The Human Factors of Thermal Comfort, with Implications for Energy Efficiency

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Contents

List of Figures

List of Tables

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Introduction

This book delves deeply into the complex field of thermal comfort, highlighting its critical importance for enhancing energy efficiency. Rather than viewing energy efficiency through the traditional lens, this study adopts a sophisticated perspective, focusing on the intricacies of energy use and its sustainability implications. The research extensively utilises data gathered from both the United Kingdom and Spain, benefitting from various projects financed by the European Union and the United Kingdom. This approach ensures a comprehensive understanding of thermal comfort's role in achieving greater energy efficiency across different climatic and cultural contexts.

A comprehensive methodological framework informs this study, addressing salient research questions and utilising a multi-stage data collection strategy. Each data collection phase, meticulously planned and executed, targeted specific environments—ranging from residential to office spaces—and climatic conditions primarily in the UK and Spain. These phases were instrumental in gathering a diverse array of data, from ambient temperature readings to participant feedback on thermal comfort, thereby ensuring a rich and comprehensive dataset. Across all data collection phases, 131 participants contributed, enriching the study with a broad spectrum of insights. The seven research questions, central to the book, probe into the accuracy of existing models for predicting thermal comfort, the relationship between energy consumption and thermal comfort, and the impact of thermal comfort on productivity in office settings. The methodological narrative in this chapter articulates the rationale behind the multi-stage data collection strategy, detailing the objectives and outcomes expected at each stage. The methodology serves to elucidate the intricate relationships between thermal comfort and energy efficiency.

This research introduces an innovative suite of digital tools designed to enhance the research's analytical capabilities across different dimensions of energy efficiency and thermal comfort. The Bibliometric Analysis Tool, developed using R, streamlines the literature review process, enabling a thorough analysis of existing academic works. The Energy Baseline Tool, through detailed simulations, offers insights into energy consumption patterns and potential efficiency improvements in various building types. Utilising MATLAB, the Energy Consumption Simulations tool delves into the complexities of building energy use, providing a dynamic

understanding of how different factors interact to affect energy efficiency. Finally, the Thermal Comfort-based Thermostat Algorithm, implemented in the latter stages of the research, optimizes indoor climate controls based on real-time thermal comfort assessments, bridging the gap between theoretical insights and practical energy management solutions. Together, these tools form a cohesive framework that significantly advances the study's aim to explore the nuanced relationship between thermal comfort and energy efficiency.

This study meticulously explores thermal comfort, scrutinising the efficacy of the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models. It reveals nuanced gender differences in thermal perception and questions the universal applicability of the PMV model, while also pointing out the PPD model's limitations in accurately predicting discomfort across varied comfort levels. Further, the investigation into the relationship between energy consumption and thermal sensation highlights the complexity of this interaction, advocating for adaptive models that can accommodate individual differences. An innovative algorithm developed for setting temperature points showcases a potential strategy for enhancing thermal comfort while optimising energy efficiency, particularly in office environments. These findings underscore the importance of a more individualised approach to thermal comfort, suggesting adjustments to current standards to better reflect human perfromance and ennergy efficiency.

The book culminates in a comprehensive synthesis of findings and contributions across all explored research questions, offering a solid foundation for future research directions. By integrating insights from psychology and engineering, this work significantly enhances occupant well-being and promotes sustainable energy utilisation. A pioneering approach was adopted through the bibliometric analysis method that clusters abstract terms, enriching the depth of literature review insights. The introduction of the HDD.E concept emerges as a pivotal link between thermal sensation and energy modelling, advocating for a more nuanced incorporation of human factors into thermal comfort research. This book advances methodologies for evaluating improvements in building energy performance, while also spotlighting gender-based differences in thermal perception, thus making a case for adjustable temperature settings to accommodate diverse needs.

It critically assesses the Predicted Percentage of Dissatisfied (PPD) model's efficacy in capturing the nuances of thermal discomfort, advocating for a more intricate understanding of comfort. Notably, a significant link between thermal comfort and productivity within office settings is established, underscoring the potential benefits of optimising indoor climates for enhanced work performance. Moreover, the introduction of a novel thermostat algorithm that provides real-time feedback marks a groundbreaking advancement in indoor climate control, recognised

for its innovative impact. These manifold contributions signify a considerable leap towards more sustainable, occupant-centred building practices and energy management. They guide future investigations and practical applications in the quest for creating indoor environments that are not only energy-efficient but also supremely comfortable for their occupants.

List of Abbreviations

TU . . . . . Teesside University.

PMV . . . . . Predict Mean Vote.

SSSHL . . . . School of Social Sciences, Humanities & Law.

RQ . . . . . Research Question.

PPD . . . . . Predict Percentage Dissatisfied.

EU . . . . . European Union.

UK . . . . . United Kingdom.

UK.S . . . . . United Kingdom Summer.

UK.W . . . . . United Kingdom Winter.

ES . . . . . Spain.

ES.S . . . . . Spain Summer.

GHG . . . . . Green House Gases.

ASHRAE . . . American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

DR . . . . . Demand Response.

CSCC . . . . . Conference on Circuits, Systems, Communications and Computers.

IEEE . . . . . Institute of Electrical and Electronics Engineers.

ICESF . . . . . International Conference on Energy and Sustainable Futures.

NNSS . . . . . Nudge nudge switch switch.

HVAC . . . . . Heating Ventilation Air Conditioning.

PD . . . . . Proportional Derivative controller .

PID . . . . . Proportional Integrative Derivative controller.

SSL . . . . . Solid State Lighting.

DH . . . . . District Heating.

ACC . . . . . Adaptive Cruise Control.

BIM . . . . . Building Information Modelling.

DREAMS . . Data-driven Engine for Archetype Models of Schools .

ELM . . . . . Extreme Learning Machine.

ANN . . . . . Artificial neural network .

HRV . . . . . Heart rate variation.

EEG . . . . . Electroencephalograph.

AC . . . . . Air conditioning.

MAE . . . . . Mean absolute error.

MSE . . . . . Mean squared error.

TCL . . . . . temperatureof the clothing .

CLO . . . . . Clothing factor.

HL . . . . . Heating los.

HDD . . . . . Heating degree days.

HDD.E . . . . Effective Heating degree days.

TA . . . . . Air temperature.

DC . . . . . Data Collection.

RQ . . . . . Research question.

GBA . . . . . Government Buildings Agency.

GTO . . . . . Weighted Temperature Exceeding Hours.

TO . . . . . Total hours.

WF . . . . . Weighted factor.

ATG . . . . . Adaptive temperature limits guidelines.

TS . . . . . thermal sensation.

TD . . . . . Thermal Deviation.

Overview

This book offers an in-depth exploration into the multifaceted domain of thermal comfort, underscored by its paramount implications for energy efficiency. Central to this research is the notion of energy efficiency as a 'hidden fuel', a conceptual framework that enables a more nuanced approach to energy consumption and sustainability. This research predominantly draws upon data from the United Kingdom and Spain, supported by various projects funded by the European Union and the United Kingdom.

The underpinnings of this research are grounded in a Panorama of erspectives, spanning a year-long period and updated to encapsulate the most recent scholarly contributions. A bibliometric analysis tool aids in the thematic clustering of literature, illuminating nine key themes that range from engineering principles to psychological factors affecting thermal comfort and energy efficiency.

A comprehensive methodological framework informs this study, addressing salient research questions and utilising a multi-stage data collection strategy. Data are gathered from residential and office settings across different climatic conditions, focusing on the United Kingdom and Spain. The methodology elucidates the intricate relationships between thermal comfort and energy efficiency.

This research is further enriched by developing four novel digital tools tailored to specific research needs. These tools, from bibliometric analysis to energy consumption simulations, lay a robust foundation for data analysis and interpretation, exemplifying the study's innovative approach.

A rigorous analytical survey of thermal comfort unfolds in this section, dissecting various research questions related to models like Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). The analyses reveal existing models'

limitations, propose optimisation avenues, and suggest that thermal comfort is interlinked with energy consumption and productivity.

The book culminates in synthesising findings and contributions, offering recommendations for future research and summarising Key themes and discoveries, providing the reader with a coherent understanding of the study's academic contributions and implications.

Cogito, ergo sum
"I think, therefore I am"

— Descartes, R (1637).

1 Foundations

1.1 Chapter overview

This chapter delineates an exposition of the research. It serves as the conceptual framework for exploring the motivations inciting the research, the importance of this endeavour, and its potential constraints. The chapter aims to familiarise the reader with constructs that relate directly or tangentially to the subject.

Governments worldwide, like the United States, the United Kingdom, and the European Union, are formulating policies to advocate for energy efficiency [Vavrek and Chovancová (2020)];Doris et al. (2009)], underlining its centrality in global discourse. One of the salient energy objectives within the European Union is the improvement of energy efficiency. This research reveals the latent potential of energy efficiency, regarded herein as the 'hidden fuel'.

This research aids in quantifying actual fuel costs and promotes the conceptualisation of energy efficiency as a 'hidden fuel'. Such an approach will facilitate the achievement of energy efficiency intervention targets with reduced power consumption. This, in turn, lessens the environmental footprint while enhancing thermal comfort within architectural constructs. The human element is integral to energy consumption; by comprehensively understanding this aspect, it becomes

possible to improve human comfort and reduce energy usage by modifying the energy consumption profile.

A profound grasp of engineering principles and psychological underpinnings is indispensable for facilitating this research. This section elucidates terminologies that may bear different connotations within varying contexts. Aided by references and citations, this section provides the reader with an understanding of the terminological framework utilised within this book. Data aggregation and review of the extant literature were performed within the ambit of several energy efficiency projects funded by the European Union and the United Kingdom. This project predominantly uses data from the United Kingdom and Spain. This chapter offers an expansive insight into the pertinent concepts within this contextual structure.

1.2 Navigating the Book: A Guide for Readers

To facilitate a smooth reading experience and to assist in understanding the complex interplay of factors discussed, this book utilises specific typographical conventions.

- Chapter References: When referring to specific chapters that detail data collection methods or elaborate on research questions, the text will be highlighted like chapter 1.2. This is intended to draw attention to key areas where in-depth information can be found.

- Terminology: Terms that have been explicitly defined in the "Definition of Terms" section will appear in *italics*. This serves to remind the reader that these terms carry specific meanings within the context of this research.

- Statistical Significance: in chapter 5 results from statistical tests that are deemed to be statistically significant will be **bold**. This is to highlight the particular importance of these findings in the interpretation of the data and the implications for the research questions at hand. Thereby aiding the reader in the critical evaluation of the research outcomes.

By adhering to these conventions, this document aims to offer a coherent and easily navigable structure. Readers are encouraged to refer to this section as needed to maximise their understanding and engagement with the material presented.

These guidelines aim to make the text more accessible, allowing readers to delve deeper into the research while knowing exactly where to find supplementary information.

1.3 The Spark of Inquiry: Why This Matters

The current research approaches energy efficiency from a multidisciplinary perspective, using programming, mechanical and electrical engineering, psychophysics, and psychology insights. This research investigates thermal sensation and its potential impact on energy efficiency.

The concept of energy efficiency is not new and has been gaining importance in recent years. This is because energy efficiency is valuable for addressing energy security, reducing energy costs, and mitigating climate change. The literature suggests that energy efficiency can be considered an 'energy resource' because it allows the same resource to be used more effectively [Thoyre (2015)]. This means energy efficiency reduces consumption and contributes to the energy mix. In other words, it is a way to increase the availability of energy resources without resorting to new energy sources.

People use energy to move around, heat homes, illuminate the streets, and many other things. Unfortunately, the indiscriminate use of accessible fuels is leaving a mark on our planet, contributing significantly to the production of greenhouse gases. Every day, humanity consumes 75 million barrels of oil, an increasing number[Brown and Huntington (2017). Several projects, such as the European Union 202020 goals [Backlund et al. (2012), focus on preventing global warming.

The European Union 202020 policy is to increase energy generation by renewable sources by 20%, reduce greenhouse gas generation by 20% and increase energy efficiency by 20% [Backlund et al. (2012). The least understood may be the one

corresponding to energy efficiency, which still has significant power to develop and is synergistic with the other two. Indirectly increasing the energy can reduce the generation of greenhouse gases. Energy efficiency technology provides consumption flexibility, allowing renewable energy to be coupled to the existing grid.

One critical problem with renewable energy is that it is not programmable. Unfortunately, it is not possible to program the wind or the sun. However, with intelligent consumption and energy efficiency, it is possible to give the grid the necessary degree of flexibility so that renewable energies are more widely used in electrical grids. Still, research on the impacts of energy efficiency beyond energy savings has yet to be done.

Energy efficiency and the search for comfort should synergise and strengthen each other. For this reason, this research reflects the effect of comfort on energy efficiency. In this way, it aims to help develop energy efficiency policies and improve people's interaction with technologies. This research goal is to continuously enhance people's lives while minimising their environmental impact.

1.4 The Research in Focus: Its Value and Impact

Throughout history, society has prioritised optimising the use of limited resources. By doing so, we can accomplish more with the same resources, which helps meet the needs of more people. This concept has been applied to many areas of life, particularly to material resources. People also strive to make the most of their time, utilising vehicles for transportation, computers and phones for quick access to information, and electric lights to artificially extend daylight hours [Matzinger et al. (1996)]. As a result, humans have achieved a level of comfort and productivity that was once unimaginable [Jaffe and Stavins (1994)]. However, the increased reliance on technology has led to a significant increase in the consumption of natural resources such as coal, natural gas, oil, and uranium.

The energy cost significantly impacts the economy, affecting various aspects such as manufacturing, transportation, and daily life. Several factors determine energy