THERMAL PERFORMANCE ANALYSIS OF NET-ZERO ENERGY BUILDING USING EVOLUTIONARY ALGORITHMS

ANÁLISE DO DESEMPENHO TÉRMICO DE EDIFICAÇÃO DE BALANÇO ENERGÉTICO NULO VIA ALGORITMO EVOLUTIVO

Gisele Goulart Tavares
Marcus Vinícius Ferraz
Eric Vargas Loureiro
Vitor de Castro Nobre
Leonardo Goliatt
Priscila Capriles

Abstract: The zero-energy building, also known as Net-Zero Energy Building (NZEB), is based on the concept of an energy-efficient building that balances its total energy using solutions that aim to mitigate CO2 emissions and reduce energy use in the constructions. Energy consumption in residential and commercial buildings increased between 20% and 40% in developed countries and exceeded the industry and transportation sectors. Due to climate change, by 2050 buildings can consume 20% more energy, with energy performance being the critical element in achieving climate goals and improving energy security. The objective of this paper is to maximize the thermal comfort in an NZEB through the evolutionary algorithm PSO (Particle Swarm Optimization), a technique inspired by the collective intelligence of the animals. For this, different constructive parameters were inserted in a geometric model to identify combinations that offer greater comfort. For the optimization problem of this work, the design parameters were: block type, concrete thickness used in the solid slab, mortar type, window size, door size, and cover type. From the geometric model, an IDF file was generated for the parameterization and subsequent energy simulation of the scenarios created by the PSO in the EnergyPlus software. The exchange of materials and parameter values of the model reached lower hours of discomfort per year in comparison to results obtained in the literature.

1Ph.D. candidate in Computational Modeling, UFJF, giselegoulart@ice.ufjf.br.
2Ph.D. candidate in Computational Modeling, UFJF, marcus.ferraz@engenharia.ufjf.br.
3Ph.D. candidate in Computational Modeling, UFJF, eric.vargas@engenharia.ufjf.br.
4Mechanical Engineer, UnB, vitorcnobre@yahoo.com.br.
5Professor, UFJF, leonardo.goliatt@ufjf.edu.br.
6Professor, UFJF, priscila.capriles@ufjf.edu.br.
Resumo: A edificação de balanço energético nulo, também conhecida como Net-Zero Energy Building (NZEB), baseia-se no conceito de edifício eficiente energeticamente, que equilibra sua energia total usando soluções que visam mitigar as emissões de CO₂ e reduzir o uso de energia nas construções. O consumo de energia em edifícios residenciais e comerciais aumentou entre 20% e 40% nos países desenvolvidos e excedeu os setores industrial e de transportes. Devido às mudanças climáticas, até 2050 os edifícios poderão consumir 20% mais energia, com o desempenho energético sendo o elemento crítico para alcançar as metas climáticas e melhorar a segurança energética. O objetivo deste artigo é maximizar o conforto térmico em um NZEB através do algoritmo evolutivo PSO (Particle Swarm Optimization), uma técnica inspirada na inteligência coletiva dos animais. Para isso, diferentes parâmetros construtivos foram inseridos em um modelo geométrico para identificar combinações que ofereçam maior conforto. Para o problema de otimização deste trabalho, os parâmetros de projeto foram: tipo de bloco, espessura do concreto usado na laje sólida, tipo de argamassa, tamanho da janela, tamanho da porta e tipo de cobertura. A partir do modelo geométrico, um arquivo IDF foi gerado para a parametrização e subsequente simulação de energia dos cenários criados pelo PSO no software EnergyPlus. A troca de materiais e os valores dos parâmetros do modelo atingiram menores horas de desconforto por ano em comparação aos resultados obtidos na literatura.

1 INTRODUCTION

The Net-Zero Energy Building (NZEB) concept is no longer perceived as a concept of a remote future but as a realistic solution for the mitigation of CO₂ emissions and/or the reduction of energy use in the building sector. The increasing number of NZEB demonstration projects and research interest in the field internationally highlights the growing attention given to NZEB (NOGUCHI A. ATHIENITIS, 2008; HEINZE, 2009; MUSALL T. WEISS, 2010).

Goals for the implementation of NZEB are internationally discussed and proposed, for example, in the USA within the Energy Independence and Security Act of 2007 (EISA 2007), and in Europe within the recast of the Directive on Energy Performance of Buildings (EPBD) adopted in May 2010. In Brazil, the first time it was considered energy efficiency in buildings dates back to 2007 when the National Energy Plan (PNE) discussed subjects such as estimation of demand and supply of energy, as well as energy strategies and policies.

Energy consumption of buildings, both residential and commercial, has increased reaching figures between 20% and 40% in developed countries and has exceeded the other major sectors: industrial and transportation (PÉREZ-LOMBARD; ORTIZ; POUT, 2008). By 2050, buildings may consume 20% more energy just because of changes in climate. Currently, major contributors to energy consumption are HVAC (heating, ventilation, and air conditioning) unit and electrical appliances which account for 49% and 34% of building energy usage, respectively in Brazil. Energy performance of buildings is a key element to achieve climate and energy objectives, more specifically, a 20% reduction of the greenhouse gases emissions and 20% of primary energy savings (EICHHAMMER T. FLEITER, 2009; WESSELINK, 2009; BOERMANS, 2011).

There is a growing interest in reducing building energy consumption since the potential for developments is high. For this reason, energy efficiency in buildings is today a prime objective for energy policy at regional, national and international levels. Various building automation strategies are designed focusing on balancing the energy consumption and environmental comfort.

Since air conditioning can represent 42-68% of a household’s energy consumption (PÉREZ-LOMBARD; ORTIZ; POUT, 2008), one of the main ways to reduce it is the search for passive air conditioning solutions, such as the use of natural ventilation, favoring the execution of architectural projects which, in turn, must take into account several aspects ranging from technical-constructive variables to climatic factors where the analysis building is inserted. The combination and correct application of these variables will result in adequate thermal comfort inside the building (SILVEIRA et al., 2014).
Two thermal performance standards for buildings are currently in force in Brazil: NBR 15220 (ABNT, 2005) and NBR 15575 (ABNT, 2013). The constructive guidelines of NBR 15220 (ABNT, 2005) are applied to social interest, and NBR 15575 (ABNT, 2013) is applied to all types of residential buildings. For Sorgato, Melo e Lamberts (2014), the standards show differences in the percentage of opening for ventilation of the environments, and also, small differences in the limits of thermal properties of the wall and roof components. Brazil does not have thermal comfort standards for naturally ventilated buildings. For this reason, the thermal comfort conditions are defined by ASHRAE 55/2013 - Environmental Conditions for Human Occupancy (STANDARD, 2013).

ASHRAE 55/2013 (STANDARD, 2013) presents an approach to evaluate thermal performance in naturally ventilated buildings. In order to determine the thermal comfort of occupants of the building, the proposed adaptive method defines acceptable temperature ranges for 80% and 90% of occupants and uses the concept of operating temperature - which correlates effects of dry bulb temperature, radiant temperature and air velocity - as the main indicator of comfort. The comfort temperature range varies from 17°C to 31°C for acceptability of 80%, and from 18.5°C to 30.5°C for 90% of acceptability (SUDBRACK, 2017).

This standard predicts that the average monthly external temperature used to determine the acceptable limits of internal temperatures is the simple mean of the average external temperature of the last 30 days and correlates the temperature range of comfort with the occurrence of external temperatures, allowing the comparison between buildings located in different climates (NICOL; HUMPHREYS; ROAF, 2012).

In the context of this research, we found in the literature some papers that have resorted to the adaptive method as a form of computational simulation of buildings, including the analysis of different design variable (SILVEIRA et al., 2014; FREIRE; OLIVEIRA; MENDES, 2008). Most of these simulations have been carried out through the Energy Plus software. However, intelligent algorithms are currently being developed, based on several different parameters, for the optimization of energy consumption and thermal comfort in the modeled buildings, obtaining favorable scenarios.

Carlucci e Pagliano (2013) used the particle swarm optimization algorithm (PSO) to minimize thermal discomfort rates in the design of a single-family house located in Mascalucia (CT) in southern Italy. With the same objective, Bojic, Parvedy e Boyer (2013) modeled a typical residential house with five thermal zones on Réunion Island in France via EnergyPlus and used the Hooke-Jeves optimization algorithm to find the wall compositions that provide the best thermal comfort of the building. The simulation-based artificial neural network introduced by Magnier e Haghighat (2010) was combined with NSGA-II to optimize thermal comfort and
energy consumption of a residential house.

Sudbrack (2017) and Nobre (2018) identified the potentialities and limitations that the prefabricated residential typology presents for the construction of null energy balance houses in the climatic context of Brasília, taking into account aspects of use, occupation, and natural ventilation, using the adaptive approach proposed by the ASHRAE 55/2013 standard.

The motivation of this paper emerges from the conception of a project presented by Nobre (2018), and thus, based on this residential typology, with a special focus on building materials, the aim of this study is to optimize a parametrized energy model using evolutionary algorithms to maximize the thermal comfort of the zero energy balance building. For this, other materials were inserted to the model constructed by Nobre (2018), in order to increase the sample space, aiming to better approximation with the real problem and making possible different combinations between the materials.

In this way, it is sought to identify a combination that offers greater thermal comfort to the users, and has a greater influence on the energy balance, as effective forms of contribution in the improvement of the quality of the environment and the constructed spaces experienced daily.

2 MATERIAL AND METHODS

2.1 NZEB Model

The model built in this work based on Sudbrack (2017) and Nobre (2018) consisted of a modular prefabricated dwelling of 108m$^2$, comprising of a kitchen-living room, a bathroom, three bedrooms (one suite) and a balcony. It locates on a plot of land equivalent to 700m$^2$ in a residential condominium southeast of the Plano Piloto - Santa Monica Condominium - in Brasilia/DF.

The residential occupation is that of a family of 4 residents, consisting of a couple and two children. In the period from 9 a.m. to 12 p.m. it is assumed that two persons remain in residence; From 1:00 p.m. to 7:00 p.m., three people, and from 7:00 p.m., everyone is at home. All the residents occupy the living room-kitchen. Bedroom 1 has a maximum occupancy of two people, and bedrooms 2 and 3 have a maximum occupancy of one person each. It’s worth mentioning that the model not considered the periods in which the house would be vacant.

Residents are expected to use artificial lighting only in 30% of daily hours. Once the bathrooms set up short-stay environments of the users, it established only 1h of artificial lighting use.
In order to predict the energy consumption and thermal load of the residence, it was considered the standard of use of the electrical equipment present in each environment: in the kitchen-room, an induction cooktop, oven, refrigerator, washer and dryer, dishwasher, and television; in room 2, a computer. It estimated a power equal to 50W due to LED illumination for each room.

Because it is a prefabricated house, easy to set up in any terrain and orientation, it adopted the west orientation for the façade with a higher percentage of glazed openings and lower protection angles, which corresponds to the worst direction (azimuth 0°).

Figure 1: Three-dimensional model of the Net Zero Energy Building.

Source: Authors

It inserted the brises to attenuate the effect of solar incidence on glazed surfaces. It modeled two flat surfaces on the roof that simulate the shading effect caused by photovoltaic panels to be installed in the zero house.

It carried out the simulations using the EPW - Energy Plus Weather File (INMET, 2016) for the city of Brasilia (Latitude 15° 46’ 48” South, Longitude 47° 55’ 45” West). The data files are timed, and present each of the 8760 hours of the year, allowing an accurate hourly evaluation of the simulations.

For the simulation of natural ventilation, one of the parameters of such relevance is the effective ventilation area of the openings, which allows the exchange of air between the environment and the outside. For the small glass door that communicates the kitchen room with the external environment and for the other internal doors of the house, it used an active area of 50% when opened. For the glazed sliding doors that communicate the living room with the external environment, divided into four panels of glass, the effective area considered was 75%.
when opened. It recognized an effective area of 100% for the bedroom windows and 50% for the windows of the bathrooms. Figure 1 shows the constructive model of the zero house used for the thermo-energetic simulation of the residence in question.

2.2 Design Parameters

With the objective of search options that minimize the number of uncomfortable hours, a set of design parameters was selected for building parts materials and properties be changed. Table A that is presented in Figure 2 shows the chosen variables for different scenarios simulations that will be optimized via Particle swarm optimization. In the case of roofs and walls, materials composition was changed with the purpose of evaluating the simulation performance using materials combinations.

In relation to the composition of the walls, three types of block and mortar were used: ceramic, concrete, and soil-cement blocks, and traditional, cellular, and plaster mortar. For the roof, the evolutionary algorithm considered four possibilities, namely: cross-laminated timber, solid concrete slab, trussed slab, and a green roof. In the case of solid concrete slab, the thickness was included as an extra design parameter in the optimization, being expressed when the algorithm selects the solid concrete slab as the roof of the building. Information about the composition of the roofs and properties of the materials used can be accessed through the link https://bit.ly/2ysNikY.

For the windows and outside doors, the width increase tested address to estimate the impact of the gain of the light entrance and air circulation in the modeled structure. In the case of windows, 4 possible values for the increase were distributed in the range \([0, 0.15m]\) and for the doors, 7 possible values to be tested were distributed in the range \([0, 0.3m]\).

2.3 Evolutionary Settings of Parameters

Particle Swarm Optimization (PSO) (KENNEDY, 2011) is a stochastic population-based search method inspired by the social behavior of animals such as birds and fish. In PSO, each individual, called a particle, flies through the problem space and adjusts its position according to its own experience and the experience of its neighbors. A particle can fly either fast and far from the best positions to explore unknown areas (global search), or very slowly and close to a particular position (fine-tune) to find better results. Each particle has a virtual position that represents a possible solution to some minimization problem. PSO is quite simple to implement and has few control parameters. The Equations presented in (1) are the two fundamental update
rules of standard PSO.

\[
\begin{align*}
& v_i(t + 1) = \omega v_i(t) + c_1 r_1 (p_i(t) - x_i(t)) + c_2 r_2 (p_g(t) - x_i(t)) \\
& x_i(t + 1) = x_i(t) + v_i(t + 1)
\end{align*}
\]

where \( v_i \) and \( x_i \) are velocity and position vectors of the particle \( i \), respectively, \( p_i \) is the best local position found by the particle \( i \), and \( p_g \) is the best global position found in the whole population. The two parameters \( c_1 \) and \( c_2 \) are positive constants, called learning factors; \( c_1 \) presents how much a particle is attracted to its best position, and \( c_2 \) is the same for the global position. Values of these two parameters may vary depending on the nature of the problem but they are usually considered to be equal to 2.0; \( \omega \) is the inertia weight; \( r_1 \) and \( r_2 \) are uniform random variables providing the stochastic aspect of the algorithm.

In this paper, each particle encodes a network candidate solution. Considering the PSO approach, the goal is to find one scenario that minimizes uncomfortable hours in NZEB building.

### 2.4 Computational Method

The PSO algorithm was used in association with EnergyPlus software to search for scenarios that minimize uncomfortable hours inside the NZEB. Using the geometric mean of hours of discomfort values in each room as an objective function (Equation 2), we tried to obtain an uncomfortable time homogeneity in each room of the house. This strategy avoids the occurrence of large uncomfortable periods in one room and neither in another.

\[
OF = \left( \prod_{i=1}^{n} x_i \right)^{\frac{1}{n}} = \sqrt[n]{x_1 x_2 \cdots x_n}
\]

where \( x_i \) represents values of discomfort hours and \( n \) is the number of rooms.

Initially, the geometric model IDF extension file was parameterized, allowing certain sections of the file to be modified using a script without compromising the syntax recognized by EnergyPlus. After modifying the IDF file, the script uses EnergyPlus to run the energy model simulation and parses the output files to extract acceptable limits. Thus, the PSO could be used to optimize the model parameters described in Table A that is presented in Figure 2, acting on the generation of scenarios and analysis of the objective function. Figure 2 presents the data flow in the algorithm that evaluates and simulates the design parameter combinations.
3 RESULTS AND DISCUSSIONS

In this section, we present the results obtained for the minimization of uncomfortable hours in the NZEB model described in Section 2. We ran each computational experiment 30 times. In the model selection step, PSO was set with the following parameters: 15 individuals in the population evolving under 35 generations; parameters $c_1$, $c_2$ were set to 2.05, respectively; $\omega = 0.7298$ for all generations; the objective function (to be minimized) is the geometric mean of the acceptability limits calculated using EnergyPlus. The range of parameters is shown in Table A that is presented in Figure 2.

The computational experiments were conducted based in PyGMO framework (IZZO, 2012) and implementations adapted from Hastie, Tibshirani e Friedman (2009). All codes and data are made available by the authors upon request. Computer specifications are given as follows: CPU AMD Opteron Processor 6272 (32 cores of 2.1GHz and cache memory of 2MB), RAM of 250GB and operational system Linux Ubuntu 14.04.4 LTS.

Figures 3 and 4 presents the frequencies of the evolutionary algorithm choices for the

---

**Table A with the design parameters used to generate different scenarios simulations.**

<table>
<thead>
<tr>
<th>Position</th>
<th>Description</th>
<th>Range/Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_0$</td>
<td>Block Type</td>
<td>0: Ceramic; 1: Concrete;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2: Soil-Concrete</td>
</tr>
<tr>
<td>$x_1$</td>
<td>Concrete Thickness</td>
<td>0: 0.08; 1: 0.10; 2: 0.12 m</td>
</tr>
<tr>
<td>$x_2$</td>
<td>Mortar Type</td>
<td>0: Traditional; 1: Gypsum;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2: Cellular</td>
</tr>
<tr>
<td>$x_3$</td>
<td>Increased Doors</td>
<td>0: 0.00; 1: 0.05; 2: 0.1; 3: 0.15; 4: 0.25; 5: 0.5; 6: 0.75; 7: 1.0 m</td>
</tr>
<tr>
<td>$x_4$</td>
<td>Increased Windows</td>
<td>0: 0.0; 1: 0.05; 2: 0.10;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3: 0.15 m</td>
</tr>
<tr>
<td>$x_5$</td>
<td>Roof Type</td>
<td>0: Cross Laminated Timber;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1: Solid Concrete Slab;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2: Trussed Slab; 3: Green Roof</td>
</tr>
</tbody>
</table>

---

**Figure 2:** Data flow from model IDF to PSO algorithm.

**Source:** Authors
constructive parameters used in this paper over the 30 independent executions. For the mortar used for the wall cladding of the NZEB model (Figure 3 (a)), the traditional type presented a better performance in all runs. A similar situation occurred with block type frequency distribution (Figure 3 (b)), as the concrete block was selected in 28 out of 30 runs, indicating that it is a more suitable choice for masonry wall construction when compared with ceramic and soil-cement blocks in relation to thermal comfort.

Figure 3: Frequencies of the evolutionary algorithm choices for the types of mortar, block and cover.

Source: Authors

Figure 3 (c) indicates that the use of cross-laminated timber or green roof is more efficient when it comes to minimizing discomfort hours, reaching frequencies of 16 and 14, respectively. Although cross-laminated timber was selected in just over half of the total number of executions, the use of green roof can bring benefits outside the home, both architectural and environmental.

The original size of the model’s windows was adequate because, as can be seen in Figure 4 (a), the algorithm returned solutions without increasing the size of the windows by 26 out of 30 times. For the doors (Figure 4 (b)) and, the highest frequencies occurred with the addition of 5cm and 15cm on each side of the component, indicating that increased light intake and air
circulation at NZEB from the doors produced a decrease in the hours of discomfort.

Figure 4: Frequencies of the evolutionary algorithm choices for the increments of windows and doors.

Source: Authors

For the model studied, the PSO converged to the objective function value 56.15 from the 14th generation. Considering the materials and configurations with higher frequencies in each of the parameters, the configuration that presented the lowest objective function value has in its composition: traditional mortar, concrete blocks, cross-laminated timber, windows in their original size and an increase of 5cm in the doors. Table 1 presents the values of hours of discomfort in each room for the best scenario returning by the PSO and the relative error (RE) in relation to the work developed by Nobre (2018). Considering the geometric mean as an objective function, an improvement of 27% was achieved compared to the base model developed by Nobre (2018). For all rooms, a reduction in discomfort hours was achieved by changing constructive parameters.

Table 1: Comparative between hours of thermal discomfort for the best scenario returning by the PSO and the reference model.

<table>
<thead>
<tr>
<th></th>
<th>Reference (hours)</th>
<th>PSO (hours)</th>
<th>Relative Performance Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obj. Function</td>
<td>77.88</td>
<td>56.15</td>
<td>-27%</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>3</td>
<td>1</td>
<td>-67%</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>488</td>
<td>469</td>
<td>-4%</td>
</tr>
<tr>
<td>Bedroom 3</td>
<td>41</td>
<td>37</td>
<td>-10%</td>
</tr>
<tr>
<td>Living Room/Kitchen</td>
<td>613</td>
<td>573</td>
<td>-6%</td>
</tr>
</tbody>
</table>

Source: Authors
4 CONCLUSIONS

After the end of the analysis made by the PSO, it is possible to conclude that the algorithm presented satisfactory results in the search for more energy-efficient combinations, presenting a reduction in the discomfort hours of up to 27%. In addition, in every room of the house, there was an improvement (more hours of thermal comfort), thus confirming that the material changes and parameters of the model reached the goal.

With this result, it cannot be said that this is the best combination available for this dwelling, given that only some other material and parameter options were tested among the various options currently available. However, we can say that studies like this give the possibility of predicting a better scenario, that is, a prior analysis of what will be good or bad for each type of housing. It is much more practical to build a house with all the materials right than to have to change something. It is a saving of money and time. And while in some cases the materials to be used may be more expensive than others, this investment will pay off over time, as housing comfort will be better, avoiding the use of energy-consuming electrical appliances.

To have full confirmation of an improvement it would be necessary to compare with other evolutionary algorithms, even to observe the characteristic of each algorithm and thus be sure which one is best suited to meet these types of studies. Moreover, for future work, it would be interesting to test multiobjective analyzes in order to capture more changes (through the analysis of more study variables) and thus obtain an even more satisfactory result.

ACKNOWLEDGMENTS

This work was supported by the Universidade Federal de Juiz de Fora (UFJF), FAPEMIG (grant 00334/18), CNPq (grant 429639/2016-3) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

REFERENCES


NOBRE, V. d. C. Análise da solução de climatização passiva para habitação pré fabricada de balanço energético nulo em brasília. 2018.


Edição especial - XXII ENMC (Encontro Nacional de Modelagem Computacional) e X ECTM (Encontro de Ciência e Tecnologia dos Materiais)

Enviado em: 29 mar. 2020
Aceito em: 13 mai. 2020
Editor responsável: Rafael Alves Bonfim de Queiroz