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The prototypes of energy-efficient residential Building with metal roof in Gorontalo, Indonesia

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Abstract. To optimize Gorontalo's residential building design to a sequential search technique is being used to minimize their life-cycle energy cost while improving their energy efficiency. Certain design features are included like air-conditioned, house orientation, window material, wall exterior finish, roof insulation, lighting fixtures, cooling system efficiencies, and photovoltaic while also considering the neighbor displacement. The outcomes of the sequential search methodology are contrasted with those achieved through a more time-consuming approach to brute-force optimization. Alternatively, for selected locations in Gorontalo, the best design features for residential building is determined. By using specific measures resulted from the optimization technique can cost-effectively reduce the annual energy saving by 59%, while adding the photovoltaic as a measure, we can increase the annual energy use saving percentage up to 117% compared to the reference design in the residential building in Gorontalo.

1. Introduction

To assess a wide range of energy-efficiency measures (EEM), an innovative architecture strategy is suggested to reduce building energy use and improve its energy output [1]. This method is especially necessary when constructing high-performance buildings that involve the use of net-zero electricity and carbon-neutral standards [2]. The dynamic results of different EEMs can be difficult to assess without the use of detailed simulation tools [3]. The architect usually performs a series of parametric assessments to measure the effects and cost-effectiveness of specific energy efficiency measures [4]. Krarti and Ihm, outlines the Middle East and North Africa (MENA) region's approach and cost-effectiveness potential in designing net-zero energy residential buildings in particular and also optimizing the design of residential buildings in Tunisia using a sequential search technique [2,5]. More rigorous parametric modeling requiring simultaneous assessment of several energy efficiency steps requires considerable computational work and is often not included in the design phase of residential buildings [6]. To address the limitations of the parametric analysis technique, the framework of the optimization-based design was introduced to define and pick architecture and operating steps to reduce energy costs for residential buildings [7]. Specifically, optimization-based approaches were used to select building shapes and design features of the building envelope using a wide range of optimization techniques [8–13].

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Gorontalo City is located in South Sulawesi, Indonesia, as the capital of the province of Gorontalo. Indonesia continues to grow as a developing country and aims to meet its people's needs. While there will be significant population growth over the next 25 years in the official population projections, we have not prepared for the impact [14]. As of now, Indonesia's electrification duty is performed solely by the state-owned utility "Perusahaan Listrik Negara" (PLN). Which claims and works the entire transmission and distribution organization of the country's electrification, while also maintaining the generation power plants production. Written in the Persero's report, the energy produced in 2018 was 234,617.88 GWh, increasing from the previous year to 5.15 percent. Among the garments, the significant share of electricity sold to residential was 97,832.28 GWh, around 41.70% of total customers [15]. As a consequence of these increases in housing units, over the past three decades, the energy overall consumption has steadily increased. This increase in energy use results from a change in the distribution of energy end-use, especially air conditioning-related ones. Only a few studies were conducted to examine the effect of Gorontalo residential buildings' architecture and operating conditions on energy efficiency. Some of the research concentrated on the impact of just a few design features or using simplistic methodologies of study [16–18]. Nonetheless, very limited research on residential buildings in Gorontalo has concentrated on the cost-effectiveness of a wide range of energy efficiency initiatives.

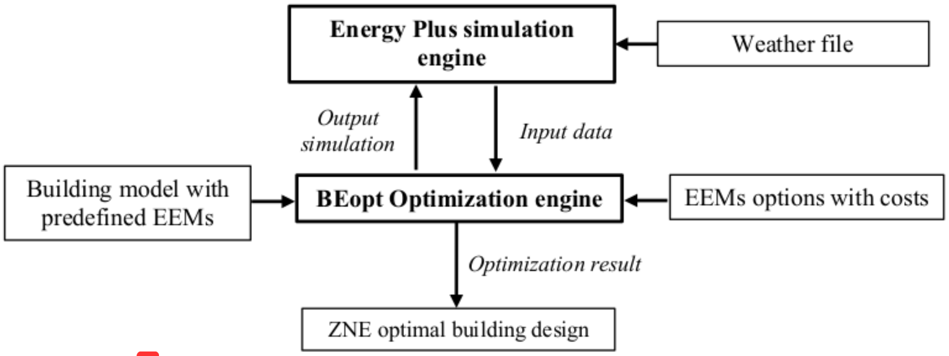


Figure 1. Flowchart for the framework of simulation used for optimization analysis [5].

The purpose of this study is to explore operational features and cost-effective design that reduce the cost of the life cycle while optimizing thermal comfort and energy efficiency for Gorontalo's residential building. Second, it explains the general characteristics and steps towards energy efficiency associated with Gorontalo's residential building prototype. The sequential search optimization results are then checked against a parametric analysis approach of full parametric analysis. Lastly, the prototypical housing recommendation is produced to improve the Gorontalo's residential building performance as the result of the optimization analysis.

2. Analysis Methodology

To carry out the study, a modeling model that uses a comprehensive simulation of the building as well as a sequential search optimization technique to determine the best way to minimize the cost of the life cycle while reducing the energy consumption of a residential building in Gorontalo. In Fig. 1, the flowchart for the simulation system and its components are illustrated.

In the following sections, the different components of the simulation environment are identified, including the essential characteristics of prototypical Gorontalo houses while keeping the energy efficiency measures and the climate zones considered.

2.1. Building Description

The basic features of a prototypical housing in Gorontalo are summarized in Table 1. Such characteristics are built based on the results of a survey conducted as part of efforts to establish a residential building energy efficiency code in Gorontalo more realistic. Fig. 2 (a) includes a 3-D rendering of a concept house in Gorontalo, while (b) is the 3-D rendering of a neighbor placement in Gorontalo, more specifically in Gorontalo city. The house has two bedrooms and two baths and is air-conditioned with a split system.

Table 1. Characteristics of a prototypical single-family house in Gorontalo

Number of Beds	**2**
Number of Baths	2
Roof Type	Gable
Roof Pitch	7:12
Roof Structure	Truss, Cantilever
Floor Area	400 sqft (37 m^2)
Wall Height	10 ft (3 m^2)
Orientation	North (180 degrees azimuth)
Window Area	155 sqft (14,4 m^2)
Window-to-wall Ratio	18% of all direction
Cooling System	Split system residential air conditioner
Heating System	None

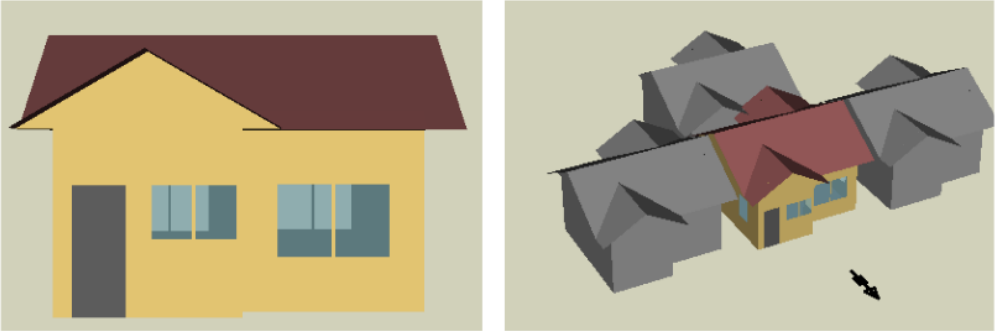
2.2. Energy Efficiency Measure

All of the energy efficiency design and operating measures that are used in this study are available in the BEopt library. Table 2 lists 10 EEMs considered for the study of optimization. These include building frames, furniture, appliances, temperature settings, and HVAC systems. A brief overview is given below on the options associated with each EEM [5]:

- Orientation identified by the angle of azimuth between the house's front and north. It is known that seven orientation choices range from 0° (baseline) to 270°.
- Outside wall and roof isolation described by the material with a different thermal conductivity. With material brick (Conductivity: 9.5 W/m-K) to fiber-cement (Conductivity: 3.1 W/m-K), five choices are considered.
- Window-to-wall ratio (WWR) specified window size. Four choices range from small windows (10% WWR) to large windows (18% WWR) are evaluated.
- Glazing style defined by the number of panels added to the glazing surfaces and the type of coating applied. In the analysis, four types of glazing are considered.
- Lighting type described by the density of lighting capacity. Five lighting choices are considered, which include 20% LED Hardwired, 40% LED Hardwire, 60% LED Hardwire, 80% LED Hardwire, and 100% LED Hardwire. All of these options are available in the BEopt library.
- Degree of air leakage identified by the rate of air infiltration. The infiltration is applied in the above-grade living space (including finished attic) which is specified by ACH50 (air change per hour at 50 Pascal). Four rates of ACH50 are considered: leaky (10 ACH50), moderate level of leakage (15 ACH50), a decent level of leakage (20 ACH50), and a solid level (25 ACH50).
- The setting of the cooling temperature specified by the maximum acceptable indoor temperature required to maintain thermal comfort. The measurement of three temperature settings is 75°F (23.89°C), 77°F (25°C), and 79°F (26.1°C).
- The energy efficiency level of the refrigerator specified by the class label [15]. The options considered are: a baseline with an annual consumption of 718 kWh/yr (Side Freezer, EF=15.7), a Class 1 refrigerator with an annual energy consumption reduction of 20 percent (Side Freezer, EF = 19.6), and a Class 2 refrigerator with an annual energy consumption reduction of 23 percent (Side Freezer, EF = 20.6).

- Type of cooling system defined by its energy efficiency ratio (EER). There are three EER that are used: EER 8.5 (low-efficiency baseline), EER 9.8 (standard efficiency), and EER 10.7 (high efficiency).

The options outlined in bold of each energy efficiency measure listed in Table 2 are the basic design options commonly used to build Gorontalo residential buildings. Baseline design characteristics are described based on the results of a comprehensive survey in Gorontalo city with more than 500 homes. For example, the baseline building model's roof construction is given by the specific material and thermal constant. Gorontalo weather data is included in the program to get results that are as close as possible to real conditions. In addition, the cost of implementing each EEM alternative is listed in Table 2. There are about more than 10 thousand possible combinations of design options for building that can be considered for a complete parametric study. A large number of combinations, as stated in the validation section of the optimization process, requires significant computation time. The simulation system uses EnergyPlus as the entire simulation engine for building energy to define the accurate performance of building energy [19–22].



(a) (b)

Figure 2. (a) Isometric of a prototypical house in Gorontalo, (b) Prototypical neighbor placement in Gorontalo

Table 2. Cost data for measurements of single-family house design and related options used for the analysis of optimization [5].

EEM	Specification	Options	Cost
Azimuth	The orientation of the building relative to the north	0°, 45°, 90°, 135°, 180°, 225°, 270°	$0 for all options
Wall Construction	Exterior Finish	Brick, Light (9.5 W/m-K)	$\$16.79/\text{ft}^2$
		Wood, Light (1.2 W/m-K)	$\$3.63/\text{ft}^2$
		Aluminum, Light (1.0 W/m-K)	$\$3.92/\text{ft}^2$
		Vinyl, Light (1.1 W/m-K)	$\$2.67/\text{ft}^2$
		Fiber-Cement, Light (3.1 W/m-K)	$\$3.38/\text{ft}^2$
Roof Construction	Ceiling	Uninsulated	$\$0/\text{ft}^2$
		Ceiling R-30 Cellulose	$\$1.42/\text{ft}^2$
		Ceiling R-30 Fiberglass Batt	$\$1.20/\text{ft}^2$
		Ceiling R-30 Closed Cell Spray Foam	$\$3.32/\text{ft}^2$
WWR	Windows to Wall Ratio	18%, 15%, 12%, 10%	0$ for all options
Window Type	Glazing Type	Clear, double, nonmetal (U:	$\$20.64/\text{ft}^2$.

		2.782349 W/m^2.K)	
		Low-E, double, nonmetal (U: 2.214523 W/m^2.K)	\$21.52/ft^2
		Low-E, double, insulated (U: 1.817044 W/m^2.K)	\$31.51/ft^2
		Low-E, triple, nonmetal (U: 1.703479 W/m^2.K)	\$33.06/ft^2
Lighting Density	Building Lighting Level	20% LED Hardwire, 34% CFL Plugin	\$0.04/ft^2 living
		40% LED Hardwire, 34% CFL Plugin	\$0.06/ft^2 living
		60% LED Hardwire, 34% CFL Plugin	\$0.08/ft^2 living
		80% LED Hardwire, 34% CFL Plugin	\$0.10/ft^2 living
		100% LED Hardwire, 34% CFL Plugin	\$0.12/ft^2 living
Infiltration	Air Infiltration Level	25 ACH50	\$0.65/ ft^2 for all options
		20 ACH50	
		15 ACH50	
		10 ACH50	
Cooling Set Point	Temperature Set Point for Cooling Electricity Consumption Level	75°F (23.89°C)	\$0 for all options
		77°F (25°C)	
		79°F (26.1°C)	
Refrigerator	Electricity Consumption Level	Side Freezer (EF = 15.7)	\$1,139.40/Unit
		Side Freezer (EF = 19.6)	\$1,373.50/Unit
		Side Freezer (EF = 20.6)	\$1,494.00/Unit
Air Conditioner	Energy Efficiency Ratio (EER)	EER 8.5	\$29.20/kBtuh
		EER 9.8	\$34.10/kBtuh
		EER 10.7	\$44.50/kBtuh

2.3. Economic Analysis

Please ensure that affiliations are as full and complete as possible and include the country. The addresses of the authors' affiliations follow the list of authors and should also be indented 25 mm to match the abstract. If the authors to carry out the optimization analysis, the simulation system will consider cost functions and the collection of constraints. The cost function is chosen in this paper as the cost of the life cycle or LCC as specified by Eq. (1)[23].

$$LCC = IC + USPW(N, r_d) * EC \qquad (1)$$

Where:

- IC: is the initial cost of incorporating both building envelope and HVAC design and operating features. The cost details for various design and operational options are given in Table 2.
- EC: is the annual energy cost to maintain indoor comfort for the selected design and operating characteristics within the residential building.
- USPW: is the useful uniform sequence that depends on the annual discount rate, rd and N lifetime.

$$USPW(N, rd) = \left[1 - \left(1 + r_d\right)^{-N}\right] / r_d \qquad (2)$$

Throughout the paper's optimization study, the lifespan is set in 30 years and the annual discount rate is 6.7%. Typically, these values are based on the lifespan of typical homes as well as Gorontalo's economic parameters [24]. In this analysis, the utility rate for Gorontalo is considered to cost 0.106 USD/kWh of electricity.

3. Optimization Approach

3.1. Overview of Optimization Technique

Using a sequential search approach, the optimization process used in the simulation setting determines the best construction design options from multiple possible alternatives. This approach to optimization is first extended to the construction of buildings with zero-net energy (ZNE) [2,25]. The sequential search optimization approach to find the path that satisfies an optimal EEM package with the lowest life cycle cost is illustrated as described by Eq. (1) is illustrated in Fig. 3. The approach of optimization also considers the suboptimal path to the development of the ZNE. First, all the EEMs are considered individually with a specific life cycle cost for an initial building design. Second, based on the steepest slope consisting of the LCC to energy savings ratio, the most cost-effective EEM option is picked. The optimal EEM option selected is then removed for future evaluation from the parameter search space, and the remaining EEMs are then simulated to find the next optimal choice [2,5]. The process will be repeated before finding the optimal solution. To choose the best combination of design features of the building. That is, the approach finds the best intermediate solutions at different levels of energy savings for the minimum cost designs. In fact, in addition to the optimal solution, the strategy can provide a set of options to achieve any number of desired savings in energy use that reduces the cost of the life cycle before achieving the optimal solution. Therefore, the sequential search technique can be used to find an optimum route to achieve different levels of energy savings at the lowest life cycle costs [2,26].

The built simulation environment used in the optimization study is designed to easily accept and recognize appropriate EEM packages to reduce the cost of building and operating residential buildings in Gorontalo during the life cycle. It should be noted that it is possible to extend and adapt the simulation model to any other type of building.

3.2. Validation of Optimization Results

The results obtained from simulation are contrasted with a parametric analysis approach that uses any possible combination options of energy efficiency measures to obtain the optimal design for Gorontalo's residential building.

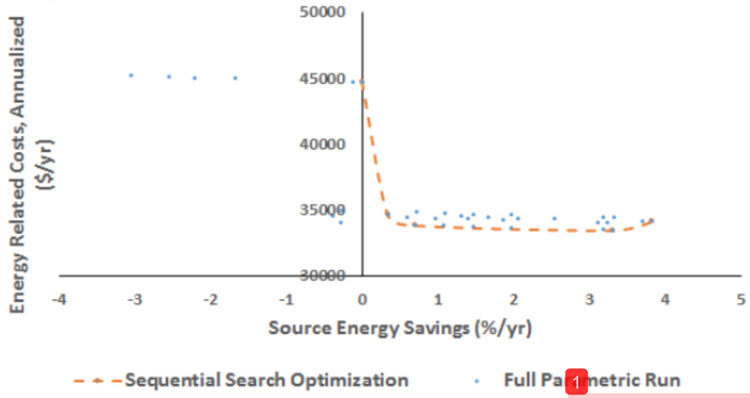


Figure 3. Comparison of optimal results obtained through parametric analysis and sequential search optimization for the 2-EEM in Gorontalo.

Computer performance is important to simulate the optimal design for 10 EEMs (produce about 10.000 possible combinations of design option) because it can affect the simulation duration (take several weeks to complete).

Alternatively, to verify the findings of the sequential search optimization method, three analytical cases are considered with different numbers of EEMs listed in Table 2. The two theoretical cases considered consist of different design methods combinations:

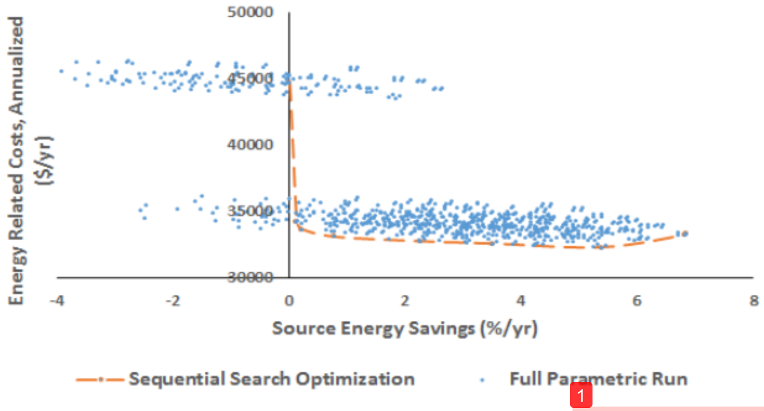


Figure 4. Comparison of optimal results obtained through parametric analysis and sequential search optimization for the 4-EEM in Gorontalo.

The two theoretical cases considered consist of different design methods combinations:
1) 2-EEM package: Orientation, and exterior wall insulation.
2) 4-EEM package: Orientation, exterior wall insulation, WWR, and glazing type.

Figures 3-4 compare the results obtained from the simulation of the two packages of EEM in Gorontalo's residential building with those obtained with the complete parametric method. The fig. 3-4 results are shown in parallel diagrams showing the expense of the life cycle as a function of the percentage savings of the total energy consumption of the building source.

4. Optimization Results

4.1. Optimization Performance

Table 3 summarizes the parametric analysis comparative performance and the sequential approach to search optimization. As shown in Fig 3 through 4, the sequential search optimization method, as well as Table 3, uses the same optimal solutions found for the three theoretical cases through the parametric technique. For the 4-EEM package analysis case using a 2.5-HGZ processor, the processing time of the sequential search technique (2.5 h) is significantly lower by up to 77.27 percent than that of the parametric analysis method (11 h).

Table 3. Characteristics of a prototypical single-family house in Gorontalo

Number of EEMs	Number of Possible Building Design Options	Computing Time for Parametric Analysis [min]	Computing Time for Sequential Search Optimization Analysis [min]
2	35	29	25

3	140	130 (2 h)	56
4	841	696 (11 h)	155 (2.5 h)

4.2. Optimal combinations of design measures

The obtained three sets of energy efficiency measures from the simulation are outlined in Fig. 5. To gain more insight into the behavior change for the set of 13 EEMs relative to the sets of 7 and 10 EEMs. While there's no significant change in the life cycle and energy savings of the search for optimum design when some of the EEMs are being added to form the 4-EEM set from the 2-EEM set as shown in *Fig. 3* and 4 [5]. However, the maximum potential source energy savings are significantly different for 7-EEM and 10-EEM sets, with 42.1% (for the 7-EEM set) and 59.1% (for the 10-EEM set). The simulation result indicates that applying insulation to the exterior layer of the outer walls, changing the orientation, changing the WWR, and changing the glazing type is not a cost-effective measure because it's not giving a noticeable change in the source energy saving. However, the results provided in Fig. 5 suggest that the optimal design configuration for the 13-EEM system (with the addition of another 3 EEMs which is, PV system, PV azimuth, and PV tilt) pushes the optimal design configuration to the higher source energy saving up to 117.1%/yr while also slightly lowering the life cycle cost.

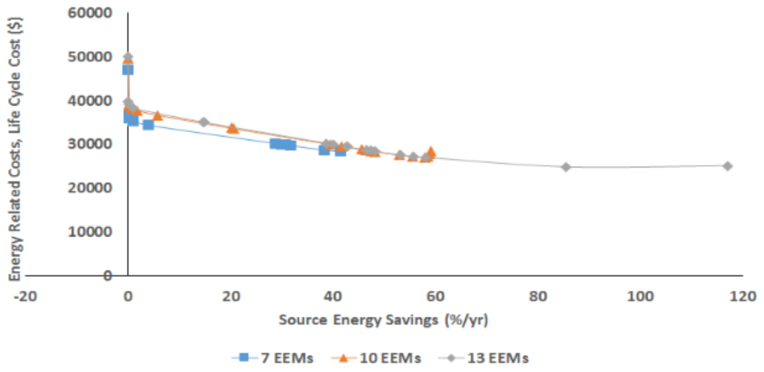


Figure 5. Comparison of the outcomes of sequential search optimization for 7, 10 and 13 EEM sets.

Table 4 shows the EEMs result after being optimized using the sequential search optimization analysis. It is shown that certain EEMs are changing between the 7-EEM set to the 13-EEM set. The unchanging EEMs which include WWR, infiltration level, and the cooling setpoint. This indicates that WWR of 12, infiltration level of 10 ACH50, and the cooling setpoint of 79 of is most likely the best option to be implemented in the Gorontalo. In addition, the ideal design for the 13-EEM set uses a lower air conditioning EER (9.8 EER) instead of larger air conditioning EER like 10.7 for 7-EEM and 10-EEM sets while also changing the glazing type to (clear, double). This selection lowers the house's initial cost due to the lower price of air conditioning with lower EER and glazing type of (clear, double), this allows cooling loads to be minimized. This reduction in initial costs allows optimization to choose less energy-efficient design options for the 13-EEM (specially to cover the PV related EEMs cost) set than those selection for the 10-EEM or 7-EEM sets.

Table 4 Description result of the optimization analysis for a residential building located in Gorontalo for sets of 7, 10 and 13 design measures.

	7 EEMs	**10 EEMs**	**13 EEMs**
Azimuth	0°	0°	180°
WWR	12	12	12
Refrigerator	EF = 15.7	EF = 20.6	EF = 15.7

Lighting Level	20%	100%	100%
Glazing Type	Low-E, Triple	Low-E, Triple	Clear, Double
Infiltration Level	10 ACH50	10 ACH50	10 ACH50
Air-Conditioning	EER 10.7	EER 10.7	EER 9.8
Roof Insulation	Ceiling R-30 Cellulose	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt
Exterior Wall Insulation	Fiber-Cement, Light	Wood, Light	Vinyl, Light
Cooling Set point	79 °F	79 °F	79 °F
Net Present Value ($)	17441.67	21267.18	24856.89
Annualized ($/yr)	152.41	82.83	-66.66
Life Cycle Cost ($)	29477.47	28357.28	25049
Energy Saving (%/yr)	42.13	59.11	117.12

5. Summary and Conclusion

By using a sequential search technique, single-family homes in Gorontalo is being simulated to optimize the energy use using life-cycle cost analysis, and comprehensive building energy modelling. A wide range of construction and the measurable feature is included in this study, including window to wall ratio (WWR), orientation, roof insulation levels, wall, glazing type, cooling system, and lighting fixtures equipment. The current Gorontalo's residential building can be optimized up to 59% cost-effectively. Recommended energy efficiency measures including adding insulation, lighting fixtures, installing energy-efficient appliances, and minimizing air penetration can be considered to optimize the energy use in Gorontalo's residential building.

In providing a wide range of desired results, the simulation environment built is found to be versatile. However, the optimum design can be achieved using the sequential search technique while also open a new consideration in the cost-effective set of energy efficiency desired in the energy-saving level, which includes the net-zero energy design configuration. As of the result, it can be used to improve the already made building and help the architects to design the better residential building in Gorontalo or a residence with the same climate condition.

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