The impact of adaptive thermal comfort on energy savings in office buildings under various insulation levels

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ABSTRACT

Heating and cooling contribute to the lion's share of building energy demand. To reach the net-zero target, building thermal management plays an important role. This is especially the case for office buildings with large, shared spaces where individual occupants have less freedom over the temperature settings. Many office buildings tend to maintain strict temperature conditions without considering adaptive thermal comfort opportunities. Some studies investigated the impact of adaptive thermal comfort on energy demand but focused only on a specific building. This work seeks to explore this impact on energy savings across various building fabric types. First, an office building based on the Civil Engineering building at Cambridge University was modelled using Dynamic modeling simulation - DesignBuilder with Energy Plus. The model was calibrated and validated using comprehensive datasets such as energy consumption, building physical parameters obtained from the building sensors, and other estate records. The model was then incorporated with a diversified profile of insulation scenarios. Forty variations have been tested in the modeling simulation to compare the energy demand changes and subsequent energy saving outputs. The results show that despite insulation variations, the percentage of energy savings achieved through an adaptive thermal comfort approach remains relatively stable, between 11% and 15%. This has implications for facility management practice in office buildings - regardless of how well the building is insulated, extending the temperature setpoints to allow comfort adaptation can yield anticipated energy demand reduction.

Introduction

Adaptive thermal comfort strategies are crucial for achieving net-zero targets in building design and operation. Traditional fixed-setpoint temperature control systems often result in excessive energy consumption as they attempt to maintain a narrow and rigid comfort range. In contrast, adaptive thermal comfort allows for a dynamic response to changing environmental conditions, permitting occupants to acclimate to a broader temperature range without compromising their well-being.

Adaptive thermal comfort is a concept where occupants tend to feel more comfortable with a wider range of indoor conditions, such as temperature settings, linked to outdoor climate conditions and more control of their own environment. This flexibility in thermal expectations empowers buildings to capitalize on natural climate variations, reducing the need for energy-intensive heating and cooling. By aligning indoor conditions with the external environment and leveraging occupants' adaptability, energy consumption decreases, making a significant contribution to the overall energy performance of a structure. The integration of adaptive thermal comfort not only aligns with sustainable and occupant-centric design principles but also proves essential in pursuing net-zero targets by minimizing the carbon footprint associated with heating, ventilation, and air conditioning (HVAC) systems.

Numerous studies have delved into the concept of adaptive thermal comfort, exploring its implications for building design, energy efficiency, and occupant satisfaction. Some notable existing research is shown in Table 1.

Table 1. Existing research on adaptive thermal comfort

Type of study/output	Example(s)
Industry standard	ASHRAE Standard 55 (2020): The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides a comprehensive standard that defines the conditions for thermal comfort and emphasizes the importance of adaptive comfort models.
Assessment tool	CBE Thermal Comfort Tool (Tartarini et al. 2020): Developed by the Center for the Built Environment (CBE) at the University of California, Berkeley, this tool incorporates adaptive comfort principles and offers a user-friendly interface for assessing thermal comfort in buildings.
Model	Fanger’s Comfort Model (1970): Pioneered by Professor Ole Fanger, this model proposes that thermal comfort is not static but rather adaptive, influenced by factors such as clothing insulation, metabolic rate, and personal preferences.
Behavioral adaptation	Research conducted by the International Energy Agency (IEA) explores how occupant behavior, including adaptive thermal comfort, affects energy use in buildings (Yan and Hong 2018). It underscores the importance of understanding and incorporating these behaviors into energy-efficient building design.
Field Studies on Adaptivity	Various field studies, such as those examining naturally ventilated buildings or those in moderate climates, have investigated how occupants naturally adapt to different thermal conditions (Lamsal, Bajracharya, and Rijal 2023; de Dear and Brager 2002; Chappells and Shove 2005; Nicol and Humphreys 2002). These studies contribute valuable insights into the practical application of adaptive comfort principles.
Acceptability of Fluctuations	Studies have explored the acceptance and tolerance levels of occupants concerning indoor temperature fluctuations (Mishra, Loomans, and Hensen 2016). Understanding the range of comfort and adaptability helps in designing energy-efficient systems that align with occupants’ expectations (Rupp, Vásquez, and Lamberts 2015).

While these studies collectively enhance our understanding of adaptive thermal comfort, there remains a need for more research, particularly in specific contexts like office buildings or regions with extreme climates, to further refine guidelines and recommendations for sustainable and occupant-friendly building design. Human behavior varies across climate zones and cultures, this is especially heterogeneous across workplace where dress code, etiquette and organizational practices are concerned.

The literature on the impact of adaptive thermal comfort on energy savings in office buildings reveals a growing recognition of the dynamic relationship between occupant comfort preferences and building energy performance. Studies have explored the benefits of allowing occupants to adapt to temperature variations, emphasizing the potential for reduced energy consumption when compared to rigid, fixed-setpoint control systems (Balaras et al. 2002; Jenkins, Liu, and Peacock 2008). Additionally, research has considered the influence of building fabrics on thermal comfort, highlighting the need for a balance that optimizes energy efficiency without compromising occupant well-being. The insulation level of building fabric also has a sizable impact on building energy consumption, offering savings of up to 25.5% (Kim and Moon 2009; Fang et al. 2014; Paraschiv et al. 2021).

However, a notable gap in the literature is the limited exploration of how occupants' adaptive thermal behaviors would yield energy savings when offices insulation levels vary. While some studies touch on adaptive comfort in residential and office spaces (O'Brien and Gunay 2014; Ming et al. 2020; Liu et al. 2021), they do not sufficiently examine the nuanced demands and occupant behaviors in office environments with varying insulation levels. Understanding how insulation impacts adaptive thermal comfort in professional settings is crucial for tailoring energy-saving strategies that align with the needs and expectations of office occupants (Lee 2006). Addressing this gap will contribute valuable insights to the ongoing discourse on sustainable building practices, informing more targeted and effective demand reduction solutions for office spaces.

This research paper delves into the intricate relationship between adaptive thermal comfort and energy conservation in office buildings, particularly when subjected to varying insulation levels. As the demand for environmentally conscious design intensifies, understanding how occupants dynamically adjust to thermal conditions becomes imperative. By scrutinizing the interplay of adaptive comfort and insulation, this study aims to illuminate nuanced strategies for optimizing energy use without compromising occupant well-being. The findings promise to inform architects, policymakers, and building practitioners, guiding the evolution of eco-friendly office spaces.

Methodology

The study used the Civil Engineering Building at the University of Cambridge as a case study (Figure 1). This building, completed in 2019, has diverse occupancy, sophisticated architectural design, and existing sensor infrastructure. It has advanced environmental design for the building's energy efficiency and renewable energy provision (Table 2). In particular, the ground source heat pump and 325m^2 photovoltaic array contribute 9080 kgCO$_2$/year and 18930 kgCO$_2$/m^2, respectively, to give a total contribution of 38% emissions reduction compared to a 'standard' design, well over the regulatory requirement. Its modern and efficient design reflects the principles of sustainable architecture, aligning with the university's commitment to environmental responsibility. Designed with the specific needs of the Civil Engineering Division in mind, the building houses approximately 5000m^2 of state-of-the-art laboratories, lecture halls, research spaces, and faculty offices. It serves as a dynamic environment where students, researchers, and faculty members converge to explore and advance the frontiers of civil engineering knowledge. The building incorporates green design principles, energy-efficient systems, environmentally friendly materials, and sustainable construction practices that contribute to the building's low environmental impact.

Table 2. Advanced environmental design for the Civil Engineering Building

	Environmental design characteristics
1)	High fabric performance
2)	Limit of solar gain
3)	Good daylighting throughout
4)	Consideration of embodied energy of materials
5)	Provision of showers to encourage cycling
6)	Use of blue roof which temporarily stores rainwater
7)	Natural ventilation with a combination of automatic and manual openings
8)	Local mechanical ventilation with heat recovery
9)	Ground source heat pump incorporating heat transfer between spaces within the building for low energy heating and cooling provision
10)	10.8 kW photovoltaic (PV) array for solar electricity production with a potential to generate 5,242 kWh/year
11)	BREEAM excellent target (BRE 2024)
12)	Compliance with the criteria set out in CIBSE TM52 (Nicol and Spires 2013) considering thermal comfort criteria
13)	Flexible provision of services including high level distribution and connectivity

Figure 1. Civil Engineering Building at Cambridge University.

Creating a comprehensive model of the office space involved utilizing cutting-edge technology and simulation tools. Dynamic modeling simulation was employed through DesignBuilder, which uses the EnergyPlus engine, to craft a highly detailed and sophisticated representation of the Civil Engineering building's office environment (Figure 2). This strategic choice was driven by the platform's capability to provide an in-depth analysis of thermal dynamics, considering a multitude of factors such as solar gains, occupancy patterns, and HVAC systems, which are critical to the overall energy performance of the space.

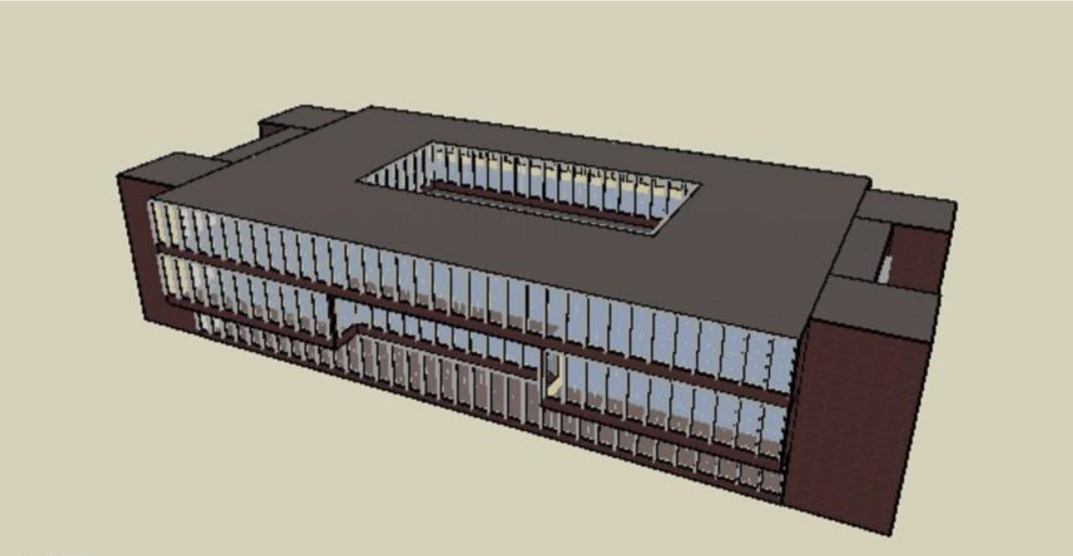
Figure 2. Model of Civil Engineering building constructed in Design Builder.

The model was calibrated and validated using comprehensive datasets such as energy consumption, building physical parameters obtained from the building sensors, and other estate records such as documents for the building design and construction from the Royal Institute of British Architects (RIBA). The calibration phase involved adjusting the model parameters to align simulated results with real-world data. Subsequent validation confirmed the model's ability to accurately predict the building's energy performance under varying conditions accurately.

The heart of our investigation lies in the exploration of diverse insulation scenarios. These scenarios were developed based on five building fabric types (Table 3: BF1 to BF5) that are representative of buildings constructed through different periods (Korolija et al. 2013). The U-values of major building fabric elements can be seen in Table 3: 1) BF1 has no insulation at all, which is typical for post second world war office buildings up to mid-sixties, representing over 40% of the existing UK office building stock (ODPM 2005); 2) BF2 has low level of insulation, representing buildings from mid-sixties and pre-1990 (with over 20% of the UK office building stock) (ODPM 2005); 3) BF3 complies with both Part L 1990 (DEWO 1990) and Part L 1995 (DEWO 1995), representing those constructed between years 1990 and 2002 (with around 15% of the UK office building stock) (ODPM 2005); 4) BF4 correspond to Part L building regulations relevant since 2002 (DTLR 2002) and have high level of insulation, which has just over 5% of the UK office building stock (ODPM 2005); 5) BF5 represents the current best practice (Korolija et al. 2013). Recognizing the pivotal role of insulation in regulating thermal conditions, we incorporated a range of insulation profiles, each representing different levels of thermal resistance. Forty variations were tested in the modeling simulation, encompassing various insulation materials, thicknesses, and placements within the building envelope, as well as strict and adaptive thermal comfort. These insulation scenarios were a mix and match of the different elements' values from the five fabric types. This is because some buildings might have had one or more insulations despite being built a long time ago. Mixing and matching these values would allow for a more comprehensive study of the insulation levels of different building types (Table 5). As such, the variations were simulated to compare the changes in energy demand and subsequent energy-saving outputs. The adaptive thermal comfort simulations, when compared with the base case conditions, i.e., strict comfort (Table 4), enable the evaluation of energy savings from adaptive thermal comfort. Studies have shown that the acceptable range of comfort temperature is 19 °C – 24 °C, considering not only health and comfort, but also workplace productivity (ANSI/ASHRAE 2020; Humphreys, Rijal, and Nicol 2013; Seppänen et al. 2004). The setback temperatures for heating and cooling are 15 °C and 32 °C, respectively, to allow optimal savings while the building is not occupied. For the simplicity of comparison, zoning and localized controls are not included but only the expanded temperature setpoints are considered. Weather profile for the simulation is set to the current year for the closest location available - London.

Table 3. Building fabric types

Building element	U-value [W/m^{2}K]				
	BF1	BF2	BF3	BF4	BF5
External wall (Ew)	1.62	0.54	0.40	0.32	0.24
Flat roof (Fr)	2.48	0.43	0.31	0.17	0.14
Ground floor (Gf)	1.03	0.82	0.34	0.25	0.14
Glazing (G)	5.87	3.15	2.73	1.92	1.78

Source: Korolija et al., *Energy and Buildings* 60 (2013) 152–162

Table 4. Thermal comfort scenarios

Scenarios	Heating temperature	Cooling temperature
Adaptive thermal comfort	19°C	24°C
Strict thermal comfort	21°C	22°C

Table 5. Modelling scenarios

No.	Combination of fabric types	No.	Combination of fabric types
1	BF1 (Ew+Fr+Gf+G)	11	BF3(Ew +Fr) +BF4(Gf +G)
2	BF1 (Ew+Fr+Gf) + BF2(G)	12	BF3(Ew) +BF4(Fr +Gf +G)
3	BF1 (Ew+Fr) + BF2(Gf + G)	13	BF4(Ew +Fr +Gf +G)
4	BF1 (Ew) + BF2(Fr +Gf + G)	14	BF4(Ew +Fr +Gf) +BF5(G)
5	BF2(Ew +Fr +Gf + G)	15	BF4(Ew +Fr) +BF5(Gf +G)
6	BF2(Ew +Fr +Gf) + BF3(G)	16	BF4(Ew) +BF5(Fr +Gf +G)
7	BF2(Ew +Fr) + BF3(Gf +G)	17	BF5(Ew +Fr +Gf +G)
8	BF2(Ew) + BF3(Fr +Gf +G)	18	BF5(Ew +Fr +Gf) +BF1(G)
9	BF3(Ew +Fr +Gf +G)	19	BF5(Ew +Fr) +BF1(Gf +G)
10	BF3(Ew +Fr +Gf) +BF4(G)	20	BF5(Ew) +BF1(Fr +Gf +G)

Results and Discussion

Our comprehensive analysis of the dynamic building energy simulation results has unveiled a surprising and noteworthy trend in the context of adaptive thermal comfort and energy savings. Findings show a significant consistency in the percentage of energy savings delivered by adaptive thermal comfort, across the diverse insulation scenarios (Figure 3). This introduces a fresh perspective into the intricate dynamics of implementing adaptive thermal comfort strategies in office buildings.

In this case, the simulations demonstrate that altering insulation levels within the building envelope does not exert a significant influence on the percentage of energy saving resulting from adaptive thermal comfort (Figure 3). This unexpected result prompts a reassessment of the traditional understanding of how insulation impacts energy efficiency in the context of adaptive thermal comfort. It suggests that, within the studied office environment, the adaptability of occupants to thermal conditions plays an important role in determining relative energy savings regardless of the insulation levels.

This result underscores the importance of considering adaptive comfort strategies as a crucial component in the pursuit of energy-efficient office spaces. While insulation is undeniably a vital factor in regulating thermal conditions, our findings suggest that its impact on overall energy savings may be less pronounced than previously thought when compared to the influence of occupant behavior and adaptability.

However, the absolute energy savings which arise from adaptive thermal comfort exhibit a direct correlation with the absolute energy demand of the building. Therefore, while the percentage of energy savings may not fluctuate significantly across different insulation scenarios, the amount of energy saved can vary significantly (between 27.05 kWh/m^2 and 51.66 kWh/m^2) (Figure 4). This correlation emphasizes the importance of a holistic approach to energy efficiency, considering both the building's thermal characteristics and the adaptive behavior of its occupants. It also demonstrates that the adaptability of occupants to thermal fluctuations could compensate for suboptimal insulation, leading to notable energy savings.

It is worth noting that this study shows the results from using one building’s geometry within one mild climate zone. Further studies would be useful to expand on this to examine different building geometries and function types across different climates. In addition, the modeling simulation has not considered the variation in temperature requirements for laboratories which might have different thermal settings compared to the rest of office spaces that are used for lectures and research offices.

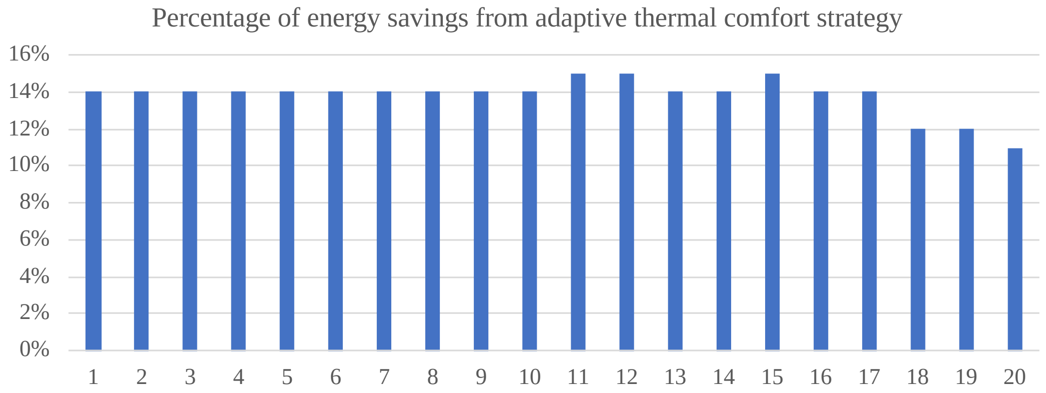

Figure 3. Relatively stable percentage of energy savings across different insulation levels (x axis indicates modelling scenarios – see Table 5).

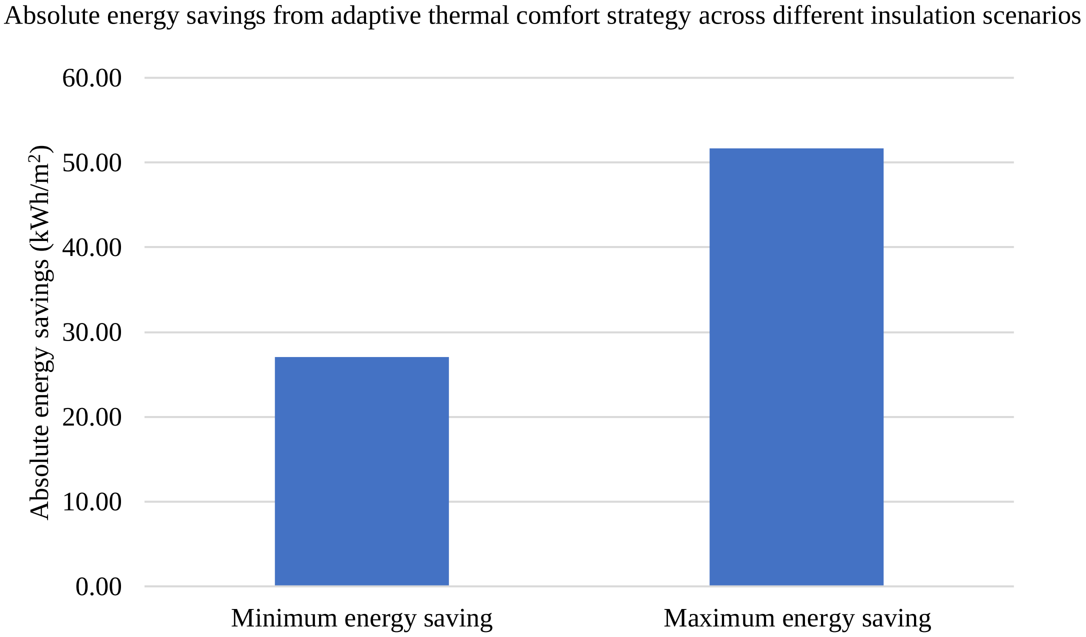

Figure 4. Minimum and maximum energy savings across different insulation scenarios using adaptive thermal comfort strategy.

Conclusions

This study shows that an adaptive thermal comfort approach can help reduce a sizable portion of building energy consumption regardless of the building insulation levels. It contributes to the growing body of knowledge on adaptive thermal comfort and its impact on energy savings in office buildings. Utilizing the Civil Engineering Building at the University of Cambridge as a case study, our dynamic building energy simulation approach provides nuanced insights into the intricate relationship between insulation scenarios, occupant adaptive thermal comfort, and energy demand. The findings underscore the potential for substantial energy savings by implementing adaptive thermal comfort strategies, informing sustainable building practices, and contributing to the global pursuit of net-zero targets. As we refine our understanding, this research lays the foundation for more targeted and effective strategies to balance occupant comfort and energy efficiency in office spaces.

These findings underscore the need for a nuanced and context-specific approach to sustainable building design. While insulation remains a critical consideration, the impact of occupant adaptability on energy efficiency cannot be understated. This knowledge contributes significantly to the ongoing discourse on optimizing office environments for energy conservation, laying the groundwork for more informed and targeted strategies to pursue sustainable and adaptive workplaces.

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