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A Multiobjective Optimization Approach for Retrofitting Decision-Making towards Achieving Net-Zero Energy Districts: A Numerical Case Study in a Tropical Climate

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Abstract: Buildings are among the main reasons for the deterioration of the world environment as they are responsible for a large percentage of CO_2 emissions related to energy. For this reason, it is necessary to find solutions to this problem. This research project consists of constructing the metamodel of an urbanization located in Panama, Herrera province. The classification and systematization of its main elements, using the software DesignBuilder and SysML diagrams, were carried out for its subsequent implementation in an optimization analysis that seeks to approach the NZED standard. The main objectives of the optimization are reducing the energy consumption at the lowest possible price while maintaining or improving thermal comfort. In this study, it was possible to reduce electricity consumption to at least 60% of the original value and about 10% of the renewable energy generation capacity by implementing optimization techniques within the retrofit category related to the envelope of the buildings and the occupant's behavior.

Keywords: energy efficiency; multiobjective optimization; NZEB; NZED; retrofit; tropics

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1. Introduction

According to the International Energy Agency and the United Nations Environment Programme (UNEP), the buildings represent one of the main reasons for the worsening of the environment worldwide as they use 36% of the final energy regarding construction and functioning. Additionally, they produce 39% of the carbon dioxide emissions associated with energy. The energy-efficient buildings' implementation of renewable energy sources allows a steady decrease in future emissions. Due to this circumstance, sustainable buildings are turning into the construction standard [1].

Among the important regulations in Panama is the National Energy Plan 2015–2019 [2], which its most important aspect is energy efficiency. It is identified as essential to achieving sustainable development. For this reason, both private companies and the public sector have joined forces in order to define and implement measures that lead the country towards a sustainable development model. Some institutions such as the National Secretariat of Energy (SNE), the Ministry of Commerce and Industries, and the Sectorial Technical Committees have recognized the need to implement measures that improve energy efficiency nationwide. For this reason, measures have been taken through Executive Order 398 of 2013 [3] and the Law 69 of 2012 [4], which stipulate mandatory compliance with the energy efficiency indices indicated in the technical specifications, not to mention the energy efficiency labels must be visible to the consumer. Those in charge of complying with these guidelines are the stores that distribute equipment such as air conditioners, refrigerators, lights, among other electrical appliances.

A concept that has become popular in recent years is that of net-zero energy buildings (NZEB), which different authors define as those buildings with considerably high energy performance, the reduced amount of energy that they require for their operation is provided by renewable energy sources, whether produced on-site or in neighboring places. Torcellini et al. give four different definitions to the concept. NZEB by site, when the building produces at least as much energy as it uses in a year while compared to the energy produced on site. NZEB according to source, when the building produces at least as much energy as it uses in a year, while compared to the source. By energy source it refers to the primary energy used to generate and deliver energy to the site, this comparison is calculated through the corresponding multipliers. NZEB based on costs is given when the amount of money the utility pays the building owner for the energy the building exports to the grid is greater than or equal to the amount the owner pays the utility for energy services and energy used during the year. Finally, the NZEB based on emissions definition is given when the building produces an amount of emission-free renewable energy greater than or equal to the energy that uses sources with emissions [5]. Similar to the previous concept, nearly zero-energy building (nZEB) consume a slightly higher amount of energy than that produced by renewable sources [6]. Equally important is the zero-energy districts (ZED), which can be defined as a group of multipurpose buildings with high energy performance where the energy consumed is produced locally [7]. Similarly, Koutra et al. defined it as a district where the energy supply is equalized by the energy demand [8].

NZEB has shown rapid growth in developed countries and/or temperate climates while facing difficulties in developing countries with tropical climates. According to the Solar Heating and Cooling Program (SHC) world map created by the International Energy Agency (IEA), more than 90% of NZEB projects are in developed regions such as the United States and Europe. Of the more than 300 projects considered in the study, only 11 are in areas with humid tropical climates but in developed countries. This leads authors such as Feng et al. to consider that the economic factor is the greatest limiting factor for NZEB in developing regions. For this reason, they consider that, in the case of NZEB in humid regions located in developing countries, a focus should be placed on passive techniques and those with a relatively low initial investment, with short payback periods [9].

As mentioned before, there has been a greater study and development of this class of buildings in Europe and the United States, so these countries developed the main regulations on the subject. An example is a European legislation created by the Energy Performance of Buildings Directive (EPBD), making nZEB a standard for all new buildings by 2020 [10]. In a similar manner, the United States is implementing new energy policies and programs such as the Building Technologies Program (BTP) developed in 2008 by the United States Department of Energy (DOE). The program aims to create technologies and design approaches that enable NZEB at low incremental costs by 2025 [11].

Currently, Panama does not have the regulation and projects previously mentioned. For this reason, the purpose of the present work is to broaden the local research field to help the development of future national regulations through the modeling of an urbanization to which, after defining the main categories of measures for energy efficiency, a multi-objective optimization was carried out. This was carried out by evaluating and comparing different renovation strategies with dynamic simulation and thus determine the best of them to achieve zero energy at the lowest possible cost. All the proposed optimization solutions achieved an electricity consumption up to 30% of the original value, were those that involve changes in the occupants' behavior with minimal changes to the envelope seemed to be the best option in terms of the study objectives.

2. Literature Review

Some studies about zero energy in Panama have been carried out. Among these is the design and construction of a two-story house located in Playa Venao, district of

Pedasí in the province of Los Santos. In this study, passive dehumidification techniques, natural lighting, and ventilation were implemented, as well as high-efficiency windows, mechanical ventilation equipment, and solar collectors to reduce electricity consumption. To comply with the NZEB standard, a photovoltaic system with batteries was installed to supply the demand of the house [12]. In another study, this time in Panama City, a test model was developed for the Technological University of Panama based on the common characteristics of the envelope of its buildings. The model was developed using DesignBuilder in order to find useful techniques to bring buildings in Panama closer to an NZEB standard. Some of the techniques considered useful by the study were: natural ventilation, determination of the orientation of the building, modifications in the occupancy profile, and the envelope [13].

Some authors have dedicated themselves to studies about technologies that mitigate the effects of climate change in buildings, focusing on NZEB. For example, Cabeza and Chàfer made a summary that includes information from 2013 up to 2019 [14], different types of strategies needed in a NZEB were identified, these were classified into four categories. The first covers everything related to the design of the building, including geometry, ventilation, and natural light. The second one includes energy-saving techniques, which consider the materials in the envelope, thermal energy storage systems, and energy-efficient equipment such as lighting and appliances. The third group introduces renewable energy sources such as solar and geothermal. Finally, backup systems are considered, such as electrical energy stores and boilers. Implementing the first two categories makes the building low energy consumption; By adding the following two, the required energy is obtained with the least possible impact on the environment. It is worth mentioning that this study does not consider the performance of the improvements implemented in existing buildings. This is why certain authors, such as the ones mentioned below, have concentrated on studying this issue as well as a large number of other important factors to bring a building to the zero-energy standard.

Ma et al. were dedicated to developing a systematic methodology that includes energy efficiency strategies in existing buildings. They achieved this through an overview of previous studies related to research and evaluation of energy performance and economic feasibility of different modernization technologies for construction applications. The authors classify the main types of energy improvement strategies into four groups: Reduction in consumption by heating and cooling, energy-efficient equipment and energy reduction technologies, human factors and renewable energy systems, and improvements in the electrical system (Figure 1) [15].

A study about the remodeling of a building located in Italy concluded that, unlike what is seen in traditional buildings, the operation phase is not responsible for most of the negative impact on the environment in NZEB buildings. The retrofit adjustments cause an increase in the embedded carbon related to the production of the materials introduced in the building, so it is necessary to consider variables such as the technologies used in the production of the incorporated materials to determine if the improvements are viable [16]. Other authors suggest that the impact on the environment caused by these materials could be mitigated by developing more friendly production processes or implementing recycling [17]. The implementation of these adaptations and renewable energy sources, characteristics of this type of buildings, undoubtedly involves a cost when bringing a building to the NZEB standard. For this reason, authors such as Nair et al. consider the cost of said modifications as one of the most important factors that should be considered when trying to achieve NZEB standards [17,18].

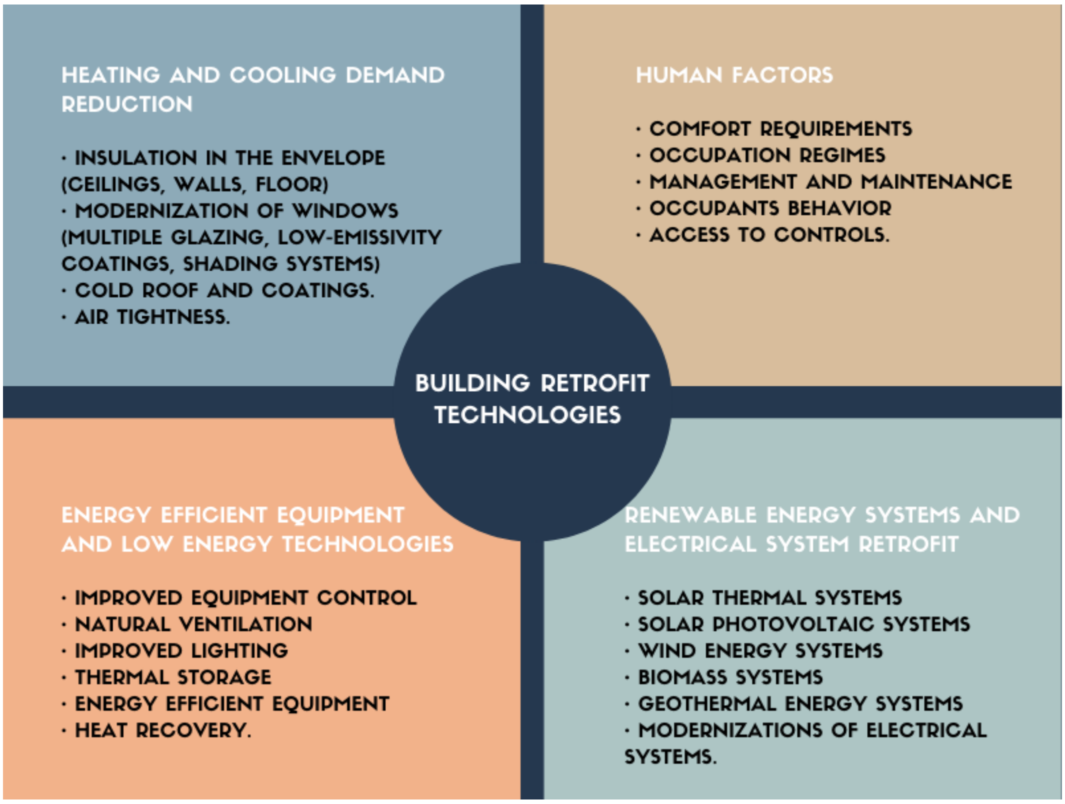


Figure 1. Categories of building retrofit technologies according to [15]. Reprinted with permission from ref. [15]. 2022 Elsevier B.V.

When examining the profitability of proposed improvements, a study concluded that the materials incorporated in the building envelope significantly increase the investment cost. At the same time, their contribution to the reduction in energy consumption is negligible compared to energy renewables with similar initial costs. For this reason, if one seeks to introduce materials to the building envelope, these must be carefully selected, ensuring that the thermal transmittance (U-value) reasonably improves consumption and keep the investment cost to a minimum [18]. Similar results were obtained in the study carried out by Bahadır et al. They concluded that increasing the thickness of the insulation in walls helps reduce the cooling load, especially when using green cladding walls. However, this type of materials represents a high initial cost, so it was determined that they are economically inefficient through a life cycle cost analysis. Consequently, it has been determined that modifications in the studied walls are energy efficient, but not economically, especially in the humid climate zone [19]. On the other hand, in a study on a school located in Italy, it was found that by implementing adjustments not only in the envelope but also in the heat generation and lighting systems and the control devices, investment recovery times shorter than the life cycle of the building analyzed are obtained [16].

Instead of considering only energy consumption and renovation cost, some authors considered in their study multiple environmental indicators such as global warming potential, ozone depletion potential, acidification potential, photochemical ozone creation potential, among others. The authors concluded that it is of great importance to consider these indicators when evaluating the sustainability of the design of the adaptations since the performance of the different alternatives varies significantly between considering the environmental indicators together with the cost and consumption analysis throughout the life cycle period and only consider the cost and energy consumption [20].

Purbantoro and Siregar recommended in their study the application of a passive design of the building by using environmentally friendly materials that can save more energy and change the behavior of the occupants to be more aware of saving energy when carrying out daily activities [21]. This is due to the difficulty of implementing NZEB standards only with the modernization of equipment and renewable energy sources.

Opposite to that, a study compared the contributions of passive and active design characteristics, only 5% of the energy savings were related to the passive design, while 40–45% of the energy savings were due to the active design, between which lighting improvements accounted for 12–17%, and air conditioning improvements accounted for 23–28% of energy savings. The study suggests that passive design should be selected carefully in existing building renovations for best results with passive strategies, considering its cost and effectiveness due to climate and density [22].

When talking about NZEB, it is important to consider factors such as optimization objectives (cost, consumption reduction, among other indicators), type of strategies implemented, climate, among others. Table 1 summarizes the information collected from different studies worldwide on buildings where energy-saving measures were implemented to bring them to NZEB standards.

Table 1. Summary of the state of the art of the different studies according to the place, climate, type of building, renovation techniques used and methodology.

Place	Climate	Type of Building	Retrofit Techniques Used	Type of Techniques Used	Methodology	Year/Ref.
Treviso, Italy	Humid subtropical	Residential	√ Expanded polystyrene insulation and rigid mineral wool panels on walls √ Wood fiber insulation in roof √ Two-layer insulating glass units with wooden window frames. √ Centralized heat pump/chiller air conditioning system with underfloor distribution √ Heat pump system for hot water production √ Photovoltaic system and solar collectors	Active	Simulation and implementation	2015 [23]
Portland, Oregon, United States	Mediterranean	Government office	Update of computer system to reduce the load on outlets √ Sealing of leaks in windows and doors √ Demand ventilation control √ Change of lamps type T8 to LED √ Replacing the HVAC system to a variable volume refrigerant system with heat recovery	Active	Simulation	2020 [24]
Sydney, Australia	Humid subtropical	Small-scale models	√ Green roof	Passive	Simulation and implementation	2015 [25]
Río de Janeiro, Brazil	Tropical savanna					
Singapore	Tropical rainforest	Government offices and academic facilities	√ Light ducts √ Natural ventilation by solar chimney √ Green walls and roof √ shading devices √ Double pane insulating glass windows √ Window films √ Controls and sensors √ LED lighting √ Air conditioning system (variable speed, radiant floor distribution, single coil with double fan) √ Photovoltaic system	Passive and active	Simulation and implementation	2018 [22]

Table 1. *Cont.*

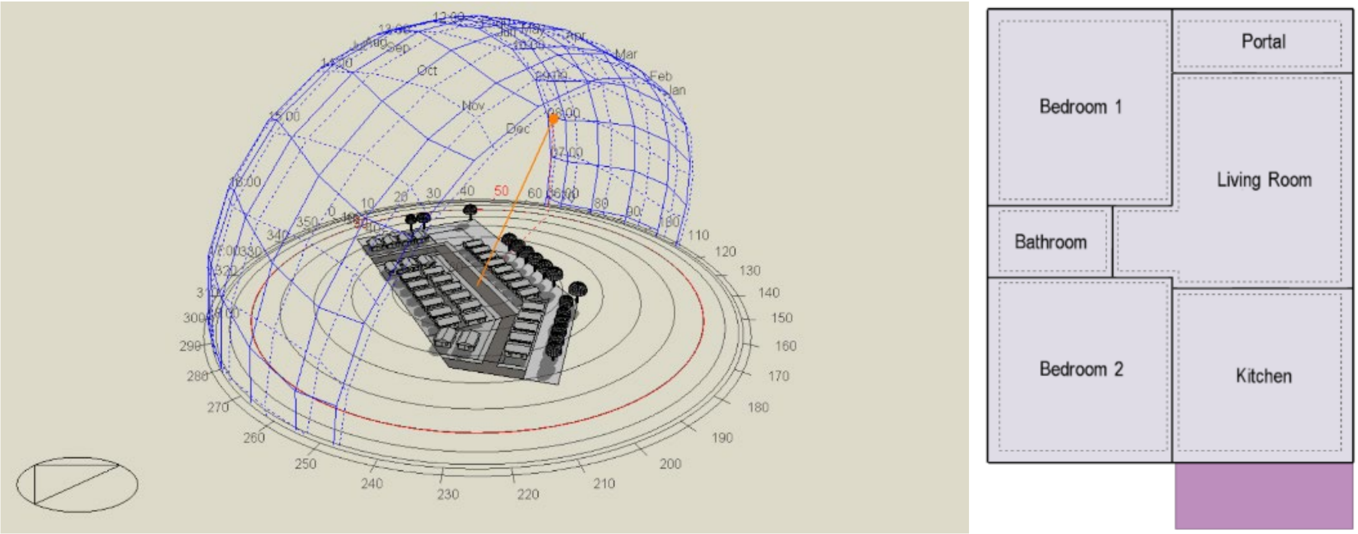
Place	Climate	Type of Building	Retrofit Techniques Used	Type of Techniques Used	Methodology	Year/Ref.
Orlando, Florida, United States	Humid subtropical	Residential	√ CFL lights √ Low flow water accessories √ Programmable thermostats √ Window films √ Reduced standby power loss	Passive and active	Simulation	2012 [26]
Miami, Florida, United States	Tropical savanna					
Berkshire, United Kingdom	Oceanic	Residential	√ Insulation in walls and ceiling √ Heat pump system for hot water production √ Mechanical ventilation system √ LED lights with presence detector √ Three-pane insulating glass windows √ Photovoltaic panel system	Active	Simulation	2020 [18]
Watford, United Kingdom	Oceanic	Commercial (Hotel)	√ Polyisocyanurate insulation in walls √ Triple glazed insulating glass windows √ LED lights √ Heat pump system for hot water production √ Mechanical ventilation system with heat recovery √ Trigeneration system	Active	Simulation	2020 [27]
Yakarta, Indonesia	Tropical monsoon	Office area	√ Replacement of high-efficiency compressors in the air conditioning system √ LED lights √ Improvements to the wastewater system so that it can be used for make-up water for the cooling tower √ Photovoltaic system integrated into the building √ Micro hydroelectric plant	Active	Simulation	2019 [21]
Ireland	Oceanic	Residential	√ Insulation in walls (polystyrene) and roof (mineral wool) √ Double glazed insulating glass windows √ Heating and hot water system consisting of gas boiler and hot water tank √ Photovoltaic system and solar collectors	Active	Simulation	2020 [20]

Table 1. *Cont.*

Place	Climate	Type of Building	Retrofit Techniques Used	Type of Techniques Used	Methodology	Year/Ref.
Barcelona, Spain	Mediterranean hot summer	Academic facilities	√ Insulation in extruded polystyrene walls √ Double glazed insulating glass windows √ LED lights √ HVAC system from biomass √ Photovoltaic system and solar collectors	Active	Simulation	2017 [28]
Ireland	Oceanic	Residential	√ Insulation in walls and roof. √ Triple glazed Low E windows. √ Heat pump for space and water heating. √ Room thermostats and on/off timers for the heating system. √ Sealing of fireplaces to reduce air infiltration. √ Demand controlled mechanical extract ventilation system. √ Insulation in ducts to prevent heat loss and condensation. √ Solar panels (17,000 W peak total).	Active	Implementation	2021 [29]
Sweden	Subarctic	Residential	√ Cooling systems (constant air volume and variable air volume). √ Mechanical ventilation system. √ Increase in the cooling set point. √ Automatic shading.	Passive and active	Simulation	2022 [30]
Brazil	Tropical	Office area	√ Mixed operation between cooling system and desk fans.	Active	Simulation	2022 [31]

3. Materials and Methods

The case study used is an urbanization located in Panama, Herrera province at Chitre district with geographical coordinates 7°58′51′′ N 80°26′31′′ W and altitude of 19 m.a.s.l. This urbanization was built between 2016 and 2019, and it comprises 34 houses with the same construction characteristics and area of 55 m^2, giving a rough total of 1.13 hectares for the whole urbanization. According to the Köppen climate classification, the urbanization presents a tropical savanna climate (Aw) with a mean annual temperature of 26 °C. Therefore, all the houses in this urbanization have the same room layout (Figure 2) and construction materials in their envelope. The following simulations were performed using standard weather data (typical meteorological data) obtained from CLIMdata Solargis © (Bratislava, Slovakia) (Table 2, Figures 3 and 4).



(**a**) (**b**)

Figure 2. Case study: (**a**) 3D urbanization model, and (**b**) plan view with the layout of each room within the houses.

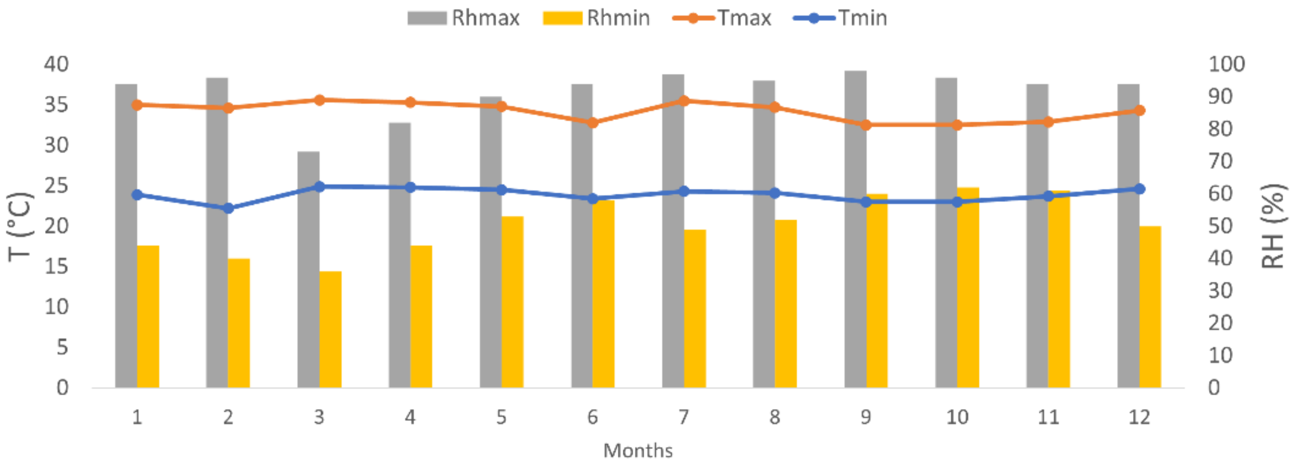


Figure 3. Comparison between maximum and minimum temperatures and relative humidity for each month of the year.

Table 2. Summary of the typical meteorological data used for simulation.

Month	Tmax [1] (°C) (Hour)	Tmin [2] (°C) (Hour)	RHmax [3] (%) (Hour)	RHmin [4] (%) (Hour)	Average Wind Speed (m/s)	Average Wind Direction (°)
3 January	35 (15:00)	23.9 (6:00)	94 (5:00)	44 (15:00)	0.43	126
20 February	34.6 (15:00)	22.2 (6:00)	93 (6:00)	40 (15:00)	2.77	85.77
17 March	35.6 (15:00)	24.9 (6:00)	73 (6:00)	36 (16:00)	2.3	49
11 April	35.3 (15:00)	24.8 (6:00)	82 (24:00)	44 (16:00)	1.75	87
20 May	34.8 (15:00)	24.5 (6:00)	90 (6:00)	53 (16:00)	0.87	83.3
23 June	32.8 (15:00)	23.4 (6:00)	94 (6:00)	58 (15:00)	0.45	108.25
21 July	35.5 (16:00)	24.3 (6:00)	97 (4:00)	49 (16:00)	0.3	89.3
19 August	34.7 (15:00)	24.1 (6:00)	95 (5:00)	52 (15:00)	3.9	188
1 September	32.5 (15:00)	23 (6:00)	98 (24:00)	60 (15:00)	2.1	83
20 October	32.5 (15:00)	23 (6:00)	96 (6:00)	62 (14:00)	2.33	90.67
11 November	32.9 (15:00)	23.7 (6:00)	94 (5:00)	61 (13:00)	2.55	80
16 December	34.3 (15:00)	24.6 (6:00)	94 (7:00)	50 (16:00)	4.2	34.5

[1] Maximum temperature. [2] Minimum temperature. [3] Maximum relative humidity. [4] Minimum relative humidity.

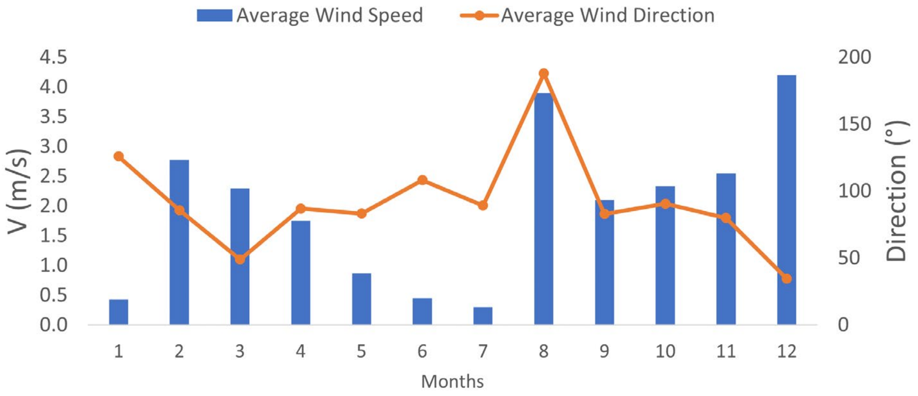


Figure 4. Average wind speed and direction for each month of the year.

A photovoltaic generation system is considered, the panel model was chosen based on market availability in the region and the main technical specifications are listed below: (1) Active area: 1.68 m^2, (2) Nominal Maximum Power: 320 W, (3) Number of cells: 72, (4) Cell type: Polycrystalline Silicon and (5) Panel efficiency: 15%. These and the other electrical specifications required for the simulation were configured in the Designbuilder.

For the modeling of the urbanization of this project, the Systems Modeling Language (SysML) was used. This is a graphic language used to model systems that present both physical and logical characteristics. This language is derived from the Unified Modeling

Language (UML) and allows the system's analysis, verification, and validation based on the implementation of structural, parametric, requirements, and behavior diagrams that are not present in the UML language [32].

As mentioned above, different diagrams are used in system modeling using SysML. A generic model of a house of the urbanization was carried out using Block Definition Diagrams (BDD), which define the system's structure through the associations between the blocks to determine its different components [33]. For this purpose, the Eclipse IDE with the Papyrus SysML 1.6. tool was used.

Based on the diagrams made, a case study model including all its characteristics was built using the software DesignBuilder version 6.1.8.021. After creating the model and using DesignBuilder, a multiobjective optimization approach was carried out to reduce the energy consumption at the lowest possible price while maintaining or improving thermal comfort, following the retrofit categories determine from the information given in the study by Ma et al. and SysML diagrams. Certain methods and procedures were followed, which are explained in detail in the section below. Figure 5 shows a simplified version of the methodology in the form of a diagram.

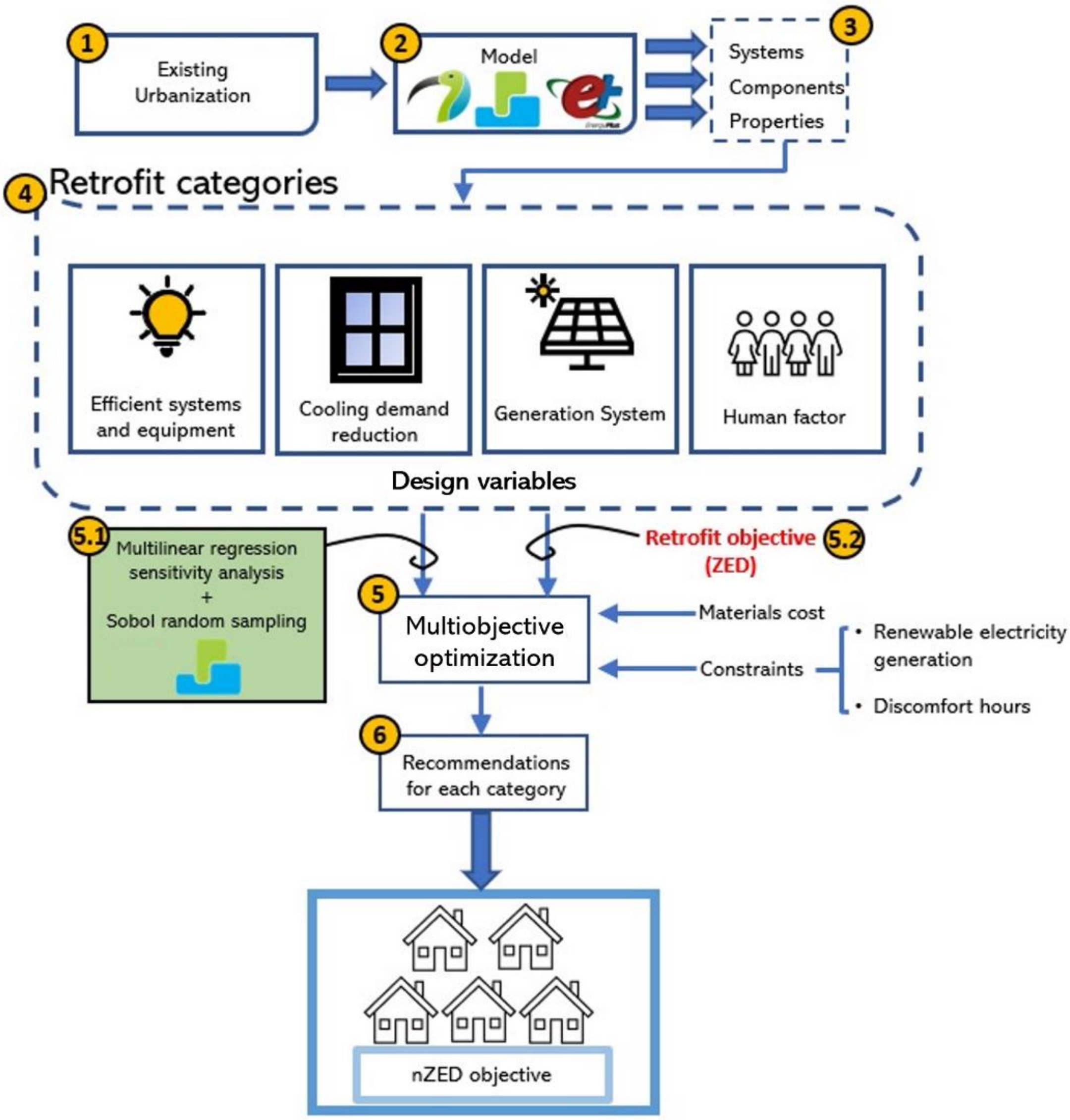


Figure 5. Diagram of the methodology followed in the study.

4. Results

4.1. Building Modeling Approach

The physical aspects of the building and its surroundings as well as the environment and the human agents affecting it were modeled for each simulated instance. The BDD in Figure 6 shows the generic model in SysML including the building's most important com-ponents. In the chosen representation, the model element '*block*' consists of two to three sections: the first one showing the stereotype and the string name of the generic component (sometimes preceded by a parent qualifier for better comprehension), the second one listing the attributes corresponding to the block's characteristics that shape its behavior relevant to the intended simulations, the optional third section giving the constraints, i.e., the restrictions considered in the optimization analysis mentioned in the multiobjective optimization approach subsection. The solid lines are composite associations representing the hierarchical structure; the diamond end indicates the parent element. The dashed lines show dependencies where the arrow end points to supplying correspondent. In Figure 6, dependencies are limited to the assembly level for clarity while in reality there could be parallel or even conflicting dependencies between several lower-level components within the pairs, e.g., the price of the electricity mix will depend at day on the payload of the PV system which again depends on the environment (sunshine, cloudiness). At night and if the batteries are empty, the unit price cannot be lowered by PV electricity generation; at the same time, there is no potential in the interplay of lighting, shading and cooling.

In the design process, a second BDD was used to solemnly focus on the building structure tree. Due to its importance in this study a better understanding of the inner interactions was required. The creation of these diagrams helped to visualize the connection between the system's different components and determine the importance of the different retrofit categories. Following this, with the help of the state-of-the-art analysis, a classification of the elements of the building in categories and techniques to be used was determined (Table 3).

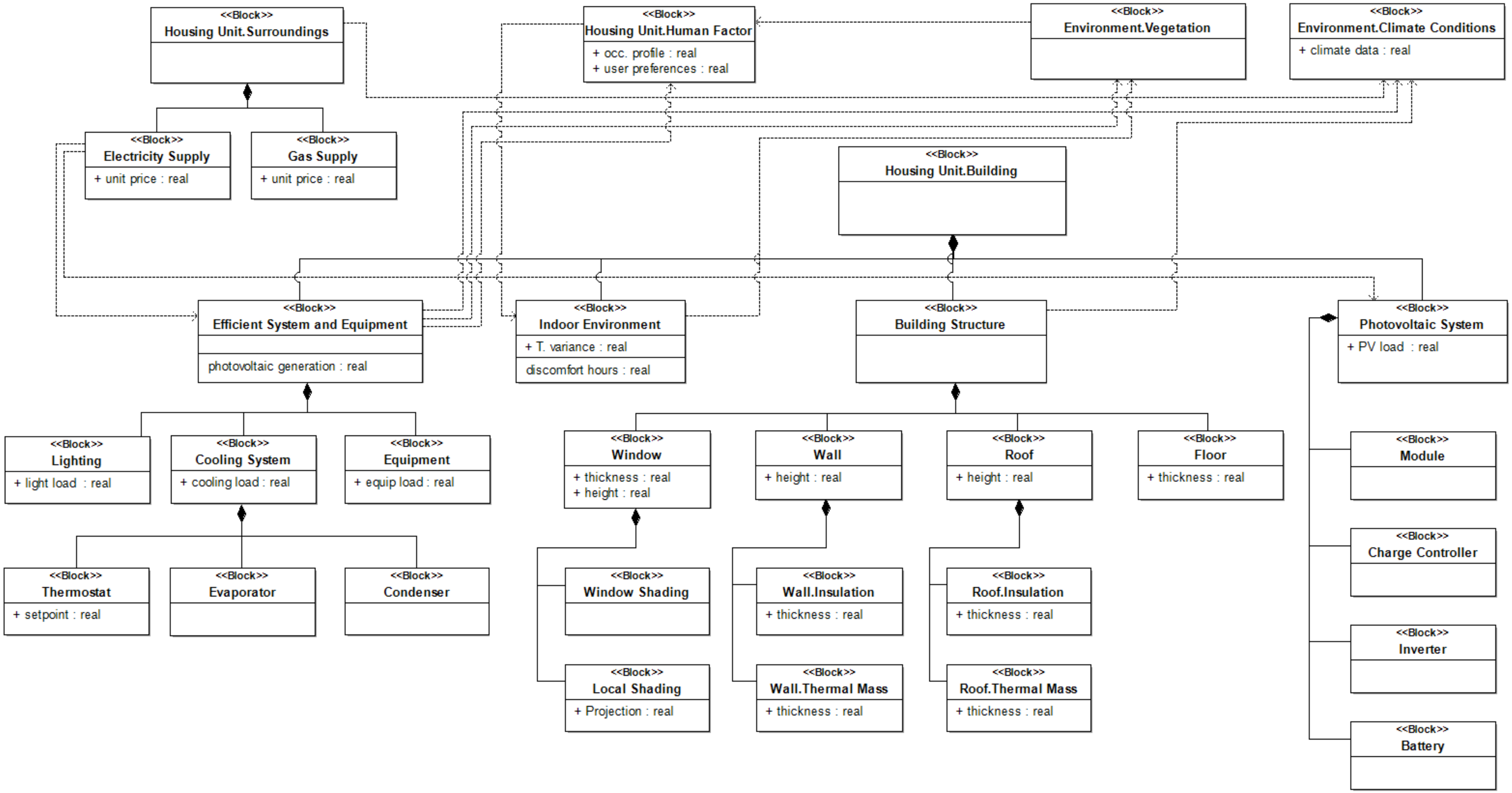


Figure 6. BDD of the physical components in a generic model of a residence in the considered Chitré estate; all blocks are elements of either package "Housing Unit" or "Environment".

Table 3. Classification of a building according to its characteristics and the possible improvement techniques to be used.

Category	Retrofit Technique
Energy efficient systems and equipment	Highly efficient appliances and office equipment Hot water system Heat pump Gas boiler Air-conditioning system Variable volume of refrigerant with heat recovery Variable speed Biomass Floor heating distribution Single coil with double fan Compressor upgrade Air quality system Control system Presence detector Demand ventilation Illumination LED CFL Light ducts Demand ventilation Heat recovery system Natural ventilation Solar chimney
heating and cooling demand reduction	Insulation in walls and roof Windows Insulating glass units with chambers Window films Solar control film Shade devices such as curtains Green roof and walls Sealing of leaks in windows and doors
Generation system	Photovoltaic solar system Solar thermal system with solar collectors Micro hydroelectric plant Trigeneration system
Human factor	Access to programmable thermostats Management of requirements in air conditioning systems

4.2. Coupling Retroffiting Categories with Building Systems

With the former mentioned BDD and the proposed categories by Ma et al. [15], it was possible to identify the retrofit categories used in this research project. These categories are efficient systems and equipment (illumination, electrical appliance, and air conditioning system), cooling demand reduction (changing in the enveloping to improve the internal environment of the building), generation system (photovoltaic system), and the human factor (usage hours and preference of the occupants).

4.3. Multiobjective Optimization Approach

A multiobjective optimization approach was carried out to reduce the energy consumption at the lowest possible price while maintaining or improving thermal comfort. First, a sensitivity analysis was performed to determine the most important variables, in other words, those that most influence the simulation results. Afterward, the multiobjective optimization was developed following two methods: optimization by retrofit categories and optimization by important design variables defined by the sensitivity analysis. This process was carried out by introducing multiple design options for each retrofit category, after multiple iterations the analysis resulted in the combination of options that meet the objectives and constraints of the analysis (Tables 4 and 5).

Table 4. Original envelope component and design options obtain from optimization analysis.

Envelope Component	Description	U (W/m^2-K)	Cost (PAB/m^2)	Nomenclature [2]
Roof	0.4 mm zinc	7.143	9.78	TCA
	Mineral wool, 100 m concrete slab	0.51	154.71	Top1
	Mineral wool, 100 m concrete slab, EPS [1]	0.50	153.04	Top2
	100 m concrete slab, EPS [1]	1.30	133.66	Top3
Walls	150 mm concrete block	2.48	73.54	PCA
	160 mm double hole brick	1.72	80.55	Pop1
	160 mm double hole brick, polystyrene	0.62	115.72	Pop2
	150 mm concrete block, polystyrene	0.69	108.75	Pop3
Windows	Single glass clear	5.788	139.15	VCA
	Single glass low emissivity	3.437	149.67	Vop1
	Single glass with solar control	3.192	171.02	Vop2
	Double glass with solar control	1.635	235.97	Vop3
	Single glass reflective	5.720	196.18	Vop4
	Double glass absorptive-reflective	4.664	218.68	Vop5
	Double glass absorptive-reflective	2.320	286.92	Vop6
	Triple glass absorptive-reflective	1.589	355.16	Vop7
Shading	No overhangs, no side fins	-	-	SCA
	Overhangs 0.25 m	-	21.81	Sop1
	Overhangs 0.50 m	-	43.63	Sop2
	Overhangs 0.75 m	-	65.44	Sop3
	Overhangs 0.50 m, side fins 0.50 m	-	66.19	Sop4
	Overhangs 0.75 m, side fins 0.75 m	-	99.28	Sop5
	Overhangs 1.00 m, late side fins 1.00 m	-	132.38	Sop6

[1] Expanded polystyrene. [2] The nomenclatures for the components including the letters CA represent the original envelope conditions, the ones including numbers represent the different design options for each component.

Table 5. Original occupancy, equipment, lighting and air conditioning schedules and design options obtain from optimization analysis.

Design Parameter	Schedule	TIME PERIOD	Nomenclature
Occupancy	00:00–24:00	Every day, all year	HCA
Equipment	00:00–24:00	Every day, all year	
Lighting	18:00–23:00	Every day, all year	
Occupancy	7:00–19:00	Weekdays, all year	Hop1
Equipment	7:00–20:00	Weekdays, all year	
Lighting	7:00–19:00	Weekdays, all year	
Occupancy	6:00–22:00	Every day, all year	Hop2
Equipment	7:00–21:00	Every day, all year	
Lighting	6:00–22:00	Every day, all year	
Air conditioner	00:00–24:00	Every day, all year	ACA
	8:00–18:00	Every day, October to December	Aop1
	19:00–07:00	Every day, all year	Aop2
	00:00–8:00	Every day, October to December	Aop3
	18:00–21:00	Weekdays, all year	Aop4
	12:00–18:00	Weekends and holidays, all year	
	19:00–24:00	Every day, all year	Aop5
	19:00–23:00	Every day, all year	Aop6
	9:00–11:00	Every day, all year	Aop7
	19:00–4:00	Every day, all year	Aop8
	7:00–19:00,	Weekdays, all year	Aop9
	8:00–20:00	Weekdays, all year	Aop10

Due to the large number of design options considered, which were previously di-vided into categories, it was necessary to simplify the simulation to reduce the amount of time. Instead of simulating for the whole year, only march (the most critical month in terms of high temperatures) was used for the simulations using the software DesignBuilder. For the same reason stated above, only one house per row is modeled (a total of six houses). Instead of simulating a single house for the whole urbanization, six were considered in these strategic positions to contemplate the different heat gains and thermal zones due to different building orientations, as suggested by [34].

4.3.1. Sensitivity Analysis

For the sensitivity analysis, the multilinear regression analysis and Sobol sampling methods were used to determine the effect of several variables such as walls and roof of the houses, occupancy hours, hours of use and temperature set point of the air conditioner on electricity consumption. This effect was measured using the standardized regression coefficient (SRC). The whole process was carried out in DesignBuilder, 100 iterations were achieved for the simulation on and using the standardized regression coefficient (SRC) the effect of each variable on the objective of the model (the reduction in electricity consumption) was measured. The SRC outputs the sensitivity of each input variable, thereby identifying the most (greater values) and least important variables (See Figure 7).

The results show that electricity consumption is strongly influenced by occupancy with a SRC value of 0.19; the same result is seen with walls (SRC of 0.6), while the influence is moderate for the set-point of the cooling system with a coefficient of −0.04. On the other hand, the cooling system and roof hours of operation, with a SRC of 0.02 and 0, respectively, do not significantly influence electricity consumption. Therefore, these variables can be ignored in further analysis.

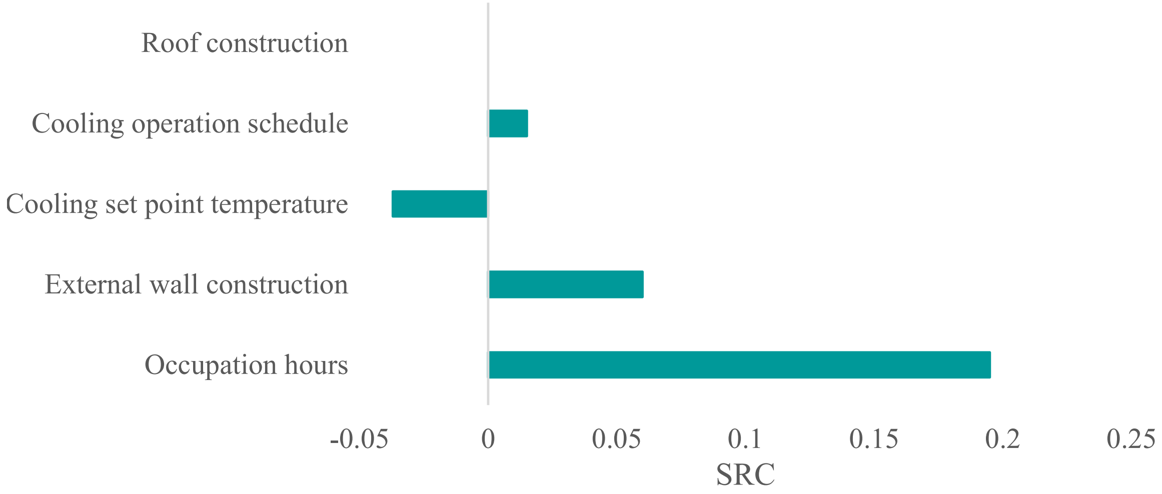


Figure 7. Design variables considered in the sensitivity analysis and their respective standardized regression coefficient.

4.3.2. Optimization Objectives and Methods

Minimizing electricity consumption and the capital cost of the urbanization were the objectives stipulated for the optimization analysis. It is important to note that the total cost shown in the results is the sum between the electrical cost and the renovation cost explained later. Other parameters such as cooling consumption, the capital cost of construction, incorporated carbon, and hours of discomfort based on the ASHRAE 55 standard with 80% acceptability were considered. In addition, within the restrictions, photovoltaic generation and the original discomfort hours of the urbanization were considered, both for March.

Optimization by Retrofit Categories

For the optimization according to the categories mentioned above, only two were simulated: human factor introducing multiple options of hours of occupation and use of equipment; and reduction in cooling demand (building envelope) considering multiple options for walls, roof, windows, and overhangs. Moreover, a combination of both categories mentioned previously was simulated, including options of both categories mentioned. The efficient equipment and systems category was not simulated since most houses currently have efficient lighting and not all houses have a cooling system, so the reduction in consumption that more efficient equipment could mean is insignificant. On the other hand, the generation systems category was not considered because there is only one design option for the photovoltaic system. It is important to mention that, due to the limited computer power for the simulations, the model was modified and simplified to only one house per row (located in the central part of it, six houses in total as shown in Figure 8). Only the representative houses were chosen from each row as in [28]. This simulation took approximately 10 min in a computer with 64 bits operative system with IntelI CoreI processor i7-8750H CPU @ 2.20 GHz with 64 Gb of RAM. The same simplification was carried out in another study of the same urbanization and a comparison between the complete model and the simplified model to determine the percentage of error of the simplified model is carried out [28]. It was found that the consumption due to equipment usage is similar in both models, however, in the consumption due to cooling, an average difference of 20% was found, which was attributed to the difference in the environmental components considered in the two models. Despite this, it was considered that this difference is not significant, so the simplification of the model in order to reduce the simulation time is acceptable [35]. It should be noted that, since only the representative houses, in terms of consumption and behavior, were used to performed both the sensitivity and optimization analyses, minor characteristics from houses less representative have been left out, which may influence the findings.

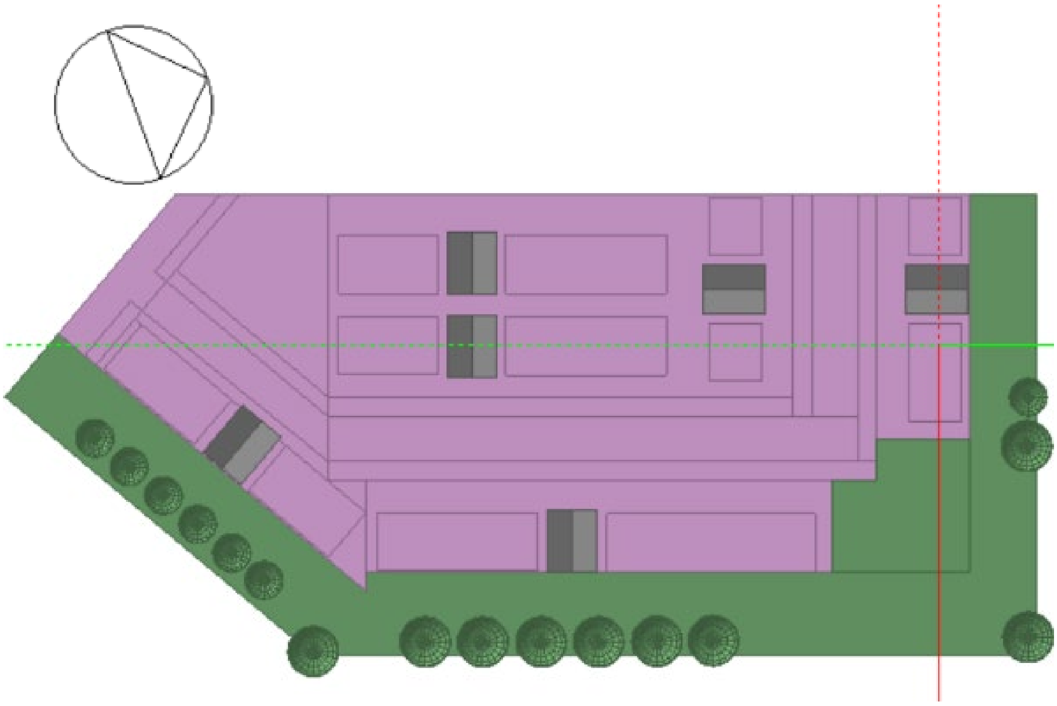


Figure 8. Plan view of the simplified model created in DesignBuilder for the sensitivity and optimization analyses.

Optimization by Important Design Variables

Considering the results obtained from the sensitivity analysis, different design options were chosen, having the variables (construction of walls and ceiling, set-point, and hours of operation of the cooling system) determined as important in electricity consumption. In this analysis, the same simplified model mentioned was used.

4.4. Design Solutions

After the execution of the optimization analysis explained previously, a total of 51 design options were obtained between the two optimization methods (see Table A1 in the Appendix A). Of these 51 options, 30 were obtained with the category of envelope + human factor, 15 with the category of cooling demand reduction, two with the category of the human factor, and four with the important design variables determined by the analysis sensitivity.

Table 4 shows the descriptions of each option obtain from the analysis separated into components that are part of the envelope, while Table 5 shows hours of occupation and preferences of the occupants. Both the costs and the thermal transmittance values were obtained from the construction price in Panama generator by CYPE Ingenieros, S.A. [36].

5. Discussion

Among all the design options resulting from the optimization, the lowest consumption was obtained with the optimization by envelope + human factor, with a reduction in electricity consumption of up to 65%. Followed by optimization by sensitivity analysis (62%) and by the human factor (58%). Regarding the optimization for the cooling demand reduction category, this is the category that presents a much higher consumption than the previous options (only 4% reduction).

On the other hand, analyzing the cost, the sensitivity analysis optimization method was the least expensive, followed by the categories human factor and envelope + human factor. In a similar manner to the target of energy consumption shortening, the cooling demand reduction category is the one that presents the options with the lowest cost savings. Based on these results, it can be concluded that modifications to the envelope entail a high cost with minimal energy savings (similar results were obtained in other studies [18,19]). This can be clearly observed in Table 6 when comparing one of the options given by the sensitivity analysis optimization and the human factor category, which only vary in favor of the sensitivity analysis on the walls. This change in the walls represents less than 5% energy saving, which can possibly be attributed in part to the difference of 3 °C in the air conditioning set-point, compared to the consumption given by the human factor option.

Table 6. Design options with similar results obtained in the optimization analysis according to the important design variables and human factor category.

Optimization Method	**Electricity Consumption (kWh)**	**Total Cost (PAB [1])**	**Comfort ASHRAE 55 (hr)**	**Embedded CO_2 (kg)**	**Cooling Set-Point (°C)**	**Cooling Operation Hours**	**Occupancy**	**External Walls**
Important design variables	504.182	371,130.03	164.458	57,795.752	26.700	7:00–19:00, Weekdays	7:00–19:00, Weekdays	150 mm concrete block (U = 2.48 W/m^2-K)
Categories: human factor	530.036	375,228.65	165.875	54,434.091	23.800	7:00–19:00, Weekdays	7:00–19:00, Weekdays	—

[1] Panamanian balboa.

Two indicators were considered when choosing the best design options according to the characteristics of the urbanization. Regarding the objective of reducing electricity consumption, viable options were those whose reduction in annual electricity consumption is equal to or greater than the current electricity consumption in a month. The results show that all the options are within the stipulated range, except for the options obtained with the cooling demand reduction category.

The second indicator that was taken into account comprises the cost reduction objective, where a return of investment analysis was carried out to determine the best options. For this, the net present value or the annual value formula that represents a future investment was used:

$$\mathrm{NPV} = \frac{\mathrm{Anual\ Savings}\ (1+\mathrm{a})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}}} - \mathrm{Renovation\ Cost} - \mathrm{Maintenance}, \tag{1}$$

where NPV: Net present value in Panamanian Balboas (PAB); Annual Savings: Savings in the annual electricity cost in PAB; Renovation Cost: Renewal cost in PAB (it is only taken into account for year zero); Maintenance: Annual maintenance cost in PAB; a: annual increase in fuel cost (for this study a value of 5% was considered); i: annual interest (for this study a value of 3% was considered); n: year of study.

Return of investment periods between 9 and 40 years after renovation were obtained; This value is an estimate given that the annual savings used were calculated based on the electricity cost for the month of March. Based on these results, the actual values for the selected option were subsequently obtained.

The most viable choice when considering both objectives of the optimization analysis is to use the design options given by the optimization according to the sensitivity analysis. This is because it presents a great reduction in consumption, similar to that seen with the optimization by envelope + human factor, but that does not involve the extra cost when modifying the roof and windows (Table 7), which represents a lower recovery of the investment (7 to 18 years). Within this category, the option that represents the lowest renovation cost was chosen (Tables 8 and 9), which leads to a recovery of the investment in the seventh year, so the investment is considered profitable. For this calculation, a zero-maintenance cost was considered due to the characteristics of the modifications of this design option. In addition to this, the selected option only represents a consumption of 10% of the photovoltaic generation, which is in line with the NZEB standards. In future studies, an analysis can be carried out about exporting this remaining generated electricity.

Table 7. Electricity consumption and cost of electricity consumption of the optimized urbanization in a year.

Month	**Electricity Consumption (kWh)**	**Total Electricity Cost (PAB [1])**
January	3117.22	464.15
February	2735.54	407.48
March	3181.47	473.69
April	3189.96	474.95
May	3350.53	498.80
June	3108.42	462.84
July	3295.69	490.65
August	3273.65	487.38
September	3126.15	465.48
October	3184.09	474.08
November	2933.26	436.83
December	3185.20	474.24
Total	37,681.17	5610.58

[1] Panamanian balboa.

Table 8. Optimal solutions selected for the case study.

Cooling Set-Point (°C)	Cooling Operation Hours	Occupancy	External Walls
24.5	8:00–20:00, Weekdays 2:00–21:00, weekends	7:00–19:00, weekdays	Concrete block 150 mm (U = 0.69 W/m^2-K)

Table 9. Optimization analysis results obtained with the design variables selected.

Electricity Consumption (kWh)	Total Cost (PAB [1])	Renovation Cost (PAB [1])	Comfort ASHRAE 55 (hr)	Embedded CO$_2$ (kg)
482.09	382,626.34	19,890.48	160.46	58,677.28

[1] Panamanian balboa.

It is important to add that the multi-objective optimization analysis was carried out considering only six houses in the urbanization and only for March to speed up the simulation process. To obtain more precise results on the payback period of the selected design option, additional simulations of the electricity consumption using DesignBuilder were carried out. These simulations included the electricity consumption of the complete urbanization with the stipulated design modifications (Table 7, Figure 9). In addition to this information, the cost of electricity consumption was calculated for one year (Figure 10), taking into account the tariff charges for customers with a consumption less than 300 kWh per month (BTS1), found in the tariff schedule given by the respective distribution company in the area EDEMET [37]. The equation for the electricity cost follows:

$$\text{Electricity cost} = \text{Fixed charge} + \text{Consumption charge}, \tag{2}$$

where the electricity cost is given in PAB, the fixed charge is 2.76 PAB for the first 10 kWh and the consumption charge is 0.15 PAB/kWh for the extra consumption.

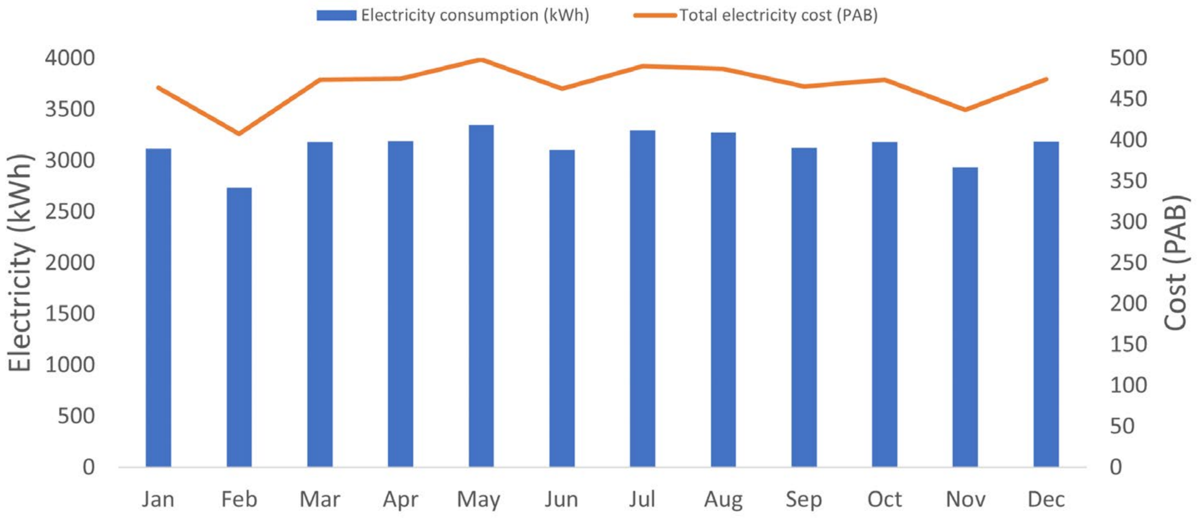
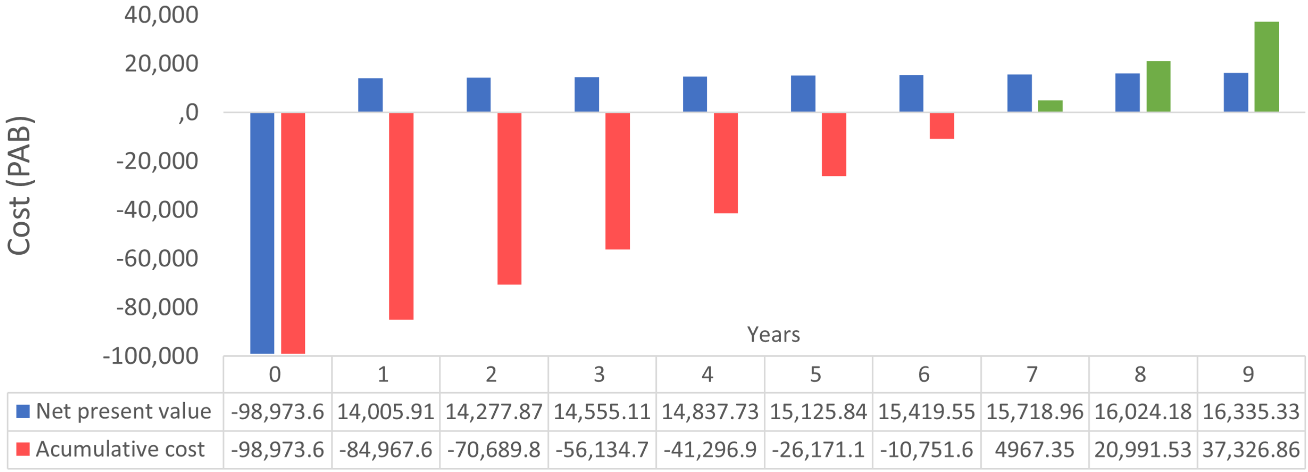


Figure 9. Comparison between electricity consumption and cost of electricity consumption of the optimized urbanization in a year.



	0	1	2	3	4	5	6	7	8	9
🟦 Net present value	-98,973.6	14,005.91	14,277.87	14,555.11	14,837.73	15,125.84	15,419.55	15,718.96	16,024.18	16,335.33
🟥 Acumulative cost	-98,973.6	-84,967.6	-70,689.8	-56,134.7	-41,296.9	-26,171.1	-10,751.6	4967.35	20,991.53	37,326.86

Figure 10. Calculation of the net present value and the return of investment period of the investment for the selected optimal option. The red color represents the years where no profit has been generated, while green is shown from the first year of profit.

Comparison with Previous Studies

A previous study with the objective of optimizing the same urbanization used for this case study suggests that the most important variables to achieve the reduction in energy consumption are modifications in windows such as the type of glass, blinds, and shading, as well as the type of roof in the construction to achieve the reduction in energy consumption [35]. Adding to this, the variation of the temperature set point in the air conditioning system was considered an active solution due to the impact of air conditioning on consumption. It is important to mention that this study does not consider the cost involved in implementing the optimal design options and the cost of the photovoltaic system implemented.

Taking this into account, it can be observed that the previous study (MO1) focuses on the modifications to the envelope to achieve the objective of reducing energy consumption. In contrast, the present study (MO2) considers only a modification to the envelope and concentrates on implementing changes in the occupant's behavior (Table 10).

Table 10. Optimal options selected for modified design variables in both compared studies.

Model	Design Variables	Optimal Solutions
MO1	A/C set point (°C) Shading Roof Windows Blinds	28 Overhangs 1.00 m, sidefins 1.00 m Insulated roof Double glass low emissivity, 6mm air None
MO2	A/C set point (°C) Cooling operation Occupancy External walls	24.5 8:00–20:00, weekdays 2:00–21:00, weekends 7:00–19:00, weekdays 150 mm concrete block (U = 0.69 W/m^2-K)

Comparing the air conditioning consumption of the present study (MO2) with the previous study (MO1) before optimization, a difference of up to 9% between both models is observed. This behavior can be attributed to changing some elements of the envelope made in MO2 to get closer to the real elements used in the construction. The previous model has the lowest consumption (Table 11, Figure 11).

Table 11. Comparison of current consumption due to air conditioning for the previous study (MO1) and the current one (MO2) and their difference percentage.

Month	Cooling Consumption (kWh) Occupancy		Percentage Difference (%)
	MO1	MO2	
January	2898	3165	8.44
February	2612	2821	7.41
March	2972	3273	9.18
April	3048	3268	6.73
May	3148	3368	6.54
June	2841	3006	5.50
July	3115	3280	5.02
August	3051	3220	5.25
September	2878	3001	4.09
October	2926	3089	5.27
November	2898	3165	8.44
December	2612	2821	7.41
Total	2972	3273	-

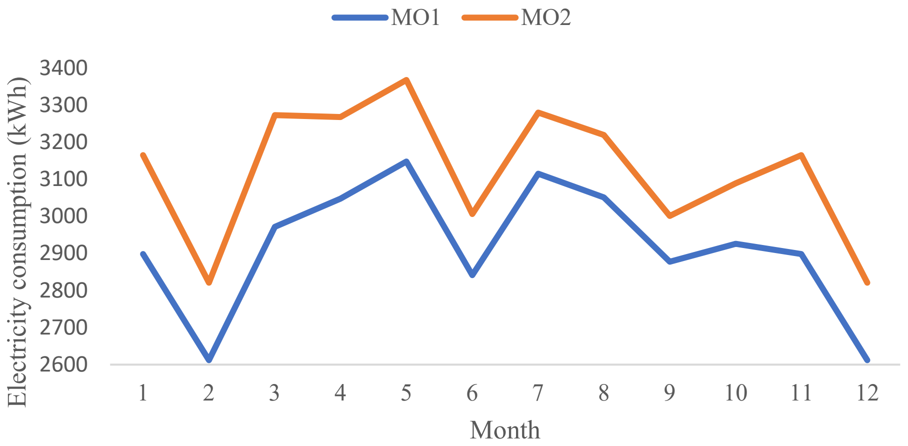


Figure 11. Comparison of current consumption due to air conditioning for the previous study (MO1) and the current one (MO2).

When comparing the results of both models, it was observed that in both cases, the consumption due to the use of the air conditioning represents a significant percentage of the total consumption, both before and after the optimization with percentages between 40% and 60% of the total consumption. On the other hand, the previous study (MO1) achieved a reduction in energy consumption of up to 30% and 43% of excess energy generated, while the present study achieved 60% energy savings and 92% excess in generation (Table 12, Figure 12). It is important to mention that the consumption and generation results shown in Table 12 are given in primary energy, which is obtained by applying an average factor of 3.15 given by ASHRAE 105, considering electrical energy.

Table 12. Primary energy values obtain in both models.

Data	Energy Values	
	MO1	MO2
Current primary energy [1]	624.27	169.45
Optimized primary energy [1]	428.2	70.53
Saved primary energy	196.07	98.92
Primary energy generated [2]	752.97	752.97
Primary energy exported	324.77	654.05

[1] Energy consumption of the urbanization in terms of primary energy. [2] Energy generated by the photovoltaic system considered.

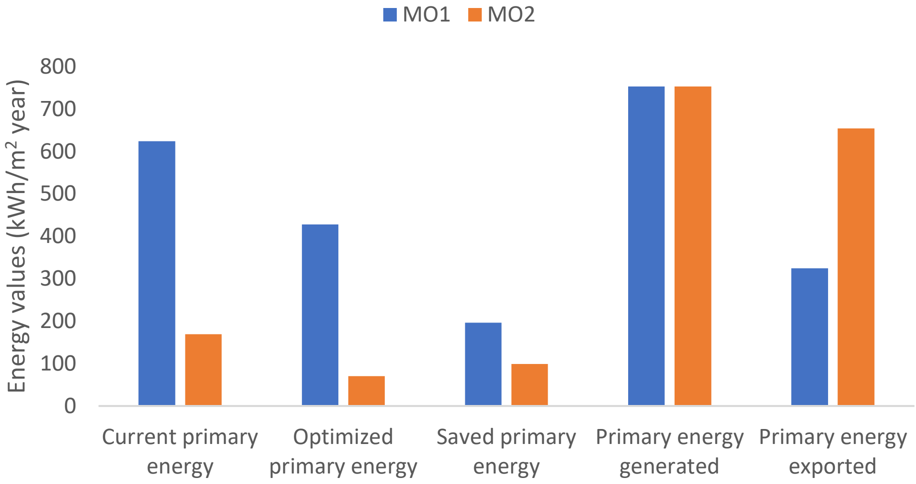


Figure 12. Comparison of Primary energy values obtain in both models.

6. Conclusions

A multi-objective optimization of an urbanization towards NZED standards was carried out. This study focused on the classification and systematization of the main elements that are part of urbanization and the implementation of said classification in the development of the optimization analysis.

A promising solution is combining both human factor with minimal changes on the building envelope, as it takes minimal money investment. The optimal solution selected achieved an electricity consumption reduction of 60% of the original value. An analysis of the methodology used indicates that implementing only modifications to the building envelope does not lead to a large decrease in energy consumption and implies a high additional cost, making its implementation unprofitable. Implementing only a change in the occupants' behavior when modifying the hours of occupation and use of equipment seems to be the best option. The best option requires to apply extreme modifications to the occupant behavior that are not practical from many perspectives, but this leads to the same indications reported from several NZEB studies where the higher the building energy performance, the greater impact the occupants' behavior will have. Future research should consider a way to implement more practical solutions in terms of the occupancy hours as well as determine a function for the remaining generated energy that is not consumed by the urbanization (e.g., other buildings nearby such as shelters, streetlights, neighborhood security systems, among others).

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Appendix A

Table A1. Simulation results of the model in its current condition and multi-objective optimization analysis with the values obtained for each factor considered and their respective design options.

Option	Electricity (kWh)	Elect. Consumption Reduction (kWh) (%)	Total Cost (PAB)	Elect. Cost Reduction (%)	Renovation Cost (PAB)	A/C (Electricity) (kWh)	Comfort ASHRAE 55 (hr)	Embedded CO_2 (kg)	Set Point (°C)	Cooling Operation	Occupancy	Ext. Walls	Roof	Windows	Shading
CC [1]	1253.410	0.00	375,416.39	0.00	187.39	0.00	375,229.00	54,434	24.000	ACA	HCA	PCA	TCA	VCA	SCA
1	437.175	65.121	93,638.50	64.68	66.19	93,572.30	452,849.58	131,683	27.90	Aop2	Hop1	Pop2	Top1	Vop7	Sop6
2	438.547	65.012	74,864.95	64.57	66.39	74,798.55	450,746.02	123,689	25.30	Aop9	Hop1	Pop3	Top1	Vop7	Sop6
3	439.416	64.942	87,070.13	64.50	66.52	87,003.61	441,290.22	131,683	23.70	Aop1	Hop1	Pop2	Top1	Vop7	SCA
4	439.474	64.938	87,070.14	64.50	66.53	87,003.61	440,481.49	124,817	25.40	Aop6	Hop1	Pop2	Top2	Vop7	SCA
5	440.088	64.889	86,968.51	64.45	66.62	86,901.89	440,434.01	129,932	25.40	Aop1	Hop1	Pop2	Top1	Vop6	Sop4
6	440.940	64.821	68,296.61	64.38	66.75	68,229.86	439,186.02	123,689	28.20	ACA	Hop1	Pop3	Top1	Vop7	SCA
7	441.613	64.767	68,194.99	64.33	66.85	68,128.14	438,330.45	121,939	28.10	Aop4	Hop1	Pop3	Top1	Vop6	Sop4
8	442.228	64.718	68,155.88	64.28	66.94	68,088.94	438,264.80	117,573	24.00	Aop1	Hop1	Pop3	Top1	Vop6	Sop3
9	442.615	64.687	67,074.22	64.25	67.00	67,007.22	436,359.91	117,573	25.40	Aop5	Hop1	Pop3	Top1	Vop6	Sop2
10	443.129	64.646	65,992.58	64.21	67.08	65,925.50	434,455.65	117,573	27.70	Aop1	Hop1	Pop3	Top1	Vop6	Sop1
11	443.289	64.633	64,910.89	64.19	67.10	64,843.79	432,550.14	121,939	28.20	ACA	Hop1	Pop3	Top1	Vop6	SCA
12	447.088	64.330	64,538.31	63.89	67.66	64,470.64	431,404.18	117,573	25.20	Aop7	Hop1	Pop3	Top1	Vop3	Sop2
13	447.605	64.289	75,322.29	63.85	67.74	75,254.55	429,599.36	130,801	24.70	Aop1	Hop1	Pop1	Top1	Vop7	SCA
14	448.233	64.239	62,375.05	63.80	67.83	62,307.21	427,593.78	117,573	28.20	ACA	Hop1	Pop3	Top1	Vop3	SCA
15	449.605	64.129	62,445.21	63.69	68.04	62,377.18	426,261.74	113,323	24.10	Aop3	Hop1	Pop3	Top2	Vop2	Sop4
16	450.032	64.095	73,018.30	63.66	68.10	72,950.20	424,868.36	124,685	25.40	Aop1	Hop1	Pop1	Top1	Vop6	Sop1
17	450.204	64.082	71,936.61	63.65	68.13	71,868.48	422,963.47	129,051	25.40	Aop1	Hop1	Pop1	Top1	Vop6	SCA
18	450.217	64.081	71,936.61	63.64	68.13	71,868.48	422,154.74	122,185	25.30	Aop3	Hop1	Pop1	Top2	Vop6	SCA
19	452.381	63.908	59,161.28	63.47	68.45	59,092.83	421,290.16	115,823	28.20	ACA	Hop1	Pop3	Top1	Vop2	SCA
20	456.939	63.544	58,102.57	63.11	69.13	58,033.44	419,212.63	115,823	28.50	Aop4	Hop1	Pop3	Top1	Vop1	SCA
21	458.684	63.405	68,517.06	62.97	69.39	68,447.68	416,044.12	122,866	25.50	Aop8	Hop1	Pop1	Top1	Vop4	Sop1
22	458.918	63.386	67,435.38	62.96	69.42	67,365.96	414,139.23	127,232	24.90	Aop1	Hop1	Pop1	Top1	Vop4	SCA
23	460.342	63.273	67,268.87	62.84	69.63	67,199.24	413,608.39	122,934	25.50	Aop1	Hop1	Pop1	Top1	Vop2	Sop1
24	460.570	63.255	66,187.19	62.82	69.67	66,117.52	411,703.50	122,934	25.40	Aop1	Hop1	Pop1	Top1	Vop2	SCA
25	460.582	63.254	66,187.19	62.82	69.67	66,117.52	410,894.77	116,069	25.40	Aop2	Hop1	Pop1	Top2	Vop2	SCA

Table A1. *Cont.*

Option	Electricity (kWh)	Elect. Consumption Reduction (kWh) (%)	Total Cost (PAB)	Elect. Cost Reduction (%)	Renovation Cost (PAB)	A/C (Electricity) (kWh)	Comfort ASHRAE 55 (hr)	Embedded CO$_2$ (kg)	Set Point (°C)	Cooling Operation	Occupancy	Ext. Walls	Roof	Windows	Shading
26	465.549	62.857	65,128.54	62.43	70.40	65,058.14	409,625.97	122,934	23.80	Aop2	Hop1	Pop1	Top1	Vop1	SCA
27	472.405	62.310	57,242.20	61.89	71.42	57,170.77	408,481.24	119,350	24.80	Aop1	Hop1	Pop1	Top3	Vop4	SCA
28	476.376	61.994	62,803.07	61.57	72.01	62,731.06	407,527.92	114,941	25.30	Aop2	Hop1	PCA	Top1	Vop1	SCA
29	480.477	61.666	38,736.86	61.25	72.62	38,664.23	384,583.02	66,671	24.10	Aop11	Hop1	Pop2			
30	482.092	61.538	19,963.34	61.12	72.86	19,890.48	382,553.48	58,677	24.50	Aop10	Hop1	Pop3			
31	489.174	60.973	48,428.31	60.56	73.91	48,354.39	406,572.71	106,990	26.40	Aop2	Hop1	PCA	Top3	VCA	Sop3
32	491.448	60.791	45,183.50	60.38	74.25	45,109.25	400,858.04	106,990	26.40	Aop2	Hop1	PCA	Top3	VCA	SCA
33	492.561	60.702	26,989.59	60.29	74.42	26,915.18	373,155.40	65,789	26.40	Aop10	Hop1	Pop1			
34	504.182	59.775	24,664.24	59.37	76.14	24,588.10	371,130.03	57,796	26.70	Aop9	Hop1	PCA			
35	530.036	57.712	79.98	57.32	79.98	0.00	375,228.65	54,434	23.80	Aop9	Hop1				
36	1094.691	12.663	163.83	12.58	163.83	0.00	375,228.65	54,434	24.70	Aop5	Hop2				
37	1205.767	3.801	59,650.22	3.775	180.320	59,469.90	485,835.18	81,610				Pop2	TCA	Vop6	Sop6
38	1206.253	3.762	58,007.87	3.737	180.392	57,827.48	482,945.34	81,610				Pop2	TCA	Vop6	Sop5
39	1206.843	3.715	56,366.03	3.690	180.479	56,185.55	480,055.50	81,610				Pop2	TCA	Vop6	Sop4
40	1207.570	3.657	56,326.94	3.632	180.587	56,146.35	479,990.48	77,243				Pop2	TCA	Vop6	Sop3
41	1208.390	3.592	37,592.51	3.567	180.709	37,411.80	478,039.70	73,616				Pop3	TCA	Vop6	Sop4
42	1208.611	3.574	54,163.66	3.550	180.742	53,982.92	476,180.70	77,243				Pop2	TCA	Vop6	Sop1
43	1208.754	3.563	53,081.97	3.539	180.763	52,901.20	474,275.81	81,610				Pop2	TCA	Vop6	SCA
44	1220.461	2.629	46,260.92	2.611	182.501	46,078.42	471,558.97	80,728				Pop1	TCA	Vop6	Sop5
45	1221.280	2.563	44,619.12	2.546	182.623	44,436.49	468,669.13	80,728				Pop1	TCA	Vop6	Sop4
46	1222.017	2.505	44,580.03	2.488	182.732	44,397.29	468,604.11	76,362				Pop1	TCA	Vop6	Sop3
47	1222.647	2.454	43,498.40	2.438	182.826	43,315.58	466,699.22	76,362				Pop1	TCA	Vop6	Sop2
48	1223.328	2.400	42,416.79	2.384	182.927	42,233.86	464,794.33	76,362				Pop1	TCA	Vop6	Sop1
49	1223.525	2.384	41,335.10	2.368	182.956	41,152.15	462,889.45	76,362				Pop1	TCA	Vop6	SCA
50	1226.836	2.120	40,117.42	2.106	183.448	39,933.97	459,844.88	78,910				Pop1	TCA	Vop4	Sop4
51	1236.059	1.384	35,623.82	1.375	184.818	35,439.00	454,239.98	70,916				PCA	TCA	Vop5	SCA

[1] CC: Current condition.

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