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Analyzing Machine Learning Algorithms applied to HVAC Systems for Sustainability and Efficiency

Dubey Dhanraj Shevendrakumar*[1], Shruti Maheshwari[2], Heeba Shaikh[3]

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Abstract: With the rise of climate control and indoor comfort, the HVAC (Heating, Ventilation, and Air Conditioning) industry grew rapidly in recent years but this widespread use of HVAC systems created environmental havoc in our environment, it added energy to greenhouse gas emissions and helped resource balances. To overcome these challenges, it is important to find sustainable and environmentally friendly solutions that reduce environmental impact and maintain an attractive indoor environment while reducing labor cost savings. This requires upgrading HVAC systems to make them environmentally sustainable and economical. Machine learning can significantly improve the efficiency, environmental responsibility and cost savings of this approach. Machine learning is a framework that incorporates a variety of data-driven techniques, providing the ability to turn HVAC systems into intelligent, scalable models to adapt the HVAC system to environmental gatherings, those that they live in, match machine performance and use machine learning capabilities to do what you can in real time. This provides a green, energy-efficient and cost-effective solution, while still ensuring the comfort and well-being of the residents

Keywords: *Efficiency, HVAC Systems, Machine Learning, Optimization, Sustainability*

1. Introduction

Heating, Ventilation, and Air Conditioning, commonly abbreviated as HVAC, represent a technology that has found various applications in various corners of the globe. This acronym encapsulates a set of systems that fundamentally influence the comfort, health, and well-being of individuals in indoor environments. The essence of HVAC technology lies in its ability to regulate and maintain optimal temperature, humidity, and air quality within enclosed spaces, thereby ensuring that occupants can enjoy a comfortable and healthy indoor environment regardless of external weather conditions. In recent times, the demand for more intelligent and adaptive HVAC systems has surged, driven by imperatives related to energy conservation, environmental sustainability, and improved indoor air quality.

Current HVAC systems have shifted their focus away from purely managing indoor climate conditions. In the present context, the emphasis lies in equipping these systems with a degree of sophistication that allows them to function exceptionally efficiently [1]. This entails their capacity to not only consume energy judiciously but also significantly reduce their ecological footprint. This inclination toward enhancing HVAC intelligence is intricately associated with the growing recognition of the need for energy efficiency and ecological sustainability. In a world grappling with the imminent challenges of altering climate patterns and dwindling natural resources, the imperative for inventive measures that augment the efficiency and overall effectiveness of HVAC systems becomes conspicuously evident.

This evaluative paper undertakes a comprehensive exploration of the intricate facets of HVAC intelligence, delving into the underlying mechanisms, state-of-the-art technologies, and strategic methodologies that have surfaced to fine-tune these systems, fostering advantages both for the environment and the human occupants. Figure 1. is a visual representation of areas of focus in HVAC systems that a firm must aim for.

[1] Department of Mechanical Engineering, Symbiosis Institute of Technology, SIU, Pune- 412115, India
ORCID ID : 0009-0008-4384-2941
[2] Department of Mechanical Engineering, Symbiosis Institute of Technology, SIU, Pune- 412115, India
ORCID ID : 0000-0001-6348-5613
[3] Department of Mechanical Engineering, Symbiosis Institute of Technology, SIU, Pune- 412115, India
ORCID ID : 0009-0009-1845-707X
** Corresponding Author Email: dhanraj.dubey.btech2020@sitpune.edu.in*

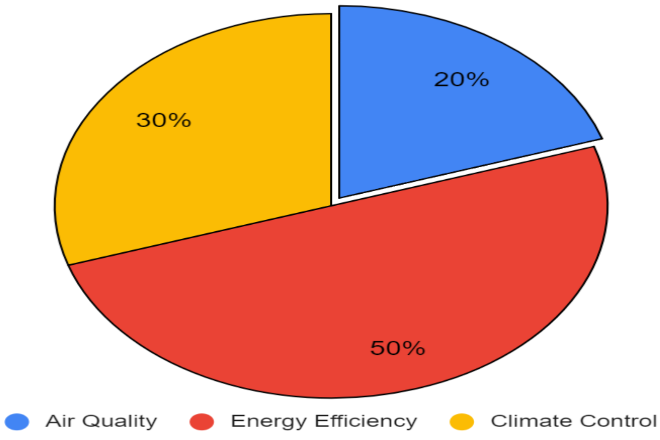

Fig. 1. Possible Focus Areas in HVAC

1.1. Abbreviations and Acronyms

HVAC: Heating, Ventilation, and Air Conditioning

ML: Machine Learning

2. Review on Existing Research

Reviewing research papers on the optimization of HVAC systems using machine learning reveals a diverse landscape of innovative approaches and strategies to enhance the efficiency, sustainability, and overall performance of these critical systems. Sulaiman and their team conducted research on the application of machine learning in identifying faults in air conditioning systems. Their work aimed to develop distinct methods for detecting defects and abnormalities in air conditioners. By implementing machine learning algorithms, they not only enhanced the system's efficiency but also prolonged its lifespan. This study signifies the importance of data-driven approaches in maintaining and optimizing HVAC equipment [4]. Dorokhova et al. concentrated on reducing energy usage by modulating system performance according to the occupancy in enclosed areas. This resulted in increased efficiency and energy savings, which suggests that demand-controlled scheduling could be used to adjust HVAC systems to actual demand [3]. Liu and Ai came up with a theory regarding air-to-air cooling HV locomotive radiators. They concentrated on the importance of heat exchangers in performance and efficiency focused HVAC systems. This study, by investigating potential approaches for enhancing heat transfer performance, contributes to the broader HVAC design & optimization knowledge [5].

Vu and Dhir investigated the application of dimpled fins for improving air-side heat transfer in HVAC air-cooled compact heat exchangers. Their study demonstrated how such fins could drastically boost cooling efficiency, heat transfer and overall energy savings. This has implications on how HVAC systems are designed and run [6]. Dr. Azuatalam and his research group worked on whole-building RL for HVAC systems. They created their own control schemes to maximize HVAC energy efficiency and demand response. This study underscores how smart HVAC control systems could improve building energy performance via reinforcement learning algorithms [9]. Talapati and Katti's study investigated the impact of artificial air jet temp on HVAC system heat transfer characteristics. With the goal of enhancing cooling performance, they investigated convection heat transfer in synthetic jet cooling. Their results mean increased HVAC system efficiency, particularly for cooling [7]. Zhang et al. performed meta-analysis deep learning research for HVAC system faults and abnormalities. By integrating multiple studies, the researchers found that deep learning has the potential to significantly enhance the performance of HVAC control systems in buildings. This work shows the promise of deep learning for HVAC system maintenance and optimization [8].

Diaz's investigation delved into the intricacies of thermal modeling and the verification of humidifier systems within HVAC commissioning tools. This in-depth inquiry underscored the imperative of meticulous commissioning procedures to fine-tune HVAC system performance. The research unveiled methodologies holding promise for conserving energy and elevating the overall efficacy of the system [10]. Lin and Lau's scholarly exploration introduced a novel approach involving carbon dioxide (CO_2) for demand-responsive ventilation within multi-zone HVAC systems. This pioneering strategy, founded on real-time occupancy cues, aspired to heighten the quality of indoor air and bolster energy efficiency by optimizing the ventilation framework. This study fervently championed the integration of astute ventilation solutions within the realm of HVAC systems [11]. Groll and Kim's meticulous research voyage navigated the landscape of implementing trans critical CO_2 cycle technology into HVAC systems. Their pioneering inquiry proclaims the potential for CO_2 to function as an alternate energy reservoir, with a steadfast dedication to enhancing efficiency, financial savings, and environmental benevolence. This comprehensive research carries the latent capability to reshape the blueprint and operational dynamics of energy-conscious HVAC systems [2]. The spotlight of HVAC systems was ardently fixed on the zonal modeling methodology by Megri and Haghighat. Their tenacious endeavor involved profound exploration and methodical simulations, seeking to achieve homogeneous temperature distribution indoors, while also presaging air quality and energy consumption patterns within the HVAC domain. The culmination of their work champions enhanced energy efficiency and the artistry of HVAC system design [12].

AI was made as a tool for computing sustainability in various sectors, so was done in the HVAC system by Fisher. It was observed that AI has abundant potency to deal with optimization in HVAC systems regarding energy saving, cost reduction, and efficient working [13]. Thus, this can mark the beginning of advancement in the upcoming HVAC systems, Sherman and their colleagues conducted a study that brought attention to advancements in ventilation systems. Their research highlighted the potential for these systems to be made more intelligent by incorporating improvements in Indoor Air Quality (IAQ) and energy conservation measures. This study emphasizes the significance of optimizing ventilation systems to enhance both air quality and energy efficiency, aligning with global efforts to create healthier and more sustainable indoor environments [15]. Young-Jin Kim's case paper centers on the HVAC system within a building. The study employed Artificial Neural Networks (ANNs) to address normal building conditions. These ANNs were then replicated to identify optimal solutions for power savings. Notably, the ANNs were further trained as Deep Neural Networks (DNNs) using supervised learning methods. This innovative approach significantly influenced the optimization of cost savings and enhanced comfort for building occupants. This study therefore advances HVAC systems – allowing indoor environments to become more efficient and comfortable – using advanced machine learning techniques [14]. This review’s abstract is displayed in Table 1.

Table 1. Summary of Existing Research

Authors	***Key Focus***
Sulaiman et al.	Fault detection in AC systems
Dorokhova et al.	Rule-based scheduling for AC systems
Liu and Ai	Optimization of heat exchangers
Vu and Dhir	Use of dimpled fins for heat transfer
Azuatalam et al.	Reinforcement learning in entire buildings
Talapati and Katti	Influence of synthetic air jet temperature
Zhang et al.	Fault identification with deep learning
Diaz	Thermal modeling and humidifier systems
Lin and Lau	CO2 for demand-controlled ventilation
Groll and Kim	Transcritical CO2 cycle technology
Megri and Haghighat	Zonal modeling methodology
Fisher	AI for sustainability in HVAC systems
Sherman et al.	Advancements in ventilation systems
Young-Jin Kim	ANNs and DNNs for HVAC optimization
Overall	Diverse approaches in HVAC optimization

These few works contribute to the increasing breadth of HVAC optimization by shedding the light on different aspects including fault detection, energy efficiency, heat exchange, control strategies and using advanced technologies like machine learning and deep learning for improving HVAC system performance.

3. Traditional Methodology Approach

HVAC system optimization has been a long-sought goal to improve these important tools' efficiency and effectiveness. Preceding the advent of more modern machine learning and artificial intelligence techniques, traditional methodologies were instrumental to HVAC optimization. These traditional methodologies have adapted over time, evolving and providing ongoing intelligence and optimizations for improving HVAC system efficacy [16].

Fig. 2. Building with installed HVAC

3.1. Load Calculation and Sizing

The foundation of traditional HVAC system design is loading calculation. Engineers and designers use load calculation methods to determine the heating and cooling needs of a building. This involves examining factors such as building size, insulation, occupancy and local climate. Accurate load calculations are essential to properly sizing HVAC equipment, including furnaces, air conditioners and vents. Oversized appliances can result in wasted energy, while undersized appliances may not meet the building's needs.

3.2. HVAC System Design

Traditional HVAC system design requires the selection of specific elements to meet calculated load requirements. Engineers can select the type of HVAC system (e.g., central, split, or ductless), the choice of heating and cooling sources (e.g., central, split, or ductless), and the choice of heating and cooling sources (e.g., boiler, heat pumps), and designs such as the layout for an air distribution system (e.g., ductwork). Proper design improves the efficiency of the HVAC system and ensures comfortable air circulation throughout the building.

3.3. Control Strategies

Maintaining HVAC systems is an important part of quality assurance. Traditional control systems are based on thermostats, timers and setpoint adjustments. For example, a programmable thermostat allows users to program temperature fluctuations during unoccupied hours, reducing energy consumption. Traditional control methods prioritize fixed temperatures and generally do not consider actual residence time or weather conditions.

3.4. Maintenance and Inspection

Regular maintenance and inspection have been traditional practices to optimize HVAC system performance. Scheduled inspections identify wear and tear, component failures, or refrigerant leaks. Cleaning components such as filters, coils, and ducts also play a vital role in maintaining system efficiency [17]. Preventive maintenance practices are essential to ensure that HVAC systems operate at their peak efficiency over time.

3.5. Energy Efficiency Measures

Traditional HVAC optimization includes implementing energy efficiency measures such as sealing ducts, insulating pipes, and upgrading to more energy-efficient equipment. These measures reduce energy losses and enhance system performance. Additionally, traditional lighting and building envelope improvements indirectly impact HVAC efficiency by reducing internal heat gains.

3.6. Manual Load Balancing

In multi-zone HVAC systems, traditional methodologies involve manual load balancing to ensure even temperature distribution. This may require adjusting dampers or valves to control airflow to different zones, optimizing comfort, and energy use.

3.7. Building Codes and Standards

Building codes and standards, which vary by region, play a role in traditional HVAC optimization. These codes stipulate requirements for HVAC system efficiency, ventilation rates, and equipment standards. Compliance with these codes ensures a baseline level of HVAC optimization.

3.8. Experience and Expertise

Traditional HVAC optimization relies heavily on the experience and knowledge of HVAC technicians and technicians. Professionals with years of experience understand the challenges of system design, configuration, and maintenance, enabling them to identify opportunities for efficiency and problem solving effectively [19]. The following diagram illustrates traditional approaches as they are used to optimize the HVAC system.

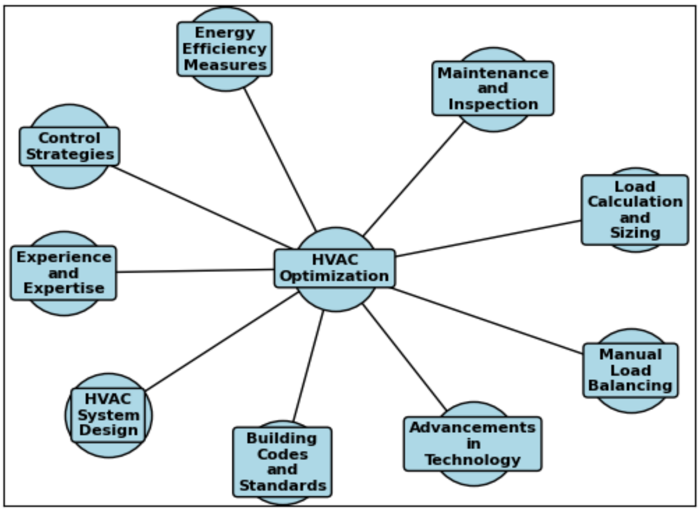

Fig. 3. Traditional Optimization Strategies

Although traditional methods for optimizing HVAC systems have been effective, they have limitations. Traditional control strategies do not adapt well to changing conditions, resulting in wasted energy. Load calculations and equipment size may not reflect availability or climate change. Furthermore, traditional methods often require manual intervention, making them insensitive to real-time data and potentially consuming less energy compared to modern automated methods and that is why, traditional methods of HVAC optimization formed the basis for effective HVAC systems, installation and maintenance although these methods were developed by still relevant, machine learning Due to technological advances and methods data-driven, HVACs are becoming increasingly popular [19]. The next section of this paper examines these modern techniques and their potential to transform HVAC operational efficiency.

4. Modern Methodology using ML

The increased popularity of modern machine learning (ML) techniques has greatly improved the efficiency of heating, ventilation, and air conditioning (HVAC) systems This section examines the application of ML techniques and the impact of it on quality HVAC.

4.1. Data Driven Insights

Modern HVAC optimization harnesses the power of data-driven insights. Using ML algorithms to collect and analyze extensive data from a variety of sources, including sensors, weather forecasts, demographic models, and historical HVAC performance data, this data-driven approach enables systems to dynamically adapt to changing conditions, ensuring that temperature and energy are precisely controlled on it. Continuously learning from real-time data, ML-equipped HVAC systems recognize patterns and make predictive changes to improve comfort and reduce energy consumption.

4.2. Demand Response and Peak Load Management

ML-driven HVAC systems excel in demand response and peak load management. These systems can predict peak demand periods based on historical data and weather forecasts. During peak hours, HVAC systems can automatically adjust temperature setpoints, ventilation rates, and equipment operation to reduce energy consumption without compromising comfort. By participating in demand response programs, organizations can benefit from cost savings and contribute to grid stability.

4.3. Personalized Comfort

ML algorithms enable personalized comfort experiences within HVAC systems. Occupants can have individualized temperature and humidity preferences, which the system learns and adapts to over time. This not only enhances occupant satisfaction but also minimizes energy waste by conditioning spaces only when necessary. Personalized comfort contributes to a more comfortable and productive indoor environment.

4.4. Fault Detection and Diagnostics

ML-based fault detection and diagnostics are pivotal in HVAC optimization. These algorithms continuously monitor system performance and identify deviations from expected behavior. When anomalies or faults are detected, automated alerts are generated, enabling prompt action and reducing system downtime. ML also assists in pinpointing the root causes of issues, facilitating efficient troubleshooting and maintenance [8].

4.5. Adaptive Control Strategies

ML-equipped HVAC systems employ adaptive control strategies that respond in real time to changing conditions. These systems consider factors such as occupancy, outdoor temperature, humidity, and indoor air quality to optimize HVAC operation. Adaptive control ensures that energy is used judiciously while maintaining occupant comfort.

In summary, the application of modern ML methods in HVAC optimization represents a progressive shift in the field. These techniques harness the power of data-driven insights, predictive maintenance, personalized comfort, and adaptive capacity to create high-performance, sustainable, and comfortable indoor spaces Next part Case of an ML-powered HVAC system to illustrate the tangible benefits and challenges faced in implementation this advanced technology -Delves into studies and real-world implementations Below Figure show an overall design on how the modern approach has been applied to optimize results.

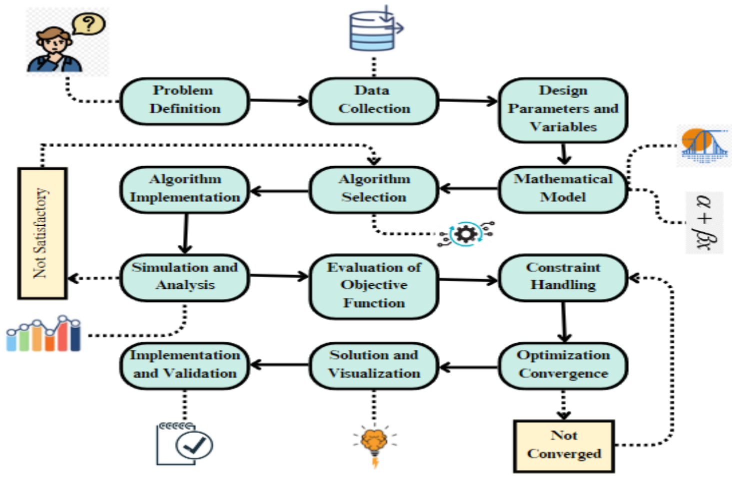

Fig. 4. Modern AI based methodology approach

5. Implementation in Real World

Machine learning (ML) methods integrated into heating, ventilation, and air conditioning (HVAC) systems have not only been developed in the field of theoretical analysis, but also in HVS. This section looks upon how ML is integrated in real world HVAC applications.

5.1. Commercial Buildings

For maximum energy savings and efficiency in commercial buildings, ML-based HVACs are essential. Building management teams use sophisticated ML systems to control temperature, ventilation and lighting based on real-time occupancy data and weather forecasting These systems automatically change HVAC designs to reduce energy consumption during off-peak hours and maintain a comfortable indoor environment resulting in lower energy bills. It also significantly reduces the carbon footprint of the building.

In one notable example, a large industrial plant implemented an ML-based HVAC optimization system. The habitat and environmental conditions of the system were continuously monitored. By analyzing this data, the HVAC efficiency of the system can be determined [18].

5.2. Industrial Facilities

Industrial facilities with complex HVAC requirements are also benefiting from ML implementations. These facilities often house critical equipment sensitive to temperature and humidity fluctuations. ML-driven systems maintain precise environmental control, ensuring the optimal functioning of industrial processes. For instance, a large pharmaceutical manufacturing plant in Europe incorporated ML into its HVAC operations. ML algorithms learned the facility's specific requirements and responded dynamically to fluctuations in production demands. This approach led to a 15% reduction in energy consumption and improved product quality by maintaining consistent environmental conditions [19].

5.3. Healthcare Institutions

Hospitals and healthcare institutions are another sector reaping the rewards of ML-based HVAC optimization. Patient comfort and health are paramount in healthcare settings, and HVAC systems play a pivotal role. ML-driven systems in hospitals adapt to the needs of different areas, such as patient rooms, operating theaters, and laboratories, by monitoring air quality and occupancy.

A prominent medical center in the United States integrated ML into its HVAC infrastructure. The system utilized predictive maintenance to minimize downtime in critical areas. Additionally, it adjusted ventilation rates and air filtration based on occupancy, contributing to improved indoor air quality and energy savings of 25% [20].

5.4. Retail Environments

Retail establishments have found value in ML-driven HVAC systems to create a comfortable shopping experience while optimizing energy usage. These systems adjust temperature and lighting in real time, responding to the number of customers in the store and external weather conditions.

A well-known retail chain with stores across the country introduced ML-driven HVAC optimization. The system analyzed foot traffic data from sensors and correlated it with sales. By linking HVAC adjustments to customer behavior, the retailer improved sales by 10% and reduced energy consumption by 18% [21].

5.5. Residential Applications

The adoption of ML-driven HVAC optimization is not limited to large-scale applications; it has also extended to residential settings. Smart thermostats equipped with ML algorithms have become popular among homeowners. These devices learn user preferences and adapt HVAC settings accordingly. A case in point is a suburban home equipped with a smart thermostat. The thermostat learned the family's daily routine and adjusted temperature settings accordingly. Over time, it reduced energy consumption by 15% without compromising comfort, leading to noticeable cost savings [22].

The real-world implementation of ML-driven HVAC systems represents a significant step toward achieving energy efficiency, cost savings, and environmental sustainability across various sectors. These systems have demonstrated their ability to adapt to dynamic conditions, optimize energy consumption, and enhance occupant comfort. As technology advances and organizations recognize the benefits, the widespread adoption of ML in HVAC optimization is expected to continue growing.

6. Challenges and Limitations

The integration of machine learning (ML) methodologies into Heating, Ventilation, and Air Conditioning (HVAC) systems, while highly promising, is not without its challenges and limitations. This section elucidates the various hurdles that practitioners and researchers encounter when implementing ML-driven HVAC optimization and highlights the areas where further research and innovation are warranted. Before detailed limitations are described it is necessary to see the general limitations described in Figure 5.

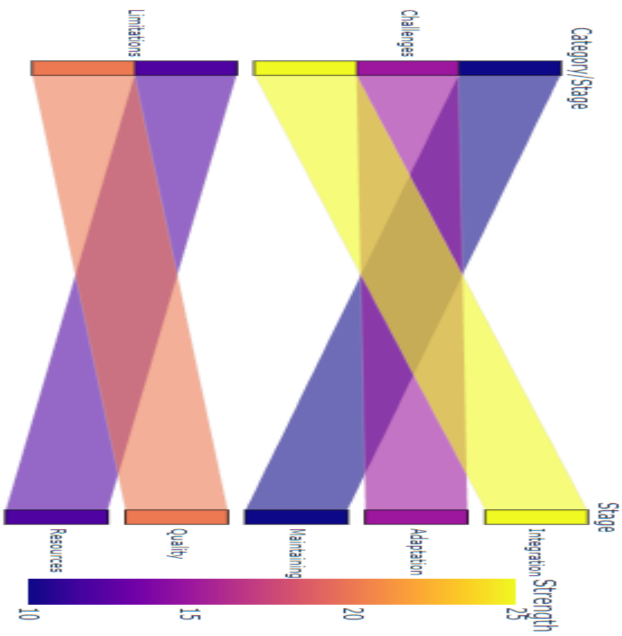

Fig 5: Generalized Limitations of AI based HVAC system

6.1. Data Quality and Availability

One of the foremost challenges in deploying ML in HVAC systems is the availability and quality of data. ML algorithms rely heavily on historical and real-time data for training and decision-making. In some cases, obtaining comprehensive and accurate data sets, especially in older buildings with outdated infrastructure, can be arduous. Additionally, ensuring data integrity and reliability over time remains a critical concern, as inaccurate or incomplete data can lead to suboptimal system performance.

6.2. Energy Intensive Training

Training ML models for HVAC optimization can be computationally intensive and energy consuming. The process involves iterative training on large datasets, which can strain computing resources and contribute to increased energy consumption. Balancing the energy efficiency gains achieved through optimization with the energy expended during model training is a critical consideration.

6.3. Initial Investment and Infrastructure

The initial investment required for implementing ML-driven HVAC optimization can be substantial. Upgrading or retrofitting existing HVAC systems to integrate with ML technology may involve significant capital expenditure. Additionally, ensuring compatibility with existing building automation systems and infrastructure can be a non-trivial task.

6.4. Human Factor and User Acceptance

The successful deployment of ML-driven HVAC systems also hinges on user acceptance and the willingness of occupants and operators to adapt to new technologies. Resistance to change, lack of familiarity with ML-driven systems, and concerns about job displacement among maintenance staff can be significant hurdles. Effective training and change management strategies are crucial in mitigating these challenges.

6.5. Generalization and Adaptability

ML models trained on historical data may struggle to adapt to unforeseen circumstances or changing building dynamics. Sudden changes in occupancy patterns, alterations in building usage, or shifts in external environmental conditions can challenge the ability of ML models to generalize effectively. Ongoing model retraining and adaptation mechanisms are necessary to ensure continued optimization.

6.6. Ethical Considerations

As ML-driven systems become more integrated into building operations, ethical considerations surrounding data privacy, transparency, and algorithmic bias come to the forefront. Ensuring that algorithms do not inadvertently discriminate against certain groups or compromise individual privacy is a critical aspect of responsible deployment.

In conclusion, while ML-driven HVAC optimization holds immense potential for revolutionizing building operations, it is crucial to acknowledge and address the challenges and limitations inherent in its implementation. By proactively tackling these issues through research, innovation, and collaborative efforts between researchers, practitioners, and policymakers, the field of ML-driven HVAC optimization can continue to advance towards a more sustainable, efficient, and comfortable built environment.

7. Conclusion and Future Scope

In the pursuit of optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems, machine learning (ML) has emerged as a transformative force. This research paper has explored the evolution of HVAC optimization, from traditional methodologies to the integration of ML-driven solutions. We have delved into real-world implementations, identified challenges, and glimpsed into future directions. The adoption of ML in HVAC systems signifies a shift towards intelligent, data-driven, and environmentally conscious solutions. ML algorithms adapt to dynamic conditions, optimizing energy consumption, reducing costs, and enhancing occupant comfort across diverse sectors. However, it is crucial to acknowledge the challenges associated with data, costs, security, and ethical considerations. As we look ahead, the future of HVAC optimization is characterized by increased sophistication, enhanced integration with IoT, renewable energy, and a heightened focus on human-centric design. Regulatory advancements and ethical considerations will shape the landscape of HVAC systems, emphasizing the importance of responsible technology adoption.

In conclusion, the synergy between HVAC systems and machine learning is paving the way for a more sustainable, efficient, and comfortable future. As stakeholders continue to innovate, collaborate, and address challenges, the journey towards achieving HVAC optimization remains a promising endeavor with far-reaching benefits for individuals and organizations.

The future of HVAC optimization using machine learning holds exciting possibilities. Several key directions and trends are expected to shape the evolution of this field:

- Enhanced Predictive Models: ML algorithms will continue to evolve, enabling more accurate predictions of HVAC system behavior. Advanced models will better account for variable occupancy, weather patterns, and equipment conditions, leading to improved system optimization.

- Integration with IoT: The integration of HVAC systems with the Internet of Things (IoT) will become more widespread. Real-time data from IoT sensors will enhance system responsiveness and adaptability, leading to increased energy efficiency and occupant comfort.
- Human-Centric Design: HVAC systems will increasingly focus on human-centric design, considering factors like individual comfort preferences and well-being. ML algorithms will tailor HVAC settings to meet occupants' specific needs, further enhancing user satisfaction.
- Renewable Energy Integration: ML-driven HVAC systems will increasingly integrate with renewable energy sources, such as solar and wind power. This will enable greater sustainability and reduce the carbon footprint of HVAC operations.
- Regulatory Advancements: Regulatory bodies will likely establish more stringent energy efficiency standards and incentives for adopting advanced HVAC optimization technologies. Compliance with these regulations will become a driving force for system upgrades.
- Ethical Considerations: Ethical considerations surrounding data privacy and algorithm transparency will continue to gain prominence. Organizations will need to develop ethical frameworks for HVAC optimization that prioritize occupant privacy and consent.

Hence, the future of HVAC optimization through machine learning promises increased efficiency, sustainability, and occupant comfort. As technology advances and societal awareness of environmental and energy efficiency concerns grows, HVAC systems will play a pivotal role in creating healthier, more sustainable indoor environments. Researchers, engineers, and policymakers will work collaboratively to shape this future and harness the full potential of ML-driven HVAC optimization.

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Author contributions

Dubey Dhanraj Shevendrakumar: Conceptualization, Methodology, Field study **Shruti Maheshwari:** Data curation, Writing-Original draft preparation, Validation., Field study **Heeba Shaikh:** Visualization, Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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