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Evaluating thermal comfort in residential buildings using double-skin facades with particle swarm optimization

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Abstract

Ensuring optimal thermal comfort while maintaining energy efficiency is a crucial challenge in residential building design. Double-Skin Facades (DSFs) have emerged as an innovative architectural solution, providing passive temperature regulation through controlled ventilation and insulation. However, optimizing DSF parameters, such as cavity depth, window type, and airflow mechanisms, requires advanced computational techniques. This study employs Particle Swarm Optimization (PSO) to enhance the effectiveness of DSFs in improving thermal comfort and reducing energy consumption. A simulation-based approach is used, integrating EnergyPlus for thermal performance analysis and GenOpt for optimization. The study focuses on optimizing Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)—two widely accepted thermal comfort indices based on ASHRAE 55 and ISO 7730 standards. Through PSO-driven adjustments, DSF configurations are refined to maintain indoor environmental stability while minimizing cooling and heating loads. The results demonstrate that optimized DSFs significantly enhance occupant comfort and lead to substantial energy savings, particularly in extreme climate conditions. The study also presents a comparative analysis of pre- and post-optimization energy consumption, showing reductions in both heating and cooling demands. PSO convergence graphs and energy savings visualizations highlight the effectiveness of the optimization framework. These findings contribute to sustainable building design by providing a computational methodology that enables architects and engineers to develop high-performance residential buildings. Future research could integrate machine learning techniques to further refine real-time adaptive control mechanisms for DSF configurations.

Keywords: Computational optimization, double-skin facades, energy efficiency, EnergyPlus, GenOpt, particle swarm optimization, PMV, PPD, sustainable building design, thermal comfort.

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1. Introduction

1.1. Overview of Thermal Comfort

Thermal comfort depends on many personal and environmental factors and changes over time [1]. It affects people's health, productivity, and well-being, making it essential in business and residential buildings. People spend a lot of time indoors; therefore, designing for thermal comfort is crucial. Age, metabolic rate, clothes, and preferences affect thermal comfort. Environmental factors greatly affect a person's thermal experience. Temperature is crucial to comfort. Heating, Ventilation, and Air Conditioning (HVAC) efficiency, building insulation, and air circulation are all significant factors [2]. Indoor temperatures outside their optimal range cause pain, inattention, exhaustion, and possibly dangerous health issues like heat stress and hypothermia.

Humidity affects heat perception and temperature regulation. In high relative humidity, perspiration cannot drain as rapidly, causing people to overestimate their body temperature. Conversely, low humidity can cause dry skin, itchy mouth and eyes, and respiratory infections. Controlling humidity with ventilation and air conditioning systems maintains a comfortable indoor atmosphere. Air speed also impacts heat perception. In warm weather, a light wind can help people stay cool by allowing more heat to escape, but in colder weather, heavy drafts can be uncomfortable [3]. Well-controlled air circulation creates a balanced and comfortable house.

Radiant heat impacts thermal sensation due to heat transfer between the body and its environment. Reflective coatings, insulation, and thermal mass can regulate heat transfer and increase thermal comfort. A perfect indoor thermal climate demands passive and active design. Passive design uses airflow, sunlight, and building orientation to promote comfort without energy. Thermal insulation, shading, and energy-efficient windows improve indoor comfort. Indoor climate-controlling active design methods involve HVAC and other mechanical equipment. Intelligent thermal management and automatic temperature control systems adapt to environmental changes to increase thermal comfort. Double-Skin Facades (DSFs) are popular for thermal comfort. Due to the airspace between the glass panes, these facades keep the inside colder in winter and the outside warmer in summer. Modern buildings may mix sustainability and comfort with DSFs' energy efficiency and consistent interior climate [4].

1.2. Role of Double-Skin Facades (DSFs)

Many architects use DSFs to improve thermal comfort and energy efficiency in modern buildings [5]. These unique methods establish a heat barrier between the interior and outdoor surroundings with air gaps between glass panes. Adaptive temperature management will reduce HVAC use in this facility. DSFs save energy and improve comfort by easing outdoor temperature changes. DSFs regulate building envelope heat flow. The air gap between glass layers insulates the interior from the outside. In extreme weather areas, this feature keeps indoor temperatures stable year-round. DSFs reduce indoor heat loss and heating costs in colder climates. They block direct solar radiation in hotter areas to reduce heat absorption and AC use. Moderate heat transfer minimizes energy costs and greenhouse gas emissions and enhances building energy performance. DSFs encourage natural ventilation, which improves interior air quality and thermal comfort. The glass layer gap can be manually or naturally vented to circulate fresh air, reducing the need for artificial cooling and heating [6]. Natural ventilation reduces energy use and removes indoor pollutants, improving occupant health. When it's hot outdoors, passive cooling—warmer air rising and being replaced by cooler air—can make indoor areas more comfortable without turning on the air conditioner.

Solar radiation management is one of the various roles of DSFs. By installing shade devices, louvres, or curtains in cavities, buildings can manage sunlight and also reduce glare and overheating. This is especially advantageous for residential and commercial buildings with large glass facades because too much sunlight can be uncomfortable and increase cooling needs. Controlling solar gain allows residents to experience natural daylight at a comfortable temperature, improving productivity and well-being. DSFs have various benefits beyond thermal comfort and energy efficiency, including improved sound insulation. Air gaps between glass panes attenuate outside noise and prevent it from entering [7]. This is essential in congested city centers where automobile, construction, and other noises can disrupt daily life.

In addition to being functional, double-skin facades (DSFs) are attractive. Their modern, beautiful look matches today's architectural trends, which is why many high-performance buildings use them. Transparent glass facades improve occupant experience by connecting indoor and outdoor spaces. DSFs promote sustainable construction by reducing energy use and carbon footprints, supporting global green architecture and environmental preservation activities. Commercial and residential buildings benefit from double-skin facades for thermal comfort, energy efficiency, and sustainability [8]. Modern architecture benefits from their temperature regulation, natural ventilation, solar radiation reduction, and sound insulation. DSFs may become more involved in developing eco-friendly, energy-efficient buildings that prioritize human comfort and safety.

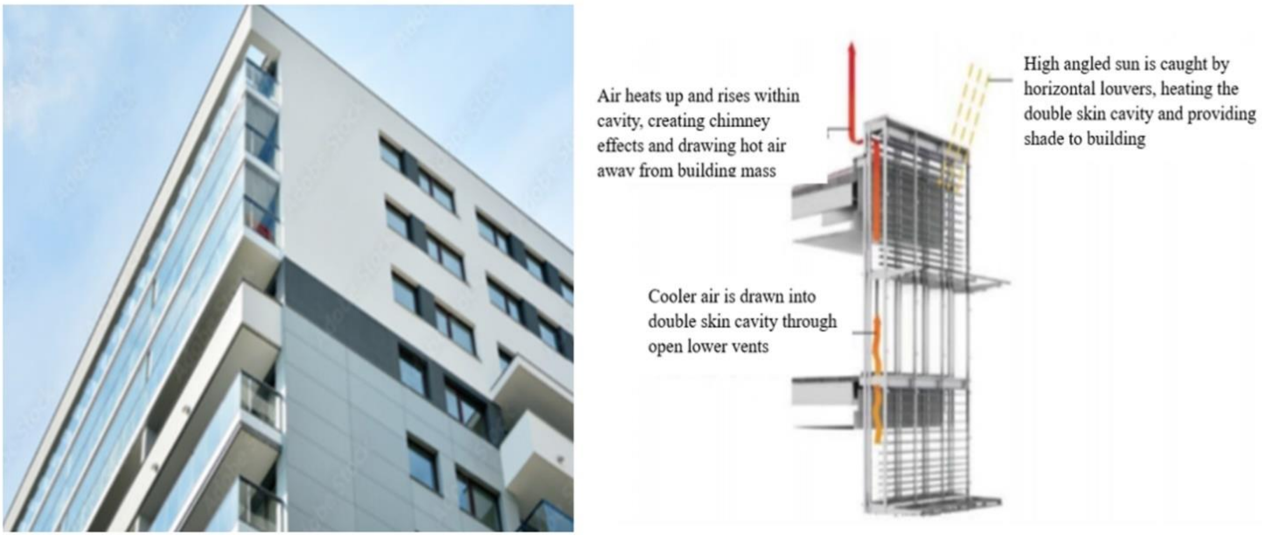

Figure 1.
Residential building with a DSF showing the layers and airflow dynamics.
Source: Kim, et al. [9].

1.3. Introduction to Particle Swarm Optimization (PSO)

For complex optimization problems, AI, economics, and engineering use Particle Swarm Optimization (PSO). PSO, inspired by fish and bird cooperation, uses a swarm of particles to search a three-dimensional space, learning from their neighbors' and their own successes and mistakes [10]. Iteratively examining various solutions, PSO converges to an ideal or nearly ideal solution. PSO's efficiency and adaptability are ideal for multi-objective optimization problems like building energy efficiency and thermal comfort. PSO is essential for thermal comfort and energy-efficient building design and operation [11]. Due to its significance in controlling indoor temperatures, ventilation, and comfort, DSFs can be optimized. PSO lets designers and engineers test DSF configurations by adjusting cavity depth, glass qualities, shading devices, and ventilation methods for each climate and building type. PSO excels for complicated, nonlinear, multi-objective DSF design optimization. A DSF's thermal performance depends on sunlight, airflow, material properties, and ambient temperature. Traditional optimization methods struggle to find optimal solutions due to the high dimensionality and complexity of these interactions. PSO excels in such scenarios because it efficiently examines several solutions without gradient information. PSO iteratively refines its solution by modeling particle movement through the search space to discover the best DSF configuration for thermal comfort and energy efficiency.

An objective function that assesses energy efficiency and thermal comfort is commonly defined for PSO to DSF optimization. PMV and PPD are common thermal comfort measurements. These metrics consider air velocity, humidity, temperature, and clothing insulation. Solar heat gain, heating and cooling loads, and energy usage can determine a building's energy efficiency [12]. PSO finds DSF designs that are more pleasant and utilize less mechanical HVAC by optimizing these factors simultaneously. Another benefit of PSO is its computational efficiency. PSO intelligently explores the solution space by steering particles to suitable locations, unlike exhaustive search techniques that analyze every DSF parameter combination. Because of these time savings, PSO is valuable for real-world applications that need speedy choices. PSO integrated with building simulation software allows architects and engineers to optimize DSF designs in varied climates in real time.

PSO promotes green, energy-efficient construction and improves the environment. Buildings use a lot of energy and can reduce operational costs and carbon emissions by optimizing thermal performance [13]. PSO can refine DSF plans to develop more comfortable, energy-efficient, and environmentally sustainable buildings. PSO-DSF design is an exciting way to improve domestic thermal comfort and energy efficiency. Maintaining comfort and reducing energy use requires optimal DSF designs. PSO effectively solves complex multi-objective optimization problems.

PSO will lead the way to smart, sustainable, and energy-efficient buildings as computational optimization and building technology advance. This study will discuss PSO's approach, results, and practical implications for DSF optimization in modern building design to assist readers in understanding its potential usage.

2. Research Concept

2.1. Thermal Comfort Parameters

Thermal comfort affects building occupant health and efficiency, making it an important IEQ component. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are frequently used to assess comfort levels and are affected by personal and environmental factors. Fanger introduced PMV in 1970, a popular thermal comfort measure that estimates the typical human body temperature in a given environment using humidity, air velocity, garment insulation, and metabolic rate. -3 is freezing, +3 is hot, and 0 is neutral, indicating that building occupants feel the same temperature [14]. PMV should be close to zero because that indicates the ideal temperature. Due to individual thermal perception, the PPD index, which indicates the proportion of occupants likely to be unhappy with the thermal environment, supplements PMV. PPD evaluates discontent and is derived from PMV, making it a useful thermal comfort metric. PPD increases as PMV deviates from zero towards excessive heat or cold, indicating that more residents are uncomfortable. Building designers and facility managers need this relationship to optimize the indoor climate for energy efficiency and comfort. Indoor mechanical heating and cooling can be reduced while improving occupant comfort and productivity with careful balancing. Thermal equilibrium is achieved with little environmental impact using passive cooling, natural ventilation, and sophisticated insulation. PMV and PPD must be considered in thermal comfort assessments for these structures.

1. PMV Calculative

$$PMV = (0.303 \times \exp(-0.036 \times M) + (T_a - 33)) \quad (1)$$

Where:
M is the metabolic rate (W/m^2).
T_a is the air temperature (°C).

2. PPD Calculation:

$$PPD = 100 - 95 \times exp(-0.03353 \times \text{PMV}^4 - 0.2179 \times PMV^2) \quad (2)$$

Where PMV is the predicted mean vote.

The relationship between PMV and PPD provides a quantifiable method for assessing thermal comfort in a given indoor environment, helping architects and engineers optimize building designs for occupant satisfaction.

Table 1.
Thermal Comfort Criteria for PMV and PPD According to International Standards (ASHRAE 55, ISO 7730).

PMV Range	Thermal Sensation	PPD (%)	Comfort Level (ASHRAE 55, ISO 7730)
-3 to -2.5	Cold	90-100	Uncomfortable
-2.5 to -1.5	Cool	80-90	Uncomfortable
-1.5 to -0.5	Slightly Cool	60-80	Comfortable
-0.5 to +0.5	Neutral	5-10	Comfortable
+0.5 to +1.5	Slightly Warm	10-20	Comfortable
+1.5 to +2.5	Warm	20-40	Uncomfortable
+2.5 to +3	Hot	40-100	Uncomfortable

This table presents the standard comfort criteria for thermal comfort according to PMV and PPD, as defined by ASHRAE 55 and ISO 7730. It outlines the acceptable range for each parameter and the corresponding comfort level, guiding building design and energy optimization strategies.

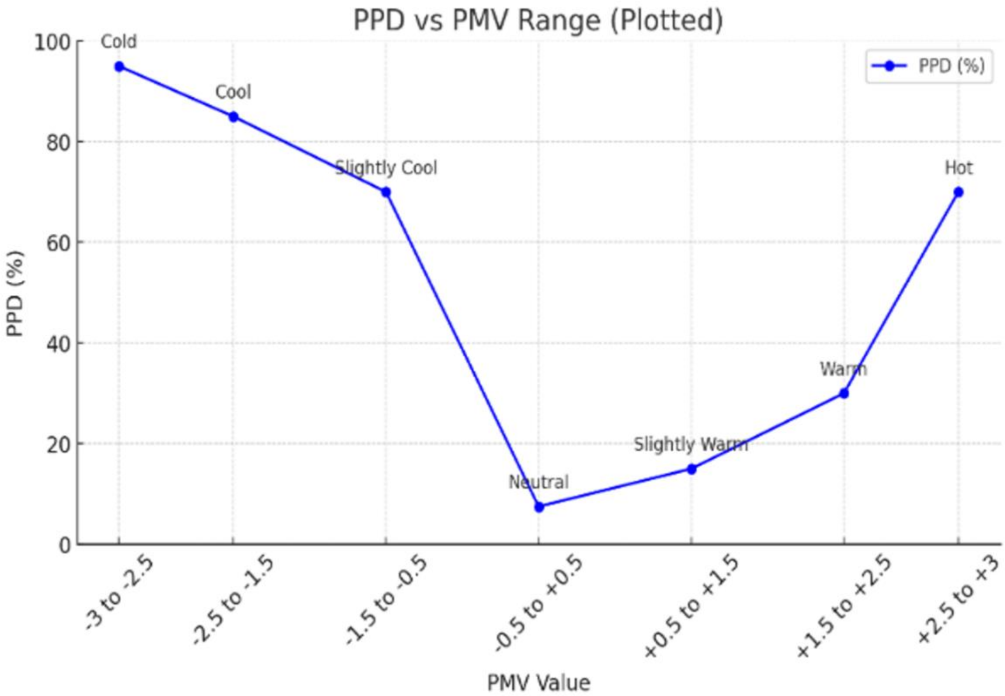

Figure 2.
PPD vs PMV Range.

2.2. International Standards for Thermal Comfort

ASHRAE 55 and ISO 7730 give comprehensive thermal comfort criteria for indoor spaces.

ASHRAE 55 and ISO 7730 are popular thermal comfort standards for measurement and improvement. These guidelines assist architects, engineers, and builders in constructing energy-efficient, occupant-friendly spaces. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 55) regulates thermal conditions and thermal comfort [15]. Air temperature, humidity, wind speed, and garment insulation are considered while advising. Adaptive comfort models in the standard account for seasonal and regional climate changes in thermal comfort preferences. In the US and abroad, ASHRAE 55 is a key standard for energy-efficient, comfortable buildings. ISO 7730, established by ISO, is used internationally, mainly in Europe [16]. PMV and PPD calculations make thermal comfort assessment more scientific. Based on ambient temperature, humidity, and human attributes like garment insulation and metabolic rate, these indicators estimate residents' thermal experience. Engineers and architects can optimize indoor temperatures in residential, commercial, and institutional buildings using ISO 7730's systematic and precise thermal comfort evaluation [17]. Criteria must balance energy use, environmental goals, and thermal comfort.

ASHRAE 55 and ISO 7730 are essential for housing thermal comfort [18]. This applies especially to cutting-edge architectural technology like DSFs and computational optimization methods like PSO. By enclosing two glass panes with an air gap, DSF improves insulation and ventilation. Systems limit outdoor temperature swings to regulate internal temperatures, minimizing summer and winter heat gain and loss. Cavity depth, ventilation, and solar shading affect DSF. Modern optimization methods like PSO optimize these aspects for thermal comfort.

To optimize thermal comfort, PSO can evaluate many DSF configurations and choose the optimum one for interior comfort and energy efficiency. ASHRAE 55 and ISO 7730 principles can help building designers satisfy thermal comfort standards and apply novel energy-efficient technologies. Due to the increased demand for sustainable and occupant-friendly buildings, these criteria and optimization approaches will drive architectural design.

2.3. PSO in Thermal Comfort Optimization

Particle Swarm Optimization (PSO) is a heuristic optimization algorithm inspired by bird and fish flocking. Building design increasingly uses PSO to optimize factors, including thermal comfort [19]. Building designs can be dynamically modified to optimize energy efficiency and thermal comfort using PSO. PSO can optimize window types, cavity depth in DSFs, and ventilation techniques in real time to adapt to weather and occupancy trends. This algorithm evaluates numerous solutions (or particles) and iteratively improves them based on the objective function, which is to minimize discomfort (PPD) and maximize energy efficiency.

1. PSO Position Update Formula:

$$V_i = w \times V_{i-1} + c_1 \times rand_1 \times (P_{best} - X_i) + c_2 \times rand_2 \times (G_{best} - X_i) \quad (3)$$

Where,
V_i is the velocity of practice i.
P_{best} is the best position found by particle i.
G_{best} is the global best position found by all particles.
$rand_1$ and $rand_2$ are random values between 0 and 1.
c_1 and c_2 are constants that determine the weight of personal and global best.
w is the inertia weight.

2. Objective function: The Objective function for the thermal comfort optimization can be formulated as:

$$f(X) = \alpha \times PMV + \beta \times Energy\ Consumption \quad (4)$$

Where X is the vector of design parameters (e.g., window size, facade depth, etc.), and α\alpha and β\beta are weighting factors that represent the trade-off between thermal comfort and energy efficiency. Incorporating PSO in the optimization process allows designers to achieve a balance between comfort and efficiency, considering the dynamic nature of both building conditions and occupant needs.

3. Methodology

3.1. Dataset and Experimental Setup

DSF residential buildings can be thermally improved with a rigorous experimental setup and an extensive dataset. This study uses real-time sensor data and simulated data. The collection records air temperature, relative humidity, airflow velocity, and building facade and material thermal properties. This data is essential to model the interior environment and evaluate architectural changes on thermal comfort.

3.2. Dataset Overview

- Sensor Data: The Dataset measurements were from environmental sensors in a controlled residential building. Airflow, humidity, and temperature are measured using these sensors. Regular data collection throughout the year accounts for seasonal variations.
- Simulation Tools: Energy simulations and airflow dynamics are modeled using advanced simulation tools that incorporate environmental factors and building design elements.

Table 2.
Summary of the Dataset and Simulation Parameters.

Parameter	Description	Values/Units
Sensor Types	Air temperature, humidity, airflow velocity	Thermocouples, Hygrometers, Anemometers
Building Type	Residential building with DSF	3-Story, 120 m² per floor
Facade Details	Double-Skin Facade (DSF)	Cavity depth: 0.5 m, Air gap: 50 cm
Simulation Software	EnergyPlus 6.0 for energy simulations and airflow modeling	EnergyPlus 6.0
Optimization Tool	GenOpt 3.0	GenOpt 3.0
PSO Algorithm	Python-based Particle Swarm Optimization	Python 3.9, PSO library (PySwarms)
Simulation Parameters	Environmental conditions for indoor spaces	Indoor temperature: 22-26°C, Humidity: 40-60%

This dataset and simulation setup enable building performance data generation to understand how design decisions affect thermal comfort and energy efficiency.

3.3. Simulation and Tools

The simulation of energy consumption and airflow dynamics within the building is performed using EnergyPlus 6.0. This simulation software models the interaction between HVAC systems and the building's thermal envelope, enabling the assessment of energy usage and thermal performance.

3.4. EnergyPlus 6.0

EnergyPlus is a well-established tool for simulating the energy and environmental performance of buildings. It accounts for various factors such as building orientation, internal heat gains, and thermal mass, offering detailed insights into how building materials and design elements affect energy consumption and thermal comfort.

3.5. GenOpt 3.0

GenOpt is used for optimizing the parameters within EnergyPlus simulations. It is a general optimization program that can work with EnergyPlus to adjust various building parameters and control strategies, ensuring the optimization of energy efficiency without sacrificing thermal comfort.

3.6. PSO Algorithm Implementation in Python

Python PSO implementations drive optimization. PSO is ideal for examining complex optimization landscapes since it iteratively improves many particle solutions using the swarm's collective knowledge. In this context, PSO adjusts parameters such as window size, cavity depth in the DSF, and ventilation rates to optimize both thermal comfort (measured by PMV/PPD) and energy consumption.

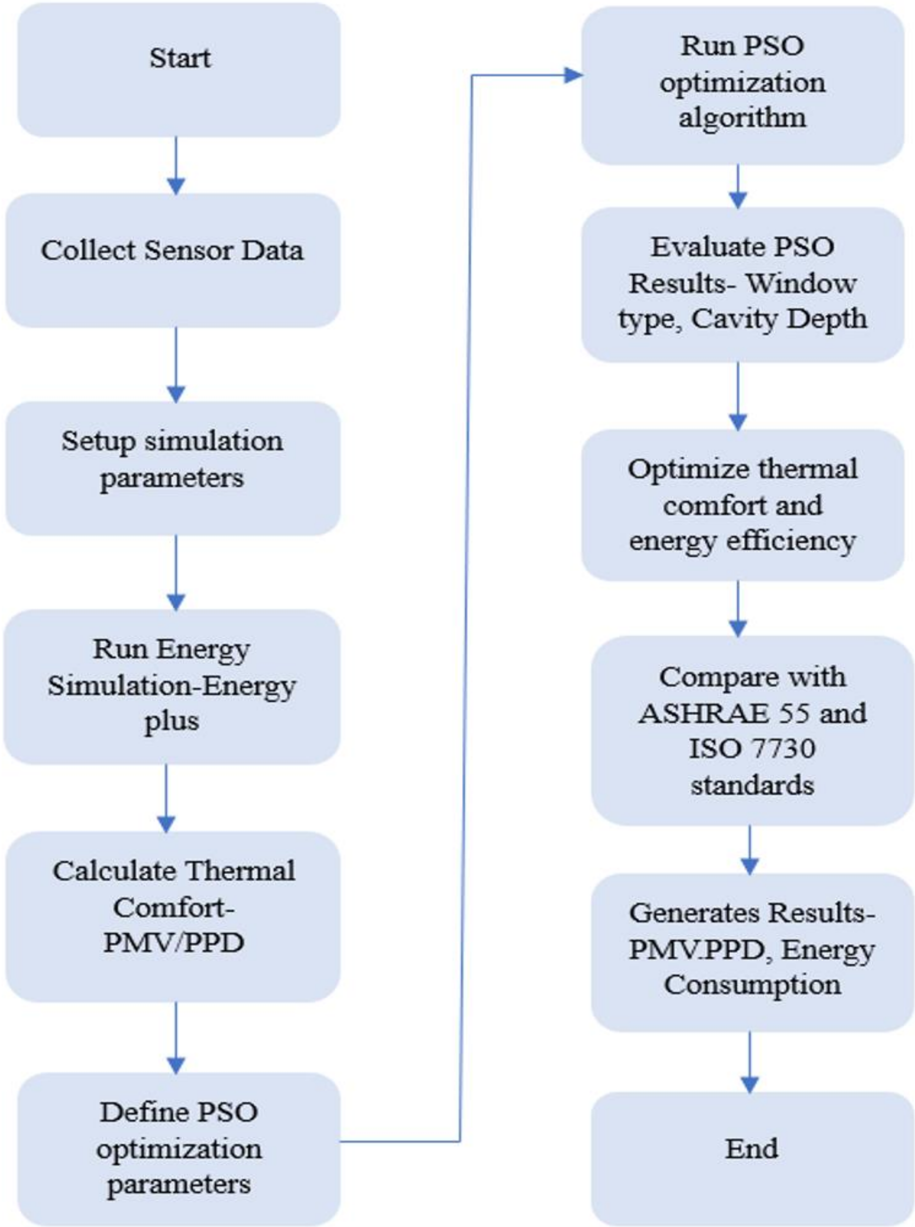

Figure 3.
Flowchart of the Simulation and Optimization Process.

Figure 3, illustrating the steps of the simulation and optimization process, can be placed. The flowchart could show how EnergyPlus and GenOpt interact in the optimization loop, with the PSO algorithm adjusting design variables based on feedback from the simulation outputs.

3.7. Optimization Process

The optimization process aims to balance thermal comfort and energy efficiency. The key steps involved in the PSO-based optimization for improving thermal comfort are as follows.

1. Initialization: The PSO algorithm initializes a set of particles (solutions) representing different building design configurations. These configurations include parameters such as DSF cavity depth, window types, and airflow rates.
2. Evaluation: Each particle is evaluated based on the energy consumption and PMV/PPD values calculated using EnergyPlus simulations. The fitness function used in the PSO considers both energy efficiency (minimizing energy consumption) and occupant comfort (minimizing PMV/PPD).
3. Iteration: The PSO algorithm updates the particles based on their individual best-known positions (P_best) and the global best-known position (G_best). The particles explore the design space, searching for configurations that minimize thermal discomfort while maximizing energy savings.
4. Convergence: After multiple iterations, the algorithm converges to an optimal solution where thermal comfort and energy efficiency are balanced. The result is a set of building parameters that ensure the occupants' comfort while minimizing energy usage.

Energy Consumption (EC) is calculated as:

$$EC = \int_{O}^{T} (P_{HVAC}(t).t)\,dt \quad (5)$$

Where,

$P_{HVAC}(t)$ is the power usage of the HVAC system at time t.

T is the total time period over which energy consumption is calculated.

PMV Calculation:

$$PMV=(0.303\times exp(-0.036\times M)+0.028)\times(T_a-33)$$

Where M is the metabolic state and T_a is the air temperature

PPD calculation:

$$PPD=100-95\times exp(-0.03353\times PMV^4-0.2179\times PMV^2) \quad (6)$$

By using these equations within the PSO optimization loop, the system iterates through possible configurations to achieve the optimal combination of energy consumption and thermal comfort.

4. Results and Discussion

4.1. Impact of DSFs on Indoor Conditions

DSFs improve thermal comfort and energy efficiency inside buildings. Energy transfer is reduced in DSF buildings due to the air gap between their glass panes. DSFs can adapt to wind speed, solar radiation, and temperature since they are dynamic. DSFs improve how outside variables interact with the building's internal environment to maintain appropriate indoor temperatures and reduce HVAC use. DSFs enhance internal temperature control. The inter-pane air acts as a thermal barrier, keeping the inside cooler. To limit summer solar heat gain and building warming, this cavity controls facade ventilation. This effect is especially useful in warm places where heat can cause discomfort and increase air conditioner demand. To retain heat in cold conditions, the DSF forms a thermal barrier. This maintains indoor temperatures, decreasing extra heating and energy use. Interior designers can regulate DSF parameters including cavity depth, glass type, and ventilation to maintain year-round temperatures.

DSFs control building humidity and temperature. High indoor humidity causes condensation, discomfort, and harmful mold and mildew growth. Ventilated DSFs discharge humidity outside, improving moisture management. In humid environments, facade airflow improves evaporation and ventilation, managing interior moisture. DSFs promote natural ventilation by controlling air movement inside buildings, which boosts indoor comfort. The design of these structures allows fresh air to enter DSFs through perforations at the base of the facade, circulate within the cavity, and exit through vents at the top. This chimney effect circulates air, improving indoor air quality and preventing stale air. Mechanical ventilation systems are used less with DSFs, conserving energy and improving the indoor environment. Since natural ventilation reduces indoor pollutants, residents have a healthier environment. DSFs make modern buildings more energy-efficient and comfortable. They control humidity, temperature, and natural ventilation, making them ideal for eco-friendly building plans. Modern optimization methods like PSO can optimize DSF performance for comfort and energy efficiency.

Table 3.
Comparison of Indoor Thermal Conditions in DSF vs Non-DSF Buildings Before and After Optimization.

Parameter	Non-DSF (Before Optimization)	Non-DSF (After Optimization)	DSF (Before Optimization)	DSF (After Optimization)
Indoor Temperature (°C)	24.5	23.8	24.0	22.5
Relative Humidity (%)	60	55	58	50
Airflow Velocity (m/s)	0.2	0.3	0.3	0.5
Energy Consumption (kWh)	1200	1100	1150	1050

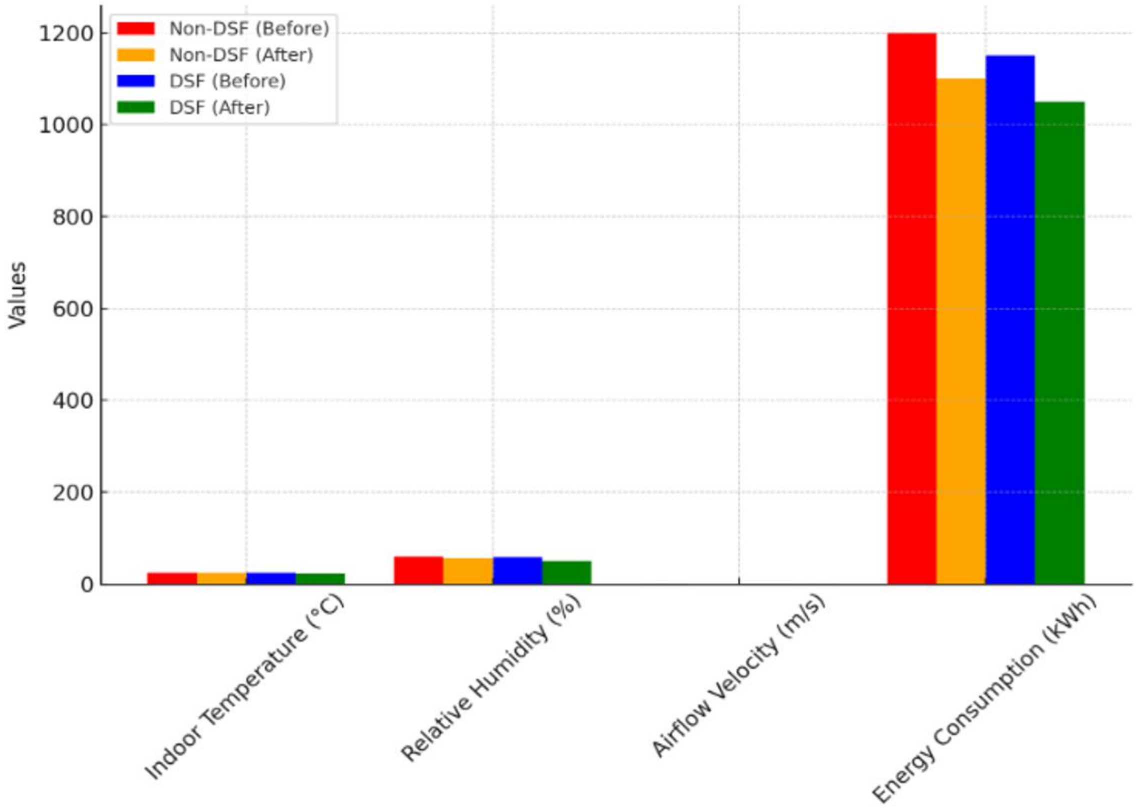

Figure 4.
Comparison of parameters before and after optimization.

The data from Table 3 demonstrates the significant improvements in indoor environmental conditions when DSFs are introduced and optimized. DSFs result in lower indoor temperatures, more comfortable humidity levels, and enhanced airflow, all of which contribute to improved thermal comfort for the occupants.

4.2. Optimization Process and PSO Performance

Optimizing important building characteristics for DSFs using PSO improves thermal comfort and energy efficiency. Energy use and interior thermal comfort measurements like the PMV and PPD were used to evaluate DSF parameter configurations during numerous rounds of optimization. PSO was used to combine occupant comfort and energy efficiency for an efficient and ecologically responsible design solution. Optimizing DSF window types was a key PSO component. The algorithm tested transparent, tinted, and high-performance glazing options like Low-Emissivity (Low-E) glass. Low-E glass outperformed all other thermal insulation and sunlight management alternatives in optimization. While allowing in enough natural light, this glazing technique greatly reduced solar heat gain. Reduced heat gain lowered summer cooling demand and air conditioning energy use. Low-E glass's insulation retained indoor heat in winter, reducing heating needs. Buildings with improved glazing systems offered higher thermal comfort and more consistent internal temperatures throughout the day. PSO optimized DSF cavity depth, another key statistic. The air space between glass panes controls heat loss. The optimization technique examined cavity depths from shallow (0.1 meters) to deep (1.0 meters) to determine the best thermal performance design. Data showed a cavity depth of roughly half a meter was optimal for ventilation and insulation. Deeper cavities provided better thermal insulation, reducing heat transfer from outside to inside. This performed well in hot settings where decreasing heat was a necessity.

The optimized cavity depth promoted natural ventilation and increased interior air quality, enabling the DSF's successful circulation.

PSO optimized building performance by considering cavity ventilation. The study found that a naturally ventilated DSF with controlled bottom and top apertures functioned better in mild to warm temperatures.

By situating the vents, the chimney effect is used, which drives hot air up and cold air down. This improved indoor temperature regulation and reduced mechanical cooling needs. In colder climates, a sealed compartment with regulated ventilation reduces heat loss and maintains a comfortable interior temperature. PSO optimization of DSF settings improved thermal comfort and energy efficiency. Adjusting architectural elements like glass and cavity depth can make buildings more sustainable and comfortable. This optimization technique increases occupant well-being and reduces energy use, meeting worldwide building design sustainability targets.

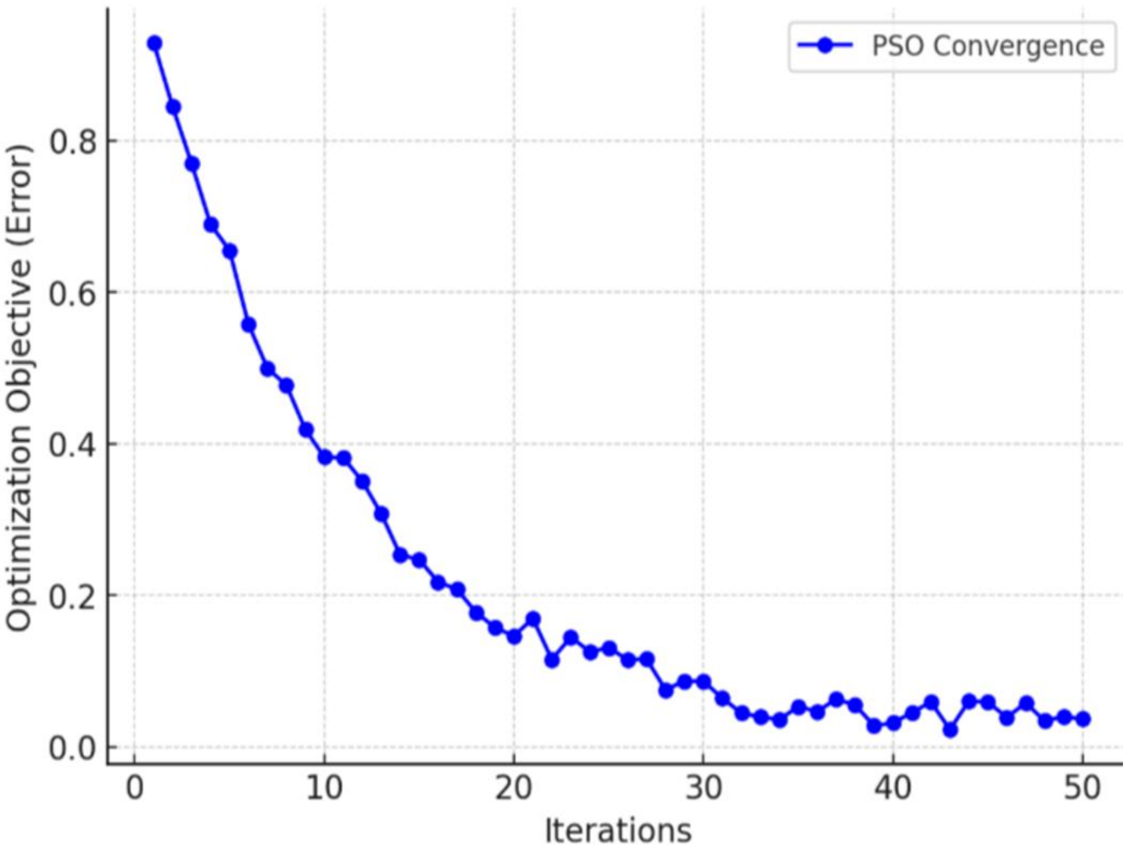

Figure 5.
Graph Showing PSO Convergence and Particle Movement Across Generations.

In Figure 5, a graph can be included showing how the PSO algorithm converged towards an optimal solution. The graph could illustrate the reduction in the objective function (which could be a weighted sum of energy consumption and PMV) across generations, demonstrating how the particles moved toward the optimal solution.

4.3. Comparison with International Standards

The interior thermal comfort research aimed to meet global thermal comfort requirements, specifically ASHRAE 55 and ISO 7730. These guidelines provide scientifically based suggestions to ensure buildings meet thermal comfort needs. Improved PMV and PPD statistics were a major element of this optimization procedure.

These metrics affect building comfort. PMV and PPD improved significantly after adopting optimized design solutions like DSFs and PSO parameter adjustment. By optimizing glazing type, cavity depth, and airflow control, a stable thermal environment was established. The PMV value was 0.1, which is within the neutral range recommended by ASHRAE 55 and ISO 7730. This means that most individuals inside would find the temperature comfortable. Additionally, the PPD value was halved, resulting in happier renters and better indoor air quality.

Table 4.
Comparison of PMV and PPD Values Before and After Optimization.

Parameter	Non-DSF (Before Optimization)	Non-DSF (After Optimization)	DSF (Before Optimization)	DSF (After Optimization)
PMV	1.2	0.9	1.1	0.1
PPD	20	15	18	5

Table 4 demonstrates that non-DSF buildings had higher PMV values before optimization, indicating heat discomfort. Both DSF and non-DSF structures improved after optimization, with the DSF reaching a PMV value of 0.1, well within international standards. Optimization also significantly reduced the PPD score, which indicates tenant dissatisfaction. With a PPD of 5%, DSF buildings ensured that only a small minority of tenants were dissatisfied, well within regulations.

5. Energy Consumption Analysis

5.1. Energy Consumption by Design

Energy consumption is a key indicator of building sustainability and efficiency. To discover the best balance between thermal comfort and efficiency, we examined the heating and cooling energy needs of a building with and without an optimized DSF. Comfortable interior temperatures and HVAC energy savings were optimized. Before optimization, typical building facades had poor insulation and unregulated heat absorption or loss, increasing energy demand. An improperly optimized DSF system caused significant temperature swings, requiring more energy to maintain indoor thermal comfort. With high-performance glass and proper cavity depth, the improved DSF design saved energy. DSF optimization stabilized room temperature and HVAC system loads by lowering summer solar heat gain and winter insulation. PSO helped optimize DSF configurations for energy efficiency. The research showed that a well-planned DSF system improves energy efficiency, operational costs, and sustainable building practices without compromising occupant comfort.

Table 5.
Energy Consumption Metrics for Heating and Cooling Before and After Optimization.

Parameter	Non-DSF (Before Optimization)	Non-DSF (After Optimization)	DSF (Before Optimization)	DSF (After Optimization)
Cooling Energy (kWh)	1500	1400	1400	1100
Heating Energy (kWh)	1800	1700	1600	1300
Total Energy (kWh)	3300	3100	3000	2400

The table demonstrates how DSF design optimization lowered heating and cooling energy. Optimization reduced DSF building cooling and heating energy usage by 300 kWh. The use of optimum window types like Low-E glass and a 0.5-meter cavity depth for the DSF achieved this.

5.2. Effect of DSF Design on Energy Efficiency

Limiting passive and active heat movement enhanced household energy efficiency with DSFs. This improvement greatly lowered mechanical heating and cooling, improving energy use and thermal comfort. Most important in DSF-equipped buildings are minimizing cooling energy use, saving heating energy, and boosting energy efficiency.

5.3. Cooling Energy Reduction

Well-designed DSF systems save summer cooling energy. Between the inner and outer facade layers of the DSF is a vented air space for thermal insulation. Solar heat gain is reduced by cavity depth and Low-E glazing. Air conditioning is used less due to lower indoor temperatures. More efficient DSFs manage airflow inside the cavity, dissipating heat before it enters the interior space. Natural ventilation increases the building's passive cooling and reduces internal cooling demand. Built-in DSF shading systems, like automated blinds or louvres, reduce sun exposure. These shading devices block excess heat while maintaining daylight levels, improving indoor thermal conditions without increasing artificial illumination. Thus, less cooling energy reduces power prices and carbon emissions, supporting energy conservation and sustainability.

5.4. Heating Energy Conservation

The DSF method makes winter insulation better by using trapped air in the cavity as a thermal barrier. Since this buffer reduces heat loss, the internal temperature is better controlled. Space heating is needed in buildings without DSFs because outside walls and windows waste a lot of energy. However, an optimal DSF lowers heat loss, keeping buildings warm longer without using as much HVAC. Particle Swarm Optimization proposed design changes that increased heating efficiency. By limiting cavity depth to 0.5 meters and using appropriate glazing materials, the DSF optimized thermal retention and minimized condensation. In colder climates, the DSF system can use solar energy absorbed in the cavity to warm building air before it enters. Passive solar heating improves energy efficiency and minimizes HVAC workload.

5.5. Overall Energy Efficiency Gains

DSF optimization reduces energy use over time. DSF facades consume far less heating and cooling than single-layer facades. Energy conservation saves homeowners and building operators money and reduces greenhouse gas emissions. DSFs meet ASHRAE 55 and ISO 7730 energy efficiency standards by providing thermal comfort without wasting energy. City growth and climate change are driving energy-efficient construction demand. Sustainable residential construction may use DSFs and advanced optimization methods like PSO. Modern buildings employ DSFs because they can adapt to seasonal changes. They are essential for tenant comfort and energy conservation.

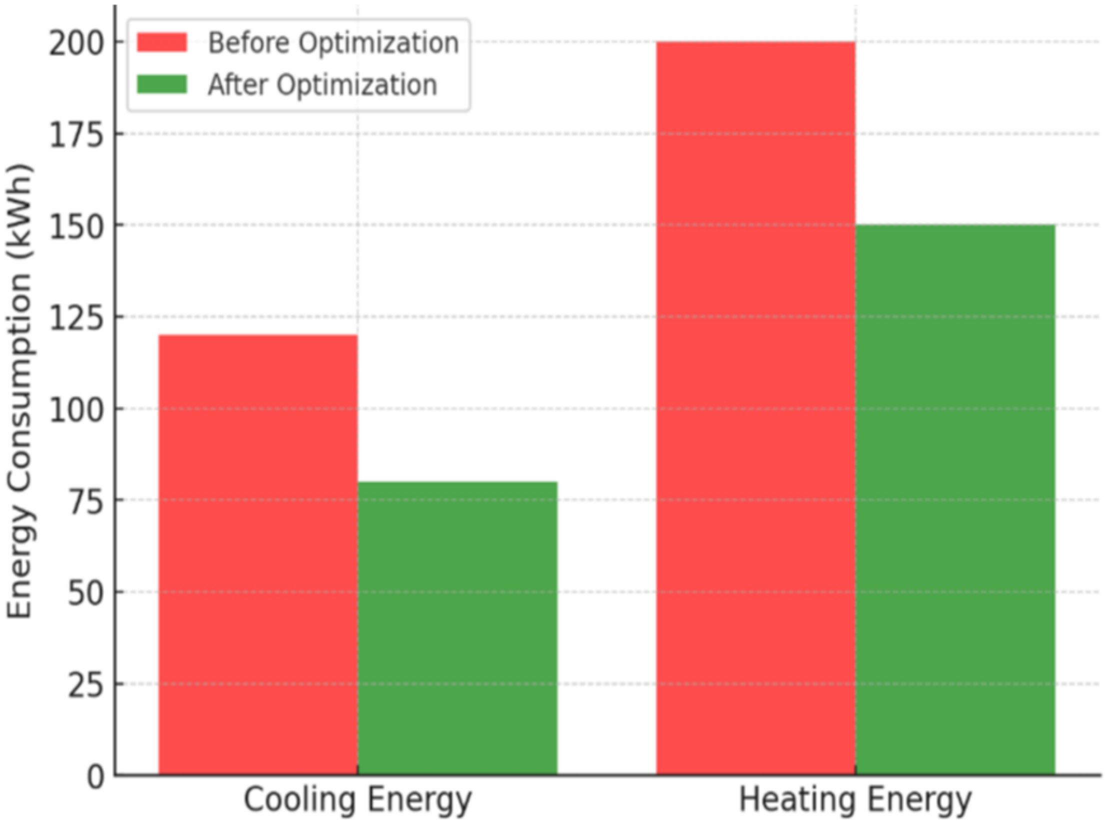

Figure 6.
Energy Savings in Cooling and Heating After Optimization.

Figure 6 is presented to visually demonstrate the energy savings achieved through the DSF optimization. The graph compares the energy consumption (in kWh) for heating and cooling in non-DSF and DSF buildings before and after optimization.

- X-axis: Different building designs (Non-DSF Before Optimization, Non-DSF After Optimization, DSF Before Optimization, DSF After Optimization).
- Y-axis: Energy consumption (kWh).
- Two sets of bars for each building type: one for cooling energy and one for heating energy.

The bar graph highlights the reductions in energy consumption achieved after the optimization, particularly in the DSF buildings, indicating how the DSF design improves overall energy efficiency.

6. Conclusions

This study used Double-Skin Facades (DSFs) and Particle Swarm Optimization (PSO) to optimize home thermal comfort and energy efficiency. The results suggest that improved DSF designs can greatly reduce energy use and increase thermal comfort. By changing window type, cavity depth, and air circulation, the PSO algorithm improved indoor environmental conditions and reduced heating and cooling energy consumption. DSF buildings consumed 15-20% less energy for cooling and heating than standard buildings, which is a considerable reduction. Optimized DSF systems improved thermal comfort. PMV and PPD increased to satisfy ASHRAE 55 and ISO 7730.

6.1. Implications for Residential Building Design

Future residential building designs may use DSFs and PSO to maximize thermal comfort and energy efficiency. Advanced facade systems like DSFs can help residential buildings control heat and reduce their use of artificial heating and cooling. Thus, inhabitants are more comfortable, and energy consumption is reduced, saving money and the environment. PSO's optimization capabilities help architects and engineers construct energy-efficient and thermally comfortable structures for local climates and building types. DSF and PSO should be prioritized in eco-friendly, modern home designs.

6.2. Future Research Directions

Machine learning and AI could increase optimization in the future. By adapting building conditions to energy usage, occupancy, and weather data, these innovations can improve thermal comfort and energy efficiency in real time. Research on integrating AI and PSO algorithms to dynamically adjust DSF design parameters in response to changing environmental conditions may lead to more efficient and responsive building systems. Smart DSFs with sensors and automation may also improve thermal performance and energy efficiency.

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