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Fuzzy logic application in the evaluation of energy efficiency in buildings in Brazil

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ABSTRACT. Energy is a resource that has become indispensable to contemporary life, as it is present in everyday life in all areas. However, this important resource is limited, and during its production, it has great potential to generate socio-environmental problems. Since buildings are one of the main energy consumers, using energy efficiency to soften consumption is essential. To this end, Brazil has the Technical Quality Regulation for the Energy Efficiency Level of Commercial, Service and Public Buildings (RTQ-C), developed by the National Electricity Conservation Program (PROCEL), which grants the evaluation of energy efficiency in buildings. Nevertheless, the RTQ-C includes only five levels of classification and does not consider the uncertainties associated with the analysis parameters. To broaden this assessment, fuzzy logic is an option that provides the determination of sub-levels and more scope for the classification. Thus, the present work aims to propose a fuzzy logic-based model that can assess the energy efficiency of buildings deriving from the RTQ-C parameters. A case study is used to show the applicability and functionality of the proposed model. Using the methodology provided by the RTQ-C manual and by fuzzy logic, it was possible to arrive at a rule base, which provides a more realistic perspective on the energy assessment of a building. The results showed that fuzzy modeling is feasible and more comprehensive, it can be used in other buildings and research with similar characteristics, as well as by managers of public and private companies that seek to evaluate, manage, and make more accurate decisions regarding the energy efficiency of buildings under their responsibility, bringing economic, social, and environmental benefits.

Keywords: RTQ-C; fuzzy inference system; Energy efficiency; buildings.

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Introduction

In addition to the growing population volume, the world is in full technological and industrial development, something that reflects in the consumption *per capita* of electrical energy, which has been increasing mainly in developed and developing countries. Associated with this phenomenon, people have also been looking for more comfort and well-being, and these factors combined create the projection that the consumption of electric energy, in the coming years, is going to remain on an exponential rise (Iwaro & Mwasha, 2010).

In Brazil, the demand for energy has also grown over the years. Between 1995 and 2019, there was an increase of 95% of this consumption and, specifically in the period from 2018 to 2019, the increase was almost 1%, while the supply increased by approximately 2%. Although there is an offer with greater growth, this difference is considered small, given the importance of this resource (Energy Research Company, 2019).

Another point to consider is that the generation of energy can generate serious socio-environmental damage. At this point, Brazil stands out for having 83% of its energy matrix based on renewable resources, mainly hydroelectric, which can account for 66% of all energy generated in the country, followed by biomass, with 8.5%, and wind energy, with 7.6 % (Energy Research Company, 2020). However, the other 17% that is not based on renewable resources can still have serious impacts on both society and the environment. Although on a much smaller scale, such problems cannot and should not be disregarded (Silveira, 2018).

In 2018, the largest energy consumers in Brazil were industries (27.0%), households (18.0%), the commercial sector (12.3%), the public sector (5.9%), the energy sector itself (4.3%), and the agricultural sector (4.1%) (Energy Research Company, 2020).

In this sense, companies in different sectors are beginning to seek practices that guarantee a lower energy consumption, without jeopardizing their results (Marques, Fuinhas, & Tomás, 2019). Therefore, the measures employed must vary in nature, considering multiple and generally competitive objectives, such as energy consumption, financial costs, environmental performance, and others (Diakaki et al., 2010).

One way to alleviate the highlighted problems is through energy efficiency that is, through the efficient use of energy to obtain results. According to the Brazilian Association of Energy Conservation Companies (ABESCO, 2024), energy efficiency consists of the difference between the amount of energy used in an activity and that which is available for its realization. Therefore, the smaller this difference, the greater the degree of efficiency, bringing a series of positive impacts to society in the economic and environmental spheres, such as the reduction of greenhouse gases and savings in operating costs (Ruparathna, Hewage, & Sadiq, 2016).

Energy efficiency plays an important role in sustainable development. The 2030 Agenda of the United Nations includes 17 Sustainable Development Goals (SDGs) and 169 targets, one of which, the SDG 7, aims to 'ensure access to affordable, reliable, sustainable and modern energy for all'. The goal 7.3 is to double the overall rate of improvement in energy efficiency and, in this sense, scientific community has intensified studies on this theme (Opoku, Edwin, & Agyarko, 2019).

One of the main consumers of energy, with the most potential for improvement, is the building, since most of those have an inefficient energy consumption, due to the fact that they were built without considering the optimization of energy consumption, mainly in relation to thermal comfort and lighting (Yi & Bing, 2017; Martinopoulos, Papakostas, & Papadopoulos, 2018; Aslani, Bakhtiar, & Akbarzadeh, 2019). In this sense, many constructions are already being made, from the beginning, seeking to meet this demand (Abu Bakar et al., 2015; Yi & Bing, 2017; Ceballos-Fuentealba, Álvarez-Miranda, Torres-Fuchslocher, Del Campo-Hitschfeld, & Díaz-Guerrero, 2019).

About 15% of all energy consumed in Brazil is related to the buildings (Energy Research Company, 2020). As a way of seeking more efficient energy consumption, the country counts on the Technical Quality Regulation for the Energy Efficiency Level of Commercial, Service and Public Buildings (RTQ-C) of the National Electricity Conservation Program [PROCEL] (2017), which grants an assessment of the energy efficiency of a given building through analyses made from the perspectives of wrap, air-conditioning, and lighting (Wong & Krüger, 2017). The RTQ-C was introduced in 2009 to create energy efficiency rating labels (Veloso, Souza, & Koury, 2015). Methodologies such as Brazil's RTQ-C and China's Three Star Rating Building System have helped developing countries to improve efficiency and the energy performance of their buildings by enabling more in-depth analysis and evaluation of energy issues (Muldoon-Smith & Greenhalgh, 2019).

However, the RTQ-C covers only five classification levels, ranging from A (maximum efficiency) to E (minimum efficiency), and it does not consider the uncertainties associated with the analysis parameters. To make the assessment broader and more accurate, fuzzy logic emerges as an option for determining sub-levels that bring more scope to this classification.

Fuzzy logic seeks to mimic human reasoning by creating computational rules that allow for a detailed assessment, applicable in different areas. Thus, by the design of generic algorithms, obtained from this logic, Fuzzy Inference Systems (FIS) are created (Zadeh, 1965).

Some works in the literature propose the use of fuzzy logic in the context of assessing energy efficiency in buildings, showing the feasibility of this approach, and providing relevant results (Chung, 2012; Kabak, Köse, Kırılmaz, & Burmaoğlu, 2014; Mpelogianni, Marnetta, & Groumpos, 2015; Killian & Kosek, 2018; Hernández, Sanz, Corredera, Palomar, & Lacave, 2018; Mpelogianni & Groumpos, 2019; among others). Nevertheless, there are no studies that address or propose improvements to RTQ-C using this mathematical modeling.

Thus, this work aims to propose a fuzzy logic-based model that can assess the energy efficiency of buildings deriving out of the RTQ-C parameters. A case study carried out in a company in the retail sector, located in the state of São Paulo, Brazil, is used to show the applicability and functionality of the proposed model.

Material and methods

RTQ-C classification of energy efficiency of a building

The object of study is a company in the meat retail sector, whose commercial building is located in a city in the western region of the state of São Paulo, Brazil. The company has four employees, one responsible for serving customers, and the others for preparing meat cuts. The company's field of action encompasses the city in which it is located and the other surrounding cities in the region.

To analyze the energy efficiency of the company, the RTQ-C, version 4, April 2017 (PROCEL, 2017) was used. For this, it was also necessary to have the blueprint of the commercial building and to carry out a data collection in the company itself.

The RTQ-C analyzes three efficiency factors in a commercial building: (1) wrap efficiency (WE), (2) lighting efficiency (LE), and (3) air-conditioning efficiency (ACE). Each factor has a level of efficiency that has an equivalent numeric index given by: A = 5 (maximum efficiency); B = 4; C = 3; D = 2; or E = 1 (minimum efficiency). Thus, the wrap efficiency index (WEI), lighting efficiency index (LEI), and air-conditioning efficiency index (ACEI), when applied in an equation, generate the overall energy efficiency index of the commercial building.

According to the RTQ-C manual (PROCEL, 2017, p. 38), WE is a ‘set of constructive elements that are in contact with the outside environment, that is, that make up the closings of the internal environments in relation to the external environment’.

To calculate the WE, it is first necessary to check in which bioclimatic zone the commercial building is located. From Figure 1, it was found that the building from this case study is located in Zone 6 (Z6).

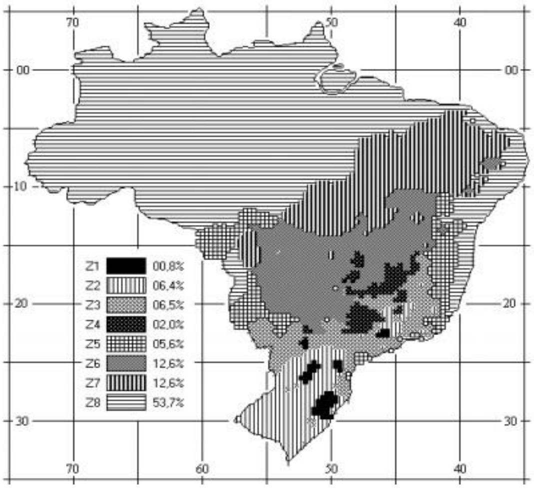


Figure 1. Map of Brazilian bioclimatic zones.
Source: Brazilian Association of Technical Standards (ABNT, 2005)

As the commercial building has a projection area of less than 500 m^2 and is located at Z6, the equation used for calculating the WE, according to the RTQ-C manual, is given by Equation 1:

$$WE = 454.47 \times W1 - 1641.37 \times W2 + 33.47 \times W3 + 7.06 \times W4 + 0.31 \times W5 - 0.29 \times W6 - 1.27 \times W3 \times W5 + 0.33 \times W3 \times W6 + 71 \quad (1)$$

where W1: Height factor (Area of coverage projection / total area); W2: Height factor (Wrap area / Total volume); W3: Opening percentage in the total façade of the building (Average of the percentage of existent openings); W4: Solar factor; W5: Vertical shading angle, and W6: Horizontal shading angle. Thus, the value obtained in Equation 1 will indicate a level of WE of the commercial building (from A to E), which has a numerical equivalent established by the RTQ-C (WEI).

To calculate the LE, it is necessary to mark each lighting spot in the commercial building, as well as the function assigned to each room, since the RTQ-C contemplates the minimum and maximum limit lighting power density (LLPD), in Watts / m^2, for each type of work performed, in order to be considered efficient in levels from A to D. In this way, to obtain the efficiency of each environment, it should be verified how many Watts of light is used in that environment, as well as its use in relation to its area.

With all the environments cataloged, the minimum and maximum limits of each environment for each level are added. Those configure the basis to compare the total Watts consumed and to obtain an LE level of the commercial building (from A to D), which presents a numerical equivalent established in the RTQ-C (LEI).

To calculate the ACE, it is first necessary to map all the devices in this category that exist in the building. Then, the data of each one of them is collected referring to the level of energy efficiency already evaluated by the National Institute of Metrology, Quality and Technology (INMETRO). The power of the devices is also collected, in BTU, and the weighted average of the efficiency indexes is calculated based on the percentage of consumption (in BTU) that each device presents, with each level of efficiency having a numerical correspondent. Therefore, a value will be obtained that will indicate an ACE level of the commercial building (from A to E), which has a numerical equivalent established in the RTQ-C (ACEI).

The equation used to calculate the general energy efficiency index (EEI) of the commercial building is given by Equation 2:

$$\mathrm{EEI} = 0.3 \times \left\{\left(\mathrm{WEI} \times \frac{\mathrm{UA1}}{\mathrm{UA2}}\right) + \left(\frac{\mathrm{UA3}}{\mathrm{UA2}} \times 5 + \frac{\mathrm{UA4}}{\mathrm{UA2}} \times \mathrm{NACEI}\right)\right\} + 0.3 \times (\mathrm{LEI}) + 0.4 \times \left\{\left(\mathrm{ACEI} \times \frac{\mathrm{UA1}}{\mathrm{UA2}}\right) + \left(\frac{\mathrm{UA3}}{\mathrm{UA2}} \times 5 + \frac{\mathrm{UA4}}{\mathrm{UA2}} \times \mathrm{NACEI}\right)\right\} + \mathrm{b} \quad (2)$$

where WEI: Numerical equivalent for WE or WE index; LEI: Numerical equivalent for LE or LE index; ACEI: Numerical equivalent for ACE or ACE index; UA1: Useful area of conditioned environments; UA2: Floor area; UA3: Useful area of transient permanence environments, as long as they are not conditioned; UA4: Useful area of non-conditioned environments of prolonged stay, with proof of percentage of hours occupied by natural ventilation using the simulation method; NACEI: Numerical equivalent or efficiency index for non-air-conditioned and / or naturally ventilated environments, and b: score obtained by the bonuses (involves a series of initiatives, such as saving water and using renewable energy sources), ranging from zero to one.

Finally, to determine the company's classification, according to the EEI of the commercial building, the general energy efficiency classification of the RQT-C (PROCEL, 2017) should be used, as described in Table 1.

Table 1. RTQ-C energy efficiency classification according to EEI.

Classification of energy efficiency	Lower limit of EEI	Upper Limit of EEI
Level A	⩾ 4.5	⩽ 5.0
Level B	⩾ 3.5	< 4.5
Level C	⩾ 2.5	< 3.5
Level D	⩾ 1.5	< 2.5
Level E	⩾ 0.0	< 1.5

Source: PROCEL, 2017.

FIS provides an extremely simple way (through mathematical modeling based on intuitive human knowledge) to solve complex problems. It is composed of variables that contain uncertain information, and it seeks precise solutions in an organized manner, with the maximum possible reliability (Piegat, 2001).

The algorithms based on fuzzy logic consider the 'possibilistic' nature (degree of pertinence) of the variables involved, whose structure is composed of three operations: Fuzzification (input processor), which transforms the initial input data into linguistic variables; Fuzzy inference, which relates the possible variables to each other, through a pre-established rule base; and Defuzzification (output processor), which translates the linguistic result of the fuzzy inference process into a numerical value (Zadeh, 1965).

Among the possible inference mechanisms and greater computational simplicity, there is the method employed by Mamdani, which is used in this work. The responses of the fuzzy controller are calculated according to the input variables, corresponding to the set of rules in the knowledge base. For each rule, the degrees of pertinence between these variables and the corresponding fuzzy sets are evaluated (Mamdani & Assilian, 1975).

The method used in this work to transform qualitative information into quantitative information (defuzzification) is the center of gravity, or centroid, which can be interpreted as a weighted average, where $\alpha(x)$ functions as the weight of the value of x.

For the development of the FIS, to classify the energy efficiency of a building, the input processor, the set of linguistic rules, the inference method, and the output processor were defined. However, to facilitate this process, the area indicators (UA1, UA3 and UA4) were transformed into percentage indicators (UA1', UA3' and UA4'), since, in Equation 2, these indexes appear divided by the UA2. Equation 3 shows Equation 2 rewritten in terms of percentage indicators:

$$\mathrm{EEI} = 0.3 \times \{(\mathrm{NACEI} \times \mathrm{UA1}') + (\mathrm{UA3}' \times 5 + \mathrm{UA4}' \times \mathrm{NACEI})\} + 0.30 \times (\mathrm{LEI}) + 0.4 \times \{(\mathrm{ACEI} \times \mathrm{UA1}') + (\mathrm{UA3}' \times 5 + \mathrm{UA4}' \times \mathrm{NACEI})\} + \mathrm{b} \quad (3)$$

Development of fuzzy model for the classification of energy efficiency of a building

To classify the energy efficiency of a building, a system based on fuzzy rules with the structure represented in Figure 2 was proposed. The FIS input variables for the classification of energy efficiency based on fuzzy rules were selected from the general energy efficiency equation (Equation 3).

The output variable is called the fuzzy energy efficiency index (EEI-fuzzy), and each of the 5 levels of efficiency classification (A, B, C, D, E) of the RTQ-C's EEI was divided into 3 subgroups (A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, D3, E1, E2, E3), totaling 15 categories, or response possibilities, as shown in Table 2. This way, the fuzzy EEI will generate a value that will be classified from A1 (maximum efficiency) to E3 (minimum efficiency).

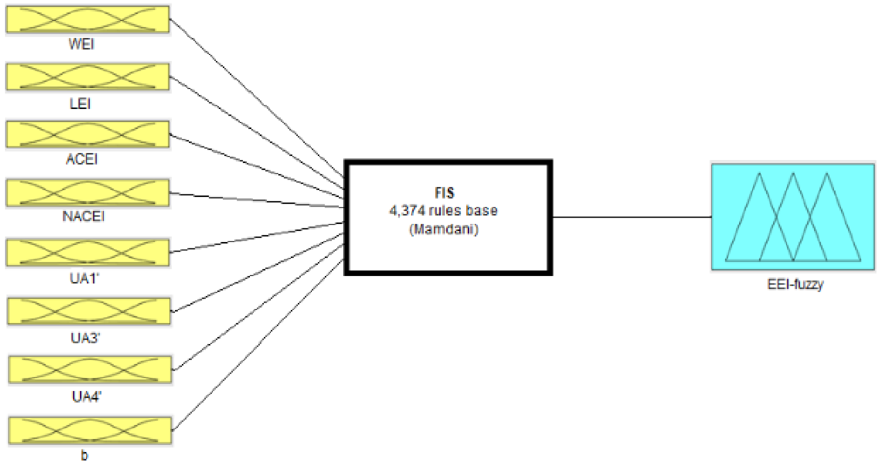


Figure 2. FIS for the classification of energy efficiency (EEI-fuzzy) of a building.
Source: Prepared by the authors.

Table 2. Fuzzy modeling for the classification of the energy efficiency of a building.

Input				Output			
Variables	Range	Fuzzy set: Number of levels	Fuzzy set: Classification levels	Variable	Range	Fuzzy set: Number of levels	Fuzzy set: Classification levels
WEI	1 to 5	3	C1, C2, C3	EEI-fuzzy	1 to 5	15	A1, A2, A3 B1, B2, B3 C1, C2, C3 D1, D2, D3 E1, E2, E3
LEI	2 to 5	3	C1, C2, C3				
ACEI	1 to 5	3	C1, C2, C3				
NACEI	1 to 5	3	C1, C2, C3				
UA1’	0 to 1	3	C1, C2, C3				
UA3’	0 to 1	3	C1, C2, C3				
UA4’	0 to 1	3	C1, C2, C3				
b	0 or 1	2	C1, C2				

Source: Prepared by the authors.

The membership functions defined for the input variables were triangular. Thus, from the variation of each one established in the RTQ-C, fuzzy sets were created, such that: for variables related to areas in percentages (UA1’, UA3’ and UA4’), values between 0.0 (0%) and 1.0 (100%) were adopted, with delimiters defined from a deviation of 0.5 (average of the maximum and minimum limits); for the variables related to efficiency indexes (WEI, ACEI and NACEI), values between 1.0 and 5.0 were adopted, with delimiters defined from a deviation of 2.0 (average of the maximum and minimum limits); and for the LEI variable, values between 2.0 and 5.0 were adopted, with delimiters defined from a deviation of 1.5 (average of the maximum and minimum limits), as shown in Table 3.

Table 3. Membership functions for the FIS input variables.

Input Variable	Range: Min	Range: Max	Fuzzy set	Delimiters: Function type	1	2	3
WEI	1.0	5.0	C1	triangular	-1.0	1.0	3.0
			C2	triangular	1.0	3.0	5.0
			C3	triangular	3.0	5.0	7.0
LEI	2.0	5.0	C1	triangular	0.5	2.0	3.5
			C2	triangular	2.0	3.5	5.0
			C3	triangular	3.5	5.0	6.5
ACEI	1.0	5.0	C1	triangular	-1.0	1.0	3.0
			C2	triangular	1.0	3.0	5.0
			C3	triangular	3.0	5.0	7.0

			C1	triangular	-1.0	1.0	3.0
NACEI	1.0	5.0	C2	triangular	1.0	3.0	5.0
			C3	triangular	3.0	5.0	7.0
			C1	triangular	-0.5	0.0	0.5
UA1’	0.0	1.0	C2	triangular	0.0	0.5	1.0
			C3	triangular	0.5	1.0	1.5
			C1	triangular	-0.5	0.0	0.5
UA3’	0.0	1.0	C2	triangular	0.0	0.5	1.0
			C3	triangular	0.5	1.0	1.5
			C1	triangular	-0.5	0.0	0.5
UA4’	0.0	1.0	C2	triangular	0.0	0.5	1.0
			C3	triangular	0.5	1.0	1.5
b	0.0	1.0	C1	triangular	-1.0	0.0	1.0
			C2	triangular	0.0	1.0	2.0

Source: Prepared by the authors.

Figure 3 shows that the membership functions defined for the fuzzy sets of the input variables are triangular with the linguistic values shown previously in Table 3.

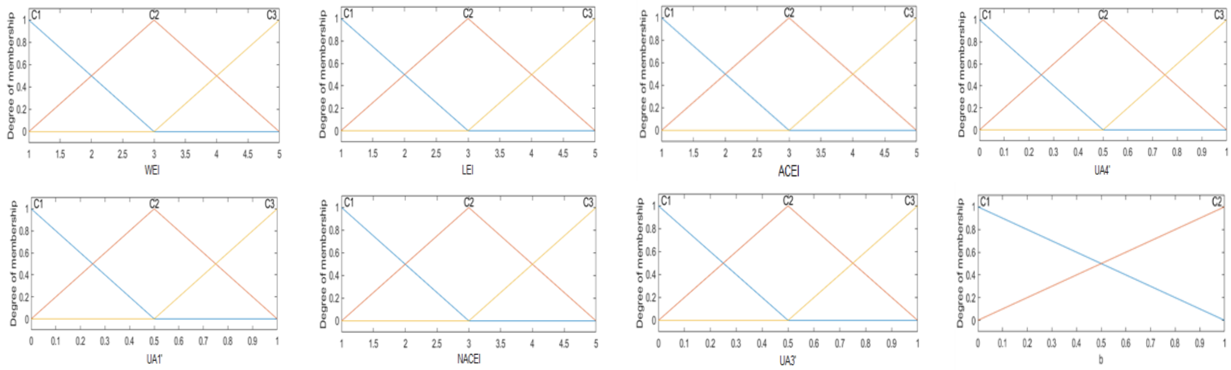


Figure 3. Graphic representation of the membership functions for the FIS input variables.
Source: Prepared by the authors.

For the output variable, pertinence functions of the triangular and trapezoidal types were defined. Accordingly, from the variation of the five classification levels with the respective indexes (A = 5; B = 4; C = 3; D = 2 and E = 1) established by the RTQ-C, fuzzy sets were created, such that, for each level, three sub-levels were determined. It was considered the difference between the maximum and minimum limits of each sub-level divided by 3, with delimiters defined from the variation between the maximum and minimum values of each level of the standard classification. Hence, as the limits of level A are 4.5 and 5.0 (Table 1), then their variation is 0.5 (= 5.0 – 4.5). In a deriving manner, the calculation for each level (A, B, C, D and E) reveals variations of 0.5, 1.0, 1.0, 1.0, and 0.9, respectively. It is observed, in particular, that the limits considered for level E were 0.6 and 1.5, since 0.6 was the lowest possible minimum limit to be obtained. Such variations associated with each category were divided by 3, thus resulting in the sub-level variations of each, as set forth in Table 4.

Table 4. Membership functions for the FIS output variable.

Output Variable	Range		Fuzzy set	Range		Function type	Delimiters			
	Min	Max		Min	Max		1	2	3	4
			E3	0.60	0.90	trapezoidal	-0.30	0.00	0.75	1.05
			E2	0.90	1.20	triangular	0.75	1.05	1.35	-
			E1	1.20	1.50	triangular	1.05	1.35	1.67	-
			D3	1.50	1.83	triangular	1.35	1.67	2.00	-
EEI-fuzzy	0.00	5.00	D2	1.83	2.16	triangular	1.67	2.00	2.33	-
			D1	2.16	2.50	triangular	2.00	2.33	2.67	-
			C3	2.50	2.83	triangular	2.33	2.67	3.00	-
			C2	2.83	3.16	triangular	2.67	3.00	3.33	-
			C1	3.16	3.50	triangular	3.00	3.33	3.67	-

B3	3.50	3.83	triangular	3.33	3.67	4.00	-
B2	3.83	4.16	triangular	3.67	4.00	4.33	-
B1	4.16	4.50	triangular	4.00	4.33	4.59	-
A3	4.50	4.67	triangular	4.33	4.59	4.76	-
A2	4.67	4.84	triangular	4.59	4.76	4.92	-
A1	4.84	5.00	trapezoidal	4.76	4.92	5.00	5.17

Source: Prepared by the authors.

Figure 4 shows that the 15 membership functions defined for the fuzzy sets of the EEI-fuzzy output variable are triangular and trapezoidal with the linguistic values indicated in Table 4.

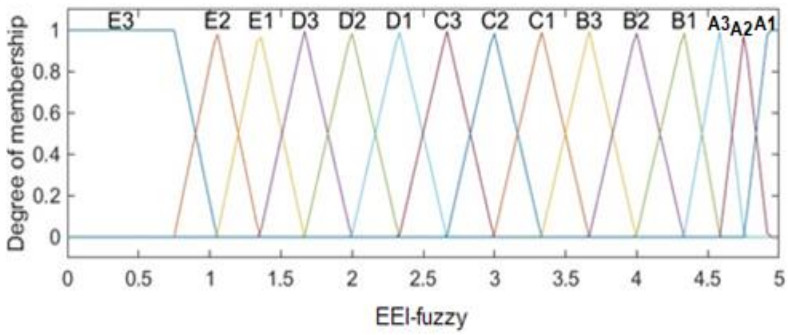


Figure 4. Graphic representation of the membership functions for the FIS output variable.
Source: Prepared by the authors.

To obtain the rule base of the fuzzy system, 4,374 ($3^7 \times 2$) different combinations were considered, from 7 independent variables with 3 fuzzy sets (membership functions with 3 levels each), and one variable with 2 fuzzy sets (membership functions with 2 levels each), treated in a linguistic way with the if-then structure, according to the Mamdani method. The knowledge base of the rules applied in this work, based on the values established in Tables 3 and 4, and in Equation 3, is found in Table 5. This procedure was used similarly by Cremasco, Gabriel Filho, and Cataneo (2010), Martínez et al. (2020), Oliveira, Cobre, and Pereira (2021), Góes, Góes, Cremasco, and Gabriel Filho (2021), and Gabriel Filho et al. (2024).

These rules allow the determining of the energy efficiency index of a building and its level of efficiency. Thus, the first fuzzy rule (rule 1, Table 5) is described as: If (WEI is '1'), (LEI is '2'), (ACEI is '1'), (NACEI is '1'), (UA1' is '0'), (UA3' is '0'), (UA4' is '0'), and (b is '0'), then (EEI-fuzzy is '0.6'). Therefore, the energy efficiency index (EEI) is 0.6 and the energy efficiency (EE) is classified as E3.

Table 5. Fuzzy system rule base.

Rule	WEI	LEI	ACEI	NACEI	UA1'	UA3'	UA4'	b	EEI-fuzzy	Level of efficiency
1	1	2	1	1	0	0	0	0	0.6	E3
2	1	2	3	1	0	0	0	0	0.6	E3
3	1	2	5	1	0	0	0	0	0.6	E3
4	1	3.5	1	1	0	0	0	0	1.05	E2
5	1	3.5	3	1	0	0	0	0	1.05	E2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4370	5	3.5	3	5	1	1	1	1	11.8	A1
4371	5	3.5	5	5	1	1	1	1	12.6	A1
4372	5	5	1	5	1	1	1	1	11.4	A1
4373	5	5	3	5	1	1	1	1	12.2	A1
4374	5	5	5	5	1	1	1	1	13.0	A1

Source: Prepared by the authors.

The last fuzzy rule (rule 4,374 in Table 5) is described as: If (WEI is '5'), (LEI is '5'), (ACEI is '5'), (NACEI is '5'), (UA1' is '1'), (UA3' is '1'), (UA4' is '1'), and (b is '1'), then (EEI-fuzzy is '13.0'). Therefore, under these conditions, the EEI is 13.0 and the EE is classified as A1. The description and interpretation are analogous to the other rules in Table 5.

In addition, the establishment of the rules for the fuzzy set is based on Table 4, so that the relationship that determines the rule base for the level of energy efficiency constitutes the following classification:

1) If EEI-fuzzy < 0.90, then the level of energy efficiency is E3.
2) If 0.90 ⩽ EEI-fuzzy < 1.20, then the level of energy efficiency is E2.
3) If 1.20 ⩽ EEI-fuzzy < 1.50, then the level of energy efficiency is E1.
4) If 1.50 ⩽ EEI-fuzzy < 1.83, then the level of energy efficiency is D3.
5) If 1.83 ⩽ EEI-fuzzy < 2.16, then the level of energy efficiency is D2.
6) If 2.16 ⩽ EEI-fuzzy < 2.50, then the level of energy efficiency is D1.
7) If 2.50 ⩽ EEI-fuzzy < 2.83, then the level of energy efficiency is C3.
8) If 2.83 ⩽ EEI-fuzzy < 3.16, then the level of energy efficiency is C2.
9) If 3.16 ⩽ EEI-fuzzy < 3.50, then the level of energy efficiency is C1.
10) If 3.50 ⩽ EEI-fuzzy < 3.83, then the level of energy efficiency is B3.
11) If 3.83 ⩽ EEI-fuzzy < 4.16, then the level of energy efficiency is B2.
12) If 4.16 ⩽ EEI-fuzzy < 4.50, then the level of energy efficiency is B1.
13) If 4.50 ⩽ EEI-fuzzy < 4.67, then the level of energy efficiency is A3.
14) If 4.67 ⩽ EEI-fuzzy < 4.84, then the level of energy efficiency is A2.
15) If EEI-fuzzy ⩾ 4.84, then the level of energy efficiency is A1.

The proposed mathematical modeling was implemented using the Fuzzy Logic Toolbox tool from MATLAB® 7.0 software, Copyright 1984-2015 The MathWorks Inc. Hence, the computational system based on fuzzy rules was represented by means of surface graphs and contour maps of the analyzed variables.

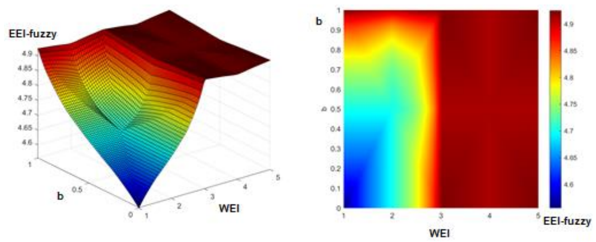
Results and discussion

Energy efficiency general classification of a building using FIS

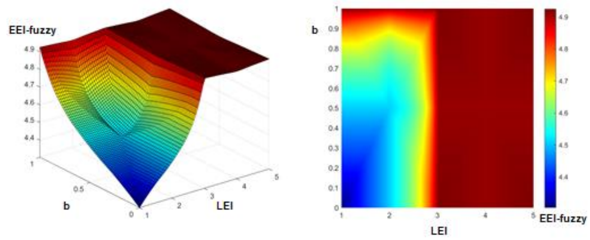
Through the procedure detailed in section 2.2, it was possible to make a general simulation of all the points of the domain membership. Figures 5 to 10 show the 3D fuzzy surfaces of the relationships between the input variables (two by two) and the output variable (EEI-fuzzy), as well as the outline map of the EEI-fuzzy surface in relation to the input variables. The surfaces and contour maps of the analyzed variables provide information that is relevant to the understanding and evaluation of the energy efficiency of a building, according to the proposed fuzzy system.

Figures 5.1 to 5.7 indicate that when WEI, LEI, ACEI, NACEI, UA1', UA3' and UA4' are at their maximum values, the EEI-fuzzy will be high, regardless of the value of the other indicator (b). This behavior shows that, although it is important to obtain bonuses, the improvement of other indexes should be prioritized when the intention is to increase the energy efficiency level of a building.

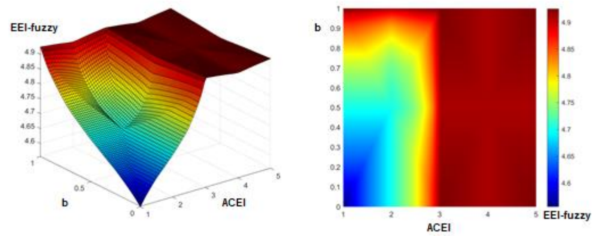
In Figures 6.1 to 6.3, it is observed that the relationship between the percentages of useful area (UA1', UA3', UA4') indicates that the EEI-fuzzy will be high when at least two of them are high, keeping the other constant. Therefore, the energy performance of a building can be substantially improved when at least two useful areas are jointly improved.



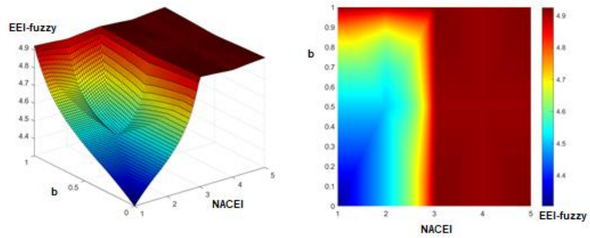
a) (5.1) b)



a) (5.2) b)



a) (5.3) b)



a) (5.4) b)

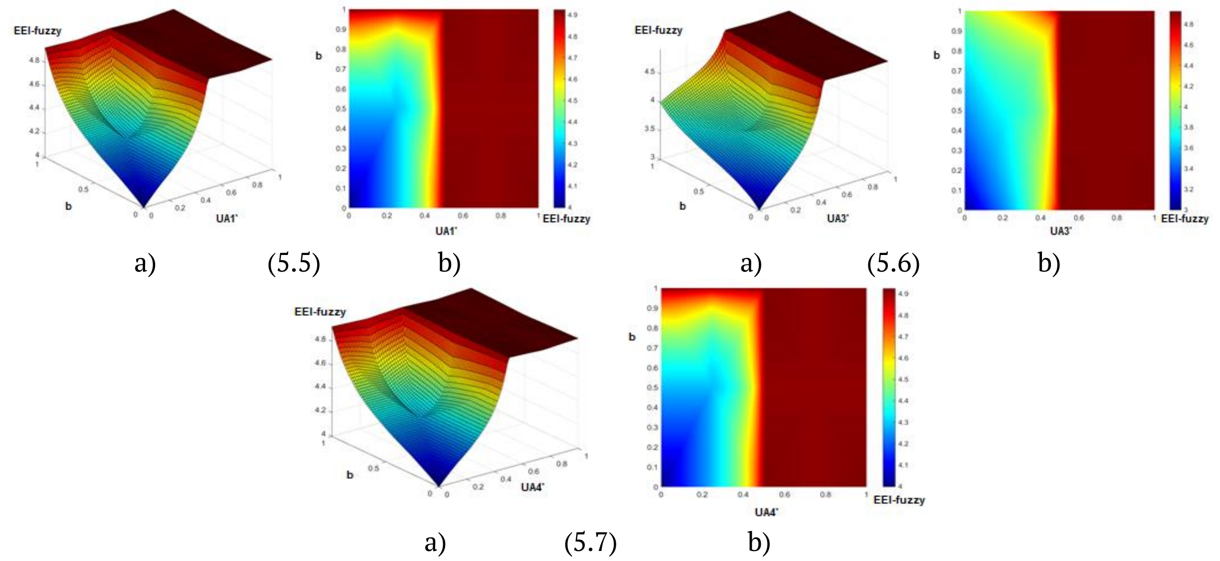


Figure 5. a) 3D fuzzy surfaces of the relationship between the WEI and b input variables (5.1), the LEI and b variables (5.2), the ACEI and b input variables (5.3), the NACEI and b input variables (5.4), the UA1' and b input variables (5.5), the UA3' and b input variables (5.6), the UA4' and b input variables (5.7), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.
Source: Prepared by the authors.

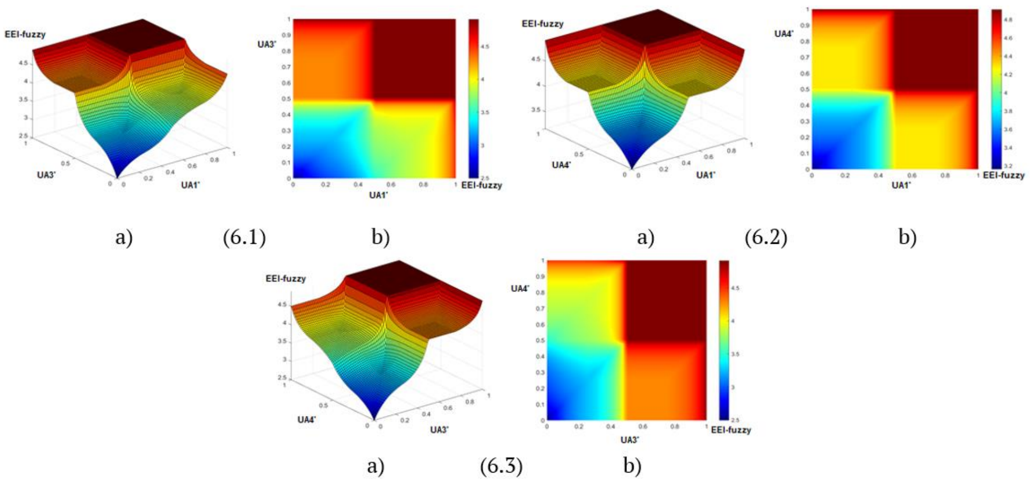


Figure 6. a) 3D fuzzy surfaces of the relationship between the UA1' and UA3' input variables (6.1), the UA1' and UA4' input variables (6.2), the UA3' and UA4' input variables (6.3), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.
Source: Prepared by the authors.

Figures 7.1, 7.2 and 7.3 show that the variation in the WEI does not reflect a significant increase in the EEI-fuzzy of a building, unless it is associated with high percentages (at least 0.4) of useful area (UA1', UA3', UA4'). In addition, Figures 7.4, 7.5 and 7.6 indicate that the variation in the WEI reflects a significant increase in the EEI-fuzzy, especially if the WEI is greater than 3.0 and it is associated with high values (at least 3.0) of the LEI, ACEI and NACEI indexes.

Concerning the percentages of useful area, Figures 8.1, 8.2 and 8.3 indicate that the variation in the LEI reflects a significant increase in the EEI-fuzzy, especially if the LEI is greater than 3.0 and it is associated with high percentages (at least 0.4) of useful area (UA1', UA3', UA4').

Figures 8.4 and 8.5 show that the variation in the LEI reflects a significant increase in the EEI-fuzzy of a building, especially if the LEI is greater than 3.0 and it is associated with high values (at least 3.0) of the ACEI and NACEI indexes.

Lighting efficiency is responsible for approximately 15% of the total energy demand of a building, which means an adequate lighting control system can reduce this demand substantially (Ruparathna, Hewage, & Sadiq, 2016). Haq et al. (2014) consider that the determination of the lighting control system should consider, above all, the behavior pattern of the people who occupy the area, geometric properties of the environment, the entry of natural light, and the type of work performed in the space.

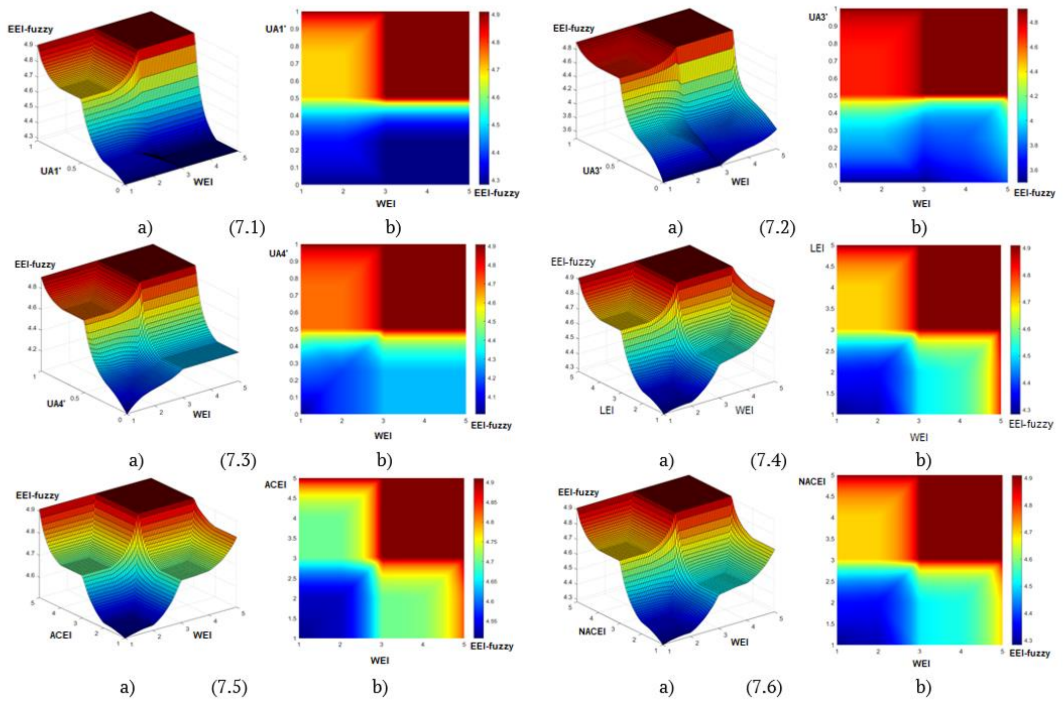
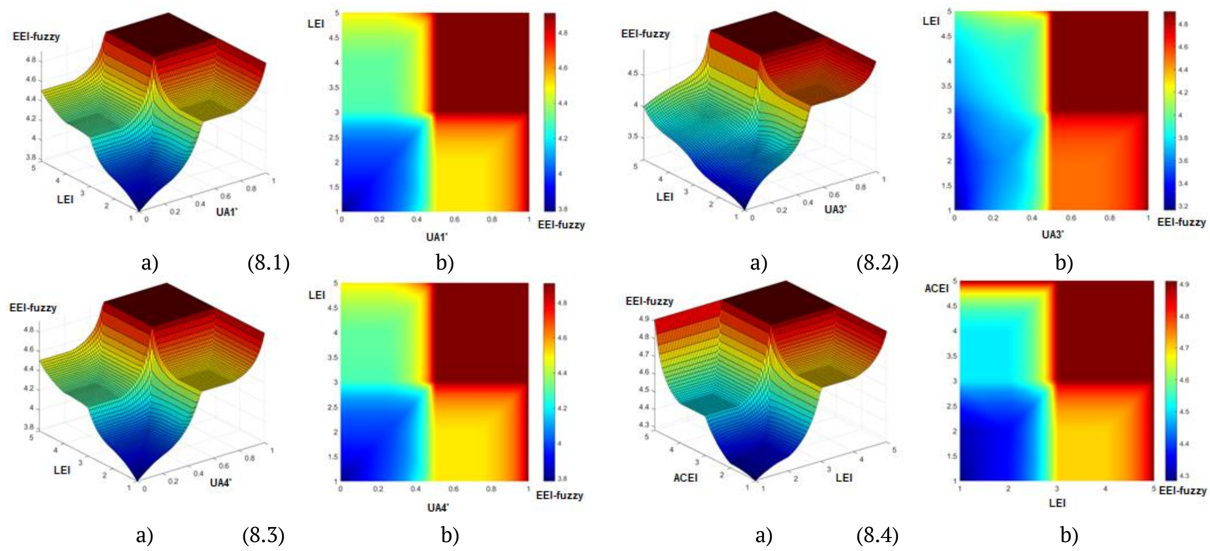
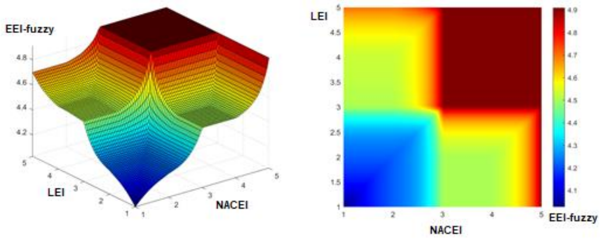


Figure 7. a) 3D fuzzy surfaces of the relationship between the WEI and UA1’ input variables (7.1), the WEI and UA3’ input variables (7.2), the WEI and UA4’ input variables (7.3), the WEI and LEI input variables (7.4), the WEI and ACEI input variables (7.5), the WEI and NACEI input variables (7.6), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.
Source: Prepared by the authors.

Air-conditioning efficiency is the component with the highest energy consumption in a building. Lin and Hong (2013) report that the main factors that can affect the energy efficiency of this component depend on the climate and the type of construction, such as internal temperature adjustment, air infiltration, type of window, window-wall ratio and internal loads. Figures 9.1 and 9.2 indicate when the percentages of useful area UA1’ and UA3’ are at their maximum values, the EEI-fuzzy will be high, regardless of the value of the ACEI. On the other hand, Figures 9.3 and 9.4 indicate that the variation in the ACEI reflects a significant increase in the EEI-fuzzy, especially if the ACEI is greater than 3.0 and it is associated with high values (at least 0.4) of the percentage of useful area UA4’ and (at least 2.5) of the NACEI.

Finally, Figures 10.1 and 10.2 show the variation in the NACEI reflects a significant increase in the EEI-fuzzy, especially if the NACEI is greater than 3.0 and it is associated with high values (at least 0.4) of the percentages of useful area UA1’ and UA3’. On the other hand, Figure 10.3 indicates that the EEI-fuzzy will be high only when NACEI and UA4’ are at their maximum values.

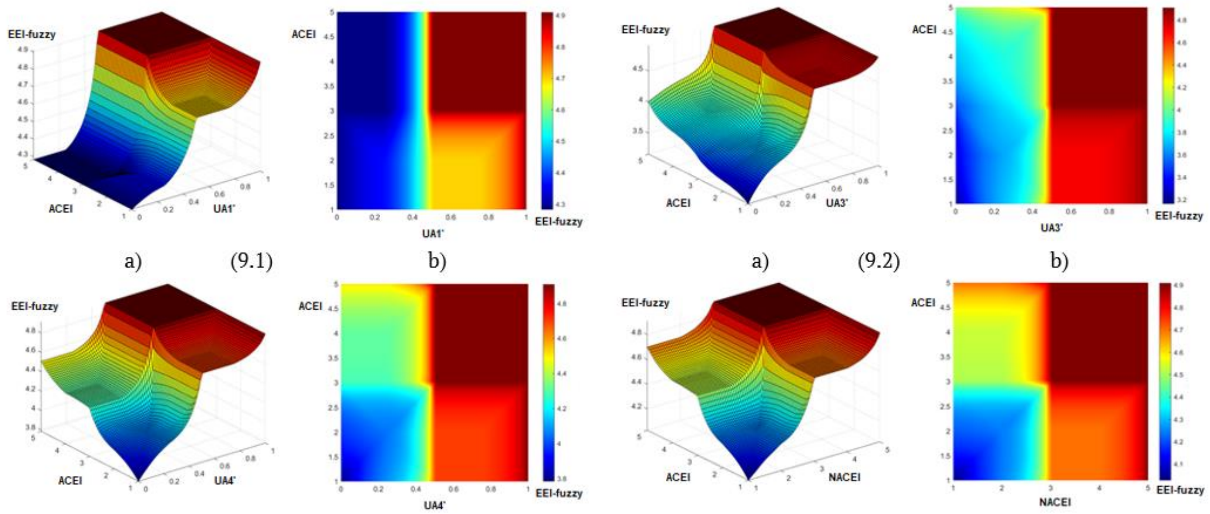




a) (8.5) b)

Figure 8. a) 3D fuzzy surfaces of the relationship between the LEI and UA1' input variables (8.1), the LEI and UA3' input variables (8.2), the LEI and UA4' input variables (8.3), the LEI and ACEI input variables (8.4), the LEI and NACEI input variables (8.5), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.

Source: Prepared by the authors.

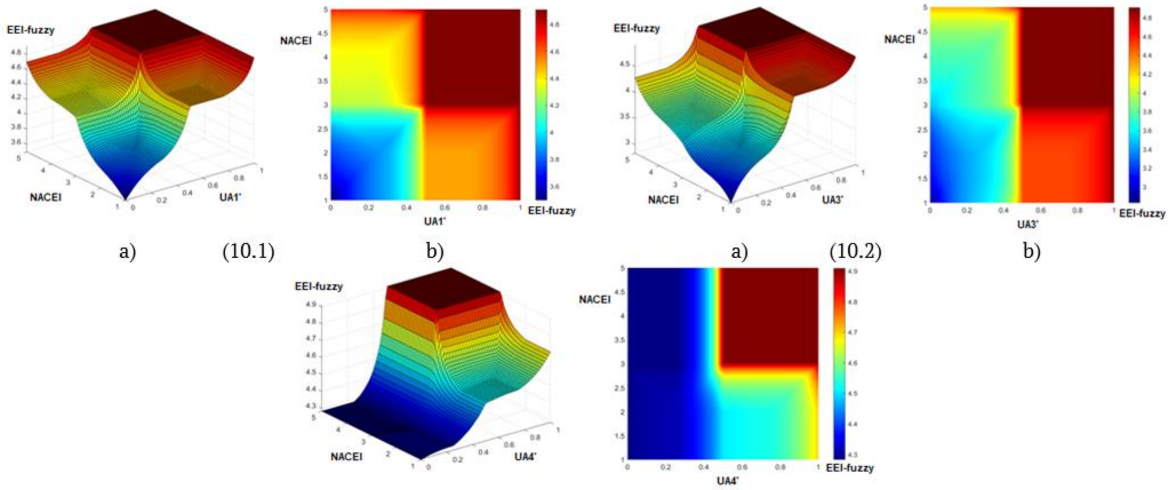


a) (9.1) b) a) (9.2) b)

a) (9.3) b) a) (9.4) b)

Figure 9. a) 3D fuzzy surfaces of the relationship between the ACEI and UA1' input variables (9.1), the ACEI and UA3' input variables (9.2), the ACEI and UA4' input variables (9.3), the ACEI and NACEI input variables (9.4), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.

Source: Prepared by the authors.



a) (10.1) b) a) (10.2) b)

a) (10.3) b)

Figure 10. a) 3D fuzzy surfaces of the relationship between the NACEI and UA1' input variables (10.1), the NACEI and UA3' input variables (10.2), the NACEI and UA4' input variables (10.3), and the output variable (EEI-fuzzy); b) Outline map of the EEI-fuzzy surface in relation to these input variables.

Source: Prepared by the authors.

Energy efficiency classification of the meat retailer company (case study) using the RTQ-C and the FIS

According to the procedure explained in section 2.1, values were obtained for each of the parameters considered in Equation 2, which are shown in Table 6, below.

Table 6. EEI results of the commercial building from the RTQ-C.

Variable	Index	Variable	Index
WEI	5.0 (level A)	UA2	148.36
LEI	5.0 (level A)	UA3	46.82
ACEI	3.0 (level C)	UA4	0
NACEI	3.0 (level C)	b	0
UA1	71.06	EEI	3.89

Source: Prepared by the authors.

Thus, through Equation 2, it was found that the EEI of the analyzed commercial building is equal to 3.90. Then, by the general classification of energy efficiency of the RQT-C (Table 1), the company was classified as level B energy efficiency, which can be considered an efficiency between medium and maximum. It was observed that the commercial building has both old and new air conditioning devices in operation, which justify the levels C obtained for the ACEI and, consequently, for the ACEI, since the old devices increase noise pollution. Furthermore, the activities carried out in that company are naturally noisy.

As for the proposed fuzzy model, it was found that the commercial building had an EEI-fuzzy = 3.61, and the company was classified as level B3 energy efficiency, which can be considered a lower efficiency within the classification B. That is, it has the potential to become B2 (coming closer to the A-level stratum of maximum levels), but it can also decline to C1 (getting to the C-level stratum, at intermediate levels).

The data in Table 6 associated with the graphical analysis of the variables that make up the EEI-fuzzy show that a more practical possibility of improvement can be achieved through the air-conditioning efficiency, which was classified as level C.

In this sense, Table 7 compares the company's current situation (in grey) with simulated situations, showing the variation of the EEI-fuzzy for different values of the ACEI, considering constant the other variables. Note that the ACEI at its maximum level (possibly the replacement of the old air conditioning units) will reflect an increase in the EEI-fuzzy and the company will be classified as level B2 energy efficiency. On the other hand, if the ACEI is at its minimum level (further degradation of the existing air conditioning devices), the company will be level C1.

Table 7. EEI-fuzzy results of the commercial building from a variation of the ACEI (other constant variables).

ACEI	1.0	2.0	3.0	4.0	5.0
EEI-fuzzy	3.34	3.37	3.61	3.78	3.84
Classification (level)	C1	C1	B3	B3	B2

Source: Prepared by the authors.

The improvement of the air-conditioning efficiency could also reflect an increase in the NACEI and consequently in the EEI-fuzzy, as shown in Figure 9.4. Furthermore, if the improvement of the air-conditioning efficiency is done jointly with the increase of the useful area of non-conditioned environments of prolonged stay, it could have a positive and significant impact on the energy efficiency of the company, as indicated in Figure 9.3.

Other actions to increase the energy efficiency index of air-conditioning in buildings are suggested in the literature, such as improvement of existing construction conditions (replacement of windows and fencing with adequate ventilation), microgeneration through sources of renewable energy, installation of direct expansion air-conditioning systems driven by variable frequency, among others. The selection and operation suitable for this purpose can provide energy savings of up to 25%, maintaining an acceptable internal condition (Ruparathna, Hewage, & Sadiq, 2016).

Conclusion

The present work proposed a model based on fuzzy logic for the evaluation of the energy efficiency of buildings deriving out of the RTQ-C, since it comprises only five levels and does not consider the uncertainties associated with the parameters of analysis. To expand this assessment, fuzzy logic was used, which allowed the determination of sub-levels that brought more scope to the classification.

A case study was used to show the applicability and functionality of the proposed mathematical modeling, which provided a more realistic perspective on the energy performance of the considered building. The results showed that fuzzy modeling is feasible and more comprehensive and could be used or expanded to other buildings and research with similar characteristics, since the RTQ-C contemplates several types of buildings.

Saving energy consumption generates a financial gain that could be invested in other areas of production, making it more efficient, sustainable and profitable, which will naturally reflect on the company's competitiveness. In addition to saving energy, companies that adopt sustainable practices could gain more relevance with their stakeholders, as the concern with environmental issues has become an essential premise in today's society.

As future proposals, it is noteworthy that the proposed methodology has potential for the development of mobile apps that could assist managers of public and private companies to assess, manage, and make more accurate decisions regarding the energy efficiency of buildings under their responsibility, bringing economic, social, and environmental benefits.

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References

Association Brazilian of Energy Conservation Companies [ABESCO]. (2024). *O Que é Eficiência Energética?* Retrieved from https://www.abesco.com.br/newpage

Abu Bakar, N. N., Hassan, M. Y., Abdullah, H., Rahman, H. A., Abdullah, M. P., Hussin, F., & Bandi, M. (2015). Energy efficiency index as an indicator for measuring building energy performance: A review. *Renewable and Sustainable Energy Reviews*, *44*, 1-11. DOI: https://doi.org/10.1016/j.rser.2014.12.018

Aslani, A., Bakhtiar, A., & Akbarzadeh, M. H. (2019). Energy-efficiency technologies in the building envelope: Life cycle and adaptation assessment. *Journal of Building Engineering*, *21*, 55-63. DOI: https://doi.org/10.1016/j.jobe.2018.09.014

Brazilian Association of Technical Standards [ABNT]. (2005). NBR 15220-3: *Thermal performance of buildings - Part 3*: *Brazilian bioclimatic zoning and construction guidelines for single-family housing of social interest*. Retrieved from https://bitily.me/GLWRJ

Ceballos-Fuentealba, I., Álvarez-Miranda, E., Torres-Fuchslocher, C., del Campo-Hitschfeld, M. L., & Díaz-Guerrero, J. (2019). A simulation and optimisation methodology for choosing energy efficiency measures in non-residential buildings. *Applied Energy*, *256*, e113953. DOI: https://doi.org/10.1016/j.apenergy.2019.113953

Cremasco, C. P., Gabriel Filho, L. R. A., & Cataneo, A. (2010). Metodologia de determinação de funções de pertinência de controladores fuzzy para a avaliação energética de empresas de avicultura de postura. *Energia na Agricultura*, *25*, 21-39. DOI: https://doi.org/10.17224/EnergAgric.2010v25n1p21-39

Chung, W. (2012). Using the fuzzy linear regression method to benchmark the energy efficiency of commercial buildings. *Applied Energy*, *95*, 45-49. DOI: https://doi.org/10.1016/j.apenergy.2012.01.061

Diakaki, C., Grigoroudis, E., Kabelis, N., Kolokotsa, D., Kalaitzakis, K., & Stavrakakis, G. (2010). A multi-objective decision model for the improvement of energy efficiency in buildings. *Energy*, *35*(12), 5483-5496. DOI: https://doi.org/10.1016/j.energy.2010.05.012

Energy Research Company (2020). *National energy balance 2019*. Retrieved from http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-bem

Energy Research Company (2019). *National Electricity Consumption on the Grid by Class*: 1995-2018. Retrieved from https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-189

Gabriel Filho, L. R. A., Amorim, F. R., Cremasco, C. P., Presumido Júnior, M., & Oliveira, S. C. (2024). Estimating sugarcane productivity: an approach using fuzzy logic. *Revista Ciência Agronômica*, 55, e20228392. DOI: https://doi.org/10.5935/1806-6690.20240012

Góes, B. C., Góes, R. J., Cremasco, C. P., & Gabriel Filho, L. R. A. (2021). Fuzzy modeling of vegetable straw cover crop productivity at different nitrogen doses. *Modeling Earth Systems and Environment*, *8*, 939-945.

Haq, M. A., Hassan, M. Y., Abdullah, H., Rahman, H. A., Abdullah, M. P., Hussin, F., & Said, D. M. (2014). A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renewable and Sustainable Energy Reviews*, *33*, 268-279. DOI: https://doi.org/10.1016/j.rser.2014.01.090

Hernández, J., Sanz, R., Corredera, Á., Palomar, R., & Lacave, I. (2018). A Fuzzy-Based Building Energy Management System for Energy Efficiency. *Buildings*, *8*(2), 14. DOI: https://doi.org/10.3390/buildings8020014

Iwaro, J., & Mwasha, A. (2010). A review of building energy regulation and policy for energy conservation in developing countries. *Energy Policy*, *38*(12), 7744-7755. DOI: https://doi.org/10.1016/j.enpol.2010.08.027

Kabak, M., Köse, E., Kırılmaz, O., & Burmaoğlu, S. (2014). A fuzzy multi-criteria decision making approach to assess building energy performance. *Energy and Buildings*, *72*, 382-389. DOI: https://doi.org/10.1016/j.enbuild.2013.12.059

Killian, M., & Kozek, M. (2018). Implementation of cooperative Fuzzy model predictive control for an energy-efficient office building. *Energy and Buildings*, *158*, 1404-1416. DOI: https://doi.org/10.1016/j.enbuild.2017.11.021

Lin, H.W., & Hong, T. (2013). On variations of space-heating energy use in office buildings. *Applied Energy*, *111*, 515-528. DOI: https://doi.org/10.1016/j.apenergy.2013.05.040

Mamdani. E. H., Assilian, S. (1975) E.H. An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-machine Studies*, *7*, 1-13. DOI: https://doi.org/10.1016/S0020-7373(75)80002-2

Marques, A. C., Fuinhas, J. A., & Tomás, C. (2019). Energy efficiency and sustainable growth in industrial sectors in European Union countries: A nonlinear ARDL approach. *Journal of Cleaner Production*, *239*, e118045. DOI: https://doi.org/10.1016/j.jclepro.2019.118045

Martínez, M. P., Cremasco, C. P., Gabriel Filho, L. R. A., Braga Junior, S. S., Bednaski, A. V., Quevedo-Silva, F., ... Padgett, R. C. M. (2020). Fuzzy inference system to study the behavior of the green consumer facing the perception of greenwashing. *Journal of Cleaner Production*, *242*(3), e116064. DOI: https://doi.org/10.1016/j.jclepro.2019.03.060

Martinopoulos, G., Papakostas, K. T., & Papadopoulos, A. M. (2018). A comparative review of heating systems in EU countries, based on efficiency and fuel cost. *Renewable and Sustainable Energy Reviews*, *90*, 687-699. DOI: https://doi.org/10.1016/j.rser.2018.03.060

MATLAB® 7.0 (2015). *MATLAB version 7.0 (R2015b).* Natick, MA: The MathWorks Inc.

Mpelogianni, V., Marnetta, P., & Groumpos, P. P. (2015). Fuzzy Cognitive Maps in the Service of Energy Efficiency. *IFAC-PapersOnLine*, *48*(24), 1-6. DOI: https://doi.org/10.1016/j.ifacol.2015.12.047

Mpelogianni, V., & Groumpos, P. P. (2019). Building Energy Management System Modelling via State Fuzzy Cognitive Maps and Learning Algorithms. *IFAC-PapersOnLine*, *52*(25), 513-518. DOI: https://doi.org/10.1016/j.ifacol.2019.12.596

Muldoon-Smith, K., & Greenhalgh, P. (2019). Suspect foundations: Developing an understanding of climate-related stranded assets in the global real estate sector. *Energy Research and Social Science*, *54*, 60-67. DOI: https://doi.org/10.1016/j.erss.2019.03.013

Oliveira, S. C., Cobre, J., & Pereira, D. F. (2021). A measure of reliability for scientific co-authorship networks using fuzzy logic. *Scientometrics*, *126*, 4551-4563. DOI: https://doi.org/10.1007/s11192-021-03915-0

Opoku, R., Edwin, I. A, & Agyarko, K. A. (2019). Energy efficiency and cost saving opportunities in public and commercial buildings in developing countries – The case of air-conditioners in Ghana. *Journal of Cleaner Production*, *230*, 937-944. DOI: https://doi.org/10.1016/j.jclepro.2019.05.067

Piegat. A. (2001). *Fuzzy Modeling and Control*. New York, NY: Springer Science and Business Media.

National Electric Energy Conservation Program [PROCEL]. (2017). *RTQ-C Application Manual*. Retrieved from http://pbeedifica.com.br/sites/default/files/projetos/etiquetagem/comercial/downloads/manualv02_1.pdf

Ruparathna, R., Hewage, K., & Sadiq, R. (2016). Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, *53*, 1032-1045. DOI: https://doi.org/10.1016/j.rser.2015.09.084

Silveira, P. G. (2018). Energia e mudanças climáticas: impactos socioambientais das hidrelétricas e iversificação da matriz energética brasileira. *Opinión Jurídica*, *17*(33), 123-148. DOI: https://doi.org/10.22395/ojum.v17n33a5

Veloso, A. C. O., Souza, R. V. G., & Koury, R. N. N. (2015). Evaluation of Electric Power Consumption of Non-Residential Buildings in the City of Belo Horizonte. *Energy Procedia*, *78*, 747-752. DOI: https://doi.org/10.1016/j.egypro.2015.11.086

Wong, I. L., & Krüger, E. (2017). Comparing energy efficiency labelling systems in the EU and Brazil: Implications, challenges, barriers and opportunities. *Energy Policy*, *109*, 310-323. DOI: https://doi.org/10.1016/j.enpol.2017.07.005

Yi, C., & Bing, X. (2017). *Building as Major Energy Consumer*. *Elsevier EBooks*, 137-148.

Zadeh, L. A (1965). Fuzzy sets. *Information and Control*, *8*(3), 338-353. DOI: https://doi.org/10.1016/S0019-9958(65)90241-X