

**Research Article**

Integration of Thermal Comfort Modelling and Digital Technologies for Sustainable Circular Economy Practices in Built Environments

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ABSTRACT

The convergence of thermal comfort research and digital technologies presents novel opportunities to enhance sustainability within built environments while simultaneously enabling circular economy practices. Thermal comfort has been extensively studied through both static and adaptive models, reflecting the complex interplay between human physiology, clothing behavior, environmental parameters, and occupant preferences (Fanger, 1970; De Dear & Brager, 1998; De Carli et al., 2007). Recent advancements in predictive maintenance, Internet of Things (IoT), and machine learning enable real-time monitoring and adaptive control strategies to optimize indoor environmental conditions, reduce energy consumption, and support sustainable practices across building operations (Farhan et al., 2015; Nayak, 2021). Furthermore, circular economy frameworks emphasize resource efficiency, product longevity, and digital integration to influence consumer behavior toward sustainable consumption (Chaudhuri et al., 2022; Charnley et al., 2022). This research synthesizes theoretical and applied knowledge from thermal comfort modeling, occupant behavior, and digital-enabled circular practices to propose a holistic framework for sustainable building management. Emphasis is placed on the interaction between occupant clothing adaptation models, digital monitoring technologies, and circular economy strategies, highlighting the potential to align human comfort with energy efficiency and resource conservation objectives. The findings suggest that combining advanced data-driven modeling of occupant thermal behavior with digital technologies can significantly reduce environmental impacts while supporting the transition toward circular operational models in buildings. This study addresses critical knowledge gaps by linking thermal comfort theory, predictive digital frameworks, and circular economy applications in a comprehensive analytical context.

KEYWORDS

Thermal comfort, adaptive modeling, digital technologies, circular economy, occupant behavior, IoT, predictive maintenance

INTRODUCTION

The built environment is responsible for a substantial proportion of global energy consumption, with heating, ventilation, and air conditioning (HVAC) systems being primary contributors (ANSI/ASHRAE, 2020). Historically, thermal comfort research has focused on static models, which predict occupant comfort based on fixed environmental and physiological parameters (Fanger, 1970). These models, while foundational, often fail to account for adaptive behaviors exhibited by occupants, such as clothing adjustments or modification of activity levels in response to indoor and outdoor environmental conditions (De Dear & Brager, 1998; People's clothing behaviour, 2007). The limitations of static models have driven the development of adaptive comfort frameworks that incorporate occupant agency and environmental context, enabling more accurate predictions of human thermal satisfaction (De Dear, 1998; Duhirwe et al., 2022).

Parallel to advancements in thermal comfort modeling, the proliferation of digital technologies, including IoT, machine learning, and predictive analytics, has transformed building management and operational efficiency (Farhan et al., 2015; Nayak, 2021). Real-time data collection and automated adaptive responses offer the potential to align thermal comfort with energy optimization, thereby reducing environmental footprints. Such technologies also serve as enablers for the circular

economy, where resource efficiency, product lifecycle extension, and sustainable consumption are prioritized (Cagno et al., 2021; Chauhan et al., 2022). The integration of digital technologies with circular economy principles extends beyond manufacturing into the operational phase of buildings, influencing occupant behavior and consumption patterns through intelligent systems and feedback mechanisms (Bücker et al., 2025; Chi et al., 2023).

Despite significant progress, critical gaps remain in synthesizing thermal comfort theory, occupant adaptive behaviors, and circular economy-oriented digital interventions. Existing research often isolates these domains, limiting the ability to design comprehensive solutions that simultaneously achieve occupant satisfaction, energy efficiency, and sustainability goals (Canto et al., 2021; Camacho-Otero et al., 2018). Additionally, most thermal comfort studies are localized and fail to consider geographically diverse occupant behaviors, which may influence the effectiveness of adaptive control strategies (Duhirwe et al., 2022; Földváry-Ličina et al., 2018). This research seeks to address these gaps by developing an integrated analytical framework that combines occupant thermal comfort modeling, data-driven digital interventions, and circular economy strategies, providing both theoretical and practical contributions to sustainable building management.

METHODOLOGY

This study adopts a multi-layered analytical methodology, integrating insights from thermal comfort research, digital technology applications, and circular economy frameworks. The approach emphasizes descriptive and theoretical elaboration, relying on extensive literature synthesis, case studies, and modeling conceptualization.

The first methodological component involves an exhaustive review of thermal comfort theories, beginning with the static model proposed by Fanger (1970), which utilizes heat balance equations and metabolic parameters to determine the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Subsequent adaptive models (De Dear & Brager, 1998) are examined, which consider occupant-driven environmental adjustments, including clothing adaptation, natural ventilation, and behavioral modifications. These models are further enriched by recent empirical studies of geographically extended clothing behavior using machine learning algorithms and convolutional neural networks to predict thermal responses across diverse climates (Duhirwe et al., 2022).

The second component of the methodology focuses on the integration of digital technologies for predictive and adaptive environmental management. IoT-enabled sensors and building management systems (BMS) provide high-resolution temporal data on temperature, humidity, occupancy, and energy consumption. Machine learning algorithms, including supervised regression models, neural networks, and reinforcement learning techniques, are applied to optimize HVAC operation, predict occupant thermal preferences, and adjust environmental

conditions in real-time (Farhan et al., 2015; Nayak, 2021). The methodology emphasizes the role of hyperparameter optimization and validation protocols to enhance prediction accuracy and generalizability.

The third component incorporates circular economy principles into building operations. Strategies include monitoring product lifecycle stages of building materials, optimizing resource utilization, and deploying digital feedback mechanisms to influence occupant behaviors toward sustainable consumption (Cagno et al., 2021; Charnley et al., 2022). Digital twin frameworks are leveraged to simulate scenarios in which energy efficiency improvements, thermal comfort adjustments, and circular economy strategies are jointly implemented, enabling a holistic understanding of operational outcomes.

Finally, the methodology emphasizes theoretical integration, examining the intersection between adaptive thermal comfort, digital technologies, and circular economy practices. The analytical approach prioritizes descriptive, high-level elaboration of potential interactions, benefits, and constraints, rather than focusing on quantitative experimentation. This enables extensive exploration of nuanced theoretical implications and practical operational insights.

RESULTS

The integration of adaptive thermal comfort models with digital technologies yields several descriptive outcomes. First, occupant thermal satisfaction is significantly influenced by clothing behavior and environmental adaptability. Models accounting for clothing insulation adjustments and

seasonal variation demonstrate higher predictive accuracy than static PMV models (De Carli et al., 2007; Duhirwe et al., 2022). Machine learning algorithms effectively predict individual thermal preferences, allowing building systems to preemptively adjust HVAC settings, thereby improving comfort while reducing energy consumption (Farhan et al., 2015).

Second, digital technologies facilitate operational efficiency by enabling real-time monitoring and predictive maintenance. IoT sensors capture granular data on indoor environmental conditions, which, when processed through machine learning algorithms, allow for optimized HVAC scheduling, anomaly detection, and preventative maintenance. These systems support both occupant comfort and environmental sustainability objectives by minimizing unnecessary energy expenditure and reducing greenhouse gas emissions (Nayak, 2021).

Third, circular economy frameworks benefit from digital integration in building management. Lifecycle monitoring of building materials, energy-efficient retrofitting, and occupancy-informed resource allocation contribute to reduced material waste and prolonged utility of infrastructure assets. Digital feedback mechanisms, such as energy dashboards and adaptive occupancy guidance, influence occupant behavior, encouraging resource-conscious consumption patterns aligned with circular economy principles (Chaudhuri et al., 2022; Chi et al., 2023).

Fourth, the combination of these approaches enables synergistic outcomes. By modeling thermal comfort adaptively, employing predictive digital technologies, and embedding circular economy principles, buildings can simultaneously

achieve high occupant satisfaction, operational efficiency, and sustainability goals. Digital twin simulations suggest potential reductions in energy consumption by up to 25-30% when these integrated strategies are applied in diverse climatic and operational contexts, though exact figures are contingent on site-specific variables and occupant behaviors (Földváry-Ličina et al., 2018; Chauhan et al., 2022).

DISCUSSION

The descriptive findings highlight several theoretical and practical implications. Adaptive thermal comfort models demonstrate the importance of considering occupant agency and context-specific behaviors in environmental management. The failure of static models to account for behavioral variability can lead to overconditioning and energy inefficiency, underscoring the necessity for integrated adaptive frameworks (De Dear & Brager, 1998; De Carli et al., 2007). Clothing behavior, as a key adaptive mechanism, exhibits geographical variation influenced by climate, culture, and seasonal patterns, necessitating context-specific modeling approaches for accurate prediction (Duhirwe et al., 2022).

Digital technologies function as critical enablers of operational efficiency and circular economy implementation. Predictive maintenance and IoT monitoring not only improve building system performance but also facilitate resource optimization and occupant-informed decision-making. Machine learning algorithms enhance system intelligence by enabling anticipatory adjustments based on historical and real-time data,

reducing both energy consumption and environmental impact (Farhan et al., 2015; Nayak, 2021). Moreover, the adoption of digital twin frameworks permits scenario testing and optimization of complex operational strategies without incurring material or energy waste.

The intersection with circular economy practices introduces additional layers of theoretical richness. By extending the lifecycle of building materials, promoting resource-efficient consumption, and reducing waste streams, circular approaches contribute to the environmental sustainability of building operations. Digital technologies facilitate these objectives by providing actionable insights, automated feedback loops, and occupant behavior nudging, thereby aligning human comfort and operational efficiency with broader sustainability goals (Cagno et al., 2021; Chauhan et al., 2022; Charnley et al., 2022).

However, several limitations warrant consideration. First, predictive accuracy is dependent on the quality and granularity of sensor data, which may be variable across installations. Second, occupant acceptance of adaptive systems and circular economy interventions may vary, requiring context-specific engagement strategies. Third, while digital simulations suggest significant potential energy savings, real-world implementation may encounter unforeseen operational constraints, highlighting the need for continuous monitoring and iterative adaptation.

Future research directions include the development of globally representative adaptive comfort datasets, integration of occupant psychophysiological monitoring, and enhanced machine learning algorithms capable of capturing

nuanced individual and group behaviors. Furthermore, the exploration of scalable digital-circular frameworks across different building typologies and climates will provide critical empirical validation and operational insights.

CONCLUSION

This research synthesizes insights from thermal comfort theory, digital technologies, and circular economy principles to propose an integrated framework for sustainable building management. Adaptive models of occupant behavior, when combined with predictive digital technologies and circular operational strategies, enable simultaneous achievement of comfort, energy efficiency, and environmental sustainability. The descriptive analysis underscores the importance of clothing adaptation, real-time monitoring, and digital feedback mechanisms in optimizing building operations. The integration of these approaches not only advances theoretical understanding of human-environment interactions but also provides practical pathways for operationalizing circular economy practices within the built environment. Continued research and implementation will be essential for scaling these strategies globally, ensuring that human comfort and sustainability objectives are mutually reinforcing rather than competing.

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