Optimized Design of Residential Building Envelope inTropical Climate Region Thermal Comfort and CostEfficiency in an Indonesian Case Study_ bang Haolia

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Case Study

Optimized Design of Residential Building Envelope in Tropical Climate Region: Thermal Comfort and Cost Efficiency in an Indonesian Case Study

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Abstract: The purpose of this study is to optimize building envelope parameters and ventilation systems by considering passive cooling strategies to improve indoor thermal comfort without any significant supplementary cost in buildings construction and operation in a tropical area. The NSGA-II algorithm is performed in this optimization study using TRNSYS and CONTAM simulation tools, with three objectives: (a) minimization of indoor thermal discomfort, (b) minimization of construction costs, and (c) minimization of the building weight. The results show that the determination of building parameters is highly affected by design objectives. By considering all objectives, the building is recommended to have low-geometry compactness, moderate roof slope, southeast main facade orientation, high roof and wall albedo, and moderate height and wall thickness. However, the final decision to determine the selected building parameters depends on user preferences. The methodology and results in this paper can help design new more comfortable residential buildings in the hot-humid tropical region at more efficient construction cost. It can also improve the energy efficiency of existing residential buildings. **DOI: 10.1061/(ASCE)AE.1943-5568.0000529.** *© 2022 American Society of Civil Engineers.*

Author keywords: Optimization study; Building envelope; Passive cooling; Thermal comfort; Construction cost.

Introduction

The building sector meets one of the fundamental needs of human beings. Humans spend at least 90% of their time inside buildings (Evans and McCoy 1998). Therefore, achieving thermal comfort of buildings is a vital factor in residential building design. Active air conditioning systems are commonly installed to ensure that buildings provide indoor thermal comfort in tropical climate regions (Yu et al. 2009). In total, 46% of the existing buildings in countries that are members of the Organization for Economic Cooperation and Development (OECD) are equipped with an active cooling system (Santamouris et al. 2007). Globally, a cooling system typically uses 43% of a building's total energy consumption (Yu and Chow 2001). In Indonesia, the highest contributors to building energy expenditure are the cooling system and lighting equipment, using 24.7% and 16% of total building energy consumption, respectively (ESDM 2010). However, the air conditioning effect can increase the sick building syndrome (SBS) 30% higher than in naturally ventilated buildings (Seppänen and Fisk 2002). Furthermore, the building sector is responsible for 36% of CO_2 gas emissions in industrialized countries, causing air pollution and global warming (IPCC 2014). Hence, energy saving in buildings is crucial in environmental conservation.

In designing a building, several significant factors must be considered, such as occupant comfort and construction cost. However, from an economic standpoint, the maintenance and operational cost for technical equipment should be minimized as low as possible. Although it is important to keep the building operating cost low, the comfort of occupants remains the main priority. In fact, there are four types of comfort in a building: thermal, visual, acoustic, and olfactory. Moreover, in earthquake-prone areas such as Indonesia, for disaster mitigation, the weight of the building envelope should be kept as low as possible to minimize damage due to earthquake shocks.

The improvement of thermal performance is an inevitable way to solve the economic, comfort, and environmental problems in the building sector. In the tropics, passive cooling techniques could be a promising solution for low-energy-consumption building. In fact, building thermal performance depends on many factors, including climate conditions, geometry, structures, building materials, and occupation. Some studies of building performances are well documented, such as building envelope design and geometry (Romani et al. 2015, 2016; Lapisa 2019), ventilation and lighting systems (Lapisa et al. 2013b; Lapisa 2015; Lapisa et al. 2018, 2020), and the effect of internal load and occupant activity (Wan and Yik 2004; Nguyen and Aiello 2013; Laghmich et al. 2019). In addition, in earthquake-prone areas, the building should be constructed with reliable structural strength with minimal construction weight to mitigate the impact of earthquake shocks. Some studies (Inel et al. 2008; Lewis 2003) have shown the risk of damage to building structures due to earthquakes.

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The current study aims to optimize building-parameters design by implementing passive cooling techniques on the envelope for more comfortable residential buildings at a more efficient construction cost in a tropical region. The optimized parameters are the building geometry and its orientation, the albedo of wall and roof, the dimension of building envelope, and the windows surface ratio. In optimizing those parameters, this study uses the Nondominated Sorting Genetic Algorithm-II (NSGA-II) optimization tool developed by Deb et al. (2002); Deb (2001). NSGA-II is performed to determine the optimal parameter configuration based on three main objectives: (a) minimizing the indoor thermal discomfort, (b) minimizing the construction costs, and (c) minimizing the weight of building envelopes. The first part of the study presents the characteristics of typical residential buildings and potential passive cooling techniques. Such a study considers the local climate for in-depth analysis related to environmental factors, as described in the first section. In the second part, the optimization method is described in detail, including the main parameters to be evaluated. Selection criteria for the optimal solutions are performed based on end-user needs. In the last part, the optimal solutions according to the three objectives are proposed. Building owners and designer can determine personal choice using the ponderation factor. However, climate change could affect the optimal solutions of building parameters for future conditions. Therefore, the climate change effect must be considered in designing optimal building parameters.

Indonesian Climate Characteristics

According to the Köppen Climate Classification, Indonesia is classified as a tropical rainforest climate and is termed an equatorial climate. The outside air temperature varies between 25°C to 34°C, with an daily average temperature of 28°C (Climatestotravel 2020; Weatheronline 2020). Since Indonesia is primarily coastal, the average annual air humidity is relatively high, around 70%–90% (Weatheronline 2020). Padang city (100.35 E and 0.95 S) is one of the big cities in the western part of the island of Sumatera, with a high average outdoor temperature and humidity (26.8°C and 80%) and a moderate average wind speed of 1.99 $m \cdot s^{-1}$ (Lapisa et al. 2020). As an equatorial region, this city has constant solar radiation throughout the year, with a maximum and mean value of 1,055 and 386.5 $W \cdot m^{-2}$ (Lapisa et al. 2020).

In addition, the global warming effect can significantly affect outdoor air temperature and humidity. In this study, we analyze the impacts of global warming on building parameters in the city of Padang. The morphing method developed by the University of Southampton (Belcher et al. 2005; Jentsch et al. 2013) is used to predict outdoor air temperature in Padang for 2050. Table 1 lists the current outdoor temperature and the climate prediction for 2050 in Padang city, with a high-emission scenario, with storyline A2 of the *Special Report on Emissions Scenarios* (SRES) summarized in the *IPCC-Third Assessment Report*. Storyline A2 assumes that the world is highly heterogeneous. with a continuously increasing global population and regionally oriented economic growth. Finally, the climate change world-weather file for numerical simulation is generated by the CCWorldWeatherGen tool based on the morphing method (Belcher et al. 2005; Jentsch et al. 2012, 2013).

Table 1. Meteorological data of Padang city

Parameters	Year 2020	Prediction for year 2050
Maximum/average temperature (°C)	34.1/26.81	35.9/28.64
Average relative humidity (%)	81.4	80.6
Mean/max—solar radiation ($W \cdot m^{-2}$)	386.5/1,055	386.7/1,055
Average wind velocity ($m \cdot s^{-1}$)	1.99	2.00

In addition, Indonesia's location is at the intersection of three main crustal moving tectonic plates: Indo–Australian, Pacific, and Eurasian. With such geological characteristics, it is no wonder that Indonesia experiences numerous tectonic earthquakes. For high seismic-potential areas such as Padang, Indonesia, the light weight of the building envelope is crucial for reducing the impact of earthquake shocks (Mishra and Mishra 2020). Therefore, reducing the weight of the building envelope becomes vital in building design in earthquake-prone areas.

Materials and Method

To perform the numerical analysis and multicriteria optimization of building parameters, this study uses the DEAP Python module that adopts the NSGA-II algorithm developed by Deb (2002). Building thermal performance is numerically analyzed using a coupling of building simulation tools TRNSYS and CONTAM (Fig. 1). Thermal characteristics of building envelopes, heat transfer in the materials and environment (ground, outdoor), and indoor temperature are calculated using type 56 TRNSYS. The aerodynamic aspects, such as the flow rate and the wind pressure coefficient, are calculated by type 87 TRNSYS connected to CONTAM. A 1-year simulation period with 1-hour time step is carried out to obtain comprehensive annual building thermal behavior. The first year of initialization has been performed to avoid initial thermal condition influences.

The multicriteria optimization in this study has three objectives, as described in the Introduction. For economic calculations on the construction cost, the effect of Indonesian currency inflation is not considered here. Furthermore, there are some hypotheses in this numerical optimization study: (a) climate change prediction using the Hadley Centre Coupled Model, Version 3 (HADCM3-Aa2) method (Belcher et al. 2005; Jentsch et al. 2013) with high-emission defined by IPCC, (b) the construction material price and Indonesian wages are considered constant by neglecting the currency inflation, and (c) building thermal comfort evaluated by the degree-hour indicator (°C h) and calculated based on the adaptive comfort limits (NF EN 15251, CEN 2007). HadCM3-Aa2 is a coupled climate model that has been used extensively for future climate prediction, detection, and attribution. It is composed of two components (atmospheric and ocean model) and does not need flux adjustment to produce a good prediction (Collins et al. 2001).

Description of the Studied Indonesian Residential Building

The Indonesian residential building for the reference case in this study is made of a masonry wall structure (Fig. 2) with a wall thickness of 15 cm. The 100 m^2 concrete–ceramic floor (L: 12.5 m and W: 8 m) lies directly on clays. In addition, the plywood ceiling (3 mm thickness) is 3.5 m above the ground floor (H). The gable roof is made of gray zinc with a slope (θ) of 30°.

The windows are a single glass with an overall heat transfer coefficient of 2.89 $W \cdot m^{-2} \cdot K^{-1}$ and transmission 0.789. The windows are on the main facade and the opposite one. These windows have a surface ratio of 10% of the floor area. The building is occupied by a family with two children. The heat transfer between the ground floor and soil is modeled by a 3D heat-transfer approach (Lapisa et al. 2013a, b). For the equatorial area, the principal facade faces to the south to reduce unwanted solar heat gain (Lapisa 2015). Table 2 presents the thermal characteristics of the building.

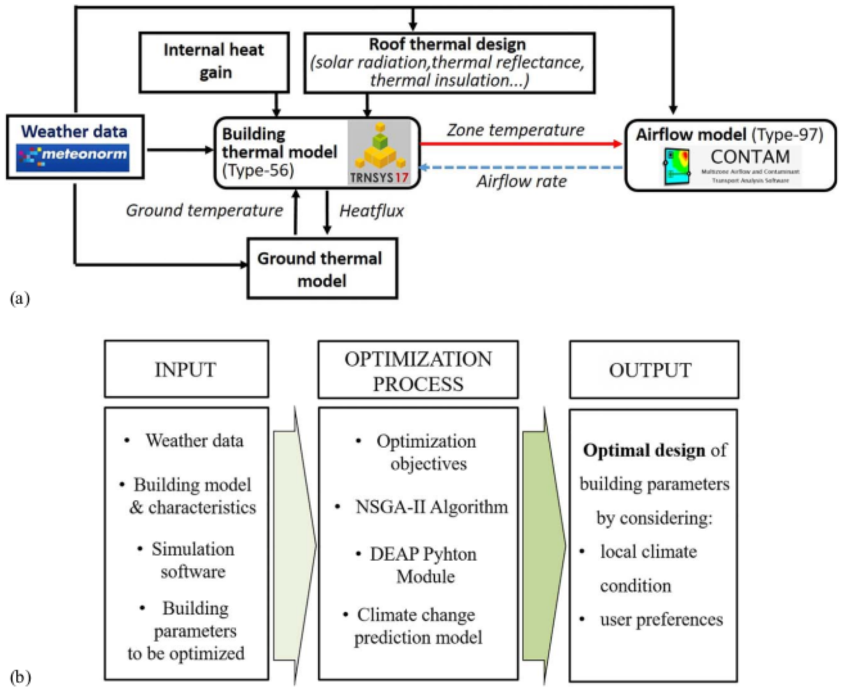


Fig. 1. Schematic representation of the simulation: (a) optimization process (reprinted with permission from Springer Nature: Springer, *Asian Journal of Civil Engineering*, "Passive cooling strategies in roof design to improve the residential building thermal performance in tropical region," R. Lapisa, A. Karudin, F. Rizal, Krismadinata, and Nasruddin, © 2019); and (b) building energy simulation coupling process.

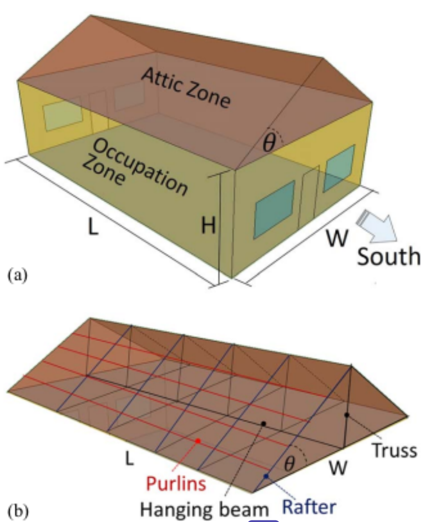


Fig. 2. (a) Geometry of studied building; *L*: length (m), *W* = width (m), *H*: height of ceiling (m), (*θ*): slope of roof (°); and (b) roof construction parts.

Gable Roof Design and Framing

The roof of the reference building is a gable roof with a slope angle (θ) of 30°. The roofing material is gray zinc roof with a thermal reflectance (albedo) value of 0.39 [Fig. 2(b)]. In this study, purlins, rafters, and truss are made of the same material. For safety, the maximum distance between the rafters is 2.5 m. The purlins are

Table 2. Thermal characteristics of building envelopes for the reference case

Elements	Materials	t	K	ρ	C
Vertical walls	Plastered clay brick	150	0.82	1,826	0.8
Roof	Zinc with steel frame	3	407.9	7,135	0.42
Slab	Concrete cement mortar	50	5.04	2,000	1
	Ceramic	15	4.32	1,800	0.8
Ceiling/plafond	Plywood board	2	0.54	1,000	1.2
Door	Plywood	8	0.54	1,000	1.2

Sources: Data from Klein et al. (2004); Laskowska (2020); Tho et al. (2018); Newman and Owens (2003); Borysiuk et al. (2012); Engineering Toolbox (2018).
Note: t = total thickness (mm); K = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$); ρ = density (kg/m^3); and C = heat capacity ($KJ \cdot kg^{-1} K^{-1}$).

zinc support holders, mounted transversely on the rafters. The maximum distance allowed between the purlins is 2 m. In optimizing the θ of the roof, several elements have dimensional changes, such as length of roof truss, length of rafters, and number of purlins. By maintaining the minimum distance between the truss, rafters, and purlins, the length of steel frame needed, L_{RB} (m), to construct the roof truss (truss, rafters, and purlins) can be calculated using

$$L_{RB} = \left(\text{roundup}\left(\frac{L}{2.5}\right) + 1\right) \times W \left(\frac{1 + \cos(\theta) + 0.5 \sin(\theta)}{\cos(\theta)}\right) + \left(\text{roundup}\left(\frac{0.5\, W}{\cos(\theta)}\right) + 2\right) \cdot L \qquad (1)$$

where L = length of the building (m); W = width of the building (m); and θ (°) = slope angle of the gable roof. Roundup is a

Table 3. Optimization parameters and its impact on thermal discomfort, cost, and building weight

Parameters	Symbols	Optimization objectives: Thermal	Cost	Weight	Values: Ref	Range	Unit
Geometry compacity	B_{gc}	X	X	X	0.64	0.64–1	—
Slope of roof	θ	X	X	X	30	15–45	(°)
Building orientation	B_O	X	—	—	180	0–359	(°)
Albedo of vertical walls	ρ_W	X	—	—	0.3	0.3–0.9	—
Albedo of roof	ρ_R	X	—	—	0.3	0.3–0.9	—
Thickness of walls	t_W	X	X	X	15	5–30	cm
Height of vertical walls	H_W	X	X	X	3.2	2.5–5	m
Window/floor surface ratio	W_{WR}	X	X	X	10	2.5–15	%
Thickness of ceiling	t_C	X	X	X	3	50–100	mm

mathematical operation in a programming language that functions to round up the value of division results.

The total surface area of zinc required as a roof cover S_{Roof} (m^2) is calculated using

$$S_{\text{Roof}} = \frac{L \cdot W}{\cos(\theta)} + 0.25 \cdot W^2 \cdot \tan(\theta) \tag{2}$$

Optimization Parameters

This study uses nine building envelope parameters on optimization analysis for three determined objectives (Table 3). The reference building orientation is 0°. This means the main facades face south. The coefficients of building geometry compactness (B_{gc}) is the ratio of the width (W) to the length (L) of the building ($B_{gc} = W/L$). When the coefficient value of $B_{gc} = 1$, the building form is square (10 × 10 m) with height H (m). Another parameter is the window/floor surface ratio (W_{WR}). This refers to the proportion of the total window area to the floor surface area (%). Table 3 lists the optimized parameters, the effect of these parameters on each objective, and the reference value and the allowable value interval in the optimization.

Construction Cost and Building Weight Calculation

In this study, there are two classifications of residential building construction costs to consider: fixed costs and variable costs. Fixed costs are the cost needed for anything that does not depend on the form of building design. The fixed costs include building preparatory work (house design drawings and material procurement), land preparation (hoarding and clearing land), sanitation and piping systems, installing doors, installing locks, and other residential equipment. Variable cost is the cost that is directly influenced by building design, such as foundation construction, brick wall installation, floor installation, roof and frame installation, ceiling installation, painting, and windows installation. Cost comparisons made in this optimization study are only on variable costs, and fixed costs are assumed to be the same for all building designs.

During the construction process, workers are estimated to work 8 hours/day. The wages for construction workers are classified into two types, namely: (1) Construction laborer (*HC*) with a wage of Indonesian rupiah (IDR) 120,000/day, and (b) workmen (*HLC*) with a wage of IDR 90,000/day (Banamitra 2020; Hargabangunan 2021). Tables 4 and 5 list the raw material price for construction and the wages for construction workers and laborers to calculate the total construction cost.

Table 4. List of construction raw material prices in Indonesia (IDR/unit)

Materials	Unit	Price/unit (IDR)	Materials	Unit	Price/unit (IDR)
Stone (St)	m^3	225,000	Brick (Br)	pcs	500
Cement (Ce)	kg	1,300	Painting (Pn)	m^2	22,900
Sand (Sd)	m^3	275,000	Plywood (Tr)	m^3	47,500
Ceramic (Cr)	m^2	40,000	Zinc (Zn)	m^2	46,000
Ligth steel (Ls)	m	15,000	—	—	—

Sources: Data from Addesia (2020); Asiatoko (2015); Ilmusipil (2020).
Note: IDR = Indonesian Rupiah (currency of Indonesia), especially for painting prices include the purchase of goods and painter wages.

In calculating the building's weight, the optimized building structure is considered the part of the building with a high risk of falling during an earthquake shock. Some of the building envelope components measured for weight analysis are walls, ceilings, roofs and frames, windows, and doors. Other structures, such as foundations and floors, are not included, because they are not at risk of falling. The weight of the building envelope elements is presented per unit of material. In this case, the brick wall with cement plaster weight is 1,826 kg/m^3; plywood for ceiling weight is 1,000 kg/m^3; louvered windows are 13.75 kg/m^2; light steel is 0.85 kg/m^1; and the gray zinc roof is 7,135 kg/m^3 (Engineering Toolbox 2018). Table 5 lists the calculated construction costs and weight for each building component.

Total construction cost (*Cost*) in IDR and total building weight (*Weight*) in tons are calculated using Eqs. (3) and (4).

$$Cost = \sum_{n=1}^{8} Cost_n \tag{3}$$

$$Weight = \sum_{n=1}^{8} Weight_n \tag{4}$$

For thermal comfort parameters, the building performance indicators are from the degree hours (DH) discomfort value. The value is the sum of all temperatures in excess of the adaptive comfort limit temperature within 1 year is calculated by

$$DH = \sum_{i=1}^{8762} (T_{\text{op},i} - T_{\text{comf},i}) \tag{5}$$

where $n = 1$: foundation, 2: ground floor, 3: brick vertical wall, 4: ceiling, 5: painting, 6: roof truss/frame, 7: zinc roof, and 8: window (Table 5); i: 1, 2, 3…8,760 = number of hours in 1 year; $T_{\text{op},i}$ = indoor operative temperature for the ith hour; and $T_{\text{Comf},i}$ = limit of the comfortable indoor temperature calculated on the ith hour using the adaptive comfort method. The better the building performance, the cooler the air in the room. If the air in the room cools down passively, the *DH* value will be lower.

Optimization Method

The optimization study aims to determine the non-dominated solution based on the set of nine design parameters (listed in Table 3): to minimize; (1) *DH* (x) of thermal discomfort in °C h, (2) construction cost (*Cost*) (y) in IDR, and (3) total building weight (*Weight*) (z) in tons, as presented in Eq. (6). The NSGA-II algorithm is used as the optimization tool in this study. NSGA-II is one of the most popular and efficient multiobjective optimization algorithms, with three characteristics: fast nondominated sorting approach, fast crowded-distance estimation procedure, and simple crowded-comparison operator (Deb et al. 2002).

Table 5. Calculation of construction costs and weight of building envelope

No.	Type of work	MC and LC per unit volume of work	Volume of work (V)	Cost	Building weight (B_W)
1	Foundation, (m^3)	$MC_1 = 1.2\ St + 202\ Ce + 0.485\ Sd$ $LC_1 = 0.9\ HC + 1.5\ HLC$	$V_1 = 0.5\ m^2 \times (2L + 2W)$, (unit: m^3)	$Cost_1 = (MC_1 + LC_1) \times V_1$ $Cost_1 = 910{,}000 \times (L + W)$	$Weight_1$ = Not considered
2	Ceramic for ground floor (m^2), Ceramic size: 20 × 20 cm	$MC_2 = 1.1\ Cr + 12.02\ Ce + 0.045\ Sd$ $LC_2 = 0.42\ HC + 0.7\ HLC$	$V_2 = L \times W$, (unit: m^2)	$Cost_2 = (MC_2 + LC_2) \times V_2$ $Cost_2 = 185{,}400 \times (L \times W)$	$Weight_2$ = Not considered
3	Brick vertical wall (m^3), *Brick size*: 5 × 11 × 22 cm	$MC_3 = 75\ Bt + 53.7\ Ce + 0.1\ Sd$ $LC_3 = 0.43\ HC + 0.9\ HLC$	$V_3 = 2.\ t\ (L.H + W.H) - A_d - A_w$, (unit: m^3)	$Cost_3 = (MC_3 + LC_3) \times V_3$ $Cost_3 = 3{,}565{,}400 \times t \times (L.H + W.H - 2.1 - Aw)$	$Weight_3 = 3{,}652.\ t.\ (W.H + L.H - A_d - A_w)$
4	Plywood plafond/ ceiling (m^3) *Plywood size* 120 × 240 × 9 mm	$MC_4 = 47{,}500/m^3$ $LC_4 = 0.06\ HC + 0.1\ HLC$	$V_4 = L \times W \times T_P$, (unit: m^3)	$Cost_4 = MC_4 \times V_4/T_F + LC_4 \times V_4$ $Cost_4 = 16{,}200 \times (L.W) + 5{,}523{,}300 \times (L.W.\ T_F)$	$Weight_4 = 1{,}000 \times L \times W$
5	Painting (m^2) *Material and labor cost included*	$MC_5 = 22{,}900/m^2$	$V_5 = L \times W + 4\ (L.H + W.H - A_d - A_w)$, (unit m^2)	$Cost_5 = MC_5 \times V_5$ $Cost_5 = 22{,}900 \times [(L \times W) + 4\ (L.H + W.H - A_d - A_w)]$	$Weight_5$ = Not considered
6	Roof truss/frame	$MC_6 = 15{,}000/m$ Labos cost is incorporated to roof	$V_6 = L_{RB}$ (unit: m; Eq. 1)	$Cost_6 = MC_6 \times V_6$ $Cost_6 = 15{,}000 \times L_{RB}$	$Weight_6 = 0.85 \times L_{RB}$
7	Zinc roof *Material and labor cost included*	$MC_7 = 46{,}000/m^2$ $LC_7 = 0.072\ HC + 0.12\ HLC$	$V_7 = S_{Roof}$ (unit: m^2; Eq. 2)	$Cost_7 = (MC_7 + LC_7) \times V_7$ $C_7 = 65{,}500 \times S_{Roof}$	$Weight_7 = 0.81 \times S_{Roof}$
8	Window *Material and labor cost included*	$MC_8 = 220{,}000/m^2$	$V_7 = A_W$ (unit: m^2)	$Cost_8 = (MC_8) \times V_8$ $Cost_8 = 220{,}000 \times A_W$	$Weight_8 = 13.75 \times A_w$

Note: A_d = door area (2.1 m^2); A_w = window area (m^2); Cost = construction cost for each work per volume (IDR); HC = construction laborer wages (IDR/work unit); HLC = workmen wages (IDR/unit); L = building length (m); LC = labor cost per unit (IDR/unit); MC = material cost per unit (IDR/unit); t_W = vertical wall thickness (m); w = building width (m); St, Ce, Sd, Cr, Ls, Br, Pn, Tr, Zn = purchase price for stone, cement, sand, ceramics, light steel, brick, paint, plywood, and zinc (Table 4).

The NSGA-II algorithm can find multiple Pareto-optimal solutions with numerous parameters in one single simulation run. It presents several advantages, including: (a) using nondominated sorting techniques to provide the solution as close to the Pareto-optimal solution as possible, (b) using crowding-distance techniques to provide diversity in solution, and (c) using elitist techniques to preserve the best solution of current population in the next generation (Subashini and Bhuvaneswari 2012). The results of several studies (Chen 2009; Kodali et al. 2008) claim that NSGA-II presents better performance than do other optimization methods.

NSGA-II has been broadly used in improving building physics, such as optimization of building parameters (Deb et al. 2002; Magnier and Haghighat 2010), renovation of existing buildings (Chantrelle et al. 2011), and reduction of energy consumption in nearly zero-energy buildings (Carlucci et al. 2015). NSGA-II is mainly based on nondominated sorting and crowding-distance sorting mechanisms. The NSGA-II input parameters include the population size, number of generations, mutation and crossover probability, and number of objectives. Based on the preliminary study, the initial population for this study was 2,000 individuals at 10 generation levels (Lapisa et al. 2018). The objective function is then defined by

$$f_{obj}(x) = \min\,[DH(x),\ Cost(y),\ Weight(z)] \tag{6}$$

The choice of a Pareto-optimal solution depends on the best compromise between all objectives. Those objectives can be normalized between the minimum and maximum values through a weighting factor (weighting coefficient): R_{DH}, R_C, and R_W, as illustrated in Fig. 3:

$$R_{DH} = \frac{DH_{(X)} - DH_{Min}}{DH_{Max} - DH_{Min}} \tag{7}$$

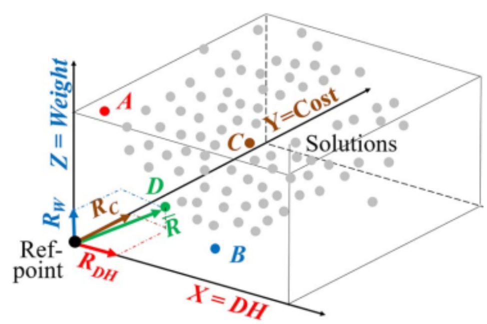


Fig. 3. Pareto optimal solutions (Solutions A, B, and C) and the compromise solution (Solution D).

$$R_C = \frac{Cost_{(Y)} - Cost_{Min}}{Cost_{Max} - Cost_{Min}} \tag{8}$$

$$R_W = \frac{Weight_{(Z)} - Weight_{Min}}{Weight_{Max} - Weight_{Min}} \tag{9}$$

Solution A is the lowest thermal discomfort (i.e., $R_{DH} = 0$), Solution B is the choice for the cheapest construction cost (i.e., $R_C = 0$), and Solution C is the lightest construction weight that can be designed (i.e., $R_W = 0$). The last, Solution D, is a trade-off between all objectives. This trade-off is defined by the weighting factors R_{DH}, R_C, and R_W determined by

$$\bar{R} = \sqrt{R_{DH}^2 + R_C^2 + R_W^2} \tag{10}$$

In selecting optimal solutions, the best compromise is represented by a minimum length of $\bar{R}$ from the reference point

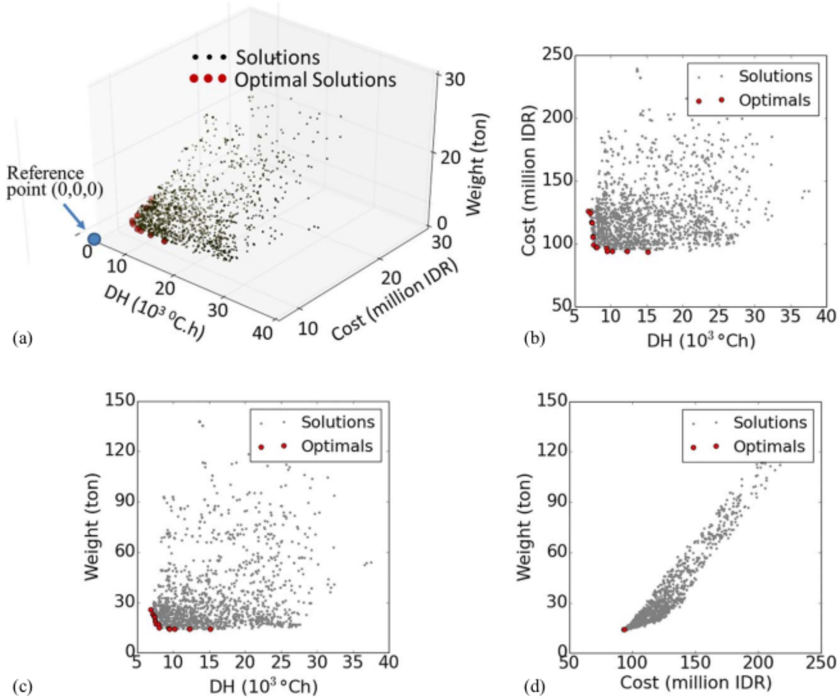


Fig. 4. (a) Pareto of the optimal solutions in three-dimensional perspectives; (b) two-dimensional (2D) projection of Pareto optimal in DH versus Cost; (c) 2D projection of Pareto optimal in DH versus Weight; and (d) 2D projection of Pareto optimal in Cost versus Weight.

[Eq. (10)], where $DH_{(X)}$, $Cost_{(Y)}$, and $Weight_{(Z)}$ are the optimal solutions selected. DH_{Min}, $Cost_{\mathrm{Min}}$, and $Weight_{\mathrm{Min}}$ are the minimum value for each objective. In addition, DH_{Max}, $Cost_{\mathrm{Max}}$, and $Weight_{\mathrm{Max}}$ are the maximum value for each objective.

Results and Discussion

The numerical optimization study conducted through the TRNSYS-CONTAM coupling and the NSGA-II optimization method uses a computation time of 28 h for each year.

Pareto-Optimal Solutions

In the genetic algorithm method, the optimal values of all possible solutions during the optimization process are presented in a Pareto line. Fig. 4(a) shows the solutions in the last generation and the optimal Pareto solutions for the three specified study objectives. After performing permutations up to the 10th generation, 15 solutions were obtained on the Pareto-optimal line. Of all the optimal solutions obtained, the *DH* value as an indicator of energy consumption for air conditioning systems varies between 6,909.6°C h to 15,203.5°C h. It indicates that no solution can effectively eliminate the overall value of *DH* in tropical climates with high outdoor temperatures. However, the optimal solution in building thermal performance can be achieved by implementing a passive strategy that can significantly reduce the *DH* of thermal discomfort (which represents the energy consumption for the cooling system) up to 45.4% compared with a reference building.

In the aspect of construction, there are two objectives of an optimization study: minimizing the construction cost and the weight of the building. Related to the building cost, the lowest construction cost in the optimal solutions varies from IDR 93.61 to 125.68 million (Table 6). The lightest building weight that can be achieved by optimal solutions varies from 13.95 to 25.78 t. However, note that the optimized parameters related to building cost and weight belong to variable parameters. Fixed parameters (foundation, floors, accessories) are not affected by changes in building design. Table 6 lists the 15 optimal solutions on the Pareto line along with details of their parameters.

The most reasonable choice of all existing parameter designs to minimize the degree of thermal discomfort (Solution A) is presented by the solution on the first row in the Table 6. If the building designer prefers the thermal comfort of occupants as the main criterion, then one of the solutions is geometry compactness value (B_{gc}) 0.7; θ 37°; building leads to 15.3° (southwest); wall albedo coefficient (ρ_W) and roof albedo coefficient (ρ_R) 0.9 and 0.89, respectively; wall thickness (t_W) 5.6 cm; building height (H_W) 4.3 m; window area ratio (W_{WR}) 3.6%; and ceiling thickness (t_C) 85.8 mm. With these parameters, the *DH* value is 6,909.7°Ch. However, the choice will cause the construction cost to be more expensive, around IDR 125.68 million, and the construction weight becomes heavier by around 25.78 t.

The best option for minimal construction cost (Solution B) is identical with the option for the minimal weight of the building (Solution C). The best choice for these two objectives is presented by the solution in row 15 in Table 6. By setting the building parameters given in line 15, the building will have the lowest construction cost and building weight of IDR 93.6 million and 13.95 t, respectively. Unfortunately, by selecting these parameters, residents will suffer more thermal discomfort than with other options. The *DH* value is twice that of Solution A. However, in cost and building weight, this is the best option.

Table 6. Pareto optimal—solutions for the current climate

No.	B_{gc}	θ	B_O	ρ_W	ρ_R	t_W	H_W	W_{WR}	t_C	DH	*Cost* (10^3 IDR)	*Weight* (ton)
1	***0.70***	***37.0***	***15.3***	***0.90***	***0.89***	***5.6***	***4.27***	***3,62***	***85.8***	***6,909***	***125,684***	***25.78***
2	0.64	32.7	13.3	0.90	0.89	6.05	3.08	3,47	95.0	7,188	124,185	22.94
3	0.56	31.1	357.1	0.89	0.89	5.67	3.24	3,47	81.2	7,352	117,191	21.62
4	0.53	36.3	11.5	0.90	0.88	5.59	3.20	4,02	78.8	7,451	116,508	21.10
5	0.53	36.4	11.5	0.90	0.88	5.59	3.20	4,02	78.5	7,453	116,355	21.07
6	0.56	32.8	347.0	0.89	0.89	5.44	3.25	3,47	60.8	7,542	105,751	19.10
7	0.55	32.7	358.2	0.89	0.89	5.29	3.25	3,52	60.3	7,553	105,303	18.77
8	0.56	32.8	347.0	0.89	0.89	5.01	3.25	3,47	50.1	7,643	98,870	17.04
9	0.54	20.0	7.9	0.88	0.88	5.04	3.13	3,99	50.2	8,003	97,084	16.65
10	***0.57***	***26.3***	***207.7***	***0.90***	***0.88***	***5.04***	***2.56***	***4,11***	***55.0***	***8,081***	***97,060***	***14.88***
11	0.97	26.2	196.7	0.85	0.88	5.02	2.58	5,60	55.0	9,408	96,293	14.42
12	0.96	26.3	281.3	0.89	0.86	5.06	2.62	5,70	50.5	9,537	94,075	14.18
13	0.96	26.3	45.5	0.83	0.86	5.06	2.61	5,70	50.5	10,301	94,011	14.13
14	0.96	26.3	45.5	0.87	0.58	5.03	2.61	5,70	50.5	12,307	93,967	14.08
15	***0.97***	***26.4***	***115.3***	***0.72***	***0.59***	***5.03***	***2.58***	***5,60***	***50.1***	***15,204***	***93,614***	***13.95***

Note: B_{gc} = geometry compactness (dimensionless); θ = slope of roof (°); B_O = building orientation (0); ρ_W = albedo of vertical walls (dimensionless); ρ_R = albedo of vertical walls (dimensionless); t_W = thickness of walls (cm); H_W = height of vertical walls (m); W_{WR} = window/floor surface ratio (%); t_C = thickness of ceiling (mm); DH = degree hour thermal discomfort (°C h); Cost = construction cost (IDR); IDR = currency of Indonesia (1 USD equivalent to 14,417.50 IDR per August 24, 2021); Weight = building weight (ton). The bold italic fonts in lines 1, 10, and 15 are the set optimal parameters for Solution A, Solution B/C, and Solution D, respectively.

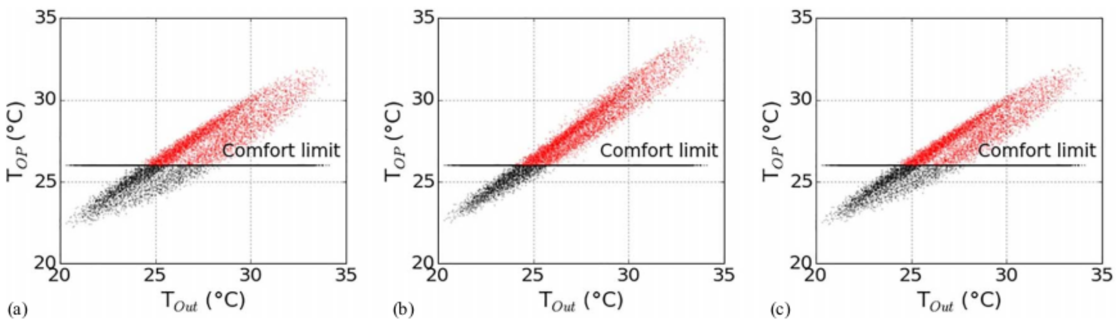


Fig. 5. Room operative temperature (T_{OP}) profile for different building design: (a) Solution A; (b) Solution B/C; and (c) Solution D (Tout is the outdoor temperature).

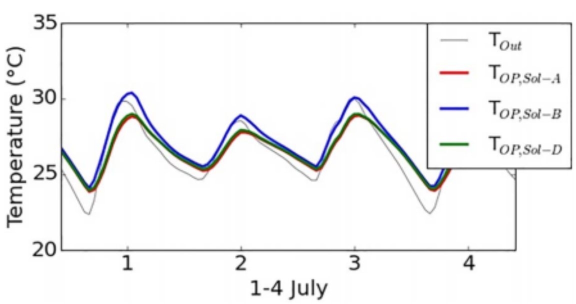


Fig. 6. Operative temperature for the different solutions.

Meanwhile, the best choice when considering the three existing objectives (Solution D) is a building designed with the parameters presented by Solution D in line 10 in Table 6. This option is the most reasonable choice for obtaining low construction costs, lowest building weight, and acceptable thermal comfort conditions in the building. The *DH*, *Cost*, and *Weight* value of the building is 8,081°C h, IDR 97.06 million, and 14.88 t, respectively.

Over the course of 1 year, the discomfort rate (percentage hours of discomfort) for each case was 65.2% for Solution A, 73.7% for Solution B/C, and 67.2% for Solution D (Fig. 5). Meanwhile, the maximum operative temperature in the room for each case of Solution A, B/C, and D, respectively, are 31.96°C, 33.9°C, and 32.1°C.

Fig. 6 presents temperature variation for the three solutions for 1 week on July 1–4. The temperature variation of Solutions A and D appears almost identical, whereas for Solution B, the operative temperature of the zone increased significantly. As an example, at noon on July 1, the operative temperatures of the room for Solutions A and D are almost identical, at 28.8°C and 28.98°C, respectively (Fig. 6). However, Solution B shows a significant difference of 30.4°C (1.56°C difference).

Evaluation of Geometry Aspects of Building

The aspect of geometry is one of the important factors that affect the thermal performance of buildings. The optimization parameters included in the geometry category are building geometry compactness, slope of the roof, height of the roof, height and thickness of the vertical wall, and thickness of the ceiling.

Building Geometry Compactness (B_{gc})

In high-temperature regions, building geometry compactness is one factor affecting occupant comfort level. The optimization results show that the room temperature will be cooler when the building geometry compactness value ranges from 0.5 to 0.7 (Table 6). The outer wall surface in a rectangular building has a wider wall surface interacting with the outside air, and can be a heat sink medium to evacuate the excess heat in the room and cool the room temperature. These results reinforce the research conducted by Premrov et al. (2016) showing that the buildings geometry shape has an impact, although not as significant on building energy demand and thermal performance in hot-humid areas. However, in areas with a cold temperature, buildings with maximum compactness (square) can save energy use for heating because of the low heat loss of a compact building structure (Lapisa 2019). A building with a compact shape (square) is the best option, from the cost and weight aspect. The more compact the building, the smaller the surface area of the building envelope. This requires less material, so the weight of the building is lighter. Thus, the required production costs will be lower.

Slope of the Roof (θ)

The design of the roof slope has a contradictory impact between the three existing objectives. A roof with a high angle of inclination will help in creating cooler room temperatures. This is the result of the increased thermal resistance of air convection in a room if it has a large attic. Table 6 details that a roof with a 37° slope angle can minimize the *DH* value of the room to half of that of a design with a low roof angle (26.5°). However, the greater the roof slope angle, the more material needed and the greater the cost. Therefore, buildings with high roof slopes are more expensive and have a higher risk of collapsing when exposed to earthquake shocks than are buildings with low-slope roofs. Based on the three objectives, the roof with an angle of 26.3° gives the most optimal results. This result is in line with the previous research conducted by Ibrahim et al. (2018), which states that the optimal angle of gable roofs in hot-humid area is 30°.

Height and Thickness of Vertical Walls (t_W and H_W)

As seen in Table 6, a wall with a small thickness is the most appropriate choice for all objectives. From a thermal perspective, the thermal inertia effect of thick brick walls does not significantly lower the indoor temperature. Small annual and daily variations in outdoor air temperatures in the tropics render the inertia effect insignificant. In addition, to decrease the building weight, walls are kept to a minimum. A wall with a thickness of 5 cm is an interesting option to consider in tropical and earthquake-prone areas. However, the practicality of installing the material is also a separate consideration in choosing a wall size.

As for the wall height, the optimal choice varies between the minimum and maximum values given. The higher the wall, the greater the volume of the room. The greater the volume of the room, the lower the indoor temperature. Plus, the higher the building wall, the greater the cost, and the heavier the building. Therefore, determining the optimal wall height to obtain a compromise from several existing options requires careful consideration of complicated factors. The most optimal building wall height considering thermal discomfort, cost, and weight of the building is 2.56 m (Table 6).

Thickness of Ceiling (t_C)

Ceilings function as a thermal barrier between hot air in the attic zone and the occupied room. The thicker the ceiling board, the better the thermal comfort, but the greater the cost and risk of falling due to earthquake shocks. The results in Table 6 indicate that the optimal ceiling thickness is 5.5 cm. In addition, in choosing the ceiling thickness, it is necessary to pay attention to the availability of raw materials needed.

Effect of Outer Surface Albedo of Walls and Roofs (ρ_W and ρ_R)

Roof and wall surfaces are parts of the building directly exposed to solar radiation. The solar radiation is the main heat gain source causing uncomfortable indoor temperatures. Therefore, the thermal characteristics of roof and wall materials have a significant influence on room comfort. A roof with a high solar reflectance (albedo), often called a *cool roof* and *cool wall*, is the optimal solution for all building designs in tropical areas. Increasing the solar reflectance can be performed by coating the surface of the roof and walls with a reflective membrane. The results in Table 6 indicate that the optimal albedo coefficient is 0.9. In contrast to cold and temperate climates, the reduction of solar heat gain in tropical climates through increasing the albedo coefficient of the roof and walls is an indispensable solution.

Effect of Windows Ratio (W_{WR})

According to studies on the effect of window, the recommended window-to-building floor ratio for hot and humid region is 10% (Alibaba 2016). The window area will affect the amount of solar heat gain entering the room. For cold areas, more solar heat gain will reduce heating loading and energy consumption for artificial lighting. Thus, increasing the percentage of windows is an option to consider in cold climates. Conversely, in hot climates, the large window surface area can cause overheating in the room. Moreover, note that the use of natural lighting through windows has a maximum limit. The results showed that the optimal window ratio for Padang city ranges from 3.2% to 5.6%. This confirms the results of previous research on the effect of skylights/roof ratio on warehouse building, energy balance, and thermal/visual comfort in a hot-humid climate area, which shows the same optimal ratio of skylight area in a warehouse building (Lapisa et al. 2020). The data in Table 6 indicate that the window surface area must be reduced to a minimum percentage, 2.5% of the floor area, to reduce room discomfort.

Building Orientation (B_O)

In the tropics, the building orientation must be arranged so that the main facade with wide windows is protected from direct solar radiation. Reducing direct solar radiation reduces excess heat in the room. The optimization results indicate that the best building orientation in the city of Padang is facing southwest, southeast, or northeast. This makes sense since these directions keep the windows from being directly exposed to solar radiation.

Effect of Global Warming on the Optimal Design of Building Parameters

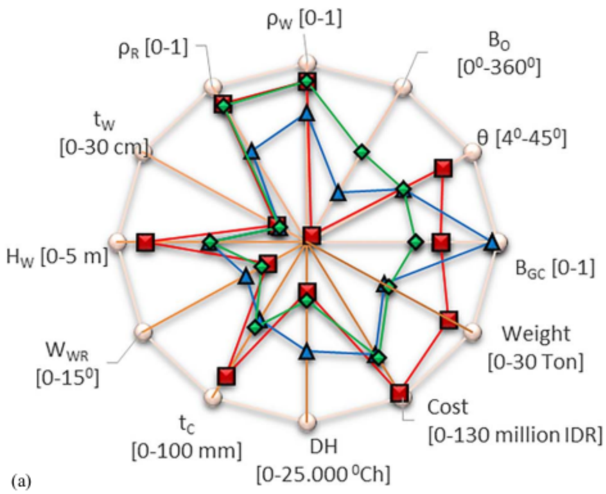
Climate change has a significant effect on building performance. In this study, the projection of the optimal design of building parameters until 2050 is something interesting to discuss. Due to CO_2 emissions, it is anticipated that the average outside air temperature will increase by 1.8°C in 2050 compared with 2020 (Table 1). As a highly influential factor, the increasing outdoor air temperature will cause a significant increase in indoor thermal discomfort.

Table 7 presents the Pareto-optimal of the seven solutions along with the parameters offered for building design in 2050. By comparing the current condition and 2050 (Tables 6 and 7), the number

Table 7. Pareto in optimal design of building parameters for 2050

No.	B_{gc}	θ	B_O	ρ_W	ρ_R	t_W	H_W	W_{WR}	t_C	DH	Cost (10^3 IDR)	Weight (ton)
1	***0.85***	***38.1***	***39.3***	***0.90***	***0.88***	***5.01***	***4.46***	***2.85***	***56.5***	***18,452***	***108,695***	***21.73***
2	0.79	38.6	319.3	0.89	0.75	5.08	4.34	3.08	56.9	19,833	108,619	21.60
3	0.83	38.3	170.8	0.89	0.75	5.08	4.15	3.00	56.9	19,873	107,499	20.84
4	0.76	18.3	185.0	0.89	0.78	5.21	4.04	5.17	52.2	20,305	102,395	20.18
5	***0.47***	***16.6***	***327.9***	***0.89***	***0.88***	***5.14***	***2.59***	***3.18***	***57.3***	***20,513***	***98,615***	***15.78***
6	0.83	26.5	161.0	0.89	0.79	5.19	2.71	3.36	51.1	21,619	94,984	15.05
7	***0.71***	***26.2***	***159.5***	***0.89***	***0.82***	***5.08***	***2.52***	***8.73***	***50.8***	***23,788***	***93,952***	***13.75***

Note: B_{gc} = geometry compacity (dimensionless); θ = slope of roof (°); B_O = building orientation (0); ρ_W = albedo of vertical walls (dimensionless); ρ_R = albedo of vertical walls (dimensionless), t_W = thickness of walls (cm); H_W = height of vertical walls (m); W_{WR} = window/floor surface ratio (%); t_C = thickness of ceiling (mm); DH = degree hour thermal discomfort (°C h); Cost = construction cost (IDR); IDR = currency of Indonesia (1 USD equivalent to 14,417.50 IDR per August 24, 2021); Weight = building weight (ton). The bold italic fonts in lines 1, 10, and 15 are the set optimal parameters for Solution A, Solution B/C, and Solution D, consecutively.



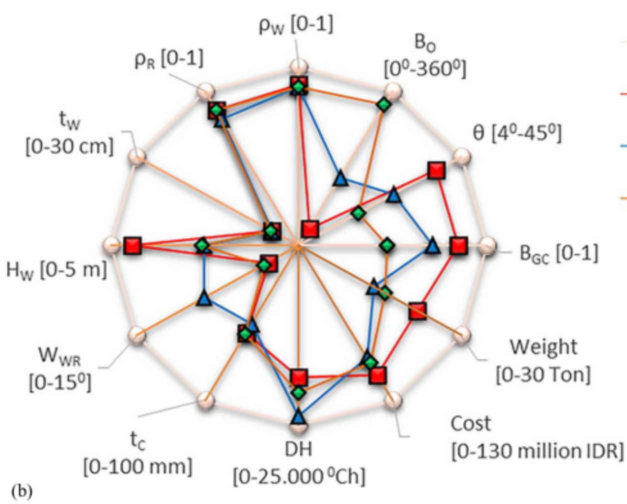


Fig. 7. Radar chart for comparison of optimal solutions in: (a) year 2020; and (b) year 2050.

of DH of thermal discomfort in the best building design in thermal perspective (Solution A) increased from 6,909.7°C h to 18,452°C h (Fig. 7). In fact, the increase in the number of DH is equivalent to the increase in energy consumption for a building with a cooling system. The need for cooling energy in 2050 under these conditions is predicted to increase by 2.67 times compared with today. In addition, by assuming that currency inflation in the period 2020 and 2050 is negligible, the optimal cost to construct a residential building will vary from IDR 93.95 to 108.87 million. Meanwhile, the construction weight changes from approximately 13.75 to 21.73 t (Table 7).

Fig. 7 shows a comparison of the parameters for the three optimal solutions chosen between 2020 and 2050. By 2050, the optimal B_O will not change. To avoid excessive solar heat gain, the main facade of the building should not face east or west. In terms of B_{gc}, the building shape does not have to be square to make the air temperature cooler in the room. However, to achieve cheaper construction and minimal building weight, a compact square shape is recommended. In the trade-off solution of the three objectives (Solution D), a low slope angle of the roof ($\boldsymbol{\theta}$) can be used as an alternative solution. A vertical wall with a t_W of 5.14 cm and a H_W of 2.59 m can also be an interesting choice. The parameters for roof albedo (ρ_R) and walls (ρ_W) will not be different from 2020. Roofs and walls with a high albedo coefficient approaching 0.9 are options that must be considered so that the building becomes cooler without adding more construction costs and building weight (Fig. 7). The W_{WR} should be between 3% and 5% (Table 7). A ceiling with a t_C between 5 and 6 cm can be the optimal choice for achieving the trade-off of the three objectives.

Conclusion

This optimization study of residential building by minimizing the *DH* of thermal discomfort, construction costs, and building weight based on nine parameters shows useful results in designing a comfortable and inexpensive building. Since this study is in tropical climates, three optimal solutions are offered based on the respective objectives. However, the final choice of building parameter depends on the end-user/developer preferences. If the user wants a more comfortable building with the least thermal discomfort (Solution A), then a sloping angle for the gable roof with a reflective coating is needed. Solution A also requires higher vertical walls with a large albedo coefficient in its outer surface. In addition, the orientation of the building should not be facing east or west. To achieve a cheaper building construction with less weight (Solution B/C), the walls should be shorter and the roof slopes less canted. In obtaining the design with the best compromise, the nine building parameters must be selected based on the three objectives. However, note that the design of the nine parameters of the optimal solution cannot eliminate the indoor thermal discomfort *DH* value. Thus, the use of an active cooling system remains a necessity in hot-humid climates such as Padang.

In addition, global warming must be an important consideration in building design for the future. Increasing outdoor air temperature will exacerbate uncomfortable conditions for the occupants. Therefore, it is necessary to develop studies on passive cooling techniques to improve indoor thermal comfort conditions. From this research, an increase in thermal comfort is achieved through other suitable passive cooling techniques for residential buildings, such as natural ventilation and lighting control. It is hoped that the methodology and the results presented in this article can be useful and serve as a good benchmark for an Indonesian architect in designing a residential building that is comfortable, energy-efficient, and require minimal construction costs. Meanwhile, for other regions outside Indonesia with almost the same climate characteristics, it is necessary to adjust the calculation of construction costs based on local material prices and worker wages in each region.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (e.g., TRNSYS and Contam simulation files, Excel files).

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