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Original Article

Human-Centric HVAC Systems: Linking Thermal Comfort, Cognitive Performance, and Energy Efficiency

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Abstract - *Human-centric Heating, Ventilation, and Air Conditioning (HVAC) systems symbolize a new paradigm of changing the energy-focused functionality of the building climate control to the performance-oriented and occupant-conscious design. Traditional HVAC systems are based on fixed set point and simplistic comfort factors, and tend to ignore the dynamic relationship between the indoor environmental condition, human thermal comfort, cognitive performance and energy use. The paper introduces a combination of human-centred HVAC system, which identically connects the models of thermal comfort, cognitive performance, and energy optimization in the smart building conditions. The presented framework will utilize real-time environmental monitoring, occupancy and behavioral data collection and subjective feedback on comfort to build a holistic image of the indoor environment and occupancies. Predicted Mean Vote (PMV) and adaptive comfort models are used to determine the relationship between thermal comfort and contextual and behavioral data, using cognitive performance indicators. Models using machine learning are utilized to represent non-linear relationships between the comfort and the performance, as well as to predictive evaluate the response of occupants. These models guide all forms of intelligent control and optimization procedures that dynamically determine and modify HVAC operation in order to yield harmony in comfort, cognitive performance and energy consumption. Through experimental assessment and comparative analysis, it has been shown that occupant-focused control systems can be very effective in enhancing thermal comfort and cognitive performance and lead to substantial savings in energy consumption relative to traditional fixed-setpoint HVAC systems. These findings justify the use of human-centered HVAC systems as an effective strategy to improve occupant health, performance, and sustainability that can be implemented as the main element of the next-generation intelligent and energy-efficient buildings.*

Keywords - *Human-Centric HVAC, Thermal Comfort, Cognitive Performance, Energy Efficiency, Smart Buildings, Adaptive Comfort Models.*

1. Introduction

Buildings contribute an enormous portion of the total energy consumption in the world with Heating, Ventilation, and Air Conditioning (HVAC) systems constituting one of the highest operational energy consumption. Traditional HVAC control policies are largely modeled as based on fixed thermal setpoints, and aggregate occupancy considerations, [1,2] with the main objective of minimizing energy requirement and simple thermal comfort. Nevertheless, these methods fail to measure human comfort that is dynamic and subjective, which results in dissatisfaction of occupants, low productivity, and poor use of energy in the current built environments.

The design has been made more flexible and responsive to the occupant with current developments in smart building technologies, sensing infrastructures, and data-driven control systems. Also, anthropocentric HVAC systems have a greater focus on the combination of physiological, behavioral, and contextual data to make the indoor environment more in line with the needs of occupants. Thermal comfort is finally being seen as a multidimensional concept not only dependent on temperature and humidity but also on occupancy schedules, metabolic rate, cloth insulation and adaptive mechanisms. In addition, new studies show that there is a close relationship between indoor thermal states and cognitive performance, including attention, decision-making, and general work productivity. Regardless of these developments, current HVAC systems tend to take thermal comfort, cognitive performance and energy-efficiency as independent goals, leading to sub-optimal trade-offs. The urgent necessity is still in the clear frameworks that would put the occupant wellness and energy optimization of the systems into consideration. The gap has been addressed in this paper by suggesting a humanistic based HVAC architecture to connect thermal comfort modeling with cognitive performance factors and smart energy management. The proposed solution will contribute to providing additional occupant comfort and cognitive performance and attaining sustainable energy performance in intelligent building contexts by employing real-time sensing, adaptive comfort models, and data-driven control schemes.

2. Related Work and Literature Review

2.1. Thermal Comfort Models (PMV, PPD, and Adaptive Comfort)

The modeling of thermal comfort has been an underlying aspect in designing and controlling of HVAC systems. The Predicted Mean Vote (PMV) and Predicted Percentage [3-5] Dissatisfied (PPD) indices are some of the most commonly used models which are based on the human heat balance principle and are standardized according to international building standards. PMV is used to measure the mean thermal feeling of occupants on a scale of seven between cold and hot, whereas PPD is used to estimate the percentage of occupants who will probably feel uncomfortable. In spite of their consistent performance in steady-state and mechanically conditioned conditions, long term field experiments have shown that they are not effective in the real world where thermal conditions are not uniform, occupant behavior is not uniform, and the pattern of occupancy is dynamic.

To address these shortcomings, adaptive comfort models have been introduced, particularly for naturally ventilated and mixed-mode buildings. Adaptive models take into consideration the physiological acclimatization of occupants and behavioral changes, including clothing change and the use of windows, through consideration of the outdoor climatic conditions in the prediction of comfort. The available literature reviews and longitudinal field studies to date have shown that adaptive comfort models provide a much better accuracy when it comes to prediction in diverse building types and climates, and thus they will be more applicable to occupant-based HVAC control systems.

2.2. HVAC Energy Optimization Techniques

Energy optimization in HVAC systems has evolved from rule-based scheduling to advanced control strategies driven by artificial intelligence and optimization algorithms. Model Predictive Control (MPC) uses prediction of the future of the weather and occupancy and uses it to manage future energy consumption to meet the comfort limits. Controllers based on reinforcement learning (RL) have an added advantage of learning optimal control policies through direct interaction with the environment and exhibit superior behavior in dynamic and unpredictable environments. Empirical research records a saving of 18-25% of energy than the conventional control measures do. Genetic algorithms and particle swarm optimization (PSO), are also metaheuristic techniques that have been broadly used in HVAC tuning and real-time control. These methods find use in the appreciative aspects of their fast convergence and the capability to handle multi-objective optimization tasks especially in large-scale or industrial situations where algorithmic performance is paramount.

2.3. Impact of Indoor Thermal Conditions on Cognitive Performance

An expanding body of research has investigated the relationship between indoor thermal conditions and human cognitive performance. Experimental and field-based research findings have always demonstrated that high indoor temperatures can adversely impact cognitive abilities in the form of reaction time, attention, and speed of information processing. The ideal temperatures of cognitive functioning are moderate temperatures 20 °C and 23 °C and ventilation and low indoor CO_2 levels. Nevertheless, results also indicate that task types with complex reasoning are less affected by thermal variations which support the hypotheses that performance is constant over wide comfort limits at moderate conditions.

2.4. Human-in-the-Loop and Occupant-Centric HVAC Systems

Human-in-the-loop (HITL) and occupant-centric HVAC systems represent a convergence of sensing technologies, data analytics, and intelligent control. Such systems include real-time occupancy sensors, environmental sensors, as well as direct or indirect feedback on occupants to deliver personalized thermal zones. The strategies that are noted by prior surveys and taxonomies to be important enablers of energy-efficient personalization include predictive preconditioning, comfort profiling, and adaptive setpoint control. The recent developments in the use of reinforcement learning-based HITL frameworks show the possibility of learning the preference of occupants based on manual overrides and behavioral patterns and gaining better comfort satisfaction at lower operational energy expenses in different occupancy and energy pricing regimes.

3. Human Factors in HVAC System Design

3.1. Physiological Aspects of Thermal Comfort

Human thermal comfort is based on physiological reactions to the thermal conditions in the indoor environment. Thermoregulatory responses to environmental stimuli occur in the form of sweating, vasodilation, and shivering to maintain the normal body temperature. [6-9] The important environmental factors such as air temperature, relative humidity, air velocity, and mean radiant temperature interact with the personal factors such as metabolic rate and clothing insulation to determine the thermal sensation. Conventional comfort models make steady-state assumptions and average physiological responses, but occupants in the real world are characterized by a large amount of inter- and intra-individual variation. Physiological comfort thresholds are also modulated by age, health condition, acclimatization and level of activity and this indicates the limitation of standardized HVAC setpoints. The design of human-centric HVAC systems must thus be dynamic based on physiological diversity, with real time sensing and modeling based on context to ensure comfort without causing too much energy use.

3.2. Psychological and Behavioral Responses to Indoor Climate

Beyond physiological regulation, psychological perception and behavioral adaptation play a critical role in how occupants experience indoor environments. Expectations, perceived control, past experiences and cultural background have impacts on thermal comfort, which can considerably change the comfort tolerance even in the same physical conditions. Adaptive behaviors often include changing clothing, adjusting position, or opening the window or any type of personal comfort devices to recover the comfort when thermal conditions are not favorable. Researchers have found that offering perceived or actual control over the surrounding to the occupants can enhance satisfaction of comfort without necessarily reducing the range of temperatures. The insights of human-centric HVAC systems are used to base control strategies on behavioral feedback, occupancy behavior, and interactions between users to allow climate control to be more flexible and psychologically adjusted.

3.3. Cognitive Performance Metrics in Thermal Environments

Cognitive performance is an important human aspect, which connects the conditions of indoor climate to productivity and well-being. Among the aspects of the cognitive condition that thermally affect include attention, reaction time, working memory, and task accuracy. Empirical studies show that thermal discomfort as well as inadequate indoor air quality may impair cognitive performance especially in tasks that demand protracted attention and quick processing of information. Cognitive performance metrics are generally determined by a task based test as the response time, rate of error and indices of mental workload. Notably, the association between thermal situations and cognition is not linear as performance is maintained at relatively steady levels within the comfortable thermal conditions and diminishes in extreme temperatures. By including cognitive performance in the design of the HVAC systems, the systems will no longer be involved in comfort only optimization but instead act as active environments that promote human functioning and decision making.

4. System Architecture for Human-Centric HVAC

4.1. Overview of the Proposed Human-Centric HVAC Framework

The figure illustrates the layered architecture of the proposed human-centric HVAC system designed for smart building environments. The framework is based on the bottom-up data flow and top-down control feedback, which allows maintaining the constant interaction of the occupants, [10-12] environmental sensing, intelligent decision-making, and physical HVAC actuation. This modular construction has guaranteed expansiveness, interplay with current building infrastructure and flexibility to various occupancy patterns and climatic conditions. On the bottom layer, there is the sensing and data acquisition layer, which receives real time information about the environment and its occupants. This incorporates thermal parameters like temperature and carbon dioxide concentration, presence and occupancy detection by special sensors. Furthermore, wearable and behavioral inputs can give more detailed information about activity and behavior of occupants in terms of comfort. These nonhomogenous data streams structure the empirical basis of the system, which allows precise description of physical situations in addition to human factor in the indoor space.

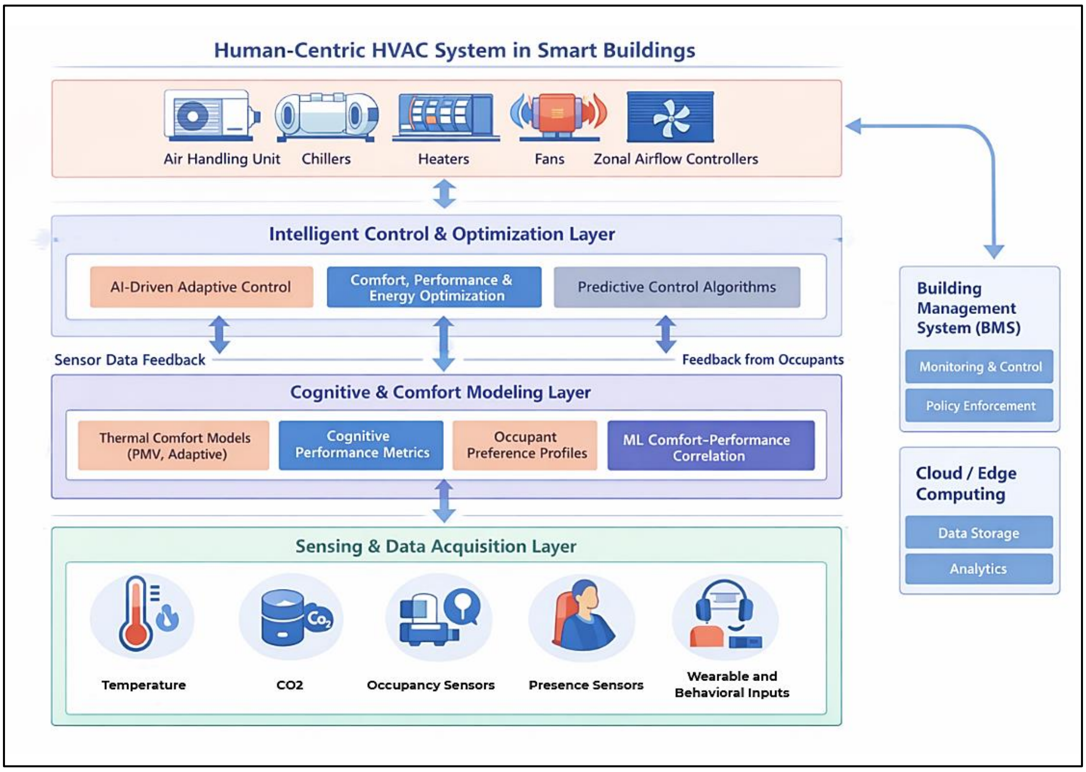

Fig 1: Architecture of the Proposed Human-Centric HVAC System for Smart Buildings

The cognitive and comfort modeling layer processes the acquired data to derive higher-level interpretations of occupant comfort and performance. Thermal comfort models such as PMV and adaptive comfort models are utilized and these are used in conjunction with cognitive performance measures and occupant preference profiles. The machine learning elements developed in this layer are trained on dependencies between the states of comfort, indicators of cognitive performance, and environmental factors, which will enable the system to go beyond the fixed-point comfort prediction to a stage of predictive and personalized modeling. Most importantly, intelligent control and optimization layer combines comfort, cognitive performance and energy goals into one integrated control strategy. Adaptive control and predictive algorithms based on AI are dynamically generated to produce HVAC control actions with sensor feedback and response to occupants. These choices are implemented by the human-oriented system components in the HVAC system i.e. the air handling units, chillers, heaters and zonal airflow controllers. It is also found in the architecture that interfaces with the building management system and cloud or edge computing platforms, which allows centralized monitoring, enforcement of policies, data storage and advanced analytics. Together, these layers form a closed-loop, occupant-aware HVAC control framework that balances comfort, performance, and energy efficiency.

4.2. Sensing and Data Acquisition Layer

The figure illustrates the sensing and data acquisition layer that forms the foundation of the proposed human-centric HVAC architecture. The task of this layer is to gather real-time data on the physical surroundings including the occupant presence in space, which allows defining the physical conditions and human activity in a proper way. The environmental sensors constantly observe the main thermal and air quality characteristics, such as temperature, humidity, and carbon dioxide concentration that has a direct impact on thermal comfort and ventilating needs. Simultaneously, occupant sensing units detect occupancy and approximate the number of occupants available to augment contextual information on dynamic HVAC control.

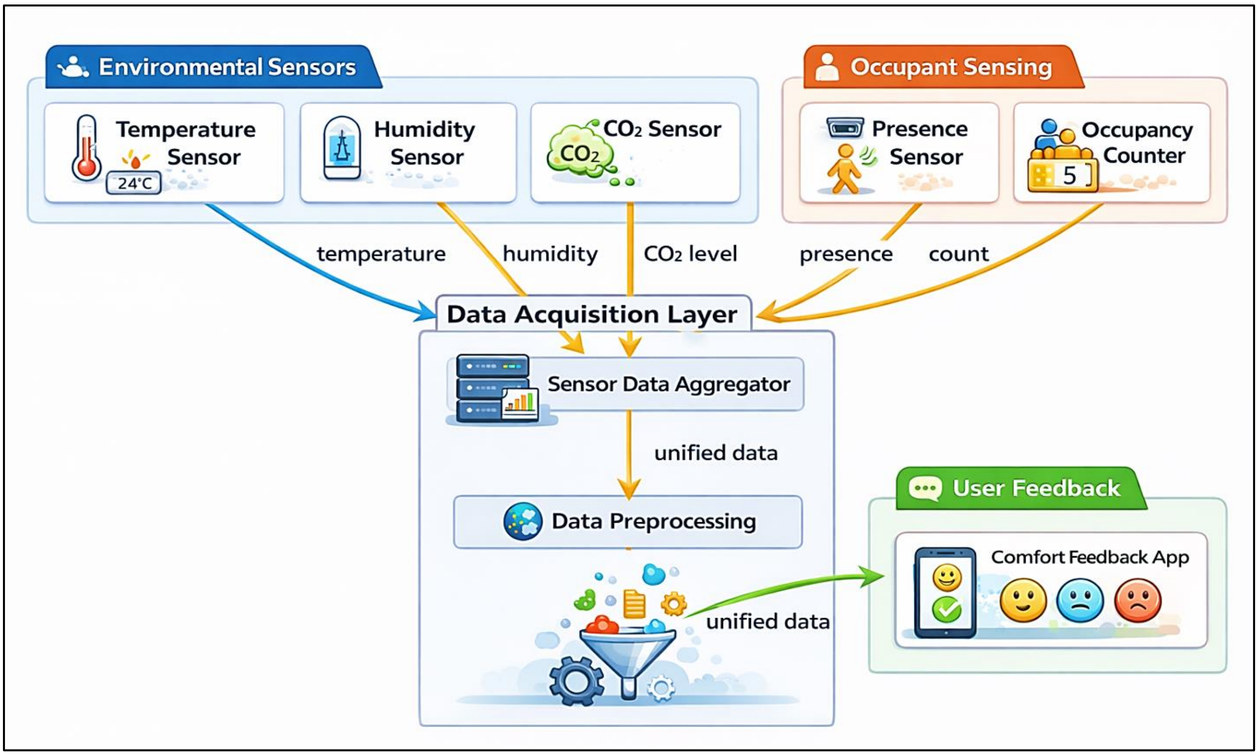

Fig 2: Sensing and Data Acquisition Layer of the Proposed Human-Centric HVAC System

The sensor data received are sent to a centralized data acquisition layer, which a sensor data aggregator is used to combine heterogeneous data into a single data stream. This consolidation model addresses disparities in sampling rate, data formats and sensor modalities and these allow coherent downstream analysis. The next data preprocessing phase carries out the necessary preprocessing which includes noise reduction, normalization, and time alignment, so that the data can be trusted and can be further processed by some more advanced comfort modeling and control methods. The raw sensor outputs are processed through these mechanisms into high-quality and structured inputs to make intelligent decisions. Besides the passive sensing, the figure calls out the incorporation of explicit user feedback in the form of a comfort feedback application. This interface will enable occupants to input subjective comfort perception and this human-in-the-loop input is appreciated and will supplement the sensor-based measurements. The layer of sensing and data acquisition considers the opinions of users and objective environmental data in order to provide more personalized comfort assessment and enhance the flexibility of the overall HVAC control framework.

4.3. Cognitive and Comfort Modeling Layer

The cognitive and comfort modeling layer serves as the analytical core of the proposed human-centric HVAC framework, transforming preprocessed sensor and user feedback data into actionable representations of occupant comfort and performance. It is a layer that associates the already existing thermal comfort models, including Predicted Mean Vote (PMV) and adaptive comfort formulations, and contextual contributions based on occupancy and environmental behaviors. With such a combination of models, the system can estimate both population-scale trends of comfort, as well as individualized comfort, taking into consideration the differences and adaptation of human beings with time.

In addition to the thermal feeling, this layer directly uses cognitive performance modeling to reflect how the indoor environmental conditions influence occupant productivity and mental effectiveness. The mental indicators, such as the level of attention, reaction time, and task performance proxies, are determined based on the context, and behavioral patterns, instead of being determined by the intrusive measurements. The methods used to learn the correlations of environmental variables, perception of comfort, and cognitive performance indices on a long-term basis are machine learning methods. Such data-driven models can be used to perform predictive evaluation of the impacts of the variation in thermal and air quality conditions on not only the comfort but also the cognitive outcomes to facilitate the proactive decisions that should be made by HVAC operations. By fusing objective sensor data with subjective occupant feedback, the cognitive and comfort modeling layer establishes a human-aware representation of the indoor environment. Such a representation enables the system to reconsider the fixed comfort thresholds and also reason concerning the dynamic comfort-performance trade-offs. Consequently, the layer delivers high-level comfort and cognitive state estimates which directly base the downstream optimization and control systems.

4.4. Control and Actuation Layer

The control and actuation layer interprets the results of the cognitive and comfort modeling layer into tangible actions of the HVAC control. This layer performs the role of dynamically controlling system settings, e.g. temperature setpoints, airflow rates, ventilation and equipment run-to-run schedules, based on predicted comfort and cognitive performance. The use of intelligent control strategies, such as adaptive control and predictive optimization, is used in order to balance the occupant-centric goals with energy efficiency and operational constraints.

Sophisticated control routines in this layer take advantage of real-time feedback and future forecasting to rationalize the HVAC behavior in the varying conditions. Weather, occupancy and internal heat gain variations are foreseen in predictive control mechanisms that allow proactive responses that reduce energy use and still provide the desired level of comfort and performance. Continuous feedback loops are also supported by the system and then the control policies can be improved with time with regard to the observed responsiveness of occupants and performance of the system. Control commands are performed at the actuation level using HVAC elements that include air handling units, chillers, heaters, fans, and zonal airflow controllers. The building management system integration helps to track the coordination of the functioning of the building, monitor and implement policies throughout the building infrastructure. By providing a closed-loop interaction between the modeling, the control, and the actuation, the proposed architecture is able to provide the regulation of the indoor climate in a responsive and personalized way and also in an energy-efficient manner.

5. Thermal Comfort and Cognitive Performance Modeling

5.1. Mapping Thermal Variables to Comfort Indices

Mapping physical environmental variables to meaningful comfort indices is a fundamental step in human-centric HVAC system design. Basic thermal parameters, which include air temperature, [13-15] relative humidity, air velocity, and mean radiant temperature, are also measured all the time and combined with individual parameters like metabolic rate and clothing insulation. These inputs are calculated to derive standardized comfort indices including most noteworthy Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), to give numeric estimations of the level of thermal sensation and level of dissatisfaction with the thermal environment. Although these indices provide a stable point of reference of comfort, they may not be suitable in dynamic and non-homogeneous indoor settings. To overcome this, adaptive comfort models are used, where the indices of comfort vary with the climatic conditions, occupancy behavior and temporal adaptation to the outdoor environment. This mixed mapping technique allows more vigorous and contextual estimation of comfort in a variety of building operation regimes.

5.2. Cognitive Performance Indicators and Measurement Techniques

Cognitive performance measurements are the ones that mediate the relationships between indoor environmental quality and occupant productivity. The most important cognitive measures are attention span, the speed at which one can react, speed of task completion, error rate and perceived mental workload. Task-based tests, computer-based cognitive tests and observational performance measures are the common methods of assessing these indicators in a controlled setting. In practical building use, actual testing of the mind is not a convenient thing to do, thus the use of indirect measurement methods is commonly becoming popular. They are behavioral pattern inference, occupancy dynamics, quality of indoor air, and self-reported productivity/comfort feedback. Improved sensing and data analytics can be used to provide non-intrusive estimates of the trends in cognitive performance, which can be used by HVAC systems to account for the impact of human performance on the systems without interfering with their activity.

5.3. Machine Learning Models for Comfort–Performance Correlation

Machine learning models play a critical role in capturing the complex and non-linear relationships between thermal conditions, comfort perception, and cognitive performance. Regression model and neural networks, which are supervised learning methods, are used to predict the relationship between environmental and behavioral characteristics with comfort and performance output based on past events. The unsupervised and semi-supervised methods also enable the discovery of patterns and personalization, detecting preferences and adaptation patterns of the occupants. These models keep being updated as new data are received and the system can learn new changing relationships between comfort and performance as the system evolves. The proposed framework with predictive machine learning model incorporated into the HVAC control pipeline allows changing the states in the building proactively, prioritizing the welfare of occupants and energy efficiency of the building simultaneously.

6. Energy Efficiency Optimization Strategies

6.1. Energy Consumption Characteristics of HVAC Systems

HVAC systems are some of the highest energy consuming subsystems in commercial and residential buildings, and the energy consumption is being fueled by thermal loads, building occupancy, equipment efficiency, and control approaches. [16-18] External climatic conditions, interior heat gains associated with occupants and equipment, and the characteristics of a building envelope are all factors that affect the heating and cooling requirements. The conventional HVAC operation has been based on fixed schedules and setpoints that may be switched off leading to over-conditioning of the system during low occupancy conditions or mild weather. Also, the energy cost associated with ventilation requirements is associated with indoor air quality, which is a high cost especially in a crowded space. The knowledge of these consumption attributes is critical in pinpointing the inefficiencies and contriving optimization measures that will be dynamic in the real-time building conditions as opposed to depending on worst-case assumptions.

6.2. Trade-Off Analysis between Comfort and Energy Use

To achieve optimization of HVAC performance, there is a need to balance the objective of comfort of the occupants and the energy efficiency objectives which are usually in conflict. Narrow comfort bands and high aggressive conditioning plans are able to enhance perceived comfort, and generally result in higher energy use and peak demand. Conversely, relaxed temperature setpoints and adaptive comfort approaches can significantly reduce energy use but may introduce discomfort for certain occupants or activities. Human-focused HVAC systems can counter this trade-off by the inclusion of the range of comfort tolerance, adaptive preferences, and cognitive performance thresholds in optimization. The multi-objective optimization methods will allow considering comfort measures, the effects of the system on cognitive performance, and energy uses at the same time, such that the system can find operating points that obtain reasonable comfort levels with limited energy usage. The proposed framework can assist in choosing human-friendly and customizable HVAC control strategies, which are informed and adaptable to the given trade-offs, and can support energy sustainability and human well-being.

7. Experimental Setup and Methodology

7.1. Testbed Description and HVAC Configuration

The experimental evaluation of the proposed human-centric HVAC framework is conducted using a controlled smart building testbed designed to emulate real-world indoor environments. [19,20] The testbed has a series of conditioned areas with independent HVAC units, making it possible to control zonally the temperature, airflow and ventilation rates. Environmental sensors can measure thermal conditions and indoor air quality in each zone whereas presence and occupancy detectors can offer real-time contextual awareness. The HVAC design not only helps in the traditional rule based control of the system, but also in the smart adaptive control mode, permitting system performance to be compared under the same environmental and occupancy conditions. Coupling to a building management system can be used to undertake centralized observation, data recording, and imposition of operational limits during the experiment.

7.2. Data Collection Protocol

Continuous data collection over long periods of operation is done in order to capture a varied environment of conditions, occupancy conditions as well as the interactions of the users. The environmental parameters like temperature, humidity, and carbon dioxide concentration are sampled periodically and occupancy and presentational data is obtained in near real-time. Besides sensor-based measurements, the subjective response to comfort of the occupants is also periodically measured in the form of a digital interface allowing correlating the objective conditions with perceived comfort. After preprocessing (filtering, normalization and outlier detection) all data streams are time synchronized and stored in a central repository. This organized procedure guarantees uniformity of data, and facilitates powerful training and assessment of comfort, cognitive execution and control designs.

7.3. Performance Evaluation Metrics

System performance is evaluated using a combination of comfort, cognitive performance, and energy efficiency metrics. Standardized, or PMV and PPD, indices of thermal comfort are evaluated with occupant-rated measures of comfort. The performance in cognitive terms is measured using an indirect measure such as the proxies of task efficiency, where available, response times, and subjective measures of productivity. The performance measures of energy usage are total HVAC energy use, peak demand and energy savings as compared to the baseline control measures. Through a collective evaluation of these indicators, the experimental approach allows one to give a complete evaluation of how the proposed framework can propose a balance between the well-being of the occupants and energy efficiency when operating under realistic conditions.

8. Results and Discussion

8.1. Thermal Comfort Improvement Analysis

These findings suggest that HVAC control strategies, which are human-centric, are highly effective in providing thermal comfort as opposed to the traditional fixed-setpoint control systems. Long-term comfort periods through the use of field implementations of IoT-enabled sensing and reinforcement learning-based control show dynamically adjusted comfort periods with respect to occupant behavior, preferences, and changes in climatic conditions. Individual airflow regulation and zonal conditioning will decrease local pain especially in non-homogeneous indoor settings. Computational fluid dynamics (CFD)-based validations further confirm that targeted air distribution improves thermal uniformity and perceived comfort. Besides, the introduction of explicit occupant feedback into the zoning strategies allows the continual improvement of the control policies, which leads to a greater level of overall satisfaction in both building types.

Table 1: Thermal Comfort Improvement Outcomes

Metric	Improvement
Comfort Duration	+24%
Thermal Satisfaction	+18.8%
PPD Reduction	Achieved via 6 L/s PV

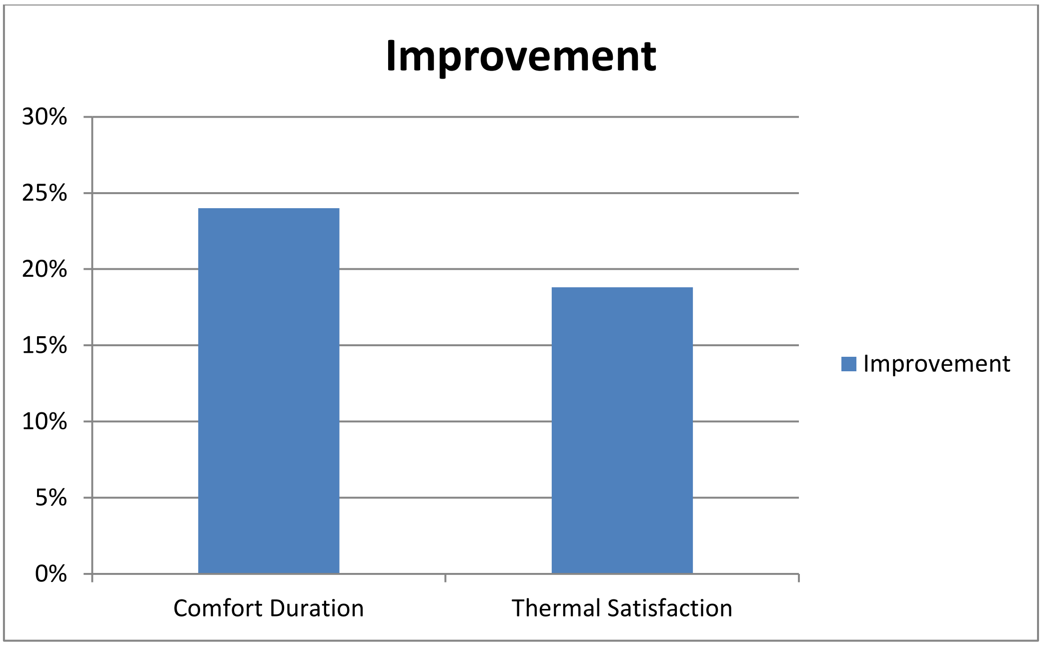

Fig 3: Improvement in Thermal Comfort Metrics under Human-Centric HVAC Control

8.2. Cognitive Performance Outcomes

The comparison of the results of a cognitive performance demonstrates that there is a definite correlation between controlled thermal conditions and increased mental efficiency. Through empirical research it has been demonstrated that keeping the internal temperatures at 20–24 °C is more efficient in improving the speed and accuracy of cognition especially in activities that involve sustained attention. Adaptive HVAC controls also aid in maintaining cognitive performance in changing thermal loads by reducing thermal stress and sudden changes in the environment. Also, the strategies to optimize ventilation do not allow impairment of attention and reasoning because the quality of indoor air remains at decent levels. These results confirm the use of cognitive performance indicators as an additional goal together with thermal comfort in the design of HVAC systems.

Table 2: Cognitive Performance Results under Controlled Thermal Conditions

Outcome	Key Result
Reaction Time	Improved at 20–23 °C
Accuracy	Stable within 22–31 °C
Productivity	Enhanced through comfort

8.3. Energy Efficiency Gains

Energy performance analysis shows that occupancy-sensitive HVAC systems save high amounts of energy with no reduction in comfort. Human-in-the-loop models based on reinforcement learning help decrease air conditioning energy use by up to 75% through learning to take the most effective control measures in different occupancy and climatic situations. Occupancy-aware model predictive control also leads to the achievement of uniform savings of energy since the system operation is adjusted in advance based on the predicted demand. New strategies based on physiological and behavioral measurements permit the fine balancing of fan use and active cooling to allow peak gains in efficiency at the zone and system scales.

Table 3: Energy Efficiency improvements Achieved by Human-Centric HVAC Systems

Gain	Savings
AC Usage	24.7% reduction
Total Energy	18–25% savings
Cooling Load	Optimized via RE-CBA

8.4. Comparative Evaluation with Conventional HVAC Systems

In comparative analysis, it is always observed that human centric HVAC systems are superior to conventional fixed-setpoint systems in terms of comfort, cognitive, and energy measures. Traditional systems are also inclined to make assumptions in relation to occupancy and use that are always static, which results in over-conditioning and waste of energy. On the contrary, occupant-based models evolve dynamically to the real-life experience of building utilization, eliminating waste, and sustaining or enhancing the comfort levels. Field experiments and computer simulation validation prove that these systems can deliver comfort and energy efficiency gains simultaneously, and that these systems improve dual-objective performance by more than 20% in comparison to operating a conventional HVAC.

Table 4: Comparison between Human-Centric and Conventional HVAC Systems

Aspect	Human-Centric HVAC	Conventional HVAC
Energy	24% lower	Baseline usage
Comfort	+20% improvement	Static levels
Savings	Dual-objective	Higher consumption

9. Future Directions and Conclusion

The HVAC human-centric systems of the future need to improve personalization, scalability, and the long-term adaptability. The modeling of the performance of comfort and cognitive issues can be enhanced further by incorporating richer physiological and behavioral cues, including wearable data that is unobtrusive and advanced occupancy inference. Moreover, implementing machine learning systems that facilitate continual and federated learning will allow the HVAC systems to be used across buildings and populations of users without violating data privacy. There will also be a need to make more emphasis on explainable and transparent control decisions in order to enhance user trust and enable real-life application in safety-critical building settings.

Another important direction involves tighter integration of human-centric HVAC systems with broader smart grid and renewable energy ecosystems. By integrating HVAC control with dynamic electricity pricing, demand response programs, and on-site renewable generation it is possible to achieve more energy savings and still ensure comfort of occupants. Moreover, the validity of the long-term effects of comfort-conscious and cognition-conscious HVAC control on the productivity, health, and sustainability outcomes requires large-scale and longitudinal field-based studies, which can be conducted across different climates and typologies of buildings. To sum up, this paper shows that the association of thermal comfort, human cognitive performance, and energy efficiency in one integrated human-incentive HVAC approach can be quite advantageous compared to the traditional control approaches. The proposed solution can help to attain better occupant well-being and significant energy savings by integrating real-time sensing, advanced comfort and cognitive modeling, and intelligent control. These results demonstrate the promise of human-centric HVAC systems as an important facilitator of sustainable, intelligent, and performance-based smart buildings, as a part of the overall vision of human-aware cyber-physical infrastructure in future cities.

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