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REVIEW ARTICLE

Using IoT in Double Skin Facades toward Thermal Comfort: A Review

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ABSTRACT

Integrating the Internet of Things (IoT) into building design and operation has ushered in a new era of sustainable architecture and enhanced occupant comfort. This paper presents comprehensive case studies focused on the application of IoT technology in the context of double-skin facades, explicitly focusing on achieving and optimizing thermal comfort. These case studies, located in an urban setting, represent a paradigm shift in architectural design principles. Double skin facades, renowned for their potential to enhance energy efficiency and occupant well-being, are further empowered through the intelligent deployment of IoT devices. This synergy between architectural innovation and digital technology is instrumental in addressing the pressing challenges of energy consumption and occupant comfort in urbanized areas. It delves into the sensors, actuators, and data analytics systems employed to monitor and control the indoor environment. Special attention is given to the dynamic adaptation of the facade system in response to real-time environmental conditions, occupancy patterns, and user preferences. One of the case studies—PH01-BRK, projects the practical application of these principles in South Dakota's first custom passive and net-zero home, completed in 2016, using advanced thermal analysis tools, software for heating and cooling requirements, and solar data assessment. Furthermore, the paper investigates the impact of IoT-enabled double-skin facades on thermal comfort, energy efficiency, and indoor air quality within the Brookings Passive House. Quantitative data and occupant feedback are analyzed to assess the effectiveness of the IoT-driven system in maintaining optimal thermal conditions while minimizing energy consumption. The findings of this case study underscore the potential of IoT technology in revolutionizing the design and operation of sustainable buildings. It demonstrates that integrating IoT into double-skin facades can significantly enhance thermal comfort, reduce energy consumption, and create healthier indoor environments.

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1. Introduction

In an era marked by burgeoning urbanization, climate change, and the ever-increasing demand for energy-efficient building designs, the realm of architectural innovation stands at the forefront of addressing these contemporary challenges. One such groundbreaking development in sustainable architecture is the integration of Internet of Things (IoT) technologies into building systems. Among the myriad applications of IoT in architecture, this paper focuses on its utilization within the context of Double Skin Facades (DSFs) and its profound implications for enhancing thermal comfort in built environments.

This research explores the application of Internet of Things (IoT) technologies in the context of double skin facades (DSFs), specifically focusing on improving thermal comfort within built environments. Double skin facades have demonstrated the potential to enhance energy efficiency, but their impact on thermal comfort remains critical and requires further investigation. The proposed study will leverage advanced IoT sensors and data analytics to monitor, analyze, and optimize the thermal performance of double skin facades in real time. The research objectives include assessing the effectiveness of IoT-integrated DSFs in regulating indoor temperatures, reviewing some case studies, identifying key factors influencing thermal comfort, and proposing design and operational strategies to maximize occupant well-being. Through a multidisciplinary approach combining architecture, engineering, and data science, this research seeks to provide valuable insights for architects, designers, and building professionals striving to create sustainable and comfortable indoor environments.

2. Statement of Issue

In contemporary architecture and building design, the quest for thermal comfort and energy efficiency has taken center stage, driven by urbanization and the pressing challenges of climate change. As architects and engineers grapple with creating sustainable, comfortable, and adaptable built environments, integrating Internet of Things (IoT) technology into Double Skin Facades (DSFs) emerges as a crucial frontier. So, the main question is how IoT can be harnessed to transform DSFs into dynamic and responsive building systems that effectively mitigate thermal discomfort and energy inefficiency. By exploring this issue, we aim to uncover the potential of IoT-driven DSFs as a paradigm shift in sustainable architecture, offering new opportunities for achieving both environmental responsibility and occupant well-being.

3. Research Method

Firstly, the research design will encompass an extensive literature review to gain a nuanced understanding of the current landscape of DSF technology, IoT applications in building design, and the intersection of these domains. After this, the study will incorporate detailed insights into the research design, including data collection methods and statistical approaches. Subsequently, we will use case study analyses of existing buildings implementing IoT-driven DSFs to assess their performance, energy efficiency, and occupant comfort. Complementing this, quantitative data will be collected through on-site monitoring of selected case studies, focusing on parameters such as temperature, humidity, energy consumption, and user feedback. This research will investigate the pros and cons of different case studies that used double-skin facade systems to enhance thermal comfort. Furthermore, we will employ computational simulations and modeling to predict the potential impact of IoT-enabled DSFs on various building types and climates. Interviews and surveys with building occupants, architects, and engineers will be conducted to gather qualitative insights. The triangulation of data from literature, case studies, on-site monitoring, simulations, and stakeholder perspectives will facilitate a holistic and in-depth analysis of the research topic. Ultimately, this mixed-method approach will enable us to draw meaningful conclusions regarding the effectiveness of IoT in DSFs and its potential to revolutionize thermal comfort in built environments.

4. Overview

This paper presents a comprehensive case study focusing on integrating IoT technology into building design, specifically within double-skin facades. The study revolves around Passive Houses, a sustainable urban building that utilizes IoT technology and architectural innovation to address energy consumption and occupant comfort challenges. By combining IoT devices with double-skin facades, the study demonstrates how this approach enhances energy efficiency and occupant well-being. The paper thoroughly explores the design, implementation, and evaluation of IoT-integrated double-skin facades at Passive Houses, emphasizing sensors, actuators, and data analytics systems to regulate indoor conditions. The study assesses the impact of IoT-enabled facades on thermal comfort, energy efficiency, and indoor air quality through quantitative data and occupant feedback. Ultimately, the findings highlight the transformative potential of IoT technology in sustainable building design, offering guidance for professionals seeking to promote urban development and improve occupant well-being.

5. Literature Review

Double skin facades (DSFs) have recently gained significant attention as a sustainable architectural solution for enhancing building performance [1]. These facades consist of two layers of glass or other materials with an air cavity in between, providing insulation and ventilation benefits. With its ability to collect and analyze data in real time, IoT technology can potentially optimize the performance of DSFs in terms of thermal comfort [2]. This literature review aims to provide an overview of the research conducted in this field. Integrating IoT technology into building design has been explored extensively in the literature [3]. Researchers have emphasized the importance of IoT sensors and devices in collecting temperature, humidity, air quality, and occupant behavior data. This data is crucial for understanding the dynamic nature of thermal comfort within a building.

Numerous studies have investigated the impact of DSFs on thermal comfort [4]. These facades offer improved insulation, reduced solar heat gain, and increased natural ventilation. However, the literature highlights that the performance of DSFs can vary depending on factors like climate, building orientation, and façade design [5]. Recent research has focused on integrating IoT technology into DSFs to enhance their thermal comfort capabilities [6]. This involves the installation of sensors and actuators in the DSF structure, allowing for real-time monitoring and control of environmental conditions. IoT-enabled DSFs can adapt to changing weather conditions and occupant preferences to maintain optimal thermal comfort.

Studies have reported several benefits associated with using IoT technology in DSFs. IoT-enabled DSFs can optimize heating, cooling, and ventilation systems, reducing energy consumption [7]. Real-time monitoring and control of indoor conditions ensure occupants experience a comfortable [8]. IoT sensors can detect issues or faults in the DSF system, enabling timely maintenance and repairs [9]. IoT data can be analyzed to identify trends and patterns, improving building design and operation [7].

Another challenge for implementing Internet of Things applications in the building is the intangibility of the benefits that smart homes bring to customers; therefore, people cannot be expected to use these applications by themselves. Consequently, the upstream requirements and laws will likely be compiled to implement these applications [10]. While the potential of IoT-enabled DSFs is promising, there are challenges to address. These include privacy concerns, cybersecurity risks, and the need for standardized protocols and communication systems [11]. Future research should focus on developing cost-effective IoT solutions and conducting long-term performance evaluations of smart DSFs in real-world settings.

Numerous previous inquiries have extensively expounded on the Energy Efficiency in the Building by Using AI in Sunlight Control. Many scholarly articles ponder Using AI and emphasize its effect on energy optimization [12]. Integrating IoT technology in double skin facades for enhancing thermal comfort is a promising avenue in sustainable building design. Existing research has demonstrated the potential benefits of IoT-enabled DSFs, but challenges remain. As technology continues to evolve, further research is needed to address these challenges and unlock the full potential of IoT in improving thermal comfort and energy efficiency in buildings.

6. Finding

The research design will be outlined in greater detail, encompassing the comprehensive approach that involves a thorough literature review to understand the current state of DSF technology and IoT applications in building design. Furthermore, the section will provide explicit details on the case study analysis methodology, focusing on performance metrics, energy efficiency, and occupant comfort assessment.

Regarding data collection, the methodology will offer a more in-depth explanation of the quantitative methods employed during the on-site monitoring of selected case studies. This will involve specifying the parameters measured, such as temperature, humidity, energy consumption, and user feedback. Computational simulations and modeling techniques will be clarified, emphasizing how these methods are applied to predict the potential impact of IoT-enabled DSFs across diverse building types and climates.

Integrating IoT (Internet of Things) technology within double-skin facades represents a pioneering approach to enhancing building thermal comfort. As highlighted in "IoT Based Renewable Energy Management and Monitoring System for The First Passive House in Newfoundland", authors Sabir Manzoor and Tariq Iqbal, this paper introduces an Energy Management and Monitoring System (EMMS) prototype designed for the first house in Newfoundland constructed to meet PHIUS+2015 standards. The system utilizes a Supervisory Control and Data Acquisition (SCADA) framework based on the Internet of Things (IoT) to minimize electricity usage through self-consumption strategies. It incorporates sensors like the PZEM004T for current and voltage measurement, which an ESP32 controls. The system includes control relays and a web-based monitoring and control platform using the Ubidots development platform. Overall, this scalable system has the potential to transform the house into a smart home, promoting sustainability and ultimately leading to cost savings [13].

The Orchid House project spans a decade and illustrates passive building design's effectiveness in reducing energy consumption. Central to this effort is the implementation of House Talk, an IoT solution that intelligently manages the home's passive mechanisms to ensure indoor comfort. House Talk integrates various sensors and actuators through a user-friendly Graphical User Interface (GUI), allowing users to control IoT devices effortlessly. In order to minimize energy consumption, the system dynamically adjusts HVAC operations in private living areas while utilizing non-thermodynamic cycle systems such as mechanical ventilation and evaporative cooling in communal areas. House Talk further enhances indoor air quality, reducing CO_2 levels and maintaining optimal oxygen concentrations. Tenant feedback indicates high satisfaction with House Talk's HVAC control, and it even accelerates CO_2 reduction through indoor plant photosynthesis, underscoring its potential for eco-friendly, comfortable, and sustainable living [14].

Buildings in developed countries consume a substantial share of total primary energy, prompting a growing interest in energy efficiency due to environmental concerns and rising energy costs. This article provides a comprehensive technical review of various building envelope components and their potential improvements in terms of energy efficiency. The topics discussed are energy-efficient wall types, fenestration technologies, advancements in energy-efficient roofing, and thermal insulation materials. The article also highlights the impact of thermal mass and phase change materials on cooling and heating loads, emphasizing their effectiveness in regions with significant day-night temperature variations. Furthermore, it underscores the importance of air tightness and envelope infiltration control in reducing energy consumption. Notably, the article emphasizes that energy efficiency measures can often be cost-effective, with holistic building design approaches potentially offsetting initial investment costs by reducing the size of mechanical systems [15].

This paper analyzes the energy performance of one unit within a Passive House Standard duplex in Portland, Oregon, USA (Figure 1). The study delved into pathways for converting this unit into a net-zero energy house (NZEH) and conducted a detailed energy analysis encompassing heating, cooling, water heating, plug loads, electric appliances, and kitchen appliances. The findings suggest two critical steps for achieving this transformation: firstly, identifying energy conservation measures (ECMs), with changes in natural ventilation and occupant behavior proving most effective, reducing energy consumption. Secondly, evaluating renewable energy systems, where integrating (PV) panels appeared to be a cost-effective solution, balancing the annual energy demand (Figure 2). The paper concludes that the PV panel approach is more economically viable for transitioning a passive house to a ZEH for the Northwest US climate [16].

Figure 1. Passive house in Portland.

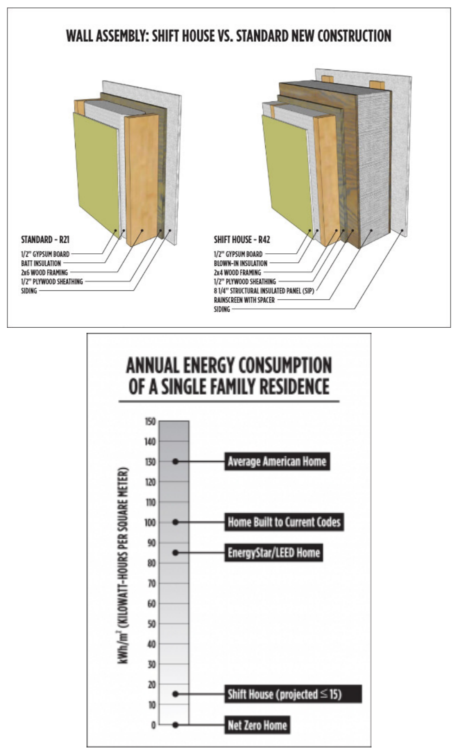

Figure 2. Wall assembly passive house.

This study aims to enhance heat transfer efficiency in passive houses in cold regions with complex climates by exploring the time-dependent fluctuations in outdoor temperature and solar irradiation. The study examines how cooling and heating loads vary with outdoor temperature and solar irradiation. By using cloud computing technology, it is demonstrated that passive buildings are energy efficient. This research employs super-thermal insulation for external walls, energy-conserving doors and windows in the enclosure structure, and a high-efficiency heat recovery system to maintain a consistent indoor temperature without relying on active mechanical heating and cooling. This approach presents a strategic framework for significantly reducing total energy consumption and annual operational costs in passive building design.

PH01: BRK represents the pioneering project of the Passive House Initiative. Completed in 2016, it is South Dakota's first custom passive and net-zero home, certified by PHIUS+. This 2,000-square-foot residence with three bedrooms and bathrooms is in a walkable neighborhood in Brookings (Figure 3). It is the first building in Brookings to incorporate solar PV technology. THERM software is employed for a detailed thermal analysis of the Passive House, focusing on critical thermal bridge areas such as ground connections, second-floor structural connections, and wall-to-roof assemblies. This program offers a wide range of materials with relevant properties, allowing users to create a 2-D model and calculate heat flow, generating various graphical outputs for analysis. Meanwhile, WUFI software assesses the annual heating and cooling requirements by incorporating data like climate, wall assembly, internal loads, and occupancy (Figure 4).

Figure 3. Passive house.

Solar Pathfinder aids in determining shade locations throughout the year by capturing images of the reflective dome positioned at the chosen site and processing them through its dedicated software, providing valuable solar data. The project involved extensive student work, including house design, mock-ups, energy modeling, site research, and various crucial tasks for successful completion [17].

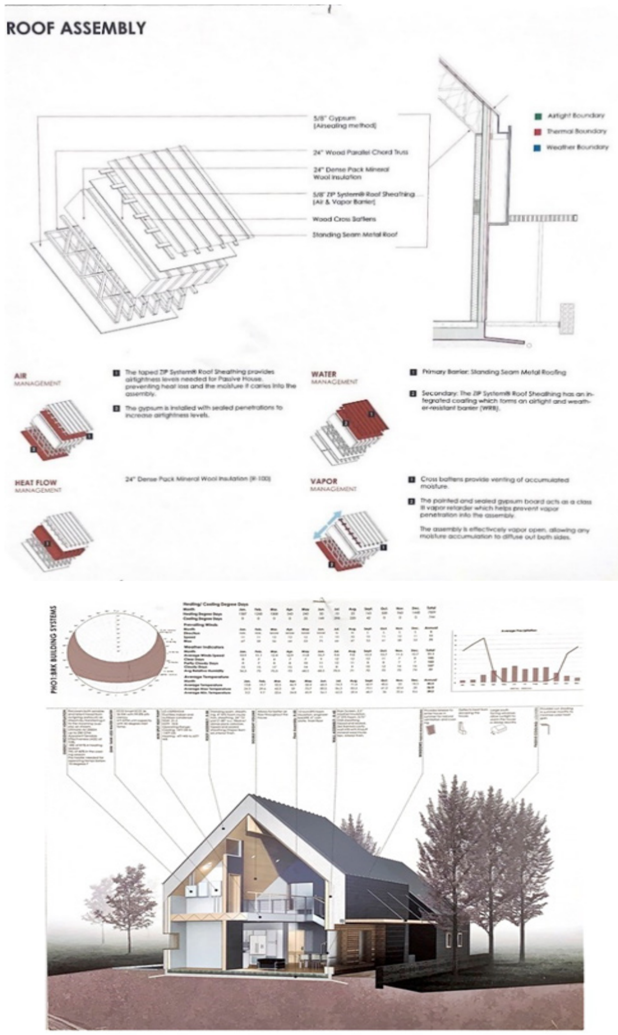

Figure 4. Passive house-interior.

The Internet of Things enables the development of a flexible system architecture that uses sensor data to improve the efficiency of passive buildings. On the other hand, the practical design of an IoT sensor network for a specific building still relies on the knowledge and experience of a diverse team of experts [18]. In Passive House sensor networks: Human-centric thermal comfort, this project aims to make Passive Houses (PH) more comfortable for people. It investigates how we can use Wireless Sensor Networks (WSN) to monitor and improve living space comfort. These sensors monitor temperature, lighting, air quality, noise, and space layout. They also consider what the people in the house are like. Using this information, we can make the living space more comfortable while using less energy. The main priority is to keep the temperature just right. This paper introduces the Java-based SunSPOT sensor, which helps us measure and improve the temperature in a living space. We also have a method for estimating temperature comfort without a sensor. The results of the experiments and simulations indicate that these methods have a high potential for improving Passive Houses [19]. The review of the case studies is summarized in the form of a table (Table 1).

Analyzation occurs within the findings of research relating to our discussion. The first source shows that the case study based on this source utilizes Supervisory Control and Data Acquisition (SCADA), which is a system based on IoT. Based on the passive house in Brookings, using similar information can help determine if supervisory control and data acquisition with a double facade provide thermal comfort and energy efficiency. Based on further analysis, this source mentions the use of sensors. For instance, the sensors control relays and a web-based monitoring and control platform using the Ubidots development platform. Using sensors with a passive double facade can help understand further how this building can be sustainable [13]. Another source further discusses the use of sensors. This provides a better understanding of how a specific system with IoT can help promote further sustainability in a house. The House Talk is an IoT system or solution that utilizes non-thermodynamic cycle systems such as mechanical ventilation and evaporative cooling in communal areas. A similar system in the passive house enhances indoor air quality while providing eco-friendly, comfortable, and sustainable living [14].

The passive house in Brookings uses THERM software to analyze the passive house's thermal comfort. This includes the ceiling, first and second floors, and walls. Further analysis of THERM software must be researched to understand how THERM software systems can be used with IoT systems. Not only the THERM software system but also WUFI. Using the WUFI system with further research can help understand how IoT in double skin façade affects thermal comfort, energy efficiency, and indoor air quality, using quantitative data and occupants' feedback [17].

The Pumpkin Ridge Passive House harnesses the simplicity of Passive House design to deliver superb comfort and efficiency at minimal added construction cost. The Pumpkin Ridge Passive House is no more expensive to own monthly than a conventional custom home when monthly energy costs are considered alongside mortgage, taxes, and insurance. However, the high-performance green building will consume 90% less heating energy and offer exceptional comfort and indoor air quality (Figure 5). The project, designed by Scott Edwards Architecture and built by Hammer & Hand, is one of six homes in the Pacific Northwest to be featured by Northwest ENERGY STAR® as a "super-efficient demonstration home" [20].

Table 1. Case studies.

Case study	Key words	Main criteria
Case study: BRK	Passive house, net-zero, term software, WUFI system.	Offers many firsts: the first custom passive and net-zero home in South Dakota and the first building to utilize solar PV in Brookings.
Case study: Passive house in Portland	Energy conservation measure, net-zero energy house.	The case study identifies energy conservation measures (ECMs), with changes in natural ventilation and occupant behavior proving most effective in reducing energy consumption. Secondly, evaluating renewable energy systems, where integrating (PV) panels appeared to be a cost-effective solution, balancing the annual energy demand
Case study: Passive house in newfoundland	IoT, Supervisory Control and Data Acquisition (SCADA), sustainability.	The case study utilizes IoT and a SCADA framework to minimize electricity consumption through self-consumption strategies. It incorporates sensors and web-based monitoring for sustainable, intelligent, and cost-saving homes.
Case study: Heat transfer and energy consumption of passive house	Heat transfer, efficiency, passive house.	The study enhances heat transfer efficiency in passive houses in cold regions with complex climates by exploring time-dependent outdoor temperature fluctuations and solar radiation.
Case study: Passive building energy savings	Energy efficiency, passive house, thermal mass.	Technical review of various building envelope components and their potential improvements in terms of energy efficiency.

Source: Authors.

Figure 5. Passive house in northwest.

The incorporation of Internet of Things (IoT) technologies into Double Skin Facades (DSFs) exerts a substantial influence on both thermal comfort and energy efficiency, offering a more nuanced comprehension of this subject [2]. IoT facilitates real-time monitoring and adaptive control of environmental parameters within building enclosures, allowing for dynamic adjustments based on prevailing conditions [22]. Specifically, within the context of DSFs, IoT technology enables the implementation of adaptive responses to external factors such as outdoor temperature, solar irradiation, and occupant behavior, ultimately optimizing thermal comfort [23].

Effective regulation of indoor temperatures is pivotal to achieving thermal comfort, and the integration of IoT in DSFs supports this goal. IoT systems empower DSFs to intelligently manage ventilation, shading, and heating based on continuous data inputs, minimizing the need for active heating or cooling interventions [25]. Furthermore, the learning capabilities of IoT-enabled DSFs, informed by historical data and user preferences, enhance predictive capabilities, proactively addressing thermal comfort concerns [2].

In energy efficiency, IoT plays a central role in optimizing the performance of DSFs. IoT systems leveraging real-time data on temperature differentials, occupancy patterns, and external weather conditions optimize heating, ventilation, and air conditioning (HVAC) systems in DSFs, ensuring thermal comfort and minimal energy wastage [23]. The remote monitoring and management enabled by IoT further empower building operators to promptly identify and rectify inefficiencies, contributing to the sustained, long-term performance of DSFs [22].

The paper will explore specific case studies and empirical evidence to illustrate how integrating IoT technologies in DSFs improves thermal comfort and energy efficiency [24]. By examining practical implementations, the paper aims to provide a comprehensive and nuanced understanding of the transformative impact of IoT on the performance of Double Skin Facades, emphasizing the pursuit of enhanced thermal comfort and energy efficiency [2].

7. Discussion

Integrating IoT (Internet of Things) technology into building design undeniably transforms how we approach energy management, comfort, and sustainability. The various projects and research highlighted in this text demonstrate the potential for IoT to revolutionize the construction and operation of buildings, particularly in the context of energy efficiency and thermal comfort [21].

7.1 Energy Management and Monitoring System (EMMS)

The EMMS prototype for the first Passive House in Newfoundland utilizes IoT and a SCADA framework to minimize electricity consumption through self-consumption strategies. It incorporates sensors and web-based monitoring for sustainable, intelligent, and cost-saving homes.

7.2 House Talk for Passive Building Design

The Orchid House project demonstrates how IoT can manage passive building systems to improve indoor comfort. House Talk dynamically adjusts HVAC operations and incorporates various sensors and actuators, reducing energy consumption and enhancing indoor air quality. Positive tenant feedback highlights the potential of user-friendly IoT interfaces for promoting sustainable living.

7.3 Broader Context of Energy Efficiency

Buildings in developed countries consume a significant share of primary energy. The text discusses various energy-efficient building components and their cost-effective potential, such as energy-efficient walls, fenestration technologies, roofing advancements, and thermal insulation materials.

7.4 Achieving Net-Zero Energy Status

An analysis of a Passive House duplex in Portland outlines steps to transition to a net-zero energy house (NZEH). It highlights the importance of energy conservation measures (ECMs) and renewable energy systems, particularly solar PV panels, in achieving this goal.

7.5 Optimizing Passive Houses in Cold Climates

Cloud computing technology optimizes passive houses in cold regions. The approach includes super-thermal insulation, high-efficiency heat recovery, and time-dependent fluctuations in outdoor temperature and solar irradiation to reduce energy consumption and operational costs.

The energy-efficient living spaces. These projects and concepts showcase the potential for technology-driven solutions to address energy consumption and environmental sustainability challenges in the construction industry.

8. Future Research Recommendations

As we conclude our review on "Using IoT in Double Skin Facades Toward Thermal Comfort", it is imperative to outline potential avenues for future research that could significantly contribute to the advancement of this field. Future studies could delve deeper into exploring and integrating emerging IoT technologies that enhance the capabilities of double-skin facades. This includes investigating the potential integration of edge computing, machine learning, and artificial intelligence to optimize the operation and control of IoT-enabled DSFs for superior thermal comfort outcomes.

While our review has provided insights into the immediate impacts of IoT integration, future research could focus on conducting long-term performance assessments of buildings with IoT-enabled DSFs. This would involve monitoring and evaluating the sustained effectiveness and energy efficiency over extended periods, considering factors like equipment durability, software updates, and evolving user behaviors. A more in-depth exploration of occupant behavior and interaction with IoT-enabled DSFs is essential for understanding the human-centric aspects of thermal comfort. Future studies could incorporate social science methodologies to investigate how occupants perceive and interact with intelligent building technologies, influencing their comfort levels and overall satisfaction [26]. Future research could develop multi-criteria optimization models considering various parameters such as energy efficiency, cost-effectiveness, and environmental impact. These models would aid in the design and decision-making process, providing a holistic approach to the implementation of IoT in double-skin facades. Given the diverse climatic conditions across regions, future research should explore climate-specific adaptations of IoT-enabled DSFs. This could involve tailoring the technology to address unique challenges posed by different climates, ensuring that thermal comfort is optimized regardless of external environmental variations. Conducting comprehensive user experience studies can uncover valuable insights into the acceptance and satisfaction levels of building occupants with IoT-driven thermal comfort systems. This can contribute to refining design principles and functionalities to align more closely with user expectations and preferences.

9. Conclusions

The text highlights how IoT technology is being leveraged to transform building design, making it more energy-efficient, environmentally sustainable, and comfortable for occupants. It discusses specific projects and concepts that showcase the potential for technology-driven solutions in addressing energy consumption and environmental sustainability challenges in the construction industry and more research on utilizing IoT systems in a passive house in Brookings.

The study uses Supervisory Control and Data Acquisition (SCADA) and sensors to monitor and control various aspects. SCADA is linked to a double facade to assess thermal comfort and energy efficiency. Furthermore, an IoT system called House Talk, which focuses on improving indoor air quality using non-thermodynamic cycle systems, is mentioned.

Furthermore, the text highlights the use of THERM software to analyze thermal comfort in various parts of the passive house, including ceilings, floors, and walls. The integration of THERM software with IoT systems is explored. The text also suggests the potential use of the WUFI system to investigate further the impact of IoT in double skin facades on thermal comfort, energy efficiency, and indoor air quality, using quantitative data and occupants' feedback. This study highlights IoT's potential to transform sustainable building design and operation. It shows that incorporating IoT into double-skin facades improves thermal comfort, lowers energy usage, and enhances indoor air quality. These findings offer valuable guidance for architects, engineers, and policymakers aiming to promote sustainable urban development and better living conditions for building occupants. The research aims to promote sustainability and eco-friendly living in the passive house.

Conflict of Interest

There is no conflict of interest.

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