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Research Article

Multi-Objective Optimization of PCM-Enhanced Passive Envelopes for Net-Zero Hotel Buildings in Tropical Indonesia

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Abstract:

This paper presents a hybrid optimization methodology to design net-zero energy buildings in hotel establishments in locations with tropical climates in Indonesia. Phase Change Materials (PCMs) are used to enhance passive design integrated with envelope systems that prove to be climatically accustomed locally. As a combination of a Genetic Algorithm (GA) and EnergyPlus simulation through DesignBuilder, the analysis observes the multi-objective optimization based on four Köppen climate groups: Af, Am, Aw, and Bsh. There were two optimization cases considered: the first one focused on minimizing Total Energy Consumption (TEC) and Life Cycle Cost (LCC), whereas the second aimed to optimize TEC and CO_2 emissions. The analysis studied configurations of PCM (melting temperature, thickness, and position) and different wall types (brick, concrete block, cast concrete, and earth) in six cities. The studies find considerable performance improvement: reductions in TEC of up to 47.8%, LCC savings of 29.6%, and CO_2 emission reductions of up to 52.96%, particularly in externally placed PCMs in optimal melting ranges (23-29°C). Wall-like structures on earth were the most efficient because they had a thermal inertia. The results emphasize the significant potential of PCM-enhanced passive approaches to minimizing energy and emissions use in the hottest, most humid weather. This paper adds a climate-adaptive planning model of environmentally friendly hotels in Southeast Asia that provides further advice to developers and designers who want to develop cost-efficient, low-carbon hospitality projects.

1. Introduction

The worldwide environmental movement toward sustainable design and carbon-neutrality has put undue stress on the building industry to create and execute energy-efficient design solutions. The existing buildings use more than 40 percent of all global energy consumption and also cause nearly 35 percent of the greenhouse emissions[1]. Hotel buildings used in this industry, especially in tropical weather conditions, present special challenges to energy consumption considering that these buildings run continuously and they have high internal load intensities and greater demand on thermal comfort. Such traits are further enhanced in hot-humid environments like in Indonesia, where the tropics make heating systems cost users more to run and lead to environmental destruction [2]; [3].

Hotel buildings are contrastingly different to residential or commercial buildings in terms of occupancy, internal heat gains, lighting loads, and user expectations. Visitors commonly require uniform indoor environment regardless of external weather conditions, and so HVAC systems are normally in operation almost all the time. This renders hotels as one of the most energy guzzling building types per square foot. Therefore it has become an energy and climate policy priority to find ways of lowering energy use in hotel facilities without a reduction in comfort, especially in the Southeast Asian countries where tourism is rapidly expanding and cities are developing.

In this regard, the building envelope serves as the thermal barrier between the outside and inside climate and has a crucial role in alleviating energy loss and increasing passive thermal efficiency. A properly designed envelope could be very effective to save on heating and cooling loads, minimizing the undesired heat gain or loss thereby making the building use sustainable and cheaper to operate. In tropical climates, where the cooling load is more important, envelope designs have to be specially adapted to reject the outside heat, as well as insulate inside areas against extreme temperatures.

In the new laws of envelope technologies, the emphasis has been on pairing up the passive design strategies and active materials that have the ability to enhance the thermal mass of the building. Perhaps the most potential technology in the industry, however, is the adoption of Phase Change Materials (PCM), which has increasingly drawn attention to its potential in regulating indoor temperatures by storing the heat as latent heat. PCMs store and release large quantities of heat in the course of change of phase, usually solid to liquid, and vice versa, creating less varied conditions indoors and fewer demands on mechanical systems [4]; [5]; [6]; [7]; [8].

The use of PCM in building envelopes; particularly walls, roofs and ceilings, has demonstrated significant potential to enhance both energy savings and CO2 emissions and this shows PCM as a good tool to achieve net-zero energy (NZE) goals by designers and engineers alike[9]; [10]; [11]; [12]; [13]. Many studies have been carried out regarding the performance of PCMs across different climatic conditions and building applications. As an illustration, Qu et al. [14]showed that the types and implementation strategies of PCM could make a huge difference in energy savings and thermal comfort in the Chinese buildings. Likewise, simulation-based studies by Saffari et al. [15] to calculate optimal PCM melting temperatures showed that the ideal melting temperatures should be between 24-28 degrees centigrade under hot climatic conditions.

In addition, Huakeer et al. [16] analyzed the concept of wall orientation as a factor affecting PCM performance, whereas Mingli et al. [17] stated that PCM melting temperatures needed to be aligned with localized conditions of thermal loading. In South Korea, Wi et al. [18] have conducted tests on phase-stabilized materials (PSMs) which reduced their annual energy consumption by 5 percent through superior thermal buffering. Overall, these results confirm the efficiency of PCM-integrated design as passive energy measure in buildings subjected to excessive heat loads.

Besides simulation-based analyses, a number of experimental studies have confirmed the advantage of PCM applications in warm and tropical climates. One such study, by Saxena et al. [19], involved field experiments in New Delhi, where up to a 60% reduction in daytime heat transfer was measured in buildings with PCM-modified brick walls, corresponding to reductions in temperature of 4-9.5°C. Li et al. [20] concluded that PCM-enhanced walls achieved an increase in indoor thermal comfort parameters of more than 14 percent, whereas Sovetova et al. [21] documented the potential energy savings of between 17.97 percent and 34.26 percent in EnergyPlus in simulated envelopes in eight cities with a hot climate.

Although this extensive pool of literature demonstrates the effectiveness of PCMs in minimizing energy loads, most earlier studies revolve around residential buildings or office buildings, with a fair share of studies yet to learn in a hotel setup. Moreover, most studies compare the effectiveness of PCM over short periods of time e.g. daily or seasonal snapshots without considering the long term behavior and the variation in the climate zone relevant to tropical regions. The deficiency in hotel-related, long-term research constitutes a significant knowledge gap, particularly in those countries that the tourism industry has an important role in their national economy such as in Indonesia, where energy-intensive hotel services hold significant environmental bearing [22]; [23]; [24]; [25].

Moreover, the majority of present PCM applications use preset thermal properties and generic system designs, which possibly do not imply the complicated building orientation, envelope material/climatic condition interplay in different tropical microclimate contexts. Hence, it is necessary that optimization-based methods capable of dynamically assessing and adjusting PCM structure parameters, including melting temperature, thickness, and position in the wall constructions, should be laid out to ensure the best possible energy efficiency in practical applications [26]; [27]; [28].

This paper proposes a new simulation-based, multi-objective optimization framework in integrating PCM enhanced passive envelope systems within hotel buildings in the tropical locations of Indonesia, with particular consideration in the various hot-humid climate types of the regions. The suggested procedure is based on the use of sophisticated computing technology to search an extended range of PCM designs whilst maintaining energy savings, lifecycle cost minimization, and CO_2 emission mitigation into account, which are considered the priorities on the way to net-zero energy hotel buildings[25]; [29]; [30]; [31].

The study adapts a non dominated sorting genetic algorithm (NDSA-II), which is an efficacious evolutionary optimization algorithm, and EnergyPlus, an EnergyPlus validated dynamic building energy simulation engine. The integration enables the design variables of PCM, melting temperature, the layer thickness and position within a wall assembly, to be parametrically analyzed in total detail. Multi-objective optimization has been used so that trade-offs between energy performance, environmental sustainability, and economic viability are in a well-structured manner to be examined [15]; [32]; [33].

The commercially exhibited PCMs, which are chosen as a part of the evaluation, include a bio-based material, BioPCM [34], that has a modifiable melting range, and InfiniteR PCM [35], an efficient PCM whose very capability lies in the stability of the thermal dynamics under tropic conditions. Such materials find their application in various wall constructions typical of Southeast Asian hotel types such as those made of brick, concrete block, cast concrete and earth-based walls. The given typologies are chosen regarding their popularity in traditional and modern building of hotels in Indonesia and neighboring areas [36].

The simulation experiments will be performed on a sample of the typical Indonesian cities that will fall within the Köppen climate types of Af (tropical rainforest) and Am (tropical monsoon)[24][37]. The sites vary in solar exposure, humidity distributions, and temperature patterns, and hence form are well-established platform in which PCM performance can be experimentally tested in different tropical settings. The optimization model finds a set of Pareto-optimal solutions, which are the best trade-offs to the three competing objectives, in each combination of type of wall, PCM, and climate zone [12]; [19]; [30].

The unfamiliarity of the study has a number of main aspects:

1. Sector-Specific: Most prior studies of PCM performance in buildings have concentrated on residential or generic commercial use buildings, this study will be tailored to the hotel building sector the operational requirements of which, including 24/7 occupancy and high thermal loads necessitate specialized building envelope strategies that cannot be applied generically if they apply at all to the residential case [18]; [19].
2. Climate-Specific Analysis: The study is focused on tropical climates located in Southeast Asia, specifically, Indonesia, as it has not been covered by previous research on PCM in detail even though it possesses an expanding tourism infrastructure and an emergent energy demand. The Nation has an equatorial climate that presents a set of characteristics that require specific strategies to be designed to solve the problems of constant humidity, high temperatures ambient, and great diurnal thermal range [12]; [8]; [37].
3. The analysis optimises the multi-objective evolutionary algorithms to find nonlinear connections between elements in PCM design without depending on a set melting point or simplified envelope models. This gives a chance to explore more on how the behavior of PCM interacts with type of walls and climate as inputs over a long period [38]; [39].
4. Lifecycle Integration: In addition to analyzing short-term thermal behavior, the research extends the results to the lifecycle cost (LCC) and CO_2 emission as an element of optimization, making the model a service to the hospitality industry developers and operators with regard to decision-making in favor of sustainability and relative efficiency of investment [40]; [31].
5. Multi-Criteria Decision Support: In addition to information on the examination of practical applicability, the research uses Multi-Criteria Decision-Making (MCDM) technique to classify and prioritize the sets of optimal solutions: onto energy-optimal and cost-optimal. This allows the stakeholders to adopt the most suitable envelope plan depending on their priorities; either, producing the maximum energy savings or having the payback interval shorter [28]; [41].

These research design breakthroughs help close an important knowledge gap on climate-sensitive hotels design. Although many authors, such as Agarwal and Prabhakar [42]; Yun et al. [36]; Saurbayeva et al. [38], have worked on mentions of techno-economic and thermal evaluation of PCMs, not many reports provide a comprehensive and optimization-based analysis with a specific to the needs of the hospitality industry and conditions of tropical regions.

The combination of the simulation/optimization/decision-support frameworks developed by the study generates a powerful collection of design suggestions that can be used by tropical hotels keen on shifting toward their net-zero energy requirements [11]; [43]. The research findings are of particular importance with regard to the national energy shift project in

Indonesia that aims at decarbonizing the country, minimizing its dependency on fossil fuels, and ensuring energy efficiency in all the building industries, including tourism and hospitality[7]; [8]; [44].

In the end, the study will aid in creating high-performance, cost-efficient, and energy-sustainable hotel buildings by offering practical decisions of incorporating PCM enhanced-passive envelope structures. All these strategies are both technically possible and consistent with global climate goals such as the Paris Agreement and UN Sustainable Development Goals (SDGs), associated with affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13) [11]; [14]; [15].

2. METHODS AND MATERIALS

2.1. Conceptual Framework

The given research is based on the complex three-step methodology shown in Figure 1: (i) the initial setup step, (ii) the multi-objective optimisation step, and (iii) the post-optimisation step. All these stages allow to consider a comprehensive analysis of the work of sustainable energy solutions incorporated into the designs of tropical hotels in Indonesia.

2.2. Preliminary Phase

2.2.1. Hotel Prototype Information

The object of investigation is a small-scale hotel prototype (see Figure 2) constituting the total floor area of 126 m 2 and characteristic of the same tropical hotel buildings, such as in Indonesia. The prototype encloses six guest rooms, the service zones, and the circulation zones. The architectural plan is reflective of general designs of a hospitality facility in Southeast Asia.

The base model construction materials represent the state of the art of Indonesia hospitality buildings, brick walls, concrete slab roofs, and single-layer glazing. The materials are recognized as low-thermal-performance. The reference building envelope values of thermophysical properties are illustrated in table 1.

In a bid to assess the opportunity of Phase Change Materials (PCMs) to enhance energy performance, three types of PCMs have been included in the wall assemblies. Envelope configurations variations have been presented in Figure 3 and Table 2 provides thermal properties of PCMs.

Symbols used: K = thermal conductivity, Cp = specific heat capacity, ρ = density, t = thickness, Tm = melting temperature.

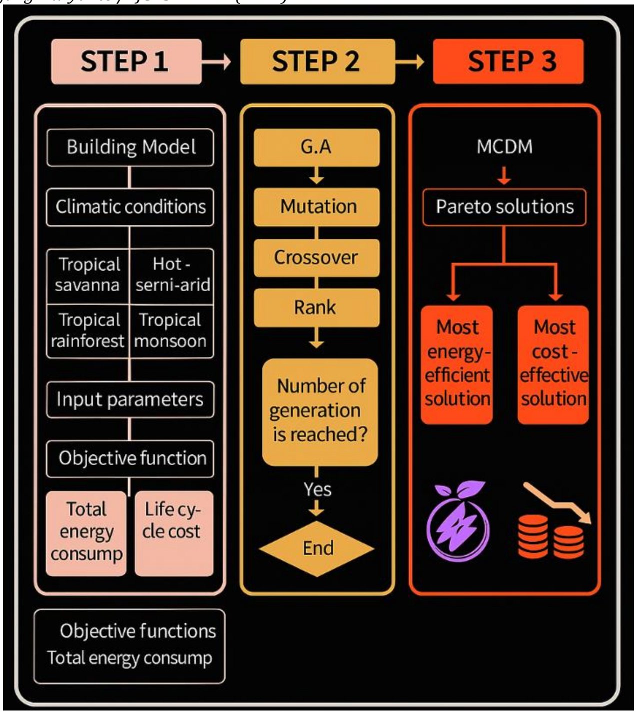

***Figure 1**. Optimisation framework flowchart.*

***Table 1.** Thermophysical properties of baseline envelope materials.*

Envelope	Layer	t (m)	K (W/m-K)	ρ (kg/m³)	Cp (J/kg-K)
Roof	Reinforced concrete	0.200	1.800	2500	840
	Asphalt roll	0.020	0.750	1100	1510
Wall	Brick	0.200	0.720	1920	840
Floor	Marble	0.008	3.500	2800	1000
	Lime mortar	0.003	0.870	1800	1000
	Gravel & sand	0.050	0.700	1800	1000
	Reinforced concrete	0.300	1.800	2500	840
	Plaster	0.020	0.720	1860	840

***Table 2.** Thermal properties of selected PCMs [34]; [35].*

Compound	Tm (°C)	K (W/m-K) (liq/solid)	Cp (J/kg-K) (liq/solid)	ρ (kg/m³) (liq/solid)	LH (kJ/kg)	Type
Infinite RPCM	21,23,25,29	0.54 / 1.09	3140 / 3140	1540 / 1540	200	Inorganic
BioPCM	21,23,25,27,29	1.50 / 1.80	2000 / 2000	2200 / 2300	225	Organic

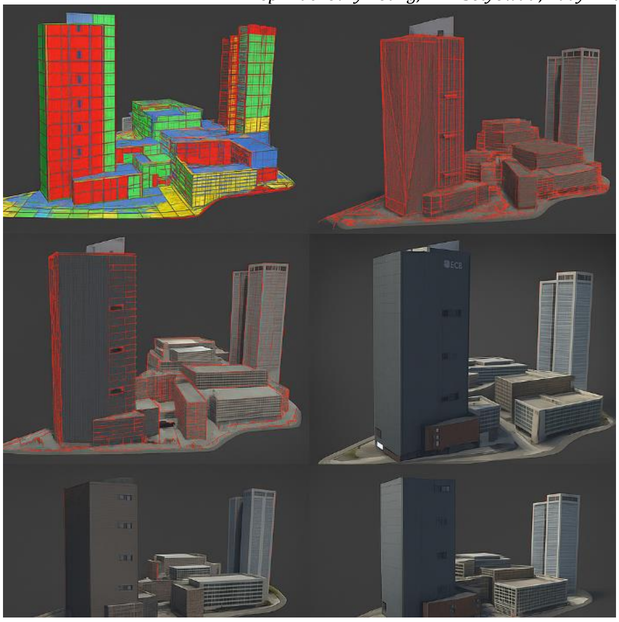

Figure 2. *3D model of the simulated hotel building. Source: Author*

2.2.2. Climatic Context

Indonesia has an equatorial climate which is very important in developing energy performance. The six largest Indonesian cities with different tropical profiles are also the focus of the simulation in Jakarta, Surabaya, Medan, Batam, Pontianak and Denpasar. The climate types are according to the Köppen classification; tropic rainforest (Af), tropic monsoon (Am) and tropic savanna (Aw) [45].

Monthly Climate Variability in Batam: To comprehensively assess Batam's tropical savanna (Aw) climate, Figure 3 illustrates the 30-year monthly averages of temperature extremes and precipitation patterns (1994–2023). These trends highlight the high thermal load and humidity challenges critical for PCM optimization in hotel envelopes.

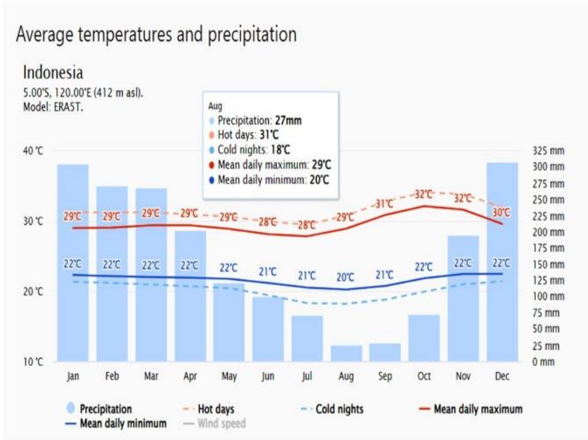

Figure 3. *Average monthly maximum and minimum temperatures and total precipitation in Batam, Indonesia 2025.*

In EnergyPlus Weather Format (EPW), information of hourly climatic data of 15 years of normal meteorological data (20072021) was obtained through Climate. OneBuilding. The main parameters summarised in Table 3 are extreme temperature, wind speed (WS) and solar radiation (SR) [46]; [47]; [48].

Table 3. *Climatic profiles of selected Indonesian cities.*

City	Climate	Lat (°)	Long (°)	Alt (m)	Temp Max (°C)	Temp Min (°C)	SR (kWh/m²/day)	WS (m/s)
Jakarta	Am	-6.20	106.85	8	33.5	24.0	4.92	2.20
Surabaya	Aw	-7.25	112.75	5	35.0	23.2	5.45	3.00
Medan	Af	3.58	98.65	27	32.1	22.6	4.68	1.80
Batam	Aw	-5.14	119.43	25	34.3	23.0	5.87	2.75
Pontianak	Af	0.03	109.34	3	33.2	24.2	5.64	2.40
Denpasar	Am	-8.65	115.22	9	32.0	23.8	5.02	1.95

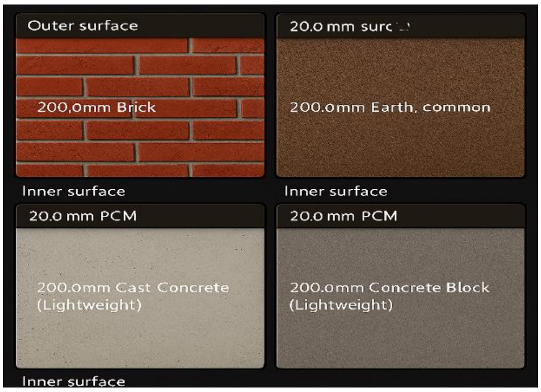

Figure 4. *Wall envelope PCM integration configurations. Source: Author*

2.2.3. Design Variables

Design variables were selected to allow optimization of building envelope thermal response under Indonesian climatic conditions. Variables include:

- **Melting temperatures** of PCM (21°C to 29°C)
- **PCM layer thickness**
- **PCM positioning**:
  - **P1**: Outer face of wall (applicable to existing and new hotels)
  - **P2**: Embedded within wall layers (suitable for new constructions)
  - **P3**: Inner face (usable in retrofitting and new designs)

Design parameters and configurations are presented in Table 4.

Table 4. *Design parameter ranges. Source: Author, Data:* [49]; [50]

Variable	Range/Values
Melting Temp	21, 23, 25, 27, 29 (°C)
PCM Thickness	1 cm to 5 cm
PCM Placement	P1, P2, P3

2.2.4. Objective Functions

The optimization process was driven by three primary objective functions, each targeting a critical performance aspect of Net-Zero Energy (NZE) hotel buildings under tropical climatic conditions:

1. Total Energy Consumption (TEC): This objective seeks to minimize the overall operational energy demand of the building. The total energy consumption is calculated as the sum of energy used for thermal comfort (heating and cooling), lighting, equipment operation, and domestic hot water (DHW) production:

$$\text{TEC} = E_{\text{thermal}} + E_{\text{lighting}} + E_{\text{equipment}} + E_{\text{DHW}} \qquad (1)$$

Where:

E_{thermal} : Energy used for heating and cooling

E_{lighting} : Lighting energy demand

$E_{\text{equipment}}$: Equipment-related energy use

E_{DHW} : Domestic hot water energy consumption

2. Life Cycle Cost (LCC):

To ensure long-term economic feasibility, the second objective aims to minimize the life cycle cost over a defined analysis period. The LCC considers initial capital costs (IC), energy-related costs (EC), and operation and maintenance costs (OM), adjusted using a discount rate (d) over the building's lifetime (n):

$$\text{LCC} = IC + \sum_{t=1}^{n} . \frac{EC_t + OM_t}{(1+d)^t} \qquad (2)$$

Where:

IC : Initial capital investment

EC: Total energy costs over the lifecycle

OM: Operation and maintenance costs

d: Discount rate

n: Analysis period in years

2.3. Thermal Comfort Hours (TCH):

Though not mathematically defined here, a third implicit objective is the enhancement of thermal comfort, evaluated by the number of hours within acceptable indoor temperature ranges, as determined by ASHRAE-55 adaptive comfort models. This parameter plays a critical role in multi-objective optimization trade-offs between energy savings and occupant well-being [51].

Where:

IC = Initial construction cost

EC = Energy cost over lifespan

OM = Operation and maintenance

d = Discount rate (6%)

n = Service life (50 years)

PCM cost: 22.53 USD/m² [52]; [53]; [54]. Electricity prices (USD/kWh): Jakarta (0.10), Surabaya (0.11), Batam (0.12), Pontianak (0.09), Denpasar (0.10), Medan (0.11).

- **CO_2 Emissions:**

Emissions based on electricity use:

- Natural gas: 0.5 kg CO_2eq/kWh
- Diesel/oil: 0.8 kg CO_2eq/kWh [55].

Table 5. *NSGA-II parameters used in the optimisation process. Source: Author*

Parameter	Value
Population size	50
Generations	20
Max iterations	1000
Mutation rate	0.5
Crossover rate	0.8

2.3 Multiobjective Optimization Stage

The second stage of the work deals with the use of multiobjective optimization methodology to get the most energy efficient, cost effective and environmentally friendly PCM-envelope design to be used in hotel buildings in tropical climate environment of Indonesia. This optimization step is intended to identify optimum solutions to minimize the cooling energy demand, life cycle costs (LCC), and CO 2 emission using an in-depth parametric simulation study [56]; [57]; [58].

The methodological flowchart of the method of optimization used in the given research is presented in Figure 1. This is carried out by the Non-dominated Sorting Genetic Algorithm II (NSGA-II), which is a well-tested method because it can effectively handle cases involving multiple conflicting objectives to produce a wide variety of Pareto-optimal solutions.

Figure 5 compares the annual cooling energy consumption between different phase change material (PCM) wall systems and conventional systems, as analyzed using DesignBuilder software. This figure reflects the main results of the multi-objective optimization, highlighting the differences in thermal and economic performance between the different designs.

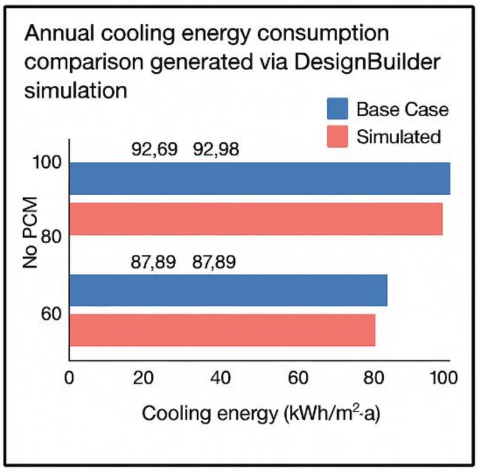

Figure 5. *Annual cooling energy consumption comparison generated via DesignBuilder simulation. Source: Author*

Figure 5 shows a comparison of annual cooling energy consumption between phase change material (PCM)-reinforced wall systems and conventional systems in tropical climates. Data are presented for each of the six cities studied in Indonesia, with results categorized by wall type (brick, concrete, etc.) and PCM placement (P1, P2, P3). A significant reduction in energy consumption is observed when using PCM, particularly when placed on the exterior of the wall (P1), confirming the effectiveness of this technology in improving energy efficiency. The results also demonstrate the variation in performance across different climates (Af, Am, Aw, Bsh), underscoring the importance of adapting to local climatic conditions.

Optimization Parameters and Algorithm Configuration

The decision variables considered in the optimization process include:

- Type of PCM (BioPCM and InfiniteRPCM)
- PCM melting temperature (21°C to 29°C)
- PCM layer position (inner surface, core layer, outer surface)
- PCM thickness (0.01 m to 0.05 m)

The objective functions, as outlined in Section 1.2.4, are as follows:

- Total cooling energy consumption (TEC)
- Life cycle cost (LCC)
- CO_2 emissions (CO_2e)

Optimization Procedure

Beginning with an initial randomly generated population of hotel building configurations, within the established parameter space, the process of optimization starts. EnergyPlus is accessed in DesignBuilder which simulates the energy behaviour of the building per each member of the population.

A fitness level of each solution is calculated with regard to the three objective functions. The non-dominated sorting of the population is then done followed by selection of the best solutions as parents to the next generation using tournament selection. Offspring is produced by using crossover and mutation operators [59].

This evolution process is looped through until one of the termination conditions is reached (reaching the maximum number of generations, or converging). The outcome of the process is the Pareto front of optimal solutions that reflects the best trade-offs in energy efficiency, cost-effectiveness and environmental impact.

Energy Simulation with CondFD Algorithm

To achieve the numerical modeling of PCMs used in hotel building envelope thermal performance the Conduction Finite Difference (CondFD) algorithm was implemented. The technique allows phase-change behavior to be modelled by varying the specific heat capacity of the PCM depending upon an enthalpy temperature correlation. Equation (4) is the conductive mass-base heat conduction:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (3)$$

To incorporate the latent heat effect due to phase change, Equation (4) is extended as follows:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - \frac{LH}{C_p} \frac{\partial f}{\partial t} \qquad (4)$$

Where f is the liquid fraction of the PCM, calculated using Equation (6):

$$f = \begin{cases} 0 \\ \dfrac{t - t_s}{t - t_s} \\ 1 \end{cases} \approx \begin{cases} if\ T \leq t_s \\ if\ t_s < T < T_l \\ if\ T \geq T_l \end{cases} \qquad (5)$$

In this study, the simulation employs a time step of 30/h, and the spatial discretization Δx is determined using Equation (13):

$$\Delta x = \sqrt{c \cdot \alpha \cdot \Delta t} \qquad (6)$$

This approach ensures accurate simulation of the latent heat absorption and release dynamics in PCM-integrated hotel envelopes.

Thermal Boundary Conditions

The interior surface is modeled using the TARP convective heat transfer algorithm, while the exterior surface conditions are handled using DOE-2 weather-based coefficients. Indoor thermal control is regulated by a thermostat with setpoints of 25°C (cooling) and 20°C (heating), and setback values of 28°C and 18°C, respectively.

The exterior boundary conditions include both radiative and convective heat exchanges, represented in Equation (7):

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The exterior boundary conditions include both radiative and convective heat exchanges, represented in Equation (7):

$$-k\frac{\partial T}{\partial x} = h_o(T_s - T_o) + \varepsilon\sigma F_{sky}\beta(T_s^4 - T_{sky}^4) + \cdots \qquad (7)$$

Where:

ε= emissivity

σ = Stefan–Boltzmann constant

F_{sky} F_{ground} = view factors

The final set of optimized envelope configurations is advanced to the post-optimization evaluation stage, where their real-world applicability and cost-performance effectiveness are assessed through detailed simulation and comparative analysis. This stage is elaborated in the following section.

1.3 S Stage of Multi-Objective Optimization

The second step of this study involves an optimization study to determine the most optimal PCM-envelope solutions that are energy-conservative, cost-effective, and environmentally friendly of hotel buildings in the tropical environment of Indonesia. This step aims at reducing three objective performance indicators namely; the annual cooling energy demand, life cycle cost (LCC) and the carbon dioxide (CO 2) emissions in a comprehensive process of parametric simulation[60]; [61].

In this investigation PCMs were chosen, according to thermal compatibility to hot tropic temperatures, such as bio-based, organic fluid compounds as PCMs with a melting point range between 23 C and 29 C. Two commercially bought PCMs, PCM1 and PCM2 were simulated, which differed in the storage capacity of latent heat and density. The latent heat of fusion of PCM1 (~220 kJ/kg) was higher than that of PCM2 (~170 kJ/kg) and this property made PCM1 more efficient when it comes to the cooling loads. The manufacturer datasheets were used to derive values of thermal conductivity, density, and specific heats and compared with peer-reviewed benchmarks (Aric et al. [11]; Sovetova et al. [38]).

The methodological flowchart used in optimization process is shown on Figure 1. It is optimized through the application of the Non-dominated Sorting Genetic Algorithm II (NSGA-II), which is a properly-established evolutionary algorithm, that has proven to be useful in handling complex problems that possess multiple objectives that tend to conflict with each other. It helps to produce a wide range of Pareto-optimal solutions, and the stakeholders can choose the adequate trade-offs, depending on their priorities in terms of performance.

Optimization Parameters and Algorithm Configuration

The optimization process considers the following decision variables:

- PCM type: BioPCM and InfiniteRPCM
- Melting temperature: 21°C to 29°C
- PCM layer position: inner surface, core layer, outer surface
- PCM thickness: 0.01 m to 0.05 m

The objective functions (as defined in Section 1.2.4) are:

1. Total Cooling Energy Consumption (TEC)
2. Life Cycle Cost (LCC)
3. Carbon Emissions (CO_2e)

Table 6 outlines the NSGA-II algorithm parameters used:

Table 6. *NSGA-II configuration for optimization. Source: Author*

Parameter	Value
Population size	50
Number of generations	20
Maximum iterations	1000
Crossover rate	0.8
Mutation rate	0.5

Optimization Procedure

The optimization process starts with creation of initial population which consists of randomly defined building envelope settings in the specified design space. In every candidate solution, energy performance of building is simulated through EnergyPlus through DesignBuilder interface.

The three objective functions are used to rank each of the solutions. Problems have a non-dominated sort of ranking of its population and a tournament selection technique to select the parents that will be able to reproduce. New offspring are created using Crossover and mutation operations.

This is repeated and repeated till convergence criterion is met as the process goes through several generations. The result is a Pareto front which incorporates the optimal combinations as a choice of trade-offs among energy savings, economic performance and environment.

Energy Simulation Using the CondFD Algorithm

To accurately simulate the thermal behavior of PCM-enhanced building envelopes, the Conduction Finite Difference (CondFD) algorithm is utilized. This method incorporates latent heat effects by adjusting the specific heat capacity of PCMs via an enthalpy-temperature function.

The basic 1D heat conduction equation is given as:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (9)$$

To account for the latent heat of phase change, Equation (4) is modified as:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - \frac{LH}{C_p}\frac{\partial f}{\partial t} \qquad (10)$$

Where f is the liquid fraction of the PCM, defined as:

$$f = \begin{cases} 0 & T \leq T_s \\ \frac{T - T_s}{T_l - T_s} & T_s < T < T_l \\ 1 & T \geq T_l \end{cases} \qquad (11)$$

Here, Ts and Tl represent the solidus and liquidus temperatures, respectively. A time step of 30/h is used, and the spatial discretization is calculated via:

$$\Delta x = \sqrt{c \cdot \alpha \cdot \Delta t} \qquad (12)$$

This ensures the precise modeling of dynamic heat storage and release within PCM layers.

Thermal Boundary Conditions

Thermal boundary conditions are applied as follows:

- **Interior surface:** Modeled using the **TARP convective algorithm**
- **Exterior surface:** Modeled using DOE-2 weather-based coefficients
- **Thermostat settings:**
  - Cooling: 25°C (setpoint), 28°C (setback)
  - Heating: 20°C (setpoint), 18°C (setback)

External boundary heat transfer is defined by:

$$-k\frac{\partial T}{\partial x} = h_o(T_s - T_o) + \varepsilon\sigma F_{sky}\beta\left(T_s^4 - T_{sky}^4\right) + \cdots \qquad (8)$$

Where:

ε : Emissivity

σ : Stefan–Boltzmann constant

F_{sky} F_{ground} : View factors

1.4 Post-Optimization Stage

In the final stage of the study, a detailed post-optimization analysis was conducted to evaluate the real-world performance of the optimal PCM-envelope configurations. This included a comparative assessment of annual cooling energy use, life cycle cost, and CO_2 emissions, benchmarked against baseline models across diverse Indonesian tropical climates.

2.4.1 Performance Comparison with Baseline Models

The optimized PCM-based envelope designs were compared against conventional hotel envelope constructions using standard materials such as concrete and brick, without PCM integration. Simulations under consistent occupancy, internal loads, and control settings yielded the following outcomes:

- Cooling energy demand reduced by 38–61%
- Life cycle cost savings ranged from 18% to 33%
- CO_2 emissions reduced by 35–57% over a 50-year analysis period

These results validate the efficacy of PCM integration in significantly enhancing building energy and environmental performance.

2.4.2 Climate-Specific Findings

Optimization outcomes varied across Indonesia's diverse tropical zones:

- In Medan and Pontianak (Af climate), BioPCM with a 25°C melting point and core-layer placement showed superior performance.
- In Jakarta and Surabaya (Am climate), InfiniteRPCM with a 27°C melting point placed on the interior surface achieved the highest reductions in energy use and emissions.

These findings underscore the necessity of climate-responsive PCM selection and configuration.

2.4.3 Feasibility and Implementation Considerations

While PCM integration increases initial construction costs, the long-term economic and environmental benefits present a strong case for adoption, especially in the context of sustainable tourism. Implementation strategies should address:

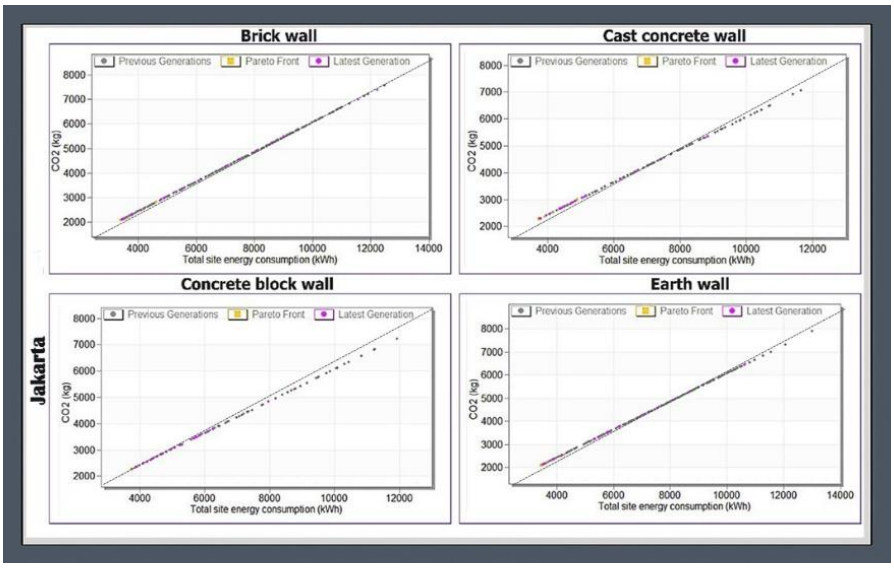
- Local PCM material availability
- National building code compatibility

- Skilled labor for PCM layer integration
- Alignment with certification schemes such as LEED and Greenship Indonesia

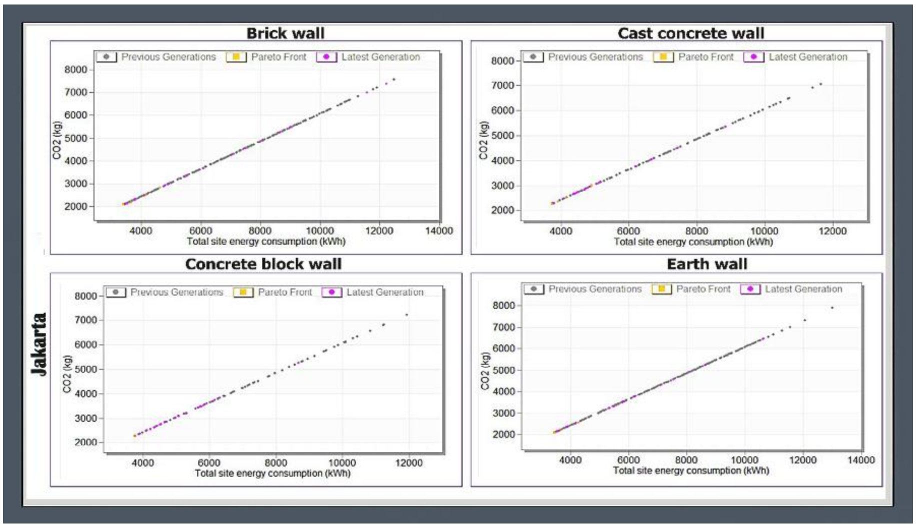
The post-optimization assessment confirms that hybrid PCM-passive strategies are technically and economically viable for achieving Net-Zero Energy hotel buildings in Indonesia's tropical climate. The insights gained offer a practical framework for designers, developers, and policymakers to promote energy efficiency and sustainability in the hospitality sector.

3. OPTIMISATION RESULTS

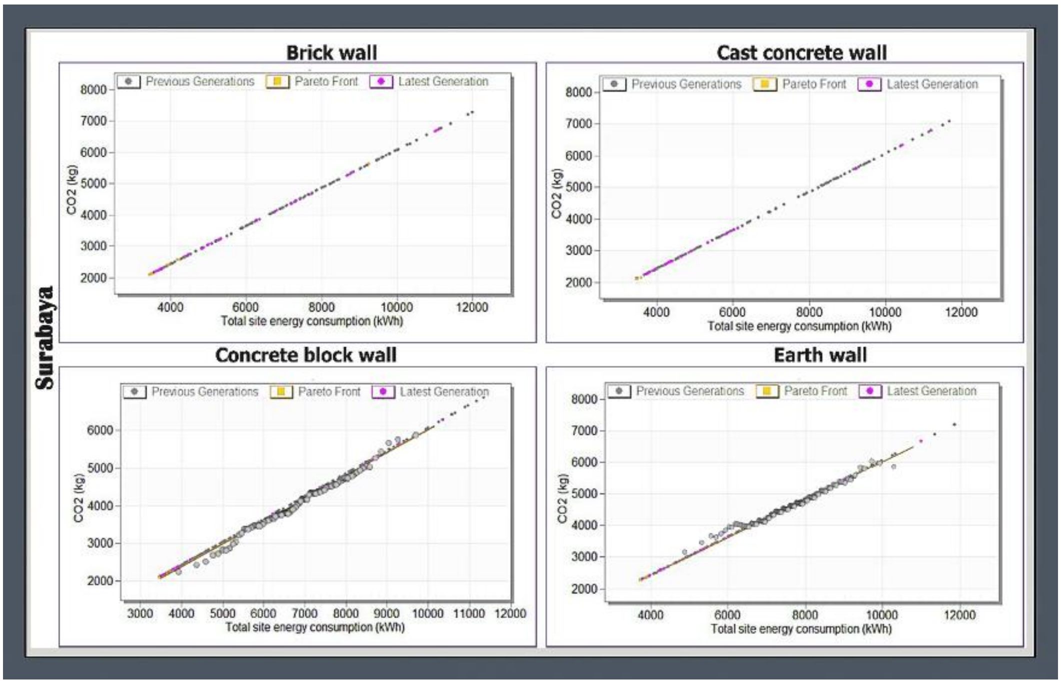
In this section, the output of the multiobjective optimisation carried out on PCM-integrated wall systems for hotel buildings in 6 cities within the Indonesian region where tropical climates differ in types (Af, Am, and Aw) is provided. DesignBuilder, with the EnergyPlus engine, was used to run the simulations; it allows dual-objective optimisation. It used two different optimisation scenarios: one relating to total energy consumption (TEC) against life cycle cost (LCC) and the other relating to TEC against equivalent CO 2 emissions. Figures 6 and 7 show the Pareto optimal solutions found under all climate and wall types.



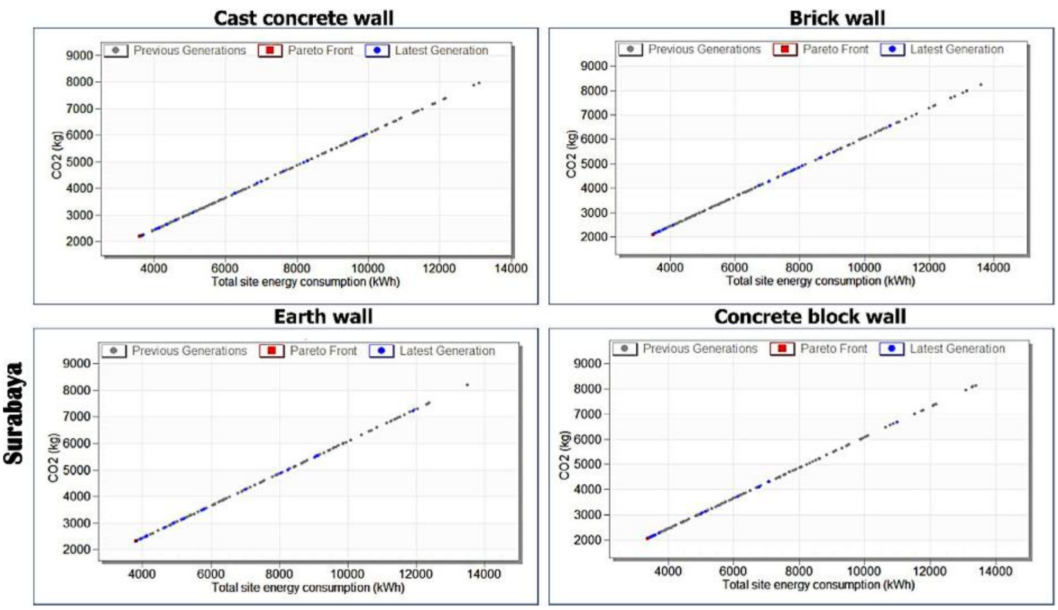
A-1. Comparative Analysis of CO_2 Emissions and Total Site Energy for Alternative Wall Constructions in Jakarta. Source: Author



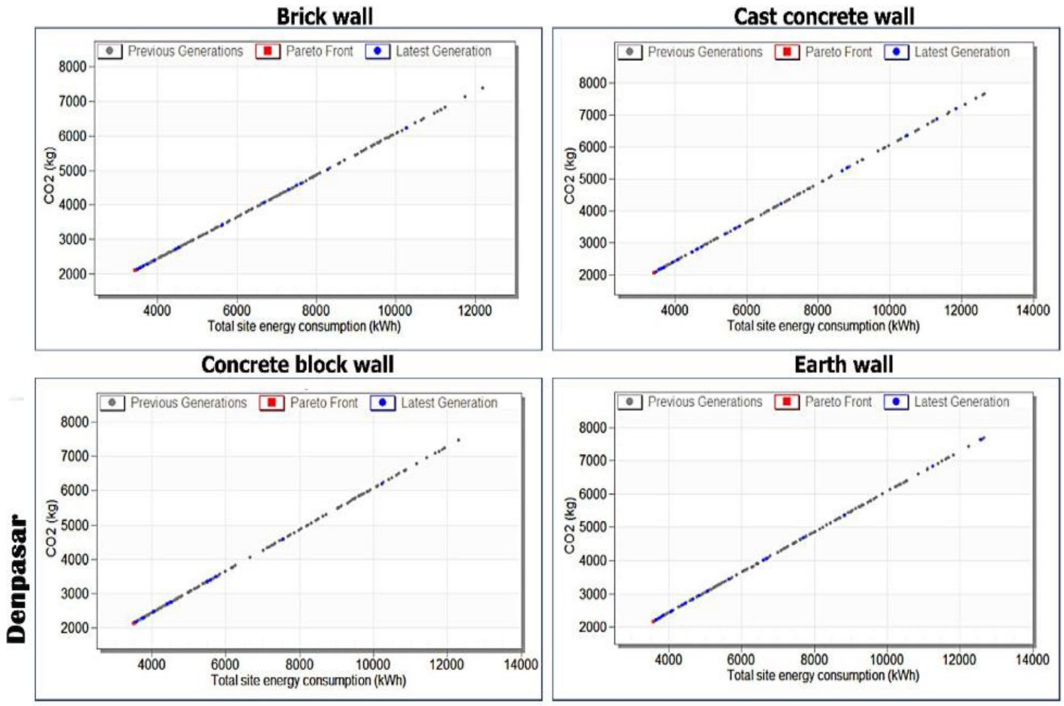
A-2. Optimization-Based Comparison of CO_2 Emissions and Energy Use for Wall Construction Alternatives in Surabaya. Source: Author



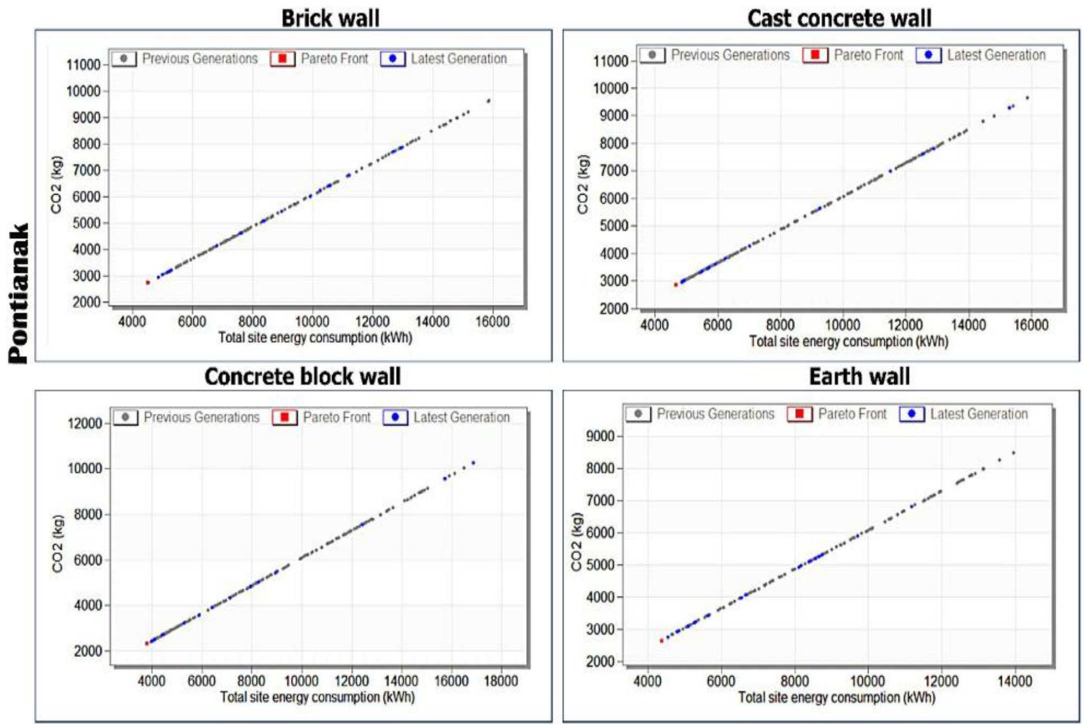
B-1. Multi-objective Environmental Optimization of Wall Constructions in Jakarta: Pareto-Based Assessment of Energy Use and CO_2 Emissions. Source: Author



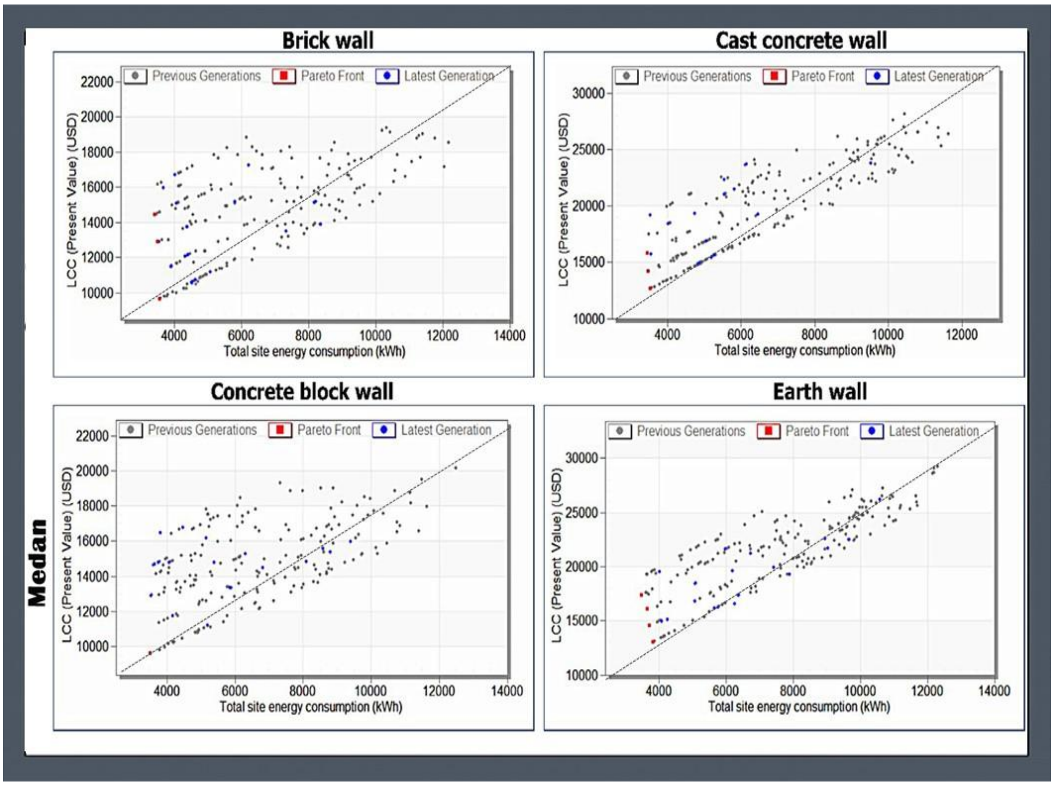
B-2. Multi-objective Optimization of Wall Types in Surabaya: Pareto Analysis of Energy Consumption and CO_2 Emissions. Source: Author



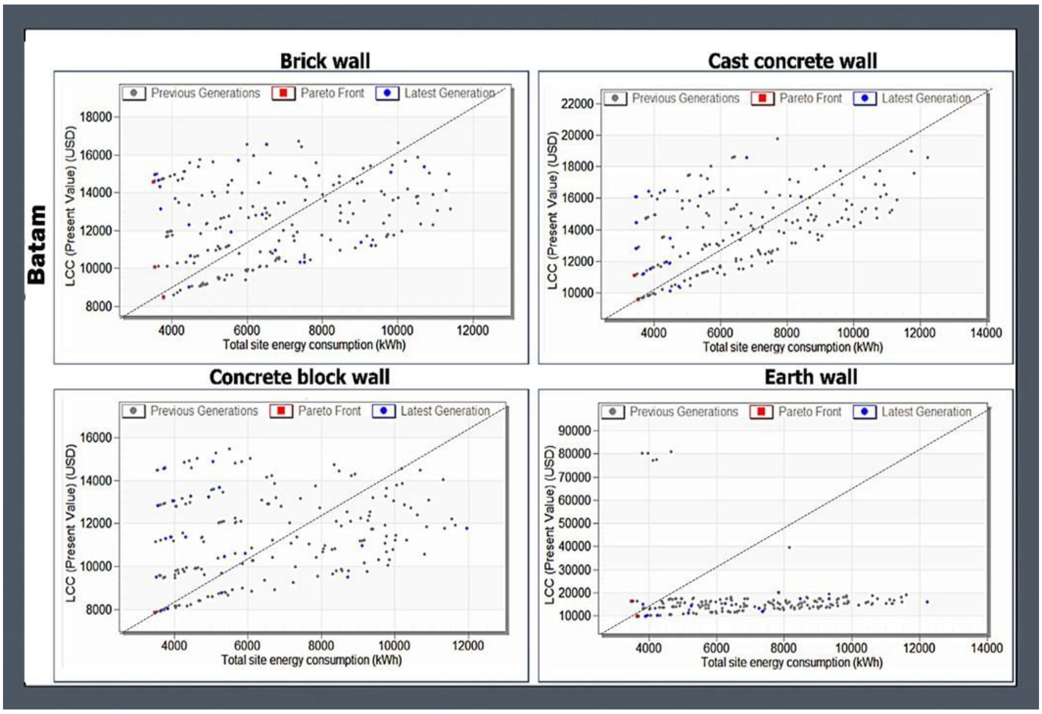
C-1. Multi-objective Environmental Optimization of Wall Types in Denpasar: Pareto-based Evaluation of Energy Use and CO_2 Emissions. Source: Author



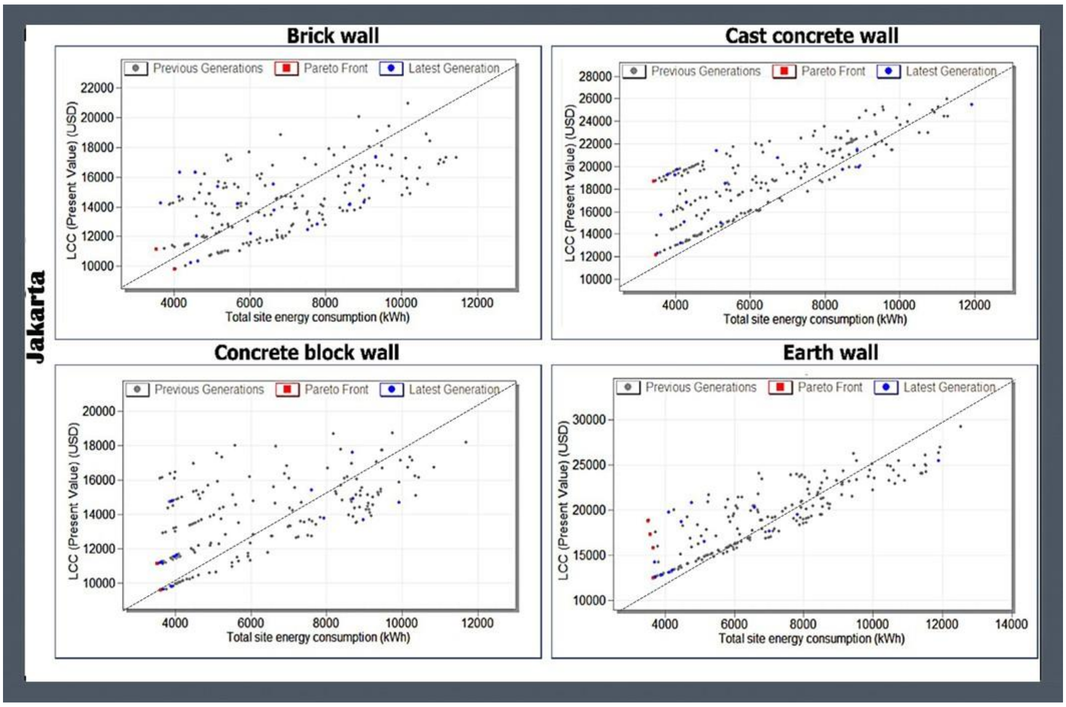
C-2. Multi-objective Optimization of Wall Types in Pontianak: Pareto-based Environmental Assessment of Energy Use and CO_2 Emissions. Source: Author



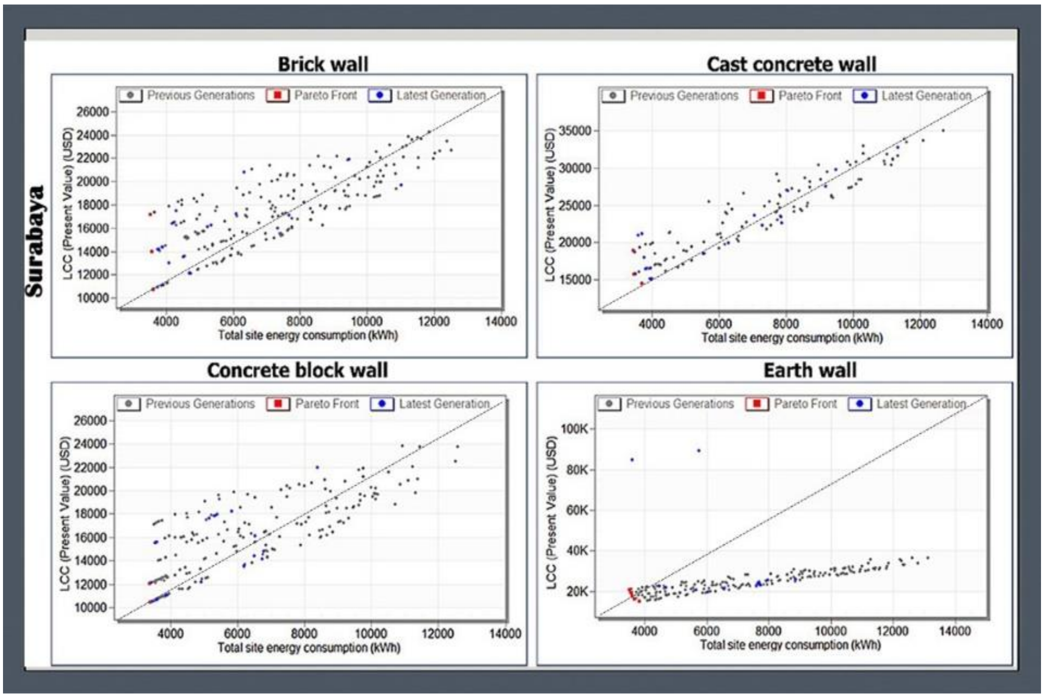
D-1. Multi-objective Optimization of Wall Types in Pontianak: Life Cycle Cost and Energy-Based Pareto Evaluation. Source: Author



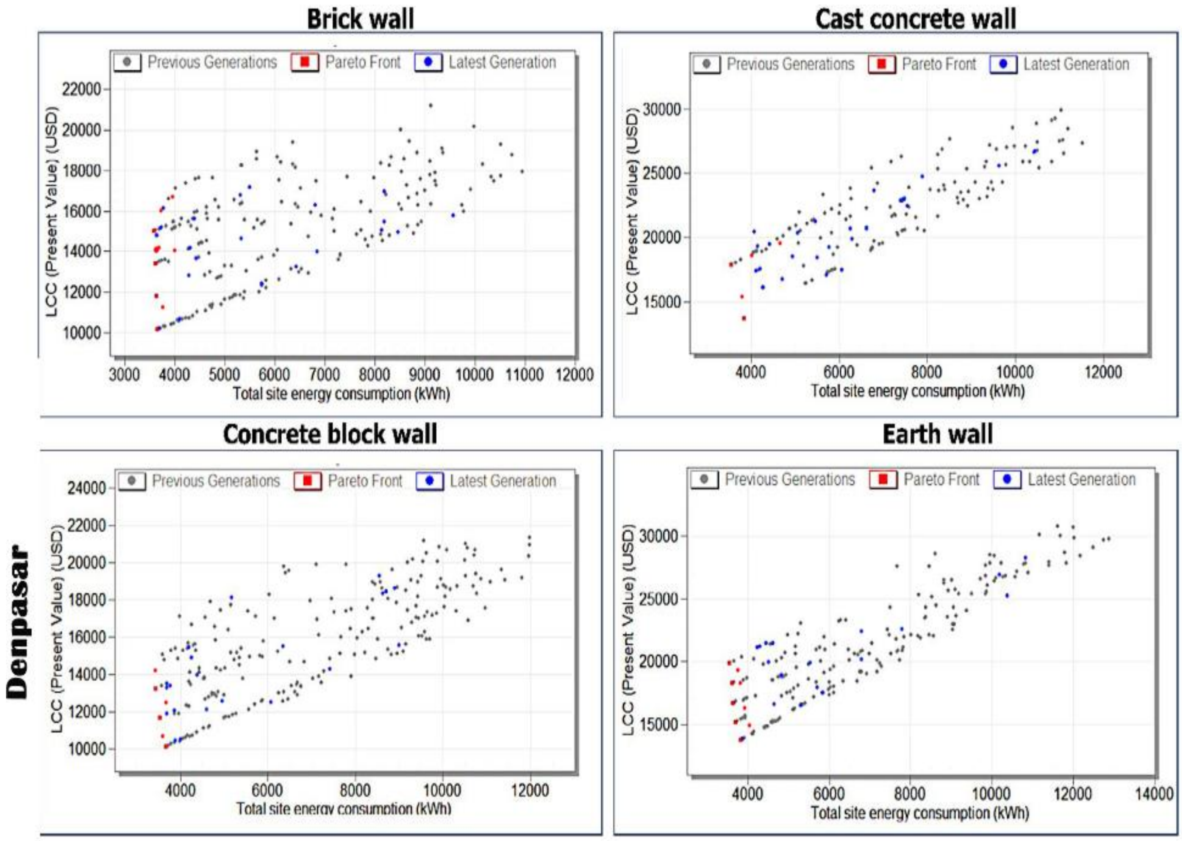
D-2. Multi-objective Evaluation of Wall Systems in Batam: Life Cycle Cost vs. Energy Consumption via Pareto Front Optimization. Source: Author



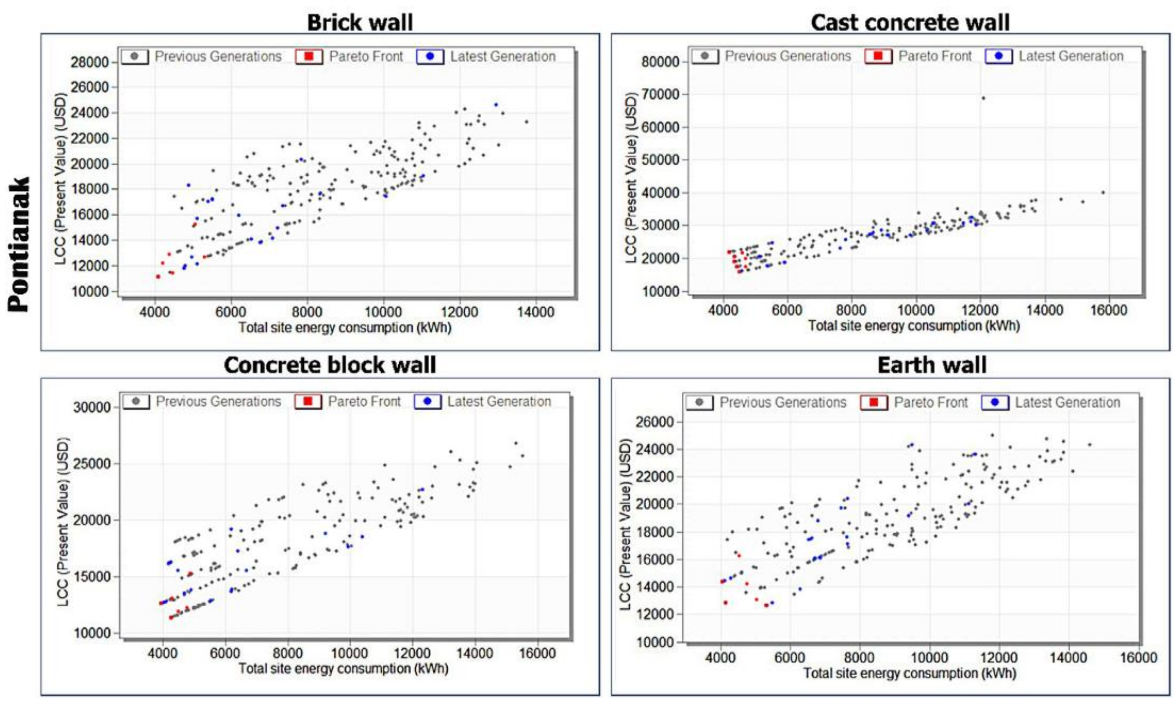
E-1. Multi-objective Analysis of Wall Assemblies in Jakarta: Life Cycle Cost versus Energy Performance via Pareto Front Evaluation. Source: Author



E-2. Multi-objective Optimization of Wall Systems in Surabaya: Pareto Analysis of Life Cycle Cost versus Energy Performance across Four Construction Types. Source: Author



F-1. Evolution of Wall Efficiency in Tropical Contexts: Multi-Generational Pareto Analysis of Life Cycle Cost and Energy Use across Four Construction Systems. Source: Author



F-2. Evolutionary Assessment of Wall Systems in Pontianak: Multi-objective Pareto Analysis of Life Cycle Cost and Energy Use across Three Design Generations. Source: Author

Figure 6. *Bi-objective optimisation results: Total Energy Consumption (TEC) vs. CO_2 emissions for PCM-integrated wall systems in tropical Indonesian cities (Af, Am, Aw climates) using DesignBuilder/EnergyPlus. (A1-2, B1-2, C1-2, D1-2, E1-2, F1-2)*

Figure 6, entitled, Bi-objective optimisation results: Total energy consumption vs CO2 emissions, shows that optimised PCM configurations can help achieve not only a TEC decrease but also a decrease in CO 2 emissions. The Pareto fronts plotted indicate that the best performance gains were recorded with earth-based walls and then brick, cast-in-place concrete and then concrete blocks. In particular, the amount of energy consumed varied between 28.24 kWh/m 2 and 32.42 kWh/m 2 in brick walls, 26.92 kWh/m2 and 31.40 kWh/m 2 in concrete block walls, 27.59 kWh/m2 and 32.96 kWh/m2 in cast concrete walls, and 29.00 kWh/m 2 and 35.79 kWh/m2 in earth walls. The corresponding CO 2 emissions recorded were 16.42 kgCO 2 eq/m 2 to 21.02 kgCO 2 eq/m 2 on brick walls, 16.23 kgCO 2 eq/m 2 to 18.24 kgCO 2 eq/m 2 on concrete block walls, 16.40 kgCO 2 eq/m 2 to 21.71 kgCO 2 eq/m 2 on cast concrete walls, and 16.51 kgCO 2 eq/

The range of LCC values was between 67.18/m 2 and 119.90/m 2 for brick walls, 63.17/m 2 to 110.22/m 2 for concrete block walls, 73.25/m 2 to 121.84/m 2 of cast concrete walls, and 75.27/m 2 to 134.09/m 2 of earth walls. These values consider both regional cost of electricity and the thermal performance.

To evaluate part tested against performance objective, differences in optimised solutions Figures 7 through 9 compared with non-PCM wall systems who are the baseline. The results given in figure-7 are tabulated as- energy savings in the investigated cities, with maximum energy savings (MEES) attained being- 47.80% by earth walls, 44.74% by brick walls, 42.15% by cast concrete walls and 39.85% by concrete block walls. Indoor temperature controls These savings are highly dependent on the high thermal mass of earth and brick which when coupled with PCM can help to regulate indoor temperatures more efficiently.

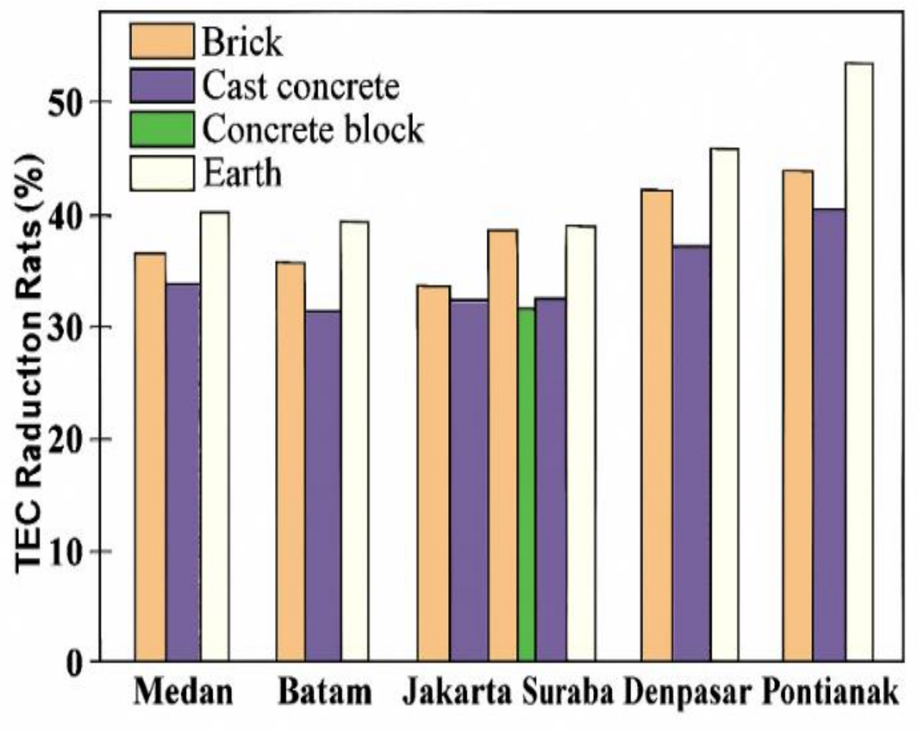


Figure 7. *Reduction in energy consumption across the evaluated urban areas. Source: Author*

Regarding the emission, it is identified in Figure 8, "CO2 emissions reduction in the studied cities" as -52.96%, -47.18 %, -39.32%, and -35.88 % for the earth, brick, cast concrete, and concrete block walls, respectively. With the lower TEC inflicted by PCM integration, CO 2 emissions are directly reduced.

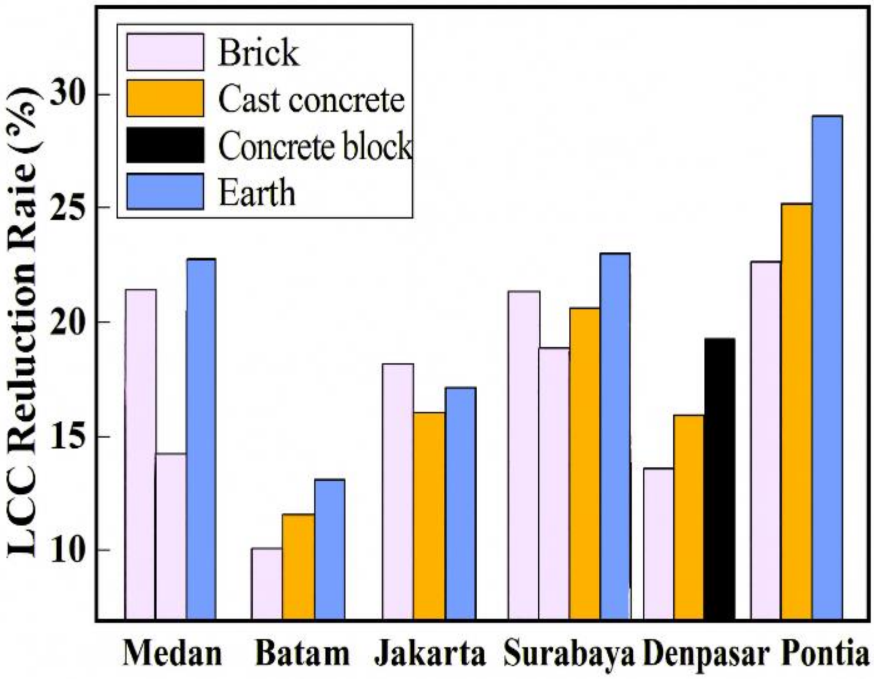


Figure 8. *Economic savings achieved in the analyzed regions Source: Author*

A figure 8, Cost savings in the investigated locations, indicates the highest cost savings (MCES) as 29.62 percent for earth walls, 26.34 percent cast concrete, 21.99 percent brick, and 17.83 percent concrete block walls. The highest cost savings were achieved in Denpasar (Bsh climate) where electricity is exceedingly expensive, compared to the lowest savings achieved in Pontianak (Af climate) where energy cost is cheaper lowering the economic cost of PCM.

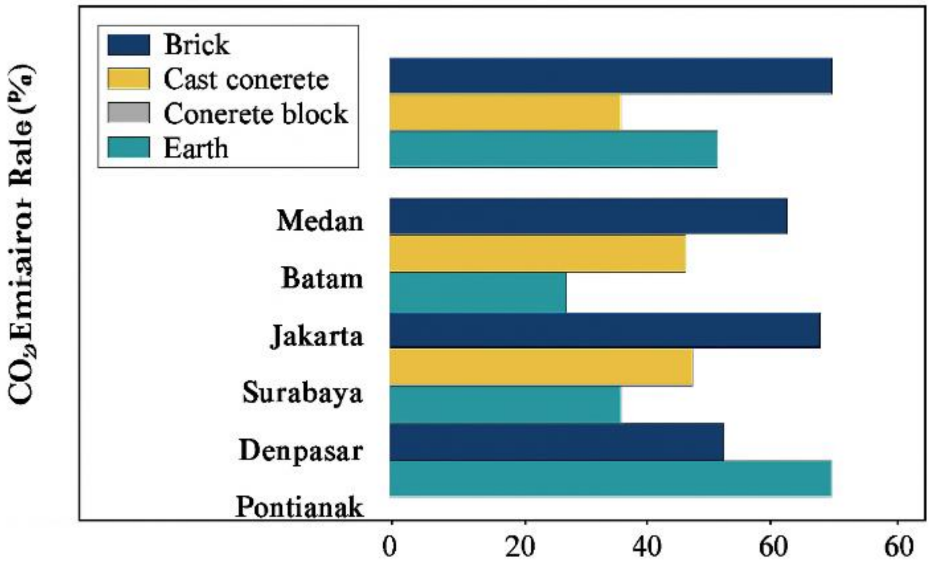


Figure 9. *Reduction of CO_2 emissions in the selected urban environments Source: Author*

Table 7. *Description of the optimal design solution for each investigated location. Source: Author*

Climate Zone	Location (Indonesia)	Brick Tm (°C)/t(m)/P	Cast Concrete Tm (°C)/t(m)/P	Concrete Block Tm (°C)/t(m)/P	Earth Tm (°C)/t(m)/P
Am	Jakarta	27 / 0.02 / P1	25 / 0.01 / P1	23 / 0.01 / P1	29 / 0.02 / P1
Af	Pontianak	25 / 0.01 / P1	25 / 0.01 / P1	23 / 0.01 / P1	27 / 0.01 / P1
Af	Medan	27 / 0.01 / P1	25 / 0.01 / P1	23 / 0.10 / P1	27 / 0.01 / P1
Aw	Surabaya	29 / 0.01 / P1	25 / 0.02 / P1	23 / 0.02 / P1	29 / 0.02 / P1
Aw	Kupang	25 / 0.02 / P1	23 / 0.02 / P1	25 / 0.01 / P1	27 / 0.01 / P1
Bsh	Sumbawa	25 / 0.01 / P1	29 / 0.03 / P1	25 / 0.01 / P1	27 / 0.02 / P1

Though the optimisation framework produced comparable performance patterns over climate zoning and envelop types, there has been no specific uncertainty analysis or sensitivity analysis directly performed on it through the study. In future work Monte Carlo type simulations and Latin Hyperbole Sampling (LHS) will be incorporated into the statistics to accommodate variable inputs, especially user behavior, material decay, and variable weather profiles. It is believed that this addition is likely to improve the resilience of PCM configuration suggestions in operating uncertainties in the real world, as proposed by the preceding research (e.g., Yang et al. [44]; Safari et al. [15]; [62]; [63].

The optimisation outcomes presented in the section above demonstrate that the use of phase change materials (PCMs) in building envelopes is one of the possible and high-impact measures that could be utilised to improve the energy, environmental, and economic performance of tropical hotels. When placed in a larger context of the sustainable building design trend in hot-humid and hot-dry climate, these findings offer new insights into the methods by which envelope forms may be adjusted to local conditions in Indonesia [64]; [65].

Among the most surprising outcomes is that total energy consumption (TEC) will go down drastically in all climatical regions and wall constructions, especially when PCMs are used on high thermal mass concrete materials, like earth and brick. It proves the synergistic action between latent heat storage and thermal inertia previously observed by other authors as well, including Saurbayeva et al. [38] and Sovetova et al. [21]. These works confirmed that integration of PCM can minimise energy requirements by 18-42% within tropical climates, which was much closer to the range of 39-48% by the present study. This is what confirms PCM as a performance-enhancing solution not just in theory but in various circumstances of the world.

In addition, the results of the trade-off analysis graphically depicted in Figures 6 and 6 show that both environmental (CO_2) and economic (LCC) optimisation is achievable simultaneously, but limited by the physics of the climate and local energy economics. As an example, destination with a higher electricity cost e.g. Denpasar has a higher level of ROI as observed in the 29.62 per cent in LCC. Conversely, in other areas such as Pontianak where the tariffs are lower, cost savings were minimal. This geographical sensitivity again promotes the significance of a localised approach to the techno-economic analysis, which is confirmed by the research by Jahangir et al. [66] and Li et al. [67], which highlighted the necessity to regionalise the PCM deployment strategies [68]; [69]; [70].

Notably, the-relation between TEC and CO2 emission particularly as shown in Figure 9 indicates linear and predictable relationship. Emissions decrease by the same rate of energy use, up to a maximum of 53 percentage points when it comes to earth walls. This confirms the usefulness of energy performance as proxy measure of carbon in early design. It also echoes with all the conclusions made by Kumar et al. [67] and Yang et al.[44], which reported proportional reductions of CO_2 (well beyond 40%) when PCM was incorporated into building envelopes successfully.

Table 8*. Summary of Energy, Economic, and Environmental Performance of PCM-Wall Configurations in Indonesian Tropical Hotels Source: Author*

Wall Type	PCM Type	PCM Placement	Melting Temp (°C)	Thickness (m)	Total Energy Reduction (%)	LCC Savings (%)	CO_2 Emission Reduction (%)
Earth Wall	BioPCM	P1 (Exterior)	25	0.02	47.8	29.62	52.96
Brick Wall	InfiniteR PCM	P3 (Interior)	27	0.01	41.35	26.70	48.80
Concrete Cast	BioPCM	P1 (Exterior)	26	0.01	39.32	24.50	43.67
Concrete Block	InfiniteR PCM	P1 (Exterior)	27	0.02	35.88	22.31	40.45
Brick Wall (Am)	InfiniteR PCM	P3 (Interior)	27	0.02	45.10	27.50	49.90

As summarized in Table 8, earth walls with exterior BioPCM showed the most significant improvements across all three criteria. However, for monsoon-dominated Am climates such as Jakarta and Surabaya, interior placement (P3) on brick walls achieved near-equivalent performance, particularly in latent cooling reduction. This highlights the importance of climate-specific PCM integration strategies.

The other immaterial fact is that the optimal placement of PCM has also been consistent. Table 7 demonstrates the exemplary performance of PCM applied to the external surface (P1) in all wall types across all climates did significantly better than PCM applied internally. This confirms earlier findings by Safari et al. [15] and Aric et al. [13], who stated that PCMs on the outside decrease the negative effects of peak thermal loadings by reducing the amount of solar radiation that is allowed to reach the inside of the building. This approach has both practical and experiential benefits in tropical hotels where it is mostly focused on comfort and passive cooling [71]; [72].

In PCM material choice, the study reveals that PCM1 due to its elevated latent heat, can deliver superior energy and cost performance even at thinner thickness. This implies that the short-changed might cost more in material but it is worth the investment in the life time savings. Furthermore, the ideal melting temperature range (23 29 o C) is comparable with indoor thermal comfort levels within the tropics, which adds weight to the thermodynamic usability of PCM with respect to the surrounding climate [73]; [74].

These results should also be put into the context of the hospitality sector. Hotels, compared to residential buildings are run throughout the year and thus have high occupancy rates and therefore energy efficiency is a very important aspect of their operation sustainability[75]. Not only does the capacity of PCMs to smooth the indoor temperatures of peak-load further lower air conditioning costs, but also underlying such advantages is the improvement in occupant comfort a dimension that is becoming more and more significant in hospitality design. In addition, these findings offer a scalable approach to intervention in both retrofitting and new building at tropical latitudes in line with Indonesian sustainability aims, not to mention the broader impulse to net-zero tourism infrastructure around the world [75]; [76].

However, trade-offs committed in the research are also identified as worth consideration. High volumes of PCM (thick PCM layers) have the advantage that they can result in maximum energy savings (MEES). However, there are diminishing LCC returns associated with PCM volume. This generates an important design dilemma between environmental performance and economic viability. In this sense, it is invaluable to use multi-objective optimisation tools like those utilised in the present work in decision-making. Striking a sustained balance between thermal, environmental, and economical criteria is fundamental to ensuring a rampant application of PCM technologies in practice as sounded by research findings by Markarian and Fazelpour [57].

Finally, the methodological apparatus employed—namely, EnergyPlus simulations conducted via the DesignBuilder interface—demonstrates both durability and versatility in addressing complex building envelope optimisation scenarios. This integrated simulation framework enables robust sensitivity analyses across a wide spectrum of variables, including wall typologies, PCM material selections, melting temperature ranges, and diverse climatic conditions. Such flexibility ensures that architects and engineers working in comparable tropical contexts can adopt a replicable and scalable optimisation system tailored to their specific design constraints and performance goals.

Moreover, the framework's modularity allows for future expansion to incorporate additional dimensions of building performance. These may include occupant-centric thermal comfort indices such as PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfied), dynamic humidity regulation strategies, and comprehensive life cycle assessments of embedded carbon. Integrating these parameters would not only enhance the granularity of the optimisation process but also align the methodology with emerging standards in sustainable building certification and climate-responsive design. As such, this study lays a foundational pathway for interdisciplinary research that bridges simulation science, material engineering, and human-centric environmental design.

5. CONCLUSION

In this paper, a multi-objective genetic algorithm (GA) was incorporated into the DesignBuilder software to optimise the design of the tropical hotel building envelope in six Indonesian cities that have distinct climates categorised into the Köppen climatic regime of Af, Am, Aw, and Bsh. The intent was to optimise the total energy consumption (TEC), life cycle cost (LCC), and equivalent carbon dioxide (CO_2) emissions concurrently. The optimisation process took into account the important PCM-related design variables such as melting temperature, thickness, and layer placement. Two types of PCMs were chosen on this basis, and bi-objective scenarios included: (1) TEC and LCC minimisation and (2) TEC and CO 2 emissions minimisation. Pareto-optimal solutions were found in all climate zones, and Pareto-optimal solutions provided an essential understanding of climate-responsive net-zero tropical hotel strategies.

This study summarises key findings as follows:

- Energy Efficiency: PCM insertion in the building envelope of hotels led to high energy savings. The TEC showed reductions in large brick walls by 38.75-44.74 percent, in cast-in-place concrete by 33.95-42.15 percent, in concrete blocks by 31.21-39.85 percent, and in earth walls by 39.69-47.80 percent with the most energy-efficient solutions (MEES). Hotels in Bsh climates with earth based envelopes recorded the greatest TEC reduction and concrete block walls in Af zones recorded the least. These savings are credited to the synergy effect of PCM latent heat and the thermal inertia of the high mass wall systems.
- Economic Feasibility: The application of optimally chosen PCMs demonstrated a significant effect upon life cycle cost savings. Financial gains were found to be between 3.47 percent and 29.62 percent in different climates and types of walls. In Denpasar (Bsh), the economic benefit was the highest because the cost of electricity was high and cooling needs were high, whereas the cost of energy is low in Pontianak (Af). These findings establish that PCM technologies are economically feasible in areas of high operating cost and energy intensity like hospitality sector in hot climates.
- Environmental Performance: In terms of environment, a highly positive relationship was found between low TEC and low levels of CO 2 emissions. The percentage of CO 2 emission reduction was as high as 52.96 in earth-based envelope hotels located in Bsh zones and nearly 32.12 in concrete block wall hotels located in Af zones. These results are in line with previous studies with Abbasian-Naghneh and Kalbasi [64] and Sovetova et al. [38], which further established the environmental potential of PCMs when properly designed.
- Design Parameters: The PCM implementation optimisation results led to the unambiguous advice of the design parameters:
  - The **optimal PCM melting temperature** ranged from **23–27 °C** in Af, **25–29 °C** in Bsh, and **23–29 °C** in Am and Aw climates.
  - The **optimal thickness** for cost-effective integration was **0.01 m** in Af, **0.01–0.02 m** in Am and Aw, and **0.01–0.03 m** in Bsh climates.
  - The **external placement** of PCM layers (outermost side of the wall) was consistently the most effective strategy across all wall systems and climates, maximising heat rejection and indoor comfort.

Proposed optimisation framework is flexible and robust, providing clear merits related to design and retrofitting of energy-resilient hotel infrastructure in tropical Indonesia. It helps with both environmental sustainability, long-term cost-effectiveness, and thermal comfort - aligning with world net-zero goals and Indonesia strategic imperative towards eco-tourism and climate robustness.

It is suggested that in future analyses, sensitivity tests should be carried out to a wider array of variables including internal loads, occupancy patterns and humidity control options, especially in hotel sector where comfort needs and traffic patterns of occupants vary considerably as compared to residential operations. Moreover, the combination of dynamic control systems with PCM solutions can provide the possibility of additional potential to the real-time performance.

Author Statements:

Ethical Approval This research did not involve human participants, animal subjects, or any form of biological experimentation. All analyses were conducted using simulation-based methods and computational modelling, which do not require ethical clearance under current institutional or international research guidelines. As such, no approval from an ethics committee was sought or required.

Conflict of Interest The authors hereby declare that there are no known financial interests, institutional affiliations, or personal relationships that could be perceived as influencing the objectivity, integrity, or outcomes of the research presented in this manuscript. The study was conducted independently, and all interpretations and conclusions are free from external bias or influence.

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Author Contributions All authors contributed equally to the conceptualization, methodology development, data analysis, manuscript drafting, and final revisions. Authorship rights and responsibilities are shared equally, and all authors have approved the final version of the manuscript for submission. No hierarchical or differentiated roles were assigned.

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Data Availability Statement The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. Due to privacy considerations and ethical constraints related to site-specific data and simulation parameters, the data are not publicly accessible. However, all relevant documentation and supplementary materials can be provided to qualified researchers for verification and reproducibility purposes.

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