope compositions, and different cases for each climate zone reached a satisfactory efficiency level. Invidiata, Lavagna e Ghisi (2018) also analysed the PMCMV housing units and used life cycle assessment to select better strategies to promote sustainability in those dwellings. One of the strategies is to modify the envelope material according to the climate where the dwelling is meant to be built. Recent studies present analysis focused on specific Brazilian climatic zones, reducing the cooling degree-hours and, consequently, the energy consumption for Brazilian climatic zone 8 (Malta; Rabbi; Rodrigues, 2022) or analysing superficial temperatures of the concrete wall by changing the absorptance and shading for Brazilian climatic zones 1, 2 and 4 (Oliveira; Alves, 2021). Some light envelope solutions, insulated or not, can present better thermal performance for today's climate and climate change in different Brazilian climates (Bracht; Costa; Melo; Lamberts, 2022). Even if lower roof absorptances allied to insulation can improve thermal performance, too much insolation cannot always present significant benefits, such as adding an insulated roof tile when the interior ceiling is insulated (Souza; Costa; Melo; Lamberts, 2022).

However, not only the envelope construction methods should be the main focus, but also the housing unity geometry. Triana, Lamberts and Sassi (2015) characterised building typologies for affordable housing in Brazil and concluded that the PMCMV designs must be adapted for each Brazilian climate zone. The study shows a mapping that analysed the building performance and concluded that the PMCMV basic single-family floorplan provides poor outcomes, especially in hot climates. Passive and bioclimatic architecture (Brunoro, 2012; Colclough; Kinnane; Hewitt; Griffiths, 2018; Muñoz Cruz *et al*., 2017; Preciado-Pérez; Fotios, 2017; Rincón; Carrobé; Martorell; Medrano, 2019; Suárez; Fernández-Agüera, 2015) has been presented in the literature as an essential factor to improve affordable housing performance. Among the strategies, optimising the solar orientation of dwellings is expected to improve their thermal performance and energy efficiency levels (Bodach; Hamhaber, 2010; Franco et al., 2019; Taleb; Yeretzian; Jabr; Hajj, 2020; Triana; Lamberts; Sassi, 2015). Souza, Bavaresco, Vaz and Lamberts (2021) presented that, despite considering insolation and natural ventilation as key parameters to design, the designers do it with inaccurate methods. In other words, they may not know how to simulate or analyse performance indicators.

In order to build a design model that can be adaptable to different climates, Mendes (2014) mentions mass customisation as a solution for the affordable housing problem. Parametric design can improve the project to address housing evolutionary principles, such as modulation and consideration of future self-construction. The author also suggests that it generates different customised solutions; its individualised components can respond to local conditions and create optimal solutions within the required variants. Nevertheless, mass customisation requires industrialised techniques to enable rapid construction. Wood and steel frame structures are light and faster to build. However, affordable housing is usually built using concrete and masonry. These techniques require more time to be constructed since their structure is heavy and usually manually built, and more space in the construction site.

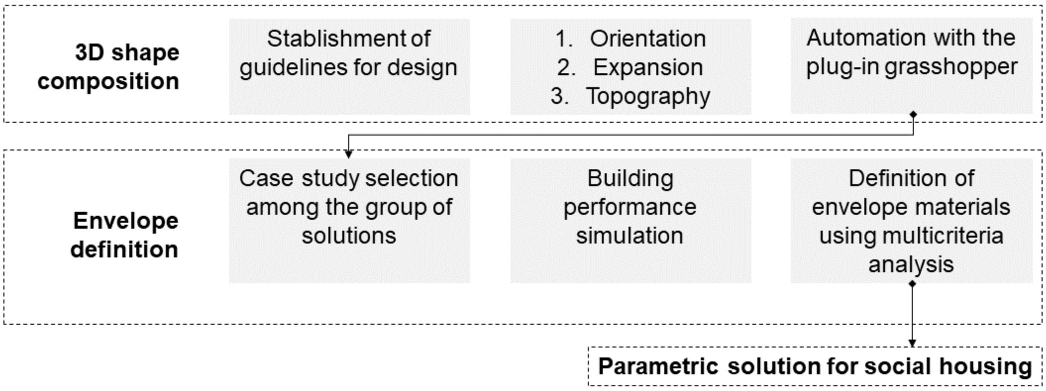
According to Yu, Gero and Gu (2015), parametric design tools could generate multiple design solutions. The authors mention two classes of cognitive design activities regarding the parametric design process: the knowledge and the algorithm. In the first one, the designer must address functional, adaptive, and shape conditions. In the second one, they apply those conditions to a rule algorithm with their logical relationships. Thus, parametric design is a suitable solution to affordable housing problems since it presents multiple solutions according to the need. It has the potential as a means to work on aesthetics or forms and as a tool to solve technical problems (Hou; Stouffs, 2018).

Considering the above, Brazilian affordable housing needs more consideration of climate adequacy, solar orientation, topography and flexibility for future expansions, and also needs to consider rapid construction. Thus, considering climate singularities makes room for creating adaptive housing units suitable for Brazilian localities. Therefore, the main objective of this work is to create an adaptive single-family housing set in which base geometry and material properties could be adapted according to variations in climate and topography and seek to mitigate problems identified in current housing.

Method

The method comprises a case study based on computer simulation to test the best solutions for social housing in different climates, considering different construction techniques. Such an approach was conceived to support decision-making during the design process, aiming to guide stakeholders towards the best solutions when designing new buildings. The study was composed of two steps: the 3D shape composition and the case study to define its envelope materials according to climate. Figure 1 shows the working flow chart describing the method used.

Figure 1 – Workflow chart



Source: the authors.

3D shape composition

The relations between rooms and between rooms and open spaces defined the 3D shape possibilities of the housing units' compositions. A series of guidelines for mass customisation was developed and later transformed into a script in Grasshopper.

The 3D shape composition was drawn according to previous analyses of the key issues that concern affordable housing in Brazil. Table 1 presents the needs identified, the guidelines drawn, and the solution proposed in this study.

Table 1 –Guidelines and solutions to develop the affordable housing design proposed in this study

Need	Guideline	Solution
Avoid construction wastes	Use predefined and prefabricated elements	Designing spaces considering the size of existing cement-bonded particleboards
Enable fast and large-scale construction	Adopt modular design for the housing units	Using prefabricated structures, walls and floors
To guarantee the housing unit identity	To consider site plan variability in the design phase	Using guidelines to define different upper-lower floors relations
Reduce the construction impact on the environment	Use recycled and eco-friendly materials	Adopting polyethylene terephthalate (PET) wool as an insulating material and local-wood structures
Improve the thermal performance of affordable housing	Consider the climate in the design phase	Using guidelines to define envelope characteristics according to different climates
Minimise the impact of topography variations	Consider topography variations in the design phase	Using shape configurations' guidelines considering topography
Foresee housing unit expansion	Predefine open spaces in the floor plan	Using a perpendicular relationship between the lower and upper floors causes open spaces

Source: the authors.

Design guidelines

Modular design (i.e., prefabricated structure, walls, and floors) helps to provide high-quality construction supported by professionals and efficient floorplans and to standardise the construction. The rooms' dimensions were defined after characterising the principal materials and the structure, which resulted in 4x4 m spaces. Prefabricated materials were considered, such as cement-bonded particleboards as cladding, a wooden structure (main pillars and beams), and wood-frame walls. Besides, the dimensions were defined to reduce construction waste and enable standardised wooden structures.

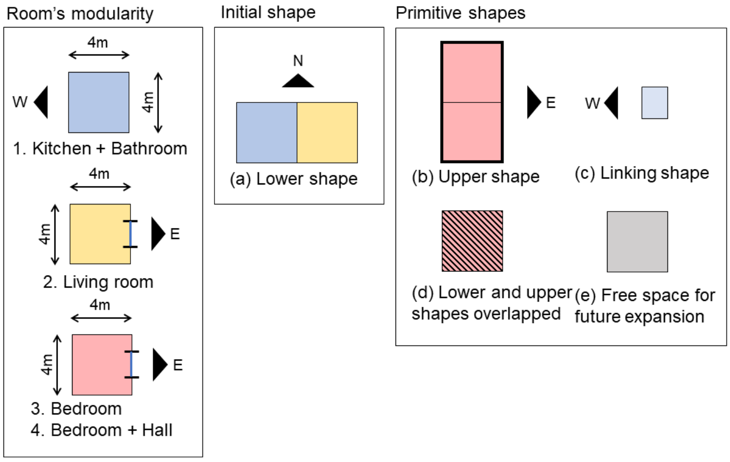
Every room (in the conceptual phase of the design) had the same dimensions, and they could be kitchen plus bathroom, living room, bedroom plus hall. Each room has a guideline regarding the most critical façade orientation, shown in Figure 2. The east façade is the main façade for long permanence rooms (living room and bedrooms), where the morning sun exposure was considered to avoid overheating these rooms. It is also why the kitchen and bathroom have the west façade as the main one, working as a buffering zone.

The essential design guideline is the relation between rooms regarding their use and orientation. As shown before, the kitchen and the bathroom must be west-oriented while the living room is east-oriented. It presents the possibility of merging these two rooms in one shape. Therefore, it leads to foreseeing a second floor, where both bedrooms can be combined in one east-oriented volume.

Additionally, such a criterion comprises needs identified in the field since another guideline was to foresee housing unit expansion and possible changes in use. To consider this subject, we presented a two-floor housing unit solution with a perpendicular relationship between upper and lower rooms ("L" shape) so that the building presents empty spaces and built areas simultaneously, contributing to foreseeing expansions. In addition, its internal area and shape enable accessibility to the first floor. Appendix A shows building details (layout and accessibility), such as construction representation and blueprint. Appendix B shows the implementation of the building considering different module combinations, terrains, and examples of the building after expansions.

Each housing room has at least two exposed façades, enabling ventilation (See Figure A2 Appendix A) and daylighting. Besides, the overlapping of volumes allows the creation of voids in the building, enabling future expansions (See Figure A3 in Appendix A for detailed blueprints). Figure 2 also shows the relations between the rooms. The initial ground-floor shape contains the combined living room, kitchen, and bathroom. The upper shape has two bedrooms. The linking shape connects the two previous shapes and represents the possible stairs. When the lower and upper shapes overlap, the (b) shape emerges. Finally, when the lower and upper shapes do not overlap (i.e., only the square on the first floor or on the second floor occurs), it becomes a free space for future expansions if needed.

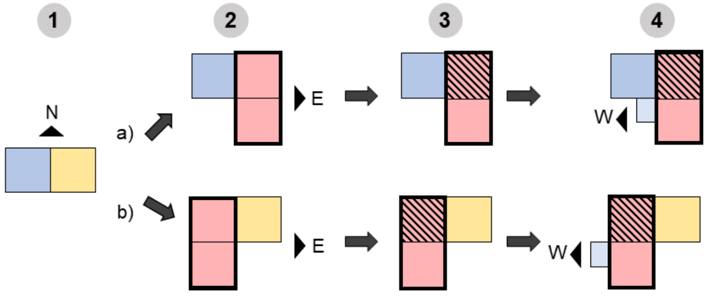
Figure 2 – Rooms' modularity and the relationship between rooms of the housing unit



Source: the authors.

Figure 3 shows the rules for the housing unit composition. The first guideline says that when a lower shape is north-oriented (1), an upper shape is placed perpendicularly. It can be placed over the kitchen (blue square) or the living room (yellow square); then, the operations can be applied (2). After that, it is necessary to identify where the upper and lower shapes overlap (3) so that the linking shape (future stairs) can be placed (4). Then, the linking shape is placed right next to the overlapped shapes and must be predominantly west oriented. Design operations, such as rotation and mirroring, can be applied according to the definitions of the site plan.

Figure 3 – Example of housing unit construction by the settled guidelines

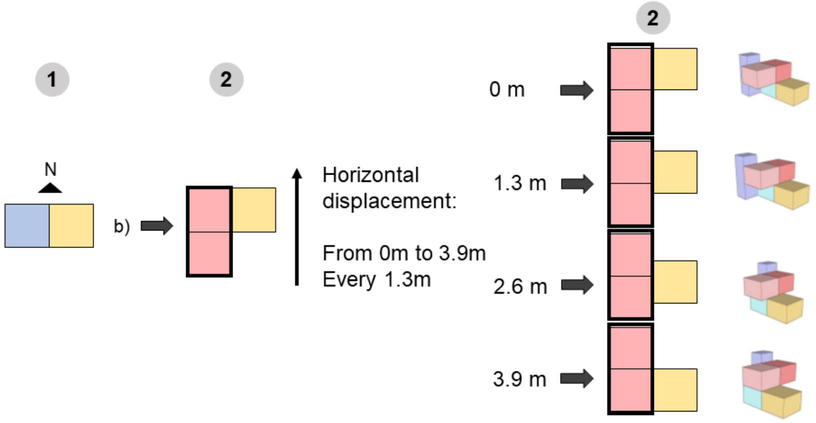


Source: the authors.

Topography

The housing unit varies according to the topography of the land as well. Figure 4 shows the topography variation. There are four possibilities of upper-shape horizontal displacement every 1.3 m, according to the modularity of prefabricated elements and structural limits of the unit (4x4 m wooden structure).

Figure 4 – Topography variations: floorplan view



Source: the authors.

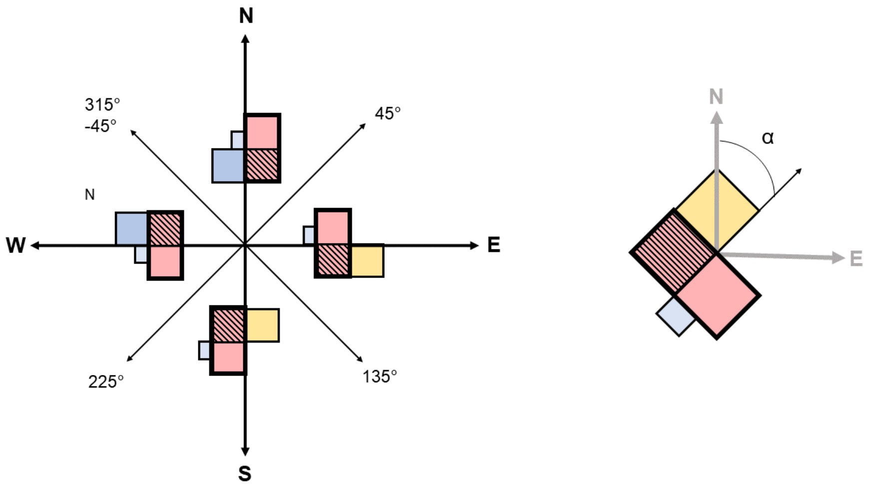
Additionally, the need for earthwork (excavation and piling) impacts the total embodied energy, and construction techniques that reduce it are presented as an alternative to reduce embodied energy in buildings (Wen; Siong; Noor, 2015; Monahan; Powell, 2011). Therefore, upper and lower shape variations are allowed in the proposition of this study.

Solar Orientation

The most prominent façade of the lower shape must be north-oriented, i.e., the azimuth must fit between -45° and 45°, so the kitchen and the living room would have good sunlight and at the same time guarantee diffuse natural light coming from the south façade (when not expanded). The linking shape must be west-oriented, i.e., azimuth must fit between 225° and 315°. The predefined orientation directly influences the guideline application, which defines the housing unit composition.

Figure 5 on the left shows the possibilities of housing unit composition, and the right shows the possibilities of housing unit rotation with the north, represented by the α angle.

Figure 5 – Possibilities of the housing unit composition



Source: the authors.

The housing unit composition varies according to solar orientation defined in the design plan: when the lower shape has an azimuth (α) equal to zero, the housing unit can have four possible configurations between -45° and 45°. When α exceeds 45°, the housing unit composition must change and meet the predefined orientation for both lower and upper shapes.

Expansion and use

The building shape design already has empty spaces, allowing a modular expansion of the building if it is needed by the user, which leads to the other guidelines. Allowing empty spaces in design makes it possible to give the built structure of the future expansion before it is needed, and at the same time, guarantees that the future room follows the modularity of the design. The final design has two planned areas: one on the first and one on the second floor. One crucial guideline is accessibility; in this case, the accessible housing unit should already have the first-floor expansion built as a bedroom.

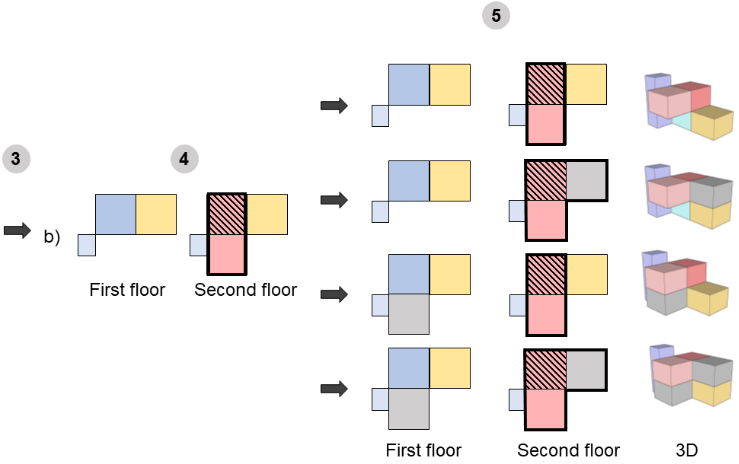
Besides the rooms' expansion, this modulation also allows the change of use in the rooms. The living room (Figure 6 in yellow) could change to commercial or service (like a shop, office, bakery, or cafe), as much as the new room on the first floor.

Envelope definition

Case study selection

After the 3D shape composition of the set of housing units, one composition was used as a case study to set the envelope characteristics considering the best combination of materials and solar absorptance of walls, window-to-wall ratio, and roofing system.

Figure 6 – Expansion guideline



Source: the authors.

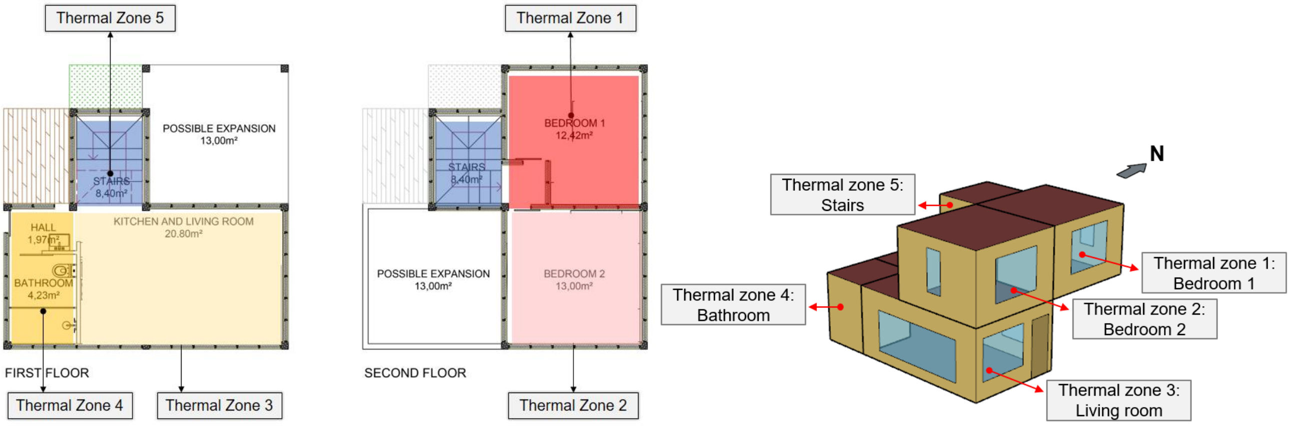
The locations chosen for the simulation were Florianópolis and São Joaquim, climate zones 3 and 1, respectively, according to the Brazilian Climate zoning (ABNT, 2005). The EPW files of 2016 were used to perform the simulations. The housing unit model was simulated considering natural ventilation (45% of the WWR available). The patterns of occupation, use of the equipment and internal loads were obtained from the work of Schaefer and Ghisi (2016), who developed a method to obtain reference models from data measured in Brazilian affordable housing. The simulations were performed considering no surroundings, and the average monthly temperatures obtained from the weather files were used for the ground heat calculation. In addition, four time-steps were configured, meaning four heat transfer balance calculations were done each hour. The simulation output was the operative temperature of each long permanence room, which was then used to calculate heating and cooling degree hours as indexes of thermal performance. Furthermore, the study evaluated some key cases from cooling and heating degree-hours analysis (lower values) through parameters recommended by NBR 15.575:2021, such as the Percentage of Hours within a Temperature Range (PHFT), minimum and maximum operative temperatures in each long permanence room. These key cases were compared to the NBR 15.575:2021 reference under natural ventilation conditions.

The Euclid plug-in for SketchUp was used to model the representative housing unit, and the EnergyPlus program was used to perform the simulations (CRAWLEY et al., 2001). Five thermal zones were considered in the whole model, as presented in Figure 7. As the Brazilian Regulation requires analyses of thermal performance in long permanence rooms (RTQ-R, 2012), thermal zones 1, 2 and 3 were evaluated.

Variations in envelope characteristics were tested regarding their influence on the thermal performance of the housing unit. Figure 8 shows the envelope characteristics considered in this study, which include wall, window-to-wall ratio (WWR), solar absorptance (wall colours), and roofing system. The WWR (%) ranged for each room and façade, resulting in three cases of WWR without external shadings. WWRs were adopted according to previous studies that addressed affordable housing's main characteristics in Brazil (Triana; Lamberts; Sassi, 2015). Green roofs were also tested as a possible alternative in both climates based on previous pieces of research that show it as a feasible alternative regarding heating and cooling energy use in buildings (Jaffal; Ouldboukhitine; Belarbi, 2012; Lundholm; Weddle; Macivor, 2014; Okeil, 2010;

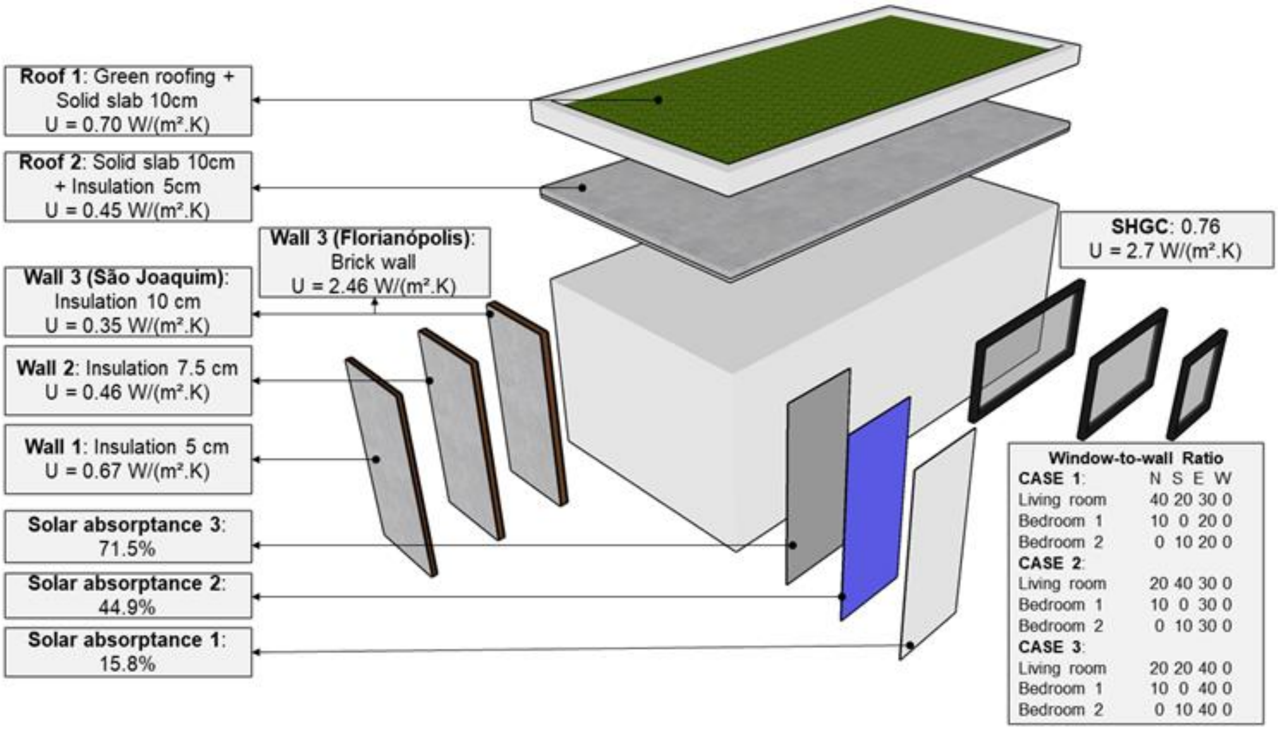
Santamouris; Kolokotsa, 2015; Zinzi; Agnoli, 2012). The simulations included all possible combinations of the characteristics for both cities, resulting in 108 tests.

Figure 7 – Housing unit configuration for computer simulations. From left to right: First floor plan; second floor plan; and building energy model developed in 3D using Euclid



Source: The authors (more details in Appendix A).

Figure 8 – Envelope characteristics considered in the simulations



Window-to-wall Ratio

CASE 1:	N	S	E	W
Living room	40	20	30	0
Bedroom 1	10	0	20	0
Bedroom 2	0	10	20	0
CASE 2:				
Living room	20	40	30	0
Bedroom 1	10	0	30	0
Bedroom 2	0	10	30	0
CASE 3:				
Living room	20	20	40	0
Bedroom 1	10	0	40	0
Bedroom 2	0	10	40	0

Source: adapted from Souza (2017).

The walls were planned to enable large-scale construction. Thus, three materials were combined: cement-bonded particleboard, Oriented Strand Board (OSB), and wool from recycling PET for thermal insulation. Using recycled Polyethylene Terephthalate (RPET) based thermal insulation relies on the environmental benefits and importance of using recycled material in building construction, as supported by the literature (Ingrao *et al*., 2014; Ingrao; Scrucca; Tricase; Asdrubal, 2016). One of the key goals of this study is that the design enables mass customisation and reduces construction waste; thus, an industrialised wood frame was taken into account. Another goal is to analyse different solutions for social housing that can enable better thermal performance and are different from what is common to use.

The only difference between the characteristics simulated for São Joaquim and Florianópolis was wall number 3. For São Joaquim, it was considered a thicker insulation layer (10 cm) with the lowest U-value, considering that this city is in the coldest climate in Brazil. For Florianópolis, it was considered a common wall made of ceramic brick, representing a wall with a higher U-value than the other wooded-frame wall compositions regarding thermal performance, considering that Florianópolis is located in a mild climate.

Thermal performance evaluation

To assess the thermal performance, it was accounted for the yearly degree-hours for cooling and heating for each long permanence room (modelled as a thermal zone) and for each city.

The degree-hours is a thermal performance indicator adopted by Brazilian Regulation (INMETRO, 2012) and is widely used in the literature as well (Bre; Silva; Ghisi; Fachinotti, 2016; Grigoletti; Sattler; Morello, 2008; Pellegrino; Simonetti; Chiesa, 2016; Schaefer; Ghisi, 2016; Silva; Ghisi, 2014; Triana; Lamberts; Sassi, 2018). The degree-hours index is the sum of differences between the internal operative temperature (outputted from the simulation) and a specified temperature limit for each hour in the year. The temperature limit adopted for cooling was 26°C, and for heating, 18°C (Schaefer; Ghisi, 2016). The cooling degree-hours were calculated according to Equation 1, and the heating degree-hours according to Equation 2.

$$DH_{Cool}^{Z} = \sum_{i=1}^{n=84600} |OT_Z - 26| \qquad (1)$$

$$DH_{Heat}^{Z} = \sum_{i=1}^{n=84600} |OT_Z - 18| \qquad (2)$$

Where:

- DH_{Cool} is the degree-hours for cooling for a given thermal zone Z;
- DH_{Heat} is the degree-hours for heating for a given thermal zone Z;
- Z is a given Thermal Zone, representing the built environment;
- OT is the Operative Temperature of a given thermal zone (°C).

Thus, the total degree-hours for each city and each long permanence room were obtained for cooling and heating. Those indicators determined the best-suited materials for each city according to the housing unit's thermal performance.

After selecting the best cases according to cooling and heating degree-hours, the research evaluated its results of PHFT and minimum and maximum operative temperatures. The PHFT and minimum and maximum operative temperatures analysis consider only the occupied hours of each room. To determine the PHFT, both cities' limits range from 18°C to 26°C.

Statistical Analysis

A statistical approach was used to analyse the influence of variations in the envelope characteristics on the cooling and heating degree-hours. In this analysis, the envelope characteristics were considered factors, and the cooling and heating degree-hours were dependent variables.

The Multivariate Analysis of Variance (MANOVA) was used to measure whether a factor's variation significantly impacts cooling and heating degree-hours simultaneously since this test considers multiple dependent variables. Equation 3 presents the general equation for the MANOVA model.

$$Y^k = \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + e \quad (3)$$

Where:

- *Y* is the vector of dependable variables, with k size;
- *βk* is the vector parameters of the independent variables with k size;
- *Xk* is the vector of independent variables (or factors), with k size;
- *e* is the inherent error because of the variability among observations.

Thus, the MANOVA table presents the F value, the degrees of freedom and the P-value for each factor and their interactions. In this case, the statistical hypothesis was:

- H0: The factors do not influence the variance of cooling and heating degree-hours.

The P-value indicates the statistical significance of the acceptance or rejection of H0. The higher the P-value, the stronger the acceptance of H0. The model's fitness was verified employing the coefficient of determination (R^2), and the model assumptions (Studentised residuals follow the normal distribution) were validated using residuals vs fitted values and the Shapiro-Wilk test.

Selecting the final housing unit envelope

Computer simulations provided degree-hours for each long permanence room (living room, bedroom 1 and bedroom 2) of each case (envelope characteristic combination), but how to select a final envelope? To solve that problem, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used as a multi-criteria approach to combine the total annual cooling and heating degree-hours of each thermal zone to decide the best solution. TOPSIS considers the Euclidean distance from each case and its corresponding best and worst ideal solutions. Table 2 shows an example to demonstrate the calculation steps.

Table 2 – Example of TOPSIS calculation (dummy values)

Cases (C0)	Cooling degree-hours			Heating degree-hours			Euclidean distance		S+ plus S- (C9)	Perfor-mance (%) (C10)
	Living room (C1)	Bedroom 1 (C2)	Bedroom 2 (C3)	Living room (C4)	Bedroom 1 (C5)	Bedroom 2 (C6)	S+ (C7)	S- (C8)		
1	0.10	0.00	0.00	0.20	0.26	0.24	0.46	0.53	0.99	53.84
2	0.11	0.01	0.03	0.18	0.20	0.19	0.44	0.48	0.92	52.06
3	0.13	0.02	0.06	0.18	0.18	0.17	0.42	0.45	0.87	51.78

Source: the authors.

Column zero (C0) lists each case. Columns C1 to C6 present the normalised degree-hours for each long permanence room (degree-hours of the room of the given case divided by the summation of degree-hours of the room of all cases). Column C7 is the square root of the sum of squares of the differences between the values in C1 to C6 and the maximum value for the corresponding room. Column C8 is the square root of the sum of squares of the differences between the values in C1 to C6 and the minimum value for the corresponding room. Column 9 (C9) is the sum of C7 and C8. Column 10 (C10) is the rate between C8 and C9, which gives the performance index for the given case.

Hence, the final housing unit envelope was selected according to the best (highest) performance index, one for each city. It gives a combination of WWR, wall, roof system and absorptance, leading to the best thermal performance in all environments, considering cooling and heating.

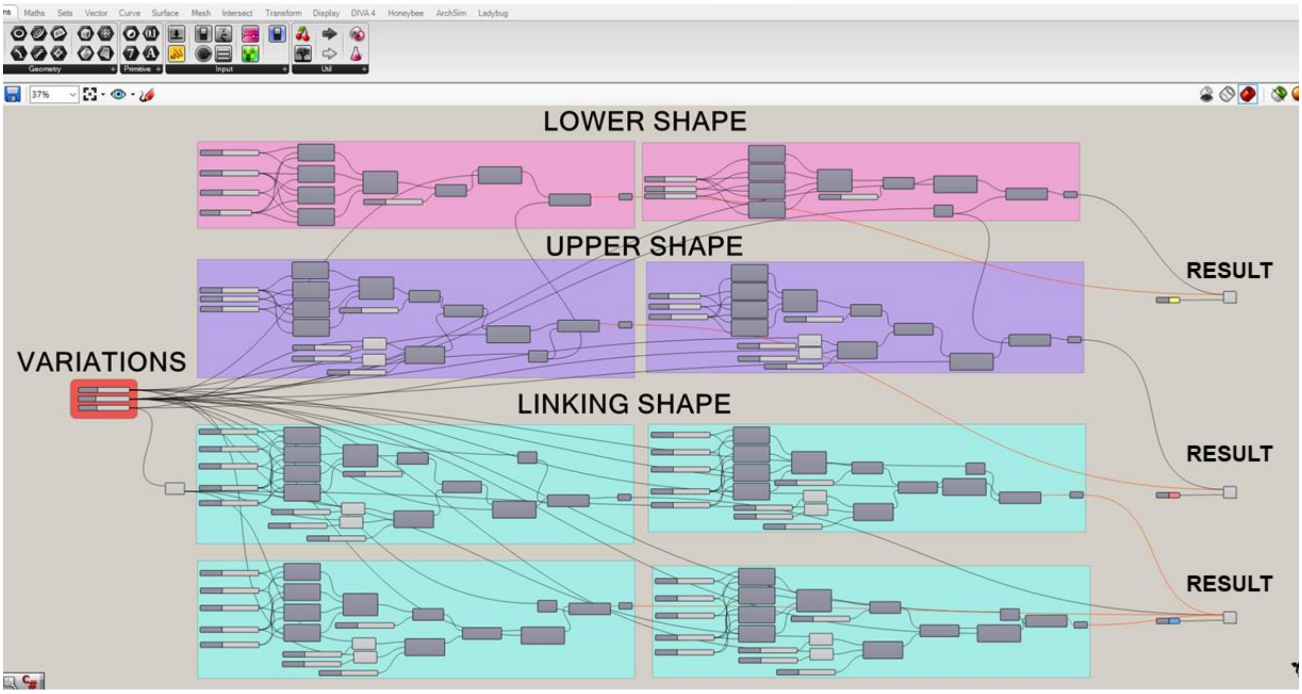
Results

Solutions for the configuration of the building

Although part of the method is to select the housing unit and perform computer simulations, the housing unit itself is a result. It was proved that housing could be parametrised to adapt according to each terrain's specific needs.

A Grasshopper script was developed to test these shapes and possible configurations regarding the set of parameters and variables, which responds to each previously settled guideline (Figure 9). The components used were points, rectangles, and extrude to create the different shapes (two possible lower shapes, two possible upper shapes, and four possible linking shapes, in which only one is selected). Three components were developed to select each variation (site location configuration, orientation, and topography), which could be combined. The number sliders (in "variations") enabled the parametric relationship between the shapes by selecting one of the possible configurations through components. The output of each component is a resulting shape.

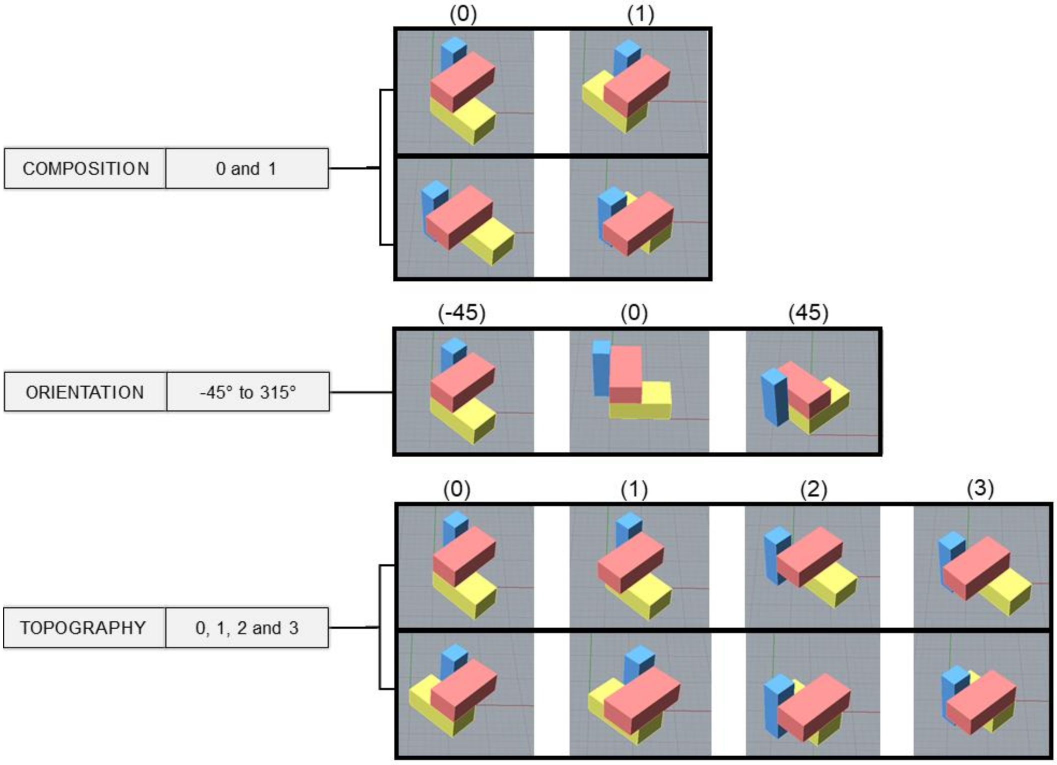
Figure 9 – Grasshopper script



Source: the authors.

The results show eight possibilities of housing unit composition for each implementation orientation in terrain. As shown in the method, four azimuth intervals change the arrangement of the unit according to the orientation guideline. Within each orientation range, the eight possible compositions do not change. Figure 10 represents how easy it is to change the 3D shape composition of the unit by changing a number in the script.

Figure 10 – Illustration of some variations allowed by the workflow programmed in the Grasshopper



Source: the authors.

A predefined script with easy possible changes can improve future constructions since the conceptual phase of the design process, allowing different external conditions and scales depending on the module combinations, as well as allowing changes regarding topography. Besides, after the conceptual phase, each variation has a predefined detailed project that can be easily constructed.

However, each variation has a different envelope exposure and is in a different climate. The envelope definition must be defined according to the climate, and the next section shows such results.

Envelope definition

Computer simulations were performed to choose the combination of materials that resulted in the lowest number of heating and cooling degree-hours throughout the year. In the simulated housing unit module, the main façades of the living room/kitchen are north-south-oriented, and the main façades of the bedrooms are east-west-oriented. The guidelines are part of the workflow established in this study.

The 54 possible envelope combinations, according to Figure 8, are summarised in Table 3. From cases 1 to 18, only the first WWR combination was applied, and changes in wall composition, wall absorptance and roof were made. In the same order, configurations were applied to the second WWR combination (cases 19 to 36) and the third WWR combination (cases 37 to 54).

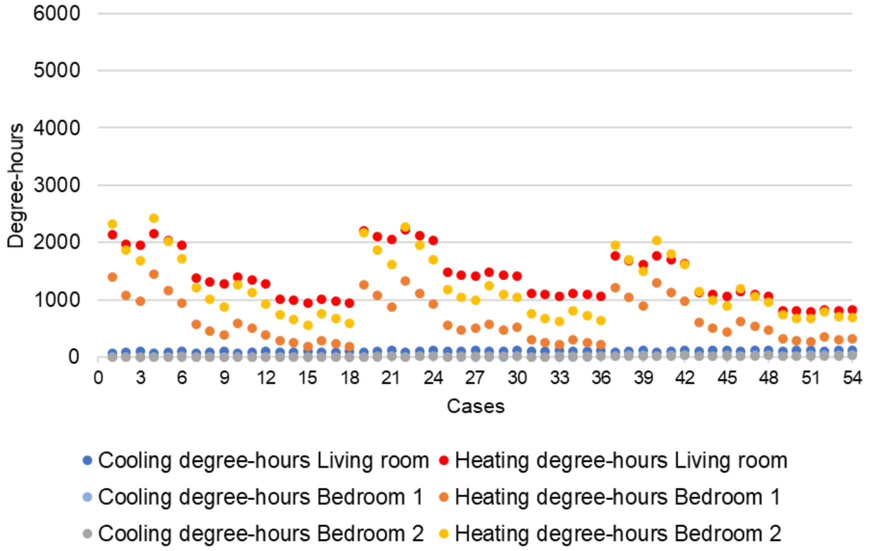
Results are presented according to the total degree-hours in each long permanence room, and each dot on the charts represents one case of envelope composition. The annual cooling and heating degree-hours for São Joaquim city are presented in Figure 11.

Table 3 – Case description according to Figure 8

Parameter	Case number																	
WWR 1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
WWR 2	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
WWR 3	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**
Wall	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	3
Absorptance	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Roof	1	1	1	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2

Source: the authors

Figure 11 – Total annual degree-hours for each case for São Joaquim



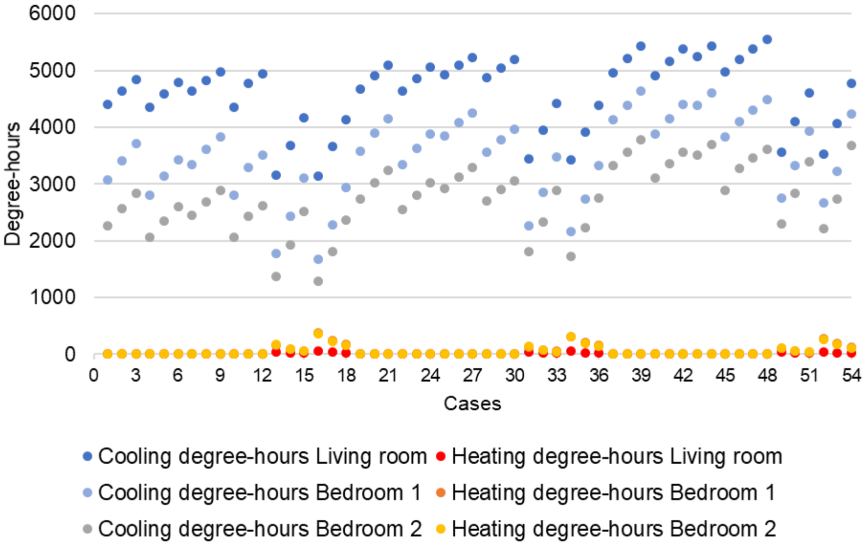
Source: the authors.

According to Figure 11, the main issue for São Joaquim is the need for heating, as the heating degree-hours are much higher than the cooling ones. As a general trend, the window-to-wall ratio that resulted in fewer cooling degree-hours is the first combination, and for the heating degree-hours, the third in all the spaces tested. Wall option 3 (thickest insulation) was the most effective in reducing heating degree-hours, according to Figure 11. Besides, option 3 was the most suitable for solar absorptance, i.e. a combination of thermal insulation with high solar absorptances improves the thermal performance of the housing unit in São Joaquim. Roof 2 (green roof) corresponds to the slightly most appropriate roof, but the result differences regarding the roof changes were less significant than the wall and absorptance. It is insignificant, even with the same absorptance and U-values (0.70 W/m².K for green roof and 0.45 W/m².K for insulated slab). Besides, green roof thermal capacity is higher than only the concrete slab with insulation, and thus, it improves thermal performance.

Insulation is a suitable strategy for cold climates like São Joaquim. Thus, the wall layers played a more important role than the absorptance. Although having a lower impact on the building performance, higher absorptance associated with greater insulation level resulted in heat accumulation in the walls and improved the thermal performance. This first analysis shows the results and identifies trends according to envelope characteristics. However, in-depth evaluations are made in the following subsection of this study. Multi-criteria analysis was used to determine the best combination of envelope characteristics when the whole-building thermal performance is considered.

Similarly, annual cooling and heating degree-hours for Florianópolis city are presented in Figure 12. The need for cooling is evident in this city, so different envelope composition is necessary to suit the housing unit to local climate conditions. As the heating is not crucial to improve thermal performance in this city, the most insulated wall (wall 3) was not tested in this case, so low and medium-insulated options were compared to a commonly used wall composition in Brazil.

Figure 12 – Total annual degree-hours for each case for Florianópolis



Source: the authors.

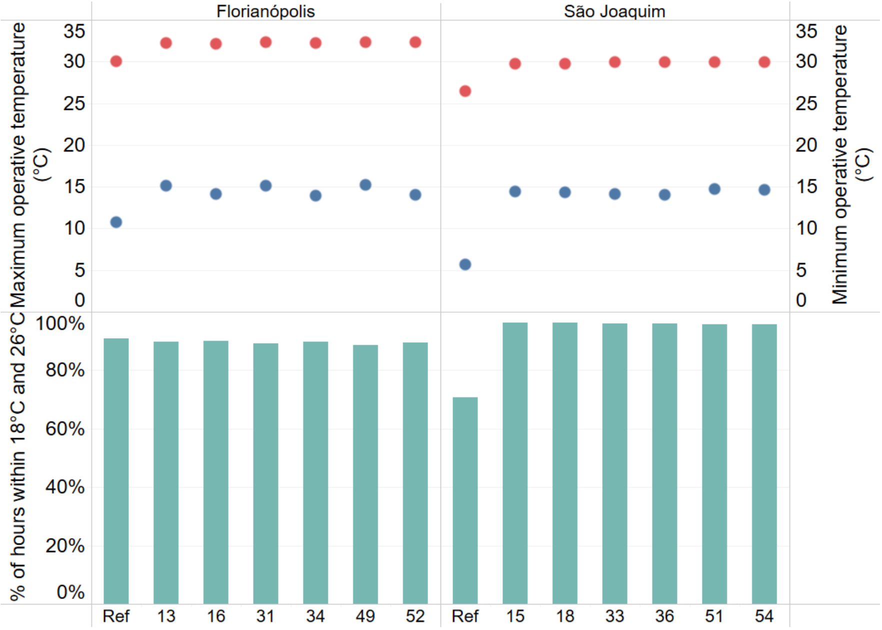
Regarding the window-to-wall ratios, the first combination of WWR resulted in the most satisfactory thermal performance. For the walls, the non-insulated wall reduced cooling degree-hours, and even increasing those of heating, was the most suitable composition. Unlike São Joaquim, the most indicated absorptance is the lowest value tested, i.e., white colour, since it reduces the heat gain and improves the building performance during hot days. These trends were found in the visual analysis of the graphic.

However, comparing both cities, bedrooms 1 and 2 have opposite behaviours: the east-north oriented (bedroom 1) has higher cooling degree-hours than the east-south oriented (bedroom 2) in Florianópolis due to the sun exposition, but the opposite happens in São Joaquim, where the heating degree-hours matter. Further studies should consider possible changes in shape compositions regarding the climate.

Furthermore, the results were evaluated according to NBR 15575:2021 parameters, such as minimum (To, min) and maximum (To, max) operative temperatures and percentage of hours within a temperature range (18°C < To < 26°C). The cases with lower cooling and heating degree-hours results in each city were selected to be evaluated and compared to the NBR 15575 reference ("Ref" case). Results are presented in Figure 13.

The NBR 15.575 reference case has a lower minimum operative temperature (To,min) in both cities. In São Joaquim, the To,min of the reference case is 5.7°C, less than 8°C in the case with the lowest value of To,min. In Florianópolis, the reference case has To,min of 10.7°C, i.e., the solutions made operative temperatures higher during the year, especially the bedrooms, avoiding heating needs. Nevertheless, the maximum operative temperature (To,max) in the reference case is the lowest in both cities, but the difference is 3°C for São Joaquim and 2°C for Florianópolis. The envelope solutions for Florianópolis could be further improved by adding shading to avoid overheating.

Figure 13 – PHFT, minimum and maximum operative temperatures for São Joaquim and Florianópolis



Source: the authors.

Furthermore, the percentage of hours within 18°C and 26°C (PHFT) difference in São Joaquim is 25%, which proves the improvement of such cases. For Florianópolis, the PHFT remains the same, comparing the reference to these cases. However, it should be noted that the reference roof is composed of a concrete ceiling with an air chamber and fibre-cement tile, while the solutions for this building need roofs that work as a slab for future expansions.

Regarding differences only among the selected cases (not comparing to the NBR 15.575 reference case), analysing the To,max of the housing unit, are not higher than 0.25°C and, thus, insignificant. To,min differences in São Joaquim were lower than 0.7°C and in Florianópolis, lower than 1.25°C. PHFT differences among cases in São Joaquim were less than 1% and in Florianópolis less than 1.5%. Nevertheless, Figure 13 shows that just analysing To,min, for example, would not be an interesting idea since the highest values in Florianópolis were also the lowest values of PHFT. Nevertheless, these results show that the shape composition allied with the suitable envelope composition can reach high levels of thermal performance (high PHFT).

Therefore, in-depth evaluations using a multi-criteria analysis are shown in the following subsection.

Statistical analysis

Statistical analysis was performed using MANOVA to assess the significance of the impact that variations in the envelope have on the degree-hours of cooling and heating. MANOVA model was developed using two dependent variables (annual degree-hours of cooling and heating) and four independent variables (WWR, wall, roof and solar absorptance). Output data of 54 cases simulated for each city were used. Table 3 shows the MANOVA model summary for São Joaquim; the degrees of freedom (Df) for the treatments of each variable, the value of the Pillai statistic, its respective value of the F statistic (approximately), the number of degrees of freedom of the combination, and the error degrees of freedom are shown. The final column shows the test's significance (P-value or probability value). The smaller the P-value, the higher the probability of the test rejecting H0. Thus, if H0 is rejected, the factors (or their interactions) influence thermal performance.

Table 4 shows the P-value for each factor and its interactions. The first-order factors, such as WWR, wall, roof, and absorptance, significantly influenced the cooling and heating degree-hours, which implies that all these factors are essential to assess thermal performance and should be considered in the design. Regarding the interactions among factors, the statistical test pointed out the following interactions as significant for the thermal performance: WWR and roof, WWR and absorptance, wall and absorptance, and WWR, wall and absorptance. The relation between those factors should be considered, i.e., the high thermal performance of a certain WWR could counterweigh the low thermal performance of specific roof systems. Other interactions could assess the same. However, it is not reliable to state that a particular high thermal performance of the absorptance could counterweigh the low thermal performance of the roof systems since the P-value resulted in inference as not significant for the test done.

Table 4 – MANOVA model for São Joaquim

Factors	Df	Pillai	Approx. F	Num Df	den Df	Pr(>F)
WWR	1	0.99316	2684.51	2	37	< 2.2e-16***
WALL	1	0.94947	347.61	2	37	< 2.2e-16***
ROOF	1	0.74182	53.16	2	37	1.32E-11***
ABS	1	0.97591	749.34	2	37	< 2.2e-16***
WWR and WALL	1	0.12011	2.53	2	37	0.09374
WWR and ROOF	1	0.40791	12.75	2	37	0.00006153***
WALL and ROOF	1	0.00666	0.12	2	37	0.88377
WWR and ABS	1	0.74485	54.01	2	37	1.061E-11***
WALL and ABS	1	0.68015	39.34	2	37	6.942E-10***
ROOF and ABS	1	0.05106	1	2	37	0.37922
WWR and WALL, and ROOF	1	0.00231	0.04	2	37	0.95817
WWR and WALL, and ABS	1	0.19093	4.37	2	37	0.01985*
WWR and ROOF, and ABS	1	0.00043	0.01	2	37	0.9921
WALL and ROOF, and ABS	1	0.00852	0.16	2	37	0.85367
WWR and WALL and ROOF and ABS	1	0.00542	0.1	2	37	0.90442
Residuals	38					

Notes: '***' is statistically significant for 99% of significance level; '*' is statistically significant for 95% of significance level; Df is "Degrees of freedom". Source: the authors.

It is crucial to note that this analysis considered both cooling and heating degree-hours. Thus, it was considered the balance of the thermal performance of the factors throughout the year. Table 5 shows the MANOVA model for Florianópolis.

Table 5 – MANOVA model for Florianópolis

Factors	Df	Pillai	Approx. F	Num Df	den Df	Pr(>F)
WWR	1	0.78234	66.494	2	37	5.61E-13***
WALL	1	0.67303	38.08	2	37	1.043E-09***
ROOF	1	0.32903	9.072	2	37	0.0006223***
ABS	1	0.56165	23.704	2	37	2.364E-07***
WWR and WALL	1	0.15247	3.328	2	37	0.0468673*
WWR and ROOF	1	0.02261	0.428	2	37	0.6549928
WALL and ROOF	1	0.57845	25.386	2	37	1.147E-07***
WWR and ABS	1	0.01143	0.214	2	37	0.8084751
WALL and ABS	1	0.1989	4.593	2	37	0.0165257*
ROOF and ABS	1	0.02005	0.378	2	37	0.6875302
WWR and WALL, and ROOF	1	0.00621	0.116	2	37	0.8911466
WWR and WALL, and ABS	1	0.03897	0.75	2	37	0.4793311
WWR and ROOF, and ABS	1	0.03375	0.646	2	37	0.5298793
WALL and ROOF, and ABS	1	0.05284	1.032	2	37	0.3663146
WWR and WALL and ROOF and ABS	1	0.00411	0.076	2	37	0.9266792
Residuals	38					

Notes: '***' is statistically significant for 99% of significance level; '*' is statistically significant for 95% of significance level; Df is "Degrees of freedom". Source: the authors.

It is possible to notice that the first-order factors, such as WWR, wall, roof and absorptance, significantly influenced the cooling and heating degree-hours, such as those for São Joaquim.

Regarding the interactions among factors, wall layers and roof were the most significant. WWR, wall layers, and absorptance interaction are also significant but in a smaller magnitude. As for São Joaquim, those factors should be considered in the design to improve the thermal performance of affordable housing. In comparison to São Joaquim, fewer interactions impacted the thermal performance. It could be explained because São Joaquim has a more extreme climate (cold) compared to Florianópolis, where mild weather prevails. Thus, the case analysed in São Joaquim had more influence on the external conditions on the interior of the housing unit.

Remarkably, both two-factor interactions that were significant for Florianópolis were not significant for São Joaquim, and the opposite is also true – the two-factor interactions there were significant for São Joaquim were not significant for Florianópolis. Since São Joaquim is mainly influenced by cold weather (high amount for heating degree-hours), one could explain that those two-factor interactions (WWR and wall layers, and absorptance) are more critical for cooling strategies. Moreover, the other interactions such as WWR and roof, WWR and absorptance, wall layer and absorptance, and WWR, wall and absorptance are more critical for heating strategies.

Final housing units obtained for both cities

The final housing unit was obtained using TOPSIS. After calculating annual cooling and heating degree-hours for each long permanence room, they were considered individual criteria for choosing the best envelope. Case 15 achieved the best thermal performance for São Joaquim (best TOPSIS performance) combines the following characteristics: WWR-set 1 (living room with WWR equal to 40% in north façade, 20% in the south, 30% in east; bedroom 1 with 10% in north façade and 20% in east; and bedroom 2 with 10% in south façade and 20% in east), wall type 3 (U = 0.35 W/m²K), roof type 2 (concrete slab, U = 0.45 W/m²K), and absorptance type 3 (71.5%). This envelope set outputted 1,673.49 heating degree-hours and 97.59 cooling degree-hours.

For Florianópolis, case 16 is the best final envelope. This case combines the following envelope characteristics: WWR-set 1 (living room with WWR equal to 40% in north façade, 20% in south, 30% in east; bedroom 1 with 10% in north façade and 20% in east; and bedroom 2 with 10% in south façade and 20% in east), wall type 3 (brick wall, U = 2.46 W/m²K), roof 1 (green roof, U = 0.70 W/m²K), and absorptance 1 (15.8%). This envelope set outputted 794.20 heating degree-hours and 6,090.38 cooling degree-hours.

Conclusions

This work focused on developing a set of housing unit designs to minimise the main issues concerning existing single-family housing projects in Brazil. Rather than offering a single solution, this work proposed an adaptive single-family housing set through parametric design guidelines. Relevant aspects considered in the parametric design were that the base geometry and material properties could be adapted according to variations in solar orientation, flexibility for future expansions, climate and topography. A set of parametric guidelines was created and applied to a group of initial shapes representing a specific part of the house. These guidelines formed the set of possible building shapes to be applied in different situations. After that, one building shape was selected, and building performance simulations were performed considering different envelope configurations for São Joaquim and Florianópolis to analyse differences in envelope solutions for the same building shape.

Overall, some main conclusions can be drawn from this study. First, there is great potential for applying parametric design guidelines in affordable housing design. One may implement rules to adapt the housing units according to actual conditions. It is the case of the solar orientation guideline presented in this work. As the most prominent façade varies, the model is resized to comply with the guideline, promoting a new model. Thus, it is possible to consider the individuality of each site plan and each project's possibilities but still follow the climate guidelines.

Additionally, it is a practical approach, as programming allows the implementation of guidelines by automating the design process (Figure 10). Besides, the future expansion or changes in the use were enabled by designing open spaces for future constructions. Future changes can be applied following the shape and orientation of the building. As the need for earthwork (excavation and piling) impacts the total building embodied energy, this work also offered a solution to minimise earthwork requirements during affordable housing implementation by topography adaptation.

Furthermore, this work shows that envelope materials played an essential role in the thermal performance of housing units. The thermal performance in São Joaquim City is more affected by the winter season, and the best envelope characteristics include higher solar absorptance and wall insulation. Besides, the roof solution with lower thermal transmittance (more insulated) was the best choice, considering the selected building shape with double glazing. Additionally, Florianópolis city is more affected by the summer season, and lower solar absorptance and non-insulated walls are more effective in guaranteeing better thermal performance for the same building shape. Also, the green roof was the best choice compared to the insulated slab, considering the selected building shape with double glazing. Finally, the study presents that the window-to-wall ratio was the most significant envelope parameter for both cities within the parameters analysed. However, even with the same chosen WWR set for each city, all parameters' envelope configurations were different. Nonetheless, there were no glazing variations in this study.

Therefore, this work supports stakeholders, including Brazilian policymakers, to consider the appropriate climate suitability of affordable housing.

This work also has some limitations. Some initial shape guidelines, such as room orientation, could be reviewed depending on the climate zone and accessibility in the whole building. Further studies should consider applying the same orientation to all long permanence rooms (bedrooms and living room) depending on the climate necessity (such as extremely hot or cold climate zones). Changes such as north-oriented bedrooms could improve thermal performance in those cases. It would lead to differences in shape composition, topography adaptation and expansion possibilities, but different solutions could be addressed.

Moreover, regarding the envelope, the energy model was simulated for climate zones 1 and 3 and should be tested for the other six Brazilian climate zones. The study must likely suffer adaptation to include new guidelines that allow shape and envelope variation to solve other climatic issues in hot zones, such as climate zone 8. Besides, different types of glazing and shading should be explored, especially in climate zone 3. Besides, a single envelope combination was chosen as the optimal case, defined based on the simulation results. An improvement for the housing unit is to include on the parametric design the possibility to vary those envelope characteristics individually according to new rules studied and applied to the model. The envelope characteristics should also be tested considering hot climate zones with other types of envelope compositions, WWR variations, and different orientation possibilities.

Regarding the HVAC system was not considered in the simulations because the reference housing unit used was based on an affordable unit in Brazil, where HVAC is not usually considered. However, future studies are encouraged to consider HVAC use as it has increased in the last few years and may continue to increase significantly in the next few years. And finally, as stated in Table 1, using predefined and prefabricated elements was a guideline, and using prefabricated structures, walls, and floors was a solution to enable fast and large-scale construction and avoid construction waste. Nevertheless, the cost analysis was not included in the study's scope. As an affordable housing project, further work should consider costs regarding materials and labour to be feasible.

Acknowledgments

This study was financed in part by the Coordination for the Improvement of Higher Education Personnel – Brasil (CAPES) – Finance Code 001.

References

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). **NBR 15220-3**: Desempenho térmico de edificações residenciais. Parte 3 – Zoneamento bioclimático brasileiro e diretrizes construtivas para habitações unifamiliares de interesse social. Rio de Janeiro: ABNT, 2005.

BAVARESCO, M.; KAMIMURA, A.; GERALDI, M. S. MELO, A. P.; LAMBERTS, R. Impacto da ausência de forros ou lajes no desempenho termoenergético de habitações de interesse social. *In*: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 19., 2022, Canela. **Anais [...].** Porto Alegre: ANTAC, 2022. DOI: https://doi.org/10.46421/entac.v19i1.2239.

BODACH, Susanne; HAMHABER, J. Energy efficiency in social housing: Opportunities and barriers from a case study in Brazil. **Energy Policy**, v. 38, n. 12, p. 7898–7910, Dec. 2010. DOI: http://dx.doi.org/10.1016/j.enpol.2010.09.009.

BRACHT, M. K; COSTA, V. A. C; MELO, A. P; LAMBERTS, R. Série histórica versus ano meteorológico típico: Desempenho térmico de modelo unifamiliar com três alternativas de envoltória em Brasília. *In*: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 19., 2022, Canela. **Anais [...].** Porto Alegre: ANTAC, 2022. p. 1-10. DOI: https://doi.org/10.46421/entac.v19i1.1992.

BRE, Facundo; SILVA, Arthur Santos; GHISI, Enedir; FACHINOTTI, Víctor D. Residential building design optimisation using sensitivity analysis and genetic algorithm**. Energy and Buildings**, v. 133, p. 853-866, Dec. 2016. DOI: https://doi.org/10.1016/j.enbuild.2016.10.025.

BRUNORO, S. Sustainable strategies and methods for the energetic improvement of social housing stock in Italy. *In*: ECO-ARCHITECTURE, 4., 2012, Kos. **Proceedings [...].** Souhampton: Wessex Institute of Techology, v. 165, p. 299-310, 2012.

BULIGON, L. B.; MACARTHY, M. R.; BERNARDES, L. C.; LEITZKE, R. K.; GRIGOLETTI, G. C.; CUNHA, E. G. Hygrothermal performance of masonry walls of residential buildings in a humid subtropical climate. **PARC Pesquisa em Arquitetura e Construção,** v. 13**,** Nov. 2022. DOI: https://doi.org/10.20396/parc.v13i00.8667258.

CAMPOS, R. B. A.; GUILHOTO, J. J. M. The socioeconomic Impacts of low income housing: An interregional input-output model for the state of São Paulo and the rest of Brazil. **Habitat Internacional**, v. 65, p. 59-69, July 2017. DOI: https://doi.org/10.1016/j.habitatint.2017.04.001.

COLCLOUGH, Shane; KINNANE, Oliver; HEWITT, Neil; GRIFFITHS, Philip. Investigation of nZEB social housing built to the Passive House standard. **Energy and Buildings**, v. 179, p. 344–359, Nov. 2018. DOI: https://doi.org/10.1016/j.enbuild.2018.06.069.

FRANCO, Luiza; MENDES, Júlia Castro; COSTA, Laís Cristina Barbosa; PIRA, Rúbia Ricceli; PEIXOTO, Ricardo André Fiorito. Design and thermal evaluation of a social housing model conceived with bioclimatic principles and recycled aggregates. **Sustainable Cities and Society**, v. 51, p. 101725, Nov. 2019. DOI: https://doi.org/10.1016/j.scs.2019.101725.

GERALDI, M. S., BAVARESCO, M. V., MELO, A. P., LAMBERTS, R. Análise longitudinal do consumo de energia elétrica do setor residencial no Brasil. *In*: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 19., 2022, Canela. **Anais [...].** Porto Alegre: ANTAC, 2022. p. 1-14. Disponível em: https://eventos.antac.org.br/index.php/entac/article/view/2005. Acesso em 3 fev. 2023.

GONÇALVES JUNIOR, Alberto Carlos; DUTRA, Ricardo Lemos; LOPES, Ricardo Luis; RODRIGUES, Rossana Lott. O impacto do Programa Minha Casa, Minha Vida na economia brasileira: uma análise de insumo-produto. **Ambiente Construído**, v. 14, n. 1, p. 177-189, jan./mar. 2014. Disponível em: https://seer.ufrgs.br/index.php/ambienteconstruido/article/view/42612/28757. Acesso em: 20 jan. 2023.

GRIGOLETTI, Giane; SATTLER, Miguel A.; MORELLO, Alessandro. Analysis of the thermal behaviour of a low cost, single-family, more sustainable house in Porto Alegre, Brazil. **Energy and Buildings**, v. 40, n. 10, p. 1961–1971, 2008. DOI: https://doi.org/10.1016/j.enbuild.2008.05.004.

HOU, Dan; STOUFFS, Rudi. An algorithmic design grammar for problem solving. **Automation in construction**, v. 94, p. 417-437, Oct. 2018. DOI: https://doi.org/10.1016/j.autcon.2018.07.013.

INGRAO, Carlo; LO GIUDICE, Agata; TRICASE, Caterina; RANA, Roberto; MBOHWA, Charles; SIIRACUSA, Valentina. Recycled-PET fibre based panels for building thermal insulation: Environmental impact and improvement potential assessment for a greener production. **Science of the Total Environment**, v. 493, p. 914-929, Sept. 2014. DOI: https://doi.org/10.1016/j.scitotenv.2014.06.022.

INGRAO, Carlo; SCRUCCA, Flavio; TRICASE, Caterina; ASDRUBALI, Francesco. A comparative Life Cycle Assessment of external wall-compositions for cleaner construction solutions in buildings. **Journal of Cleaner Production**, v. 124, p. 283-298, July 2016. DOI: https://doi.org/10.1016/j.scitotenv.2014.06.022.

INVIDIATA, Andrea; LAVAGNA, Monica; GHISI, Enedir. Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. **Building and environment**, v. 139, p. 58-68, July 2018. DOI: https://doi.org/10.1016/j.buildenv.2018.04.041.

INVIDIATA, Andrea; SOUSA, R.F.; MELO, A.P.; FOSSATI, M.; LAMBERTS, R. Análise do Desempenho Termo Energético de Habitações Unifamiliares de Interesse Social através do Método De Simulação do Regulamento Brasileiro. *In*: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 16., São Paulo. **Anais [...].** Porto Alegre: ANTAC, 2016. p. 1065-1078. Disponível em: http://www.infohab.org.br/entac/2016/ENTAC2016_paper_297.pdf. Acesso em 20 fev. 2023.

JAFFAL, Issa; OULDBOUKHITINE, Salah-Eddine; BELARBI, Rafik. A comprehensive study of the impact of green roofs on building energy performance. **Renewable Energy**, v. 43, p. 157-164, July 2012. DOI: https://doi.org/10.1016/j.renene.2011.12.004.

LIMA, F. T. A.; COSTA, C. F. R.; ROSA, A. A.; VALLONE, L. F. C. Abordagem urbana (para)métrica em áreas de habitação de interesse social. **PARC Pesquisa em Arquitetura e Construção**, Campinas, v. 11, p. e020024, Dec. 2020. DOI: https://doi.org/10.20396/parc.v11i0.8657220.

LUNDHOLM, Jeremy T.; WEDDLE, Brett M.; MACIVOR, J. Scott. Snow depth and vegetation type affect green roof thermal performance in winter. **Energy and Buildings**, v. 84, p. 299–307, Dec. 2014. DOI: https://doi.org/10.1016/j.enbuild.2014.07.093.

MALTA, N. S.; RABBI, I. M.; RODRIGUES, E. A. N. Conforto térmico, eficiência energética e viabilidade econômica em HIS. **PARC Pesquisa em Arquitetura e Construção**, Campinas, v. 13, p. e022020, June 2022. DOI: https://doi.org/10.20396/parc.v13i00.8665076.

MENDES, Leticia Teixeira. **Personalização de Habitação de Interesse Social no Brasil: o caso da implantação urbana em conjuntos habitacionais**. 2014. 263 f. Tese (Doutora em Arquitetura, Tecnologia e Cidade) - Faculdade de Engenharia Civil e Arquitetura, Universidade Estadual de Campinas, Campinas, 2014. DOI: https://doi.org/10.47749/T/UNICAMP.2014.937456.

MONAHAN, J.; POWELL, J. C. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. **Energy and Buildings**, v. 43, n. 1, p. 179-188, Jan. 2011. DOI: https://doi.org/10.1016/j.enbuild.2010.09.005.

MORAIS, Juliana Magna Silva Costa; LABAKI, Lucila Chebel. CFD como ferramenta para simular ventilação natural interna por ação dos ventos: estudos de caso em tipologias verticais do "Programa Minha Casa, Minha Vida". **Ambiente Construído**, v. 17, n. 1, p. 223-244, jan.-mar. 2017. DOI: https://doi.org/10.1590/s1678-86212017000100133.

MÜLLER, Shirley Coelho; LIMA, José Júlio Ferreira. O espaço para crianças produzido pelo Programa Minha Casa, Minha Vida: estudo de caso na região metropolitana de Belém, PA. **Ambiente Construído**, v. 17, n. 2, p. 97–117, abr.-jun. 2017. DOI: https://doi.org/10.1590/s1678-86212017000200148.

MUÑOZ CRUZ, Luis Manuel; DELGADO ECHEVERRI, John Jairo; GONZALEZ ARROYAVE, Mauricio; HERNAN BEJARANO, Danilo; MANRIQUE FLOREZ, Oscar Fernando. Bioclimatic conditions: A forgotten factor in the domestic habitat in the city of Palmira, Colombia. **Journal of Construction in Developing Countries**, v. 22, n. 2, p. 81-100, 2017. DOI: https://doi.org/10.21315/jcdc2017.22.2.6.

OKEIL, Ahmad. A holistic approach to energy efficient building forms. **Energy and Buildings**, v. 42, n. 9, p. 1437-1444, Sept. 2010. DOI: **https://doi.org/10.1016/j.enbuild.2010.03.013.**

OLIVEIRA, R. B.; ALVES, C. R. Análise do desempenho térmico de habitação de interesse social com paredes de concreto em Uberlândia-MG. **PARC Pesquisa em Arquitetura e Construção**, Campinas, v. 12, p. e021006, fev. 2021. DOI: https://doi.org/10.20396/parc.v12i00.8661094.

PELLEGRINO, Margot; SIMONETTI, Marco; CHIESA, Giacomo. Reducing thermal discomfort and energy consumption of Indian residential buildings: Model validation by in-field measurements and simulation of low-cost interventions. **Energy and Buildings**, v. 113, p. 145-158, Feb. 2016. DOI: https://doi.org/10.1016/j.enbuild.2015.12.015.

PRECIADO-PÉREZ, Oscar A.; FOTIOS, Steve. Comprehensive cost-benefit analysis of energy efficiency in social housing. Case study: Northwest Mexico. **Energy and Buildings**, v. 152, p. 279-289, Oct. 2017. DOI: https://doi.org/10.1016/j.enbuild.2017.07.014.

INMETRO. Instituto Nacional de Metrologia, Qualidade e Tecnologia. **Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais – RTQ-R**. Portaria n°018/2012. Rio de Janeiro: INMETRO, 2012.

RINCÓN, Lídia; CARROBÉ, Ariadna; MARTORELL, Ingrid; MEDRANO, Marc. Improving thermal comfort of earthen dwellings in sub-Saharan Africa with passive design. **Journal of Building Engineering**, v. 24, p. 100732, July 2019. DOI: https://doi.org/10.1016/j.jobe.2019.100732.

SANTAMOURIS, Mattheos; KOLOKOTSA, Dionysia. On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe. **Energy and Buildings**, v. 98, p. 125-133, July 2015. DOI: https://doi.org/10.1016/j.enbuild.2014.08.050.

SANTOS, Carlos Eduardo Rosa; PENTEADO NETO, Renato de Arruda. Análise de frequência de vícios construtivos em habitações de interesse social: região de Curitiba, PR. **PARC Pesquisa em Arquitetura e Construção**, Campinas, v. 11, p. e020025, dez. 2020. DOI: https://doi.org/10.20396/parc.v11i0.8656047.

SCHAEFER, Aline; GHISI, Enedir. Method for obtaining reference buildings. **Energy and Buildings**, v. 128, p. 660-672, Sept. 2016. DOI: https://doi.org/10.1016/j.enbuild.2016.07.001.

SILVA, Arthur Santos; GHISI, Enedir. Uncertainty analysis of user behaviour and physical parameters in residential building performance simulation. **Energy and Buildings**, v. 76, p. 381–391, June 2014. DOI: https://doi.org/10.1016/j.enbuild.2014.03.001.

SOUZA, L. P.; BAVARESCO, M. V.; VAZ, C. E. V.; LAMBERTS, R. Inserção de simulações de desempenho térmico no processo de projeto. **PARC Pesquisa em Arquitetura e Construção**, Campinas, v. 12, p. e021011, maio 2021. DOI: https://doi.org/10.20396/parc.v12i00.8657346.

SOUZA, L. P.; COSTA, V. A. C.; MELO, A. P.; LAMBERTS, R. O impacto do uso de isolamento na cobertura de acordo com a NBR 15575. *In*: ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO, 19., 2022, Canela. **Anais [...]**. Porto Alegre: ANTAC, 2022. DOI: https://doi.org/10.46421/entac.v19i1.2161.

SOUZA, L. P. **Desenvolvimento de um sistema habitacional**. 2017. 62 f. + 1 prancha. Monografia (Trabalho de Conclusão de Curso) – Departamento de Arquitetura e Urbanismo da Universidade Federal de Santa Catarina. Florianópolis, 2017. Disponível em: https://repositorio.ufsc.br/handle/123456789/202979. Acesso em: 20 jan. 2023.

SUÁREZ, Rafael; FERNÁNDEZ-AGÜERA, Jessica. Passive energy strategies in the retrofitting of the residential sector: A practical case study in dry hot climate. **Building Simulation**, v. 8, p. 593-602, May 2015. DOI: https://doi.org/10.1007/s12273-015-0234-7.

TALEB, Sirine; YERETZIAN, Aram; JABR, Rabih A.; HAJJ, Hazem. Optimisation of building form to reduce incident solar radiation. **Journal of Building Engineering**, v. 28, p. 101025, Mar. 2020. DOI: https://doi.org/10.1016/j.jobe.2019.101025.

TRIANA, Maria Andrea; LAMBERTS, Roberto; SASSI, Paola. Characterisation of representative building typologies for social housing projects in Brazil and its energy performance. **Energy Policy**, v. 87, p. 524–541, Dec. 2015. DOI: https://doi.org/10.1016/j.enpol.2015.08.041.

TRIANA, Maria Andrea; LAMBERTS, Roberto; SASSI, Paola. Should we consider climate change for Brazilian social housing? Assessment of energy efficiency adaptation measures. **Energy and Buildings**, v. 158, p. 1379–1392, Jan. 2018. DOI: https://doi.org/10.1016/j.enbuild.2017.11.003.

VILLAÇA, Flávio. **O que todo cidadão precisa saber sobre habitação**. São Paulo: Global, 1986. 56 p.

WEN, Thong; SIONG, Ho Chin; NOOR, Z. Z. Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. **Energy and Buildings**, v. 93, p. 295–302, Apr. 2015. DOI: https://doi.org/10.1016/j.enbuild.2014.12.002.

YU, Rongrong; GERO, John; GU, Ning. Architects' cognitive behaviour in parametric design. **International Journal of Architectural Computing**, v. 13, n. 1, p. 83-101, Marc. 2015. DOI: https://doi.org/10.1260/1478-0771.13.1.83.

ZINZI, M.; AGNOLI, S. Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. **Energy and Buildings**, v. 55, p. 66-76, Dec. 2012. DOI: https://doi.org/10.1016/j.enbuild.2011.09.024.

APPENDIX A – Representations of the building solutions

Figure A1 shows one of the building configurations in perspective, and Figure A2 is the blueprint considering ventilation. Figure A3 shows the blueprint of building solutions with layout by changing the orientation and topography and considering future expansions.

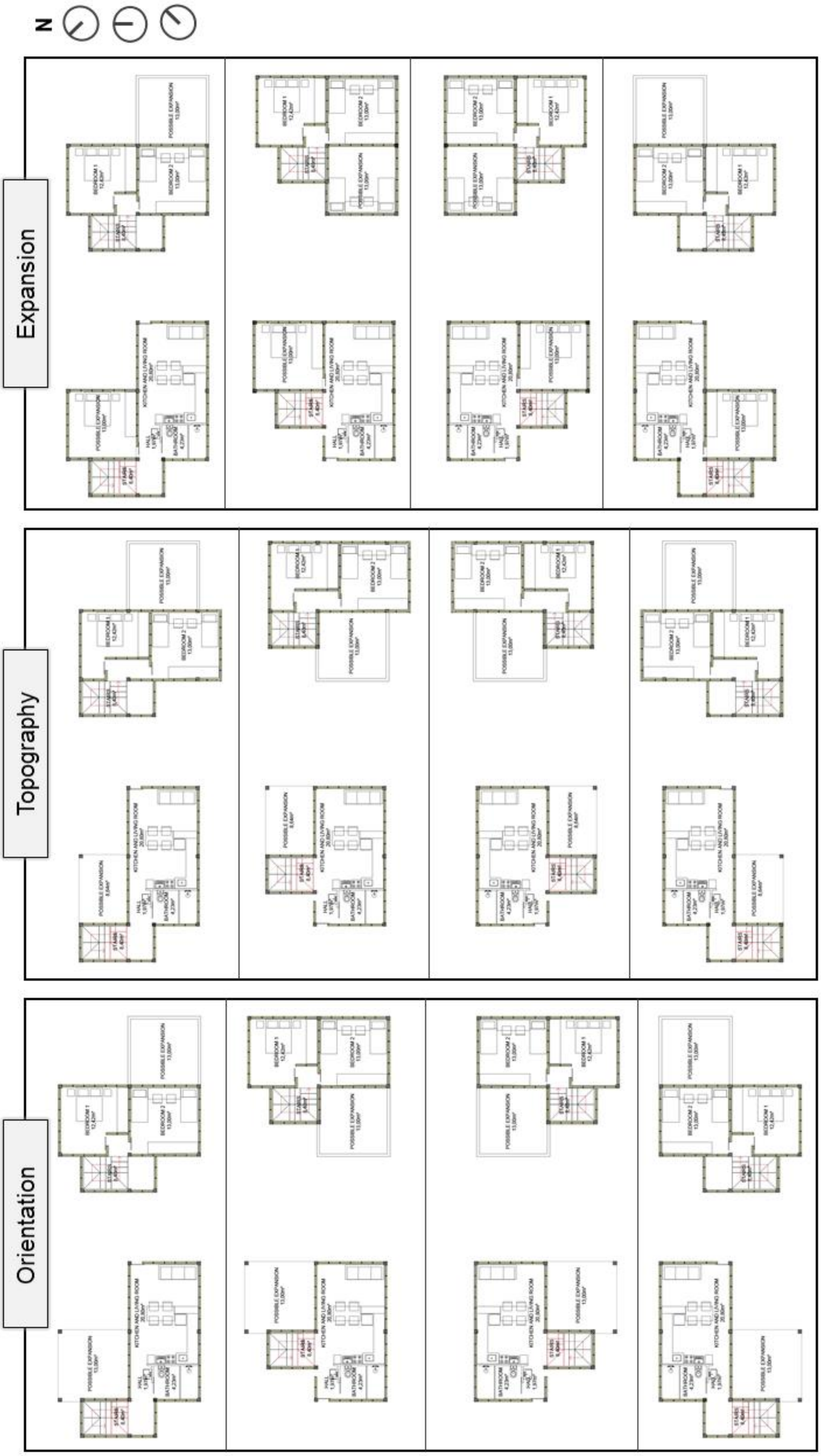
Figure A1 – Sections of one building configuration

Source: Souza (2017).

Figure A2 – Ventilation

Source: Souza (2017).

Figure A3 – Blueprints of the solutions with the layout

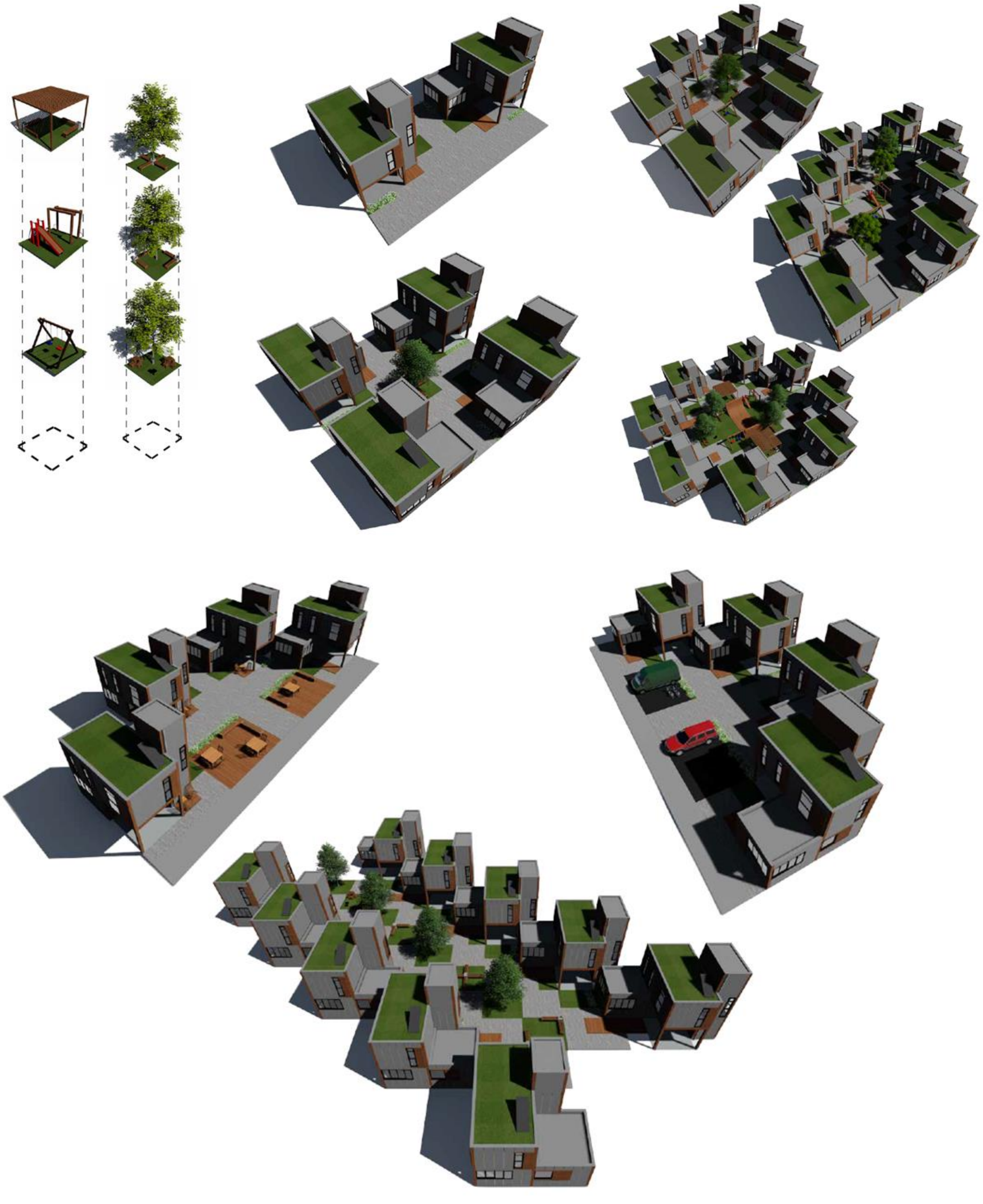


Source: Souza (2017).

APPENDIX B – Combinations of modules to implantations

Figure B1 shows some building combinations in different ways to enhance available public spaces. To better represent the implementation of the building solutions and combinations, Figure B2 shows the implementation in two terrain types, and Figure B3 some examples in perspective.

Figure B1 – Module combinations



Source: Souza (2017).

Figure B2 – Implementation in two terrain types

Source: Souza (2017).

Figure B3 – Implementation examples

Source: Souza (2017).

---

1 **Larissa Pereira de Souza**
Architect and Urban Planner. Master in Architecture and Urbanism at the Federal University of Santa Catarina. PhD student in Architecture and Urbanism at the Federal University of Santa Catarina. Postal address: Departamento de Arquitetura e Urbanismo – CTC/UFSC – Campus Trindade - Rua Eng. Agronômico Andrei Cristian Ferreira, 662, Florianópolis, SC – Brasil. 88040-900

2 **Mateus Bavaresco**
Civil Engineer. PhD in Civil Engineering from the Federal University of Santa Catarina. Post-doctorate in Civil Engineering at the Federal University of Santa Catarina. Postal address: Departamento de Engenharia Civil – CTC/UFSC – Campus Trindade - Rua João Pio Duarte Silva, 205, Florianópolis, SC – Brasil. 88040-900

3 **Matheus Soares Geraldi**
Civil Engineer. PhD in Civil Engineering from the Federal University of Santa Catarina. Post-doctorate in Civil Engineering at the Federal University of Santa Catar Postal address: Departamento de Engenharia Civil – CTC/UFSC – Campus Trindade - Rua João Pio Duarte Silva, 205, Florianópolis, SC – Brasil. 88040-900

4 **Carlos Eduardo Verzola Vaz**
Architect and Urban Planner. PhD in Civil Engineering from the University of Campinas. Professor at the Federal University of Santa Catarina. Postal address: Departamento de Arquitetura e Urbanismo – CTC/UFSC – Campus Trindade - Rua Eng. Agronômico Andrei Cristian Ferreira, 662, Florianópolis, SC – Brasil. 88040-900

5 **Enedir Ghisi**
Civil Engineer. PhD in Civil Engineering from the University of Leeds. Professor at the Federal University of Santa Catarina. Postal address: Departamento de Engenharia Civil – CTC/UFSC – Campus Trindade - Rua João Pio Duarte Silva, 205, Florianópolis, SC – Brasil. 88040-900