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Enhancing building energy system design using computational intelligence for smart buildings

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Abstract
Building Energy (BE) use, representing around one-third of global energy usage, can be substantially diminished by implementing adaptable façades. This paper proposes a computational optimization method to improve the energy efficiency of buildings through the design of an adaptable façade structure capable of adjusting its thermal and visual transmittance in response to fluctuating climatic circumstances. The core of the adaptable façade design methodology is an automated optimizing procedure that integrates the BE simulation tool (Energy-Plus) with a strategy for optimization. This work utilizes a modified firefly method, an internal optimizing tool, to create an adaptable façade system. The suggested approach is not contingent upon any specific optimization tool and does not put limitations on the type of structure. The efficacy of the proposed strategy for improving BE usage is substantiated through two instances: a standard single office space and a medium-sized workplace. Compared to static facades, the suggested adaptable façade technology significantly decreases energy usage in both the first and second case studies. These notable results illustrate adaptable exteriors' capacity to improve structures' energy usage.

Keywords – Building, Energy System, Computational Intelligence, Architecture

1. Introduction

Energy systems in structures are essential for ensuring a comfortable indoor atmosphere. High Voltage Alternative Current (HVAC) systems utilize almost 45% of Building Energy (BE) [1,2]. A system's energy efficiency is largely contingent upon the quality of its design. Traditional design of HVAC systems practices are inefficient due to the necessity to manually resolve extensive arduous and repetitive tasks, such as ducting and piping layout. Intricate optimization analyses to enhance system efficiency are conducted solely due to the team's capacity constraints. Researchers have exerted considerable effort for decades to discover technologies that facilitate or simplify the HVAC design procedure. Computational Intelligence (CI) has significantly advanced the building industries by creating automatic space layouts, efficient construction administration, and identifying issues in building electrical systems [21]. CI refers to computational frameworks capable of learning particular duties from data or observations from experiments.

In contrast to human empirical practices and mindsets, CI exhibits greater creativity and productivity when designing machines. Advanced techniques such as generative layout and genetic algorithms demonstrate significant promise in enhancing design effectiveness and quality [4]. Increasingly, research endeavors seek to implement computational intelligence to enhance and improve HVAC systems.[3].This study aims to thoroughly examine the application of CI methods in the HVAC design phase and offer practical guidance on conducting optimization design to enhance the efficiency of building HVAC systems.

Multiple approaches have been suggested to enhance the façade structure of Net Zero Electricity Buildings (NZEB), categorized under two prevalent concepts [5]. The initial technique entails the implementation of shading mechanisms to diminish solar heat gain using a façade system. Gao et al. suggested a sun-tracking photovoltaic shade element that decreases annual electricity production while enhancing glare avoidance. The second technique examines the impact of thermal transparency (U-value) or thermal resistivity (R-value) of façade solutions on energy effectiveness.[12]. Yu et al. reviewed the influence of U-value on the energy used by structures with varying thermal capacities [6]. They determined that thermal mass influences energy consumption and U-value measurements in distinct ways. The two systems aim to minimize energy consumption for heating, ventilation, and cooling in structures. Minimizing solar heat gain through blinds or substances with low thermal transparency influences the visual enjoyment of building residents, which relates to the clarity and brightness of sunlight [7]. The fluctuations in environmental circumstances (e.g., sunrise, air circulation, solar heat gain) present considerable obstacles to developing an efficient façade structure for NZEB. The energy efficiency of façade solutions is influenced by meteorological and external factors, which impede their implementation for NZEB.

The research employs Energy-Plus to assess the energy use of structures in this research. The study presents a novel computational optimization method to combine Energy-Plus with optimization methods to develop an adaptable façade solution that accommodates dynamic climatic variations.[14]. The adaptable façade system can substantially decrease the overall power usage of structures.

2. **Related Works**

An Adaptable Façade (AF) is an architectural envelope capable of often altering its functions (e.g., thermal, architectural) over time by climatic variations, daily cycles, or seasonal changes to minimize a structure's energy use [8]. This review identifies two primary research avenues for AF. The initial approach pertains to façade systems featuring active components that function by manipulating movable elements within a rotating framework. Odiyur Vathanam et al. suggested an intelligent kinetic shade device that adjusts its entrance angle via a sensor-driven computer-controlled mechanism [23]. AF can decrease the energy usage of an analogous building by 15-25%. Li et al. evaluated and contrasted the axial and translational dynamics of hexagon façade designs [10]. Their findings indicated that the suggested façade enhanced daylight penetration from 35% to 55% relative to the stationary façade design via rotational movement.

The second path emphasizes the utilization of flexible substances in AF, which can alter their mechanical characteristics (e.g., U-value) in reaction to fluctuating environmental circumstances. Photochromic and thermochromic screens alter their characteristics in response to solar energy and temperature variations [11]. Electrochromic screens can modify their attributes by applying and regulating a minor voltage, representing a more dynamic and manageable approach.[9].

The efficacy of photochromic and thermochromic screens has been demonstrated in multiple investigations. Al-Qahtani et al. created an economical photochromic screen capable of decreasing visible light and solar absorption by 20-70% and 10-30%, respectively, compared to standard glass [24]. Liu et al. introduced the perovskite thermochromic window designed for enhanced solar modification, a reduced transition temperature, and elevated luminous penetration [13]. Aburas et al. indicated that various thermochromic frames decreased BE use and enhanced perceived value relative to conventional clear double-glazed frames [26]. Electrochromic panes have garnered greater interest than passive-adaptable panes due to their management. Lee et al. executed a comprehensive outdoor experiment to assess the efficacy of an electrochromic door, manipulating the Solar Heating Gain Factor (SHGC) and visual transparency (Tvis) by utilizing a modest voltage of 2-5 Volts [15]. The electrochromic screen is separated into three zones, with controlled Tvis for all three. Chen et al. observed that a space equipped with the electrochromic screen decreased energy usage by 50% relative to a reference room featuring a conventional low-emittance screen [16]. Detsi et al. examined a control method for the electrochromic panels of the structure in Brussels [17]. They demonstrated that the yearly energy usage of a floor fitted with electrochromic windows decreased by nearly 75%. Suzuki et al. developed an optimal control for electrochromic windows to improve the thermal performance of a business structure across different environments [18].

Literature indicates that AF devices have positively influenced the overall energy usage of structures. However, forecasting the energy usage in the structure during the operational phase of AF systems entails intricate and nonlinear challenges arising from either the alteration of the façade system structure through dynamic obscuring device control or modifications to the material characteristics of glazing [19]. The AF procedure must accurately depict a series of temporally variable phases aligned with climatic circumstances.[20]. This indicates that the state of AF, including the arrangement of controlling elements or material characteristics, must constantly change to effectively accommodate various situations and consider short-term heat exchange and energy storage impacts in structures. The efficacy of the AF is predominantly contingent upon its suited condition during the operational phase, necessitating meticulous design to get the intended efficiency [25]. The selection of substances for electrochromic screens necessitates a prior understanding of the temporal variations in substance characteristics related to temperature information. This complex undertaking remains challenging due to the absence of a dependable computerized design methodology.

3. Method

A smart building, be it an office, residence, industrial facility, or recreational space, offers residents tailored services through its understanding of the embedded items. The built landscape influences the standard of life and work for all individuals; buildings should minimize energy usage and enhance occupancy and production. Installations of sensors and actuators must be managed to ensure that the economic advantages of energy reduction offset the associated costs. Managing the entirety of an enormous building is not possible or practical. Actual sensor information regarding these inputs ought to be incorporated into the ultimate energy control structure alongside the activity trends derived from data collection. The gadget will adapt to alterations in the building environment and novel circumstances not accounted for in the original designs. The design consists of three sufficiently general levels to accommodate the requirements of diverse, intelligent settings, including those relevant to innovative structures. Figure 1 illustrates the three-layer architecture of a creative structure.

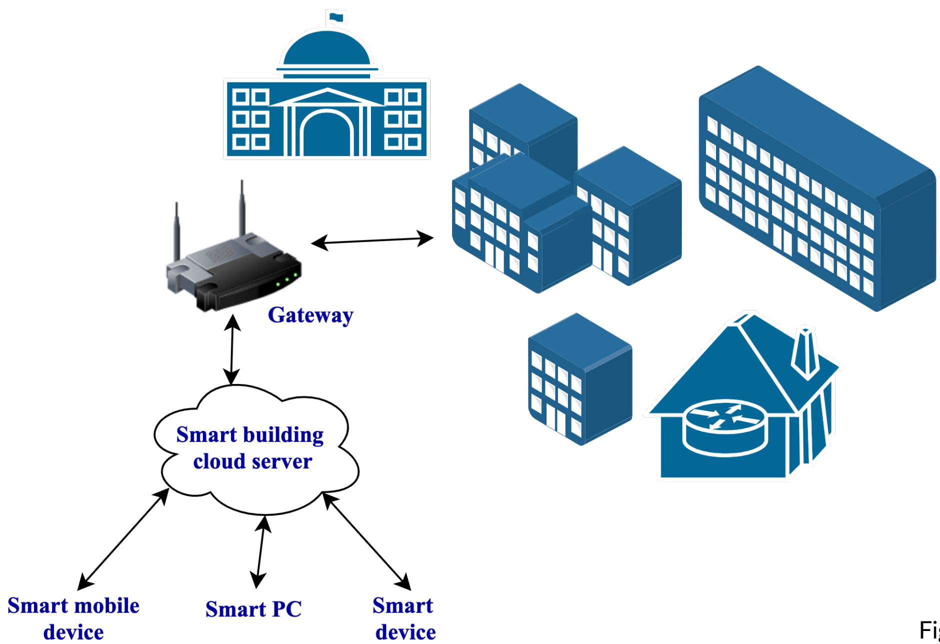

Figure 1. Smart architecture

The Data Sensitivity Layer is responsible for collecting data from devices. The information encompasses customers' requirements for appliance operational parameters, including moisture and temperature. The information is saved in a specialized cloud through a network bridge.

The Data Processor layer manages and handles the collected material. Consumer data is necessary for comfort-related concerns, including the HVAC structure, illumination, and temperature control.

The Data Replication or Application Stage involves replicating processed details, reflecting the relationships among occupants and technology in the third level. The collected data is utilized to enhance device efficacy and efficiency. It facilitates the provision of superior services to the citizens.

The proliferation of extensive data generated by cloud-based computing, Computer Systems, and new technologies in the last decade has been accompanied by increased IoT device production and shrinking. Such knowledge, devoid of analytical capability, is ineffectual in any domain.

Gathering data and making decisions necessitates concentrated efforts at several levels, rendering "Big Data Analytics (BDA)" an ever-more complicated domain. Various analytical tools have enabled individuals to gather valuable information. BDA is construed as such in specific contexts. The era of intelligent architecture has arrived, producing millions of information points through sensors embedded in advanced technologies. A structure incorporating sensors to monitor temperature, motion, sunlight, and moisture has been devised to improve building upkeep and render structures 'smart' and efficient. The client can ascertain if any individual in the residence could offer a "safe" interpretation based on the evaluated data from the internet-based service gathered by the movement sensor. A voltage regulator will ensure the attached cloud server operates smoothly without issues. Both individuals can effortlessly join a network via their mobile device services via the structure's Wi-Fi network.

Intelligent gadgets enable individuals to enhance building safety by installing sensors to monitor the environment, accessible via a mobile phone or gadget when required. The cameras are integrated with other innovative technologies to properly track the facility based on occupancy levels. Inhabitants will utilize their mobile or smart devices to interact with the safeguarding systems. The protective mechanism is accessible with the building's electric lighting, alerts, notifications, and the police department. The defense mechanism activates upon detecting irregular activity or criminals. This intelligent protection is significantly more trustworthy and proficient than the standard system provided to homeowners for the successful and productive use of gadgets.

3.1 Genetic Algorithm (GA)

GA is a metaheuristic derived from the principles of selective breeding. This technology is widely utilized to produce excellent solutions for optimizing and searching for challenges in the construction sector. Developing HVAC systems typically entails selecting from various alternatives within defined limits to guarantee the system achieves its intended efficiency. An engineer seldom has the opportunity to seek the universal optimum and typically employs a heuristic approach. The concept of organic evolution aptly exemplifies genetic algorithms. A group of persons, generally depicted as points inside the search area, is arbitrarily started and thereafter undergoes evolution; those with superior fitness possess the greatest likelihood of survival. The person is an alternate solution characterized by several qualities denoted by chromosomes, typically formatted as binary integers. The chromosomes can be modified and manipulated using specific operators. GAs possess two evolutionary operators: mutations and crossovers. Crossover, influenced by nature, entails the alteration of two selected at random genomes to generate another person known as progeny. The mutation operation entails creating alterations in an allele to preserve genetic variety. It is comparable to biological mutations. A person's choice uses a cost/fitness criterion that evaluates its efficacy. The solution exhibiting the best fitness will likely be chosen for the next generation. Figure 2 depicts the architecture of a singular population genetic algorithm.

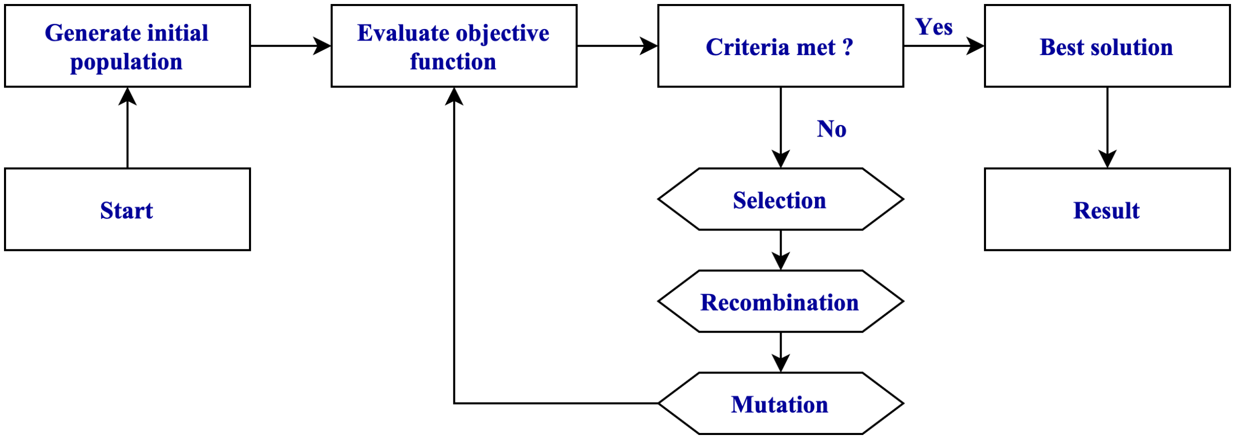

Figure 2. Workflow of the GA model for optimization

3.2 Optimization process

This study examines CI technologies that facilitate the design processes. A multitude of methods and tools have been devised and constructed. Most of these techniques and instruments remain underutilized and ultimately disregarded. A primary reason for their challenging integration into traditional design practices is that formulating problems and characterizing design issues through a mathematical method necessitates advanced skills and expertise. Such abilities and expertise exceed the competencies of HVAC experts. The traditional design is executed in two-dimensional networks. Design data must be retrieved individually.[23].The extraction process is laborious and protracted. The limitations of operations to certain research domains account for the seldom application of approaches in HVAC design.

Building Information Modeling (BIM) has gained significant appeal in architectural design in the past few years. BIM is a computerized model of the attributes and capabilities of a building, comprising data in a standardized format that can be retrieved, transferred, or interconnected to facilitate decision-making concerning a building or other constructed resources. A particular standard structure systematically stores All building data in the BIM modeling. Extracting necessary data through automated computer systems is straightforward. Design modifications can be implemented with minimal effort. For instance, the diameter value can be modified to alter the duct dimension from 450 mm to 550 mm. The relevant diagram and illustration will be produced immediately. BIM facilitates the interaction between layout and execution. Considering BIM and the conventional methodology for optimizing issues outlined in the preceding section, a combined design and optimizing methodology was suggested, as seen in Figure 3.

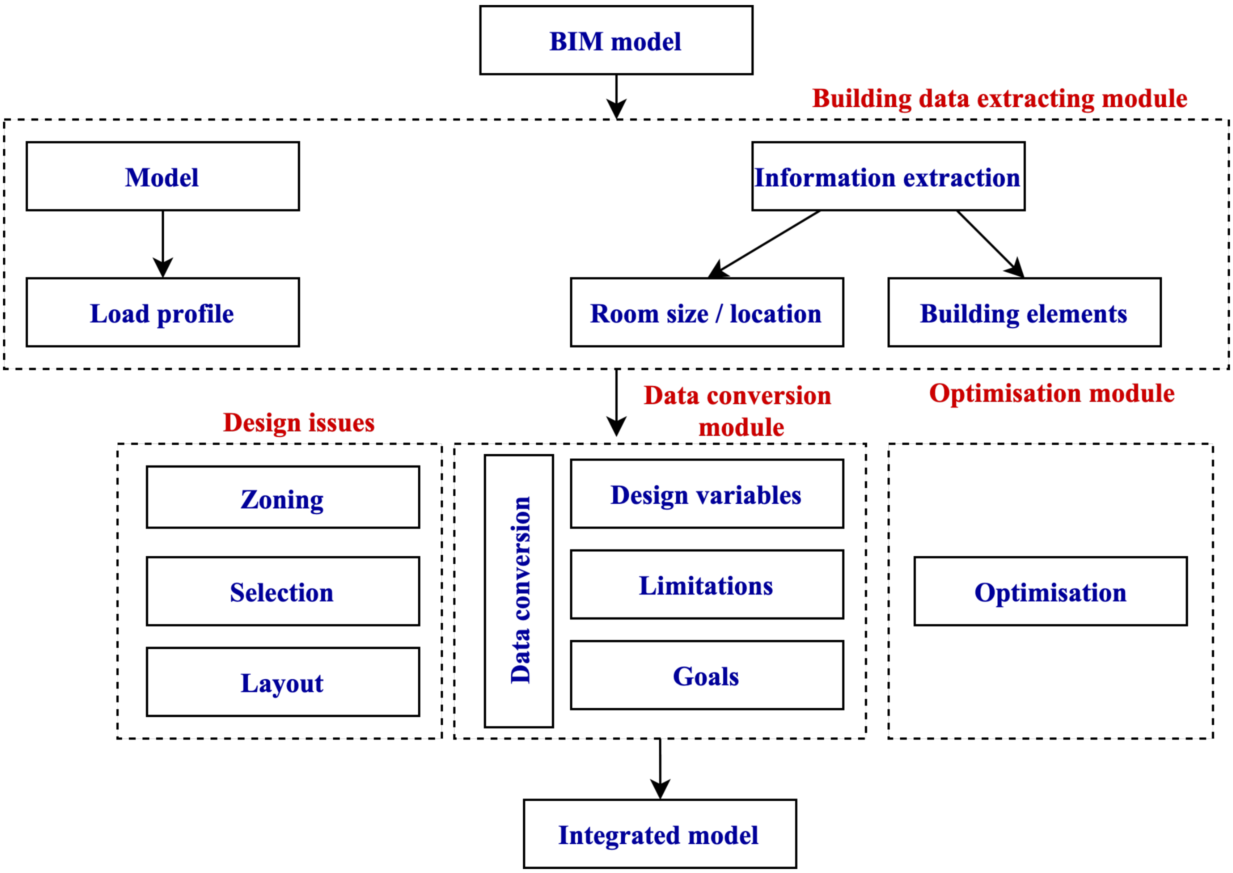

Figure 3. Integrated optimization BIM model

This structure comprises three fundamental parts. The components include data gathering, conversion, and optimizing components. The information-extracting component is engineered to interpret and retrieve data from a BIM file. This component contains an embedded utility known as SBT. It transforms a BIM design into an Energy-Plus file and generates a load assessment for subsequent studies. Upon the availability of the BIM approach, the necessary data for every HVAC layout step can be generated and retrieved utilizing this component. Data will be gathered for zoning assessment, including room shape, setting, operation, and load characteristics. Upon the completion of the design data, it is transmitted to the data conversion component. This component is an intermediary between the technical design challenge and the optimization issue expressed in mathematics. This segment will identify and prepare each element for optimizing research: design variables, goals, and limitations. The optimizing component is intended to perform optimization calculations. Customers select their favorite option or adhere to the suggested guidance provided by this tool. The computed optimal solution is transformed into the technical format via its data conversion tool. This instrument can be developed as a plug-in for the BIM program, assisting designers in making intelligent choices without the burden of complex mathematical calculations.

4. **Results**

The research monitored the aggregate energy usage of all sensing Motes that regularly generate packets to calculate energy use. The system consumes less power than the existing model, as illustrated in Figure 4. With nine simultaneous user or sky particle demands, the median energy usage for both methods escalates by the iteration size, as anticipated.

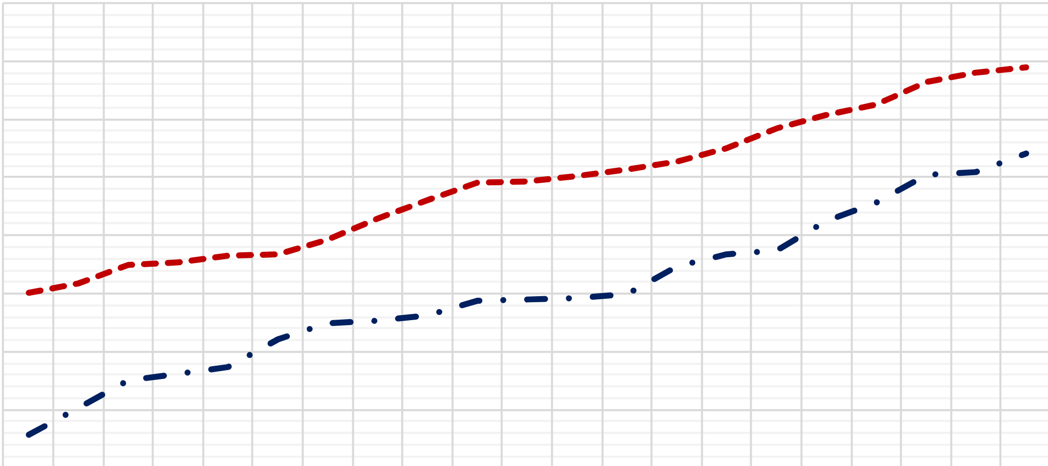

Figure 4. Energy efficiency analysis

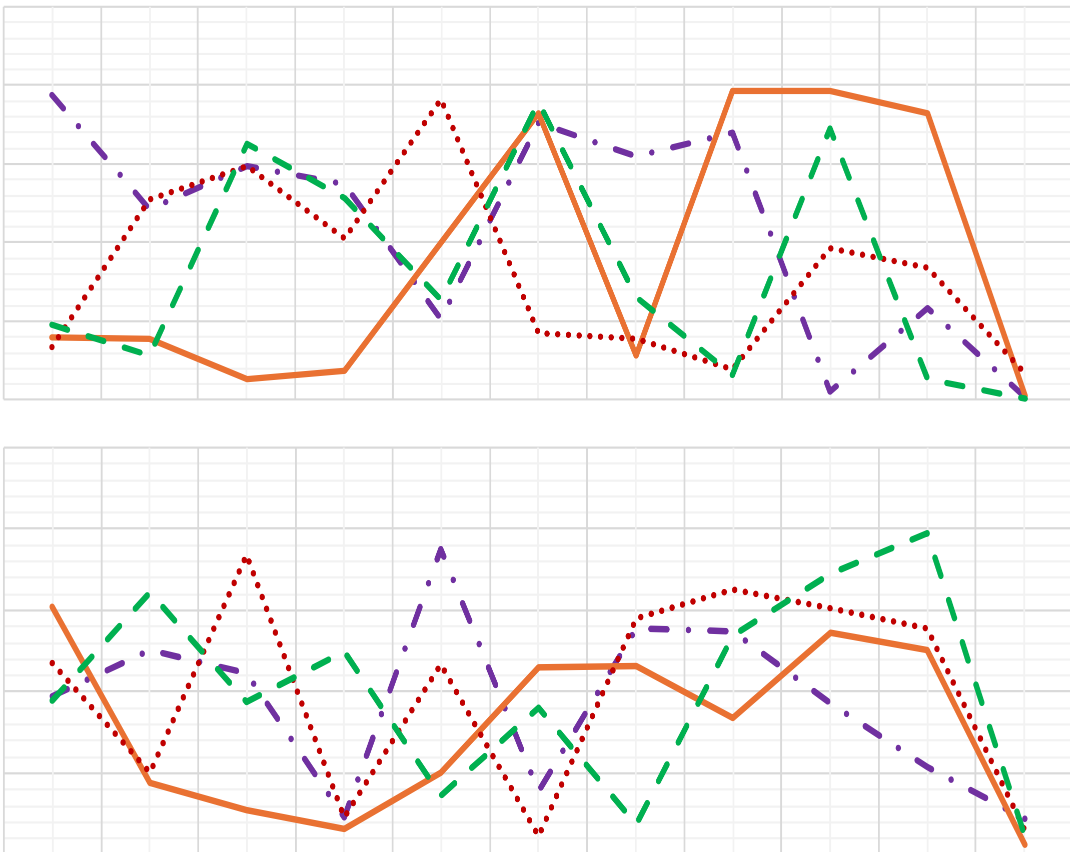

Figure 5. Energy consumption analysis (a) Case-1 (b) Case-2

In case study 1, the office featuring an adapted façade has the lowest overall energy consumption relative to the reference standards—the office featuring a highly protected façade utilized less power than the one with a poorly sealed façade. The heated interior of workplace standard five can readily dissipate into the exterior environment due to its poorly sealed façade, necessitating increased heating energy to maintain warmth during chilly winter days. A similar pattern in perception was noted in summer, where an increased Tvis leads to decreased energy consumption due to reduced lighting energy for standards 1 and 2. Standards 2, 3, and 4 fail to meet the visual comfort criteria since the visual results are below 100%. The workplace featuring a customized façade can reduce total energy usage instead of static, non-adaptable façade solutions. In contrast to the summer month, the predominant energy consumption throughout the winter week is for warmth, as illustrated in Figure 5.

The computation of building loads and the definition of objectives for GA-based planning fall within the area of modeling problems. Both physical-based and data-driven methods are relevant for resolving a model estimate challenge. The selection of a process is contingent upon numerous aspects, including the system development phase, estimating precision, time constraints, and the availability of construction and system data. The physics-based method is more precise, and the created model can facilitate additional quantitative analysis; however, creating a comprehensive physical structure is labor-intensive and necessitates extensive particular data. Intricate physical model calculations frequently impose a substantial computational load. The data-driven strategy is less precise, significantly faster, and requires fewer details. A data-driven approach is better appropriate for the initial design stage to establish an overall picture of system electrical consumption and to formulate the objectives of a complex GA-based optimization issue. It is important to note that the data-driven approach exhibits limited extensibility; the teaching cases must be as varied as feasible to encompass the specifications of the target structure or machine; the estimated results are incorrect.

5. Conclusion

The adaptable façade is seen as a viable option to improve the energy utilization of structures. The research introduced a computational optimization method that integrates the BE modeling system (Energy-Plus), the metaheuristic optimization algorithms, and the toolbox to design and evaluate the feasibility of adaptable façade systems. Two instances were performed to validate the efficacy of the suggested methodology, which was employed to derive the optimum property order for the adaptable façade structure, encompassing the thermal transference U-value and visual transference, aimed at minimizing overall consumption of energy in every single research.

In Case Study 1, a standard single-zone workplace was evaluated, revealing that the adaptable façade solution can reduce overall energy use by 20% during summer and 23% during winter weeks, compared to conventional static façade solutions. In case study 2, the suggested method can reduce total energy use by 15% to 21% compared to the benchmarking façade solutions. The research examined the ideal, time-variable U-value and Tvis of the adaptable façade structure, which effectively responds to changing environmental circumstances. The findings validate the efficacy of the suggested method in facilitating the creation of adaptable façades and demonstrate the capacity of the adaptable façade technology to decrease BE usage. The proposed computational optimizing method and the findings of this study can inform subsequent studies and endeavors for improvement. This research can be expanded to encompass various material qualities or dynamic shading mechanisms to advance the investigation of next-generation adaptable façade designs.

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