Thermal Comfort in Buildings: Scientometric Analysis and Systematic Review

Abstract: The building sector is one of the most resource-exhausting areas in global energy consumption. Maintaining good thermal comfort for occupants is the leading energy demand in buildings. The primary purpose of the current study is to identify the development of research areas on occupant comfort, pinpoint the gaps in knowledge and recommend directions for future studies. A scientometric analysis and a comprehensive systematic literature review are conducted using 792 sources. It is evident from the exponential increase in published papers that scholars are highly interested in this research topic. However, discrepancies remain between the two fundamental models of evaluating thermal comfort. There is a pressing need to balance thermal comfort while increasing energy efficiency. The foundation of achieving this balance can only be done by correctly evaluating the surrounding environment of occupants and understanding all the factors influencing human thermal comfort conditions. There is also a high potential in employing industry 4.0 technologies to assist in designing more innovative solutions for thermal comfort. Furthermore, there is a need for local thermal standards targeting specific regions. The lack of interoperability between BIM 3D modelling and energy simulation tools remains an obstacle.

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Introduction

According to statistics, people usually spend more than 80% of their time indoors (KLEPEIS *et al.*, 2001). Indoor Environment Quality (IEQ) refers to the quality of conditions that affect building occupants' health and well-being (Al Horr, Arif, *et al.*, 2016a). It encompasses several factors, including thermal, acoustic conditions, visual and Indoor Air Quality (IAQ) (Amit Kaushik *et al.*, 2020). It is vital to study occupants' thermal comfort in buildings as this can positively or negatively impact their productivity, satisfaction, and wellbeing (Wen Wei Che *et al.*, 2019; Kim *et al.*, 2020).

On the other hand, the ever-increasing world energy use has raised alarms about oversupply complications, exhaustion of energy sources and aggravation of the environmental situation. Accordingly, energy efficiency and savings strategy has become a priority objective worldwide (Pérez-Lombard, Ortiz and Pout, 2008). It is imperative with the rise of energy consumption in HVAC systems that have become essential with the increased demand for thermal comfort in indoor environments (Wen Wei Che *et al.*, 2019). More than ever, there is a need to balance the thermal comfort of occupants and energy consumption in buildings.

Thus, the current study aims to help Architecture, Engineering and Construction professionals understand all the available tools that can be used to determine each factor that influences occupants' thermal comfort. There are existing reviews of tools and literature. However, this paper provides an updated comprehensive literature review and scientometric. It will provide a holistic understanding of the topic and concepts related to thermal comfort while providing a snapshot of global research efforts on this topic using scientometric analysis. This paper is divided into five sections. Section 1 is an introduction to the research topic and its structure. The scientific methodology used for this study is detailed in section 2. Section 3 presents the findings of the scientometric analysis with various visualisation graphs. Section 4 presents a systematic review of thermal comfort in office buildings. Section 5 outlines the conclusion.

Research methodology

A four-step approach was adopted for data collection, inclusion, and exclusion criteria, followed by scientometric analysis and a comprehensive field evaluation through a systematic literature review. The summary of this methodology is presented in figure 1.

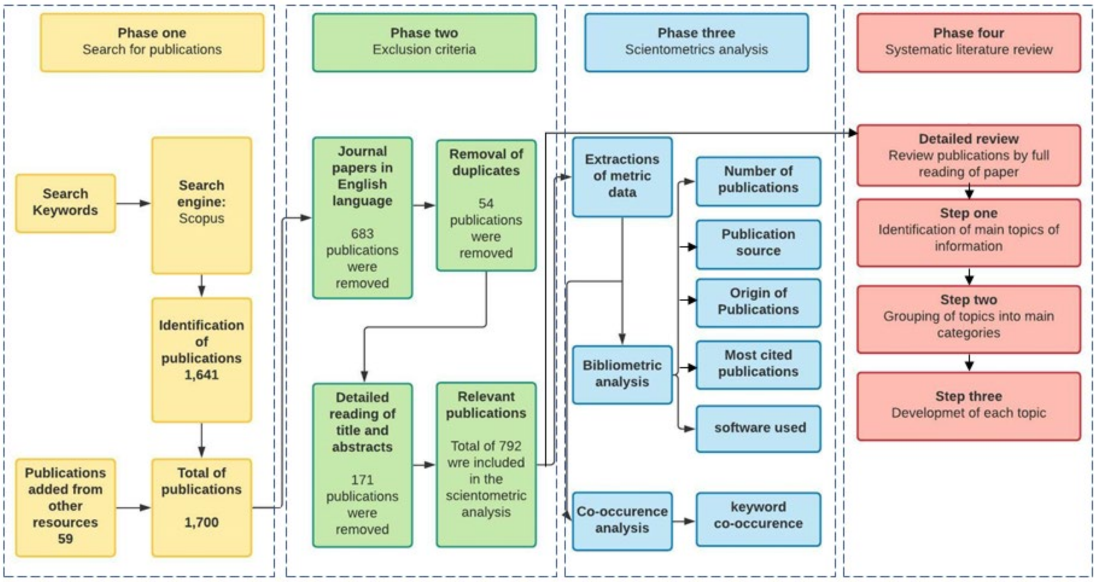

Figure 1- Research Methodology

Phase one: Search for publications

The research in this study follows systematic literature review guidelines by defining the appropriate keywords and the search database (Durach, Kembro and Wieland, 2017; Borrego, Foster and Froyd, 2014).

The scientific literature on thermal comfort in indoor environments in buildings was retrieved from Scopus, the largest abstract and citation database, one of the globally recognised enriched metadata records of scientific articles (Baas *et al.*, 2020). The publications were collected around the topic through the following retrieval formula TITLE-ABS-KEY (“thermal comfort") AND TITLE-ABS-KEY ("indoor environment"). The search for “indoor” AND “environment” produced a good result that was not focusing the indoor environment but on the environment in general and mentioned indoor in some of the text. To keep the results rich and relevant to the topic, we excluded this string. As a result, a total of 1,641 publications were obtained. It should be noted that a similar retrieval mode on a different day will yield slightly different results due to the continuous updating strategy in the Scopus database. Additionally, 59 publications were added to the results after reviewing the references of significant publications related to this research.

Phase two: Exclusion criteria

The types of publications used for the search were limited to “journal” articles and “reviews” in English, resulting in 1,017 references. From those papers, duplicate results were eliminated, leaving 963 unique papers... An Excel sheet was created to find more duplicate results, excluding a further 171.

The final number of publications included in the scientometric analysis section was 792.

Phase three: Scientometric analysis

Following the literature search, 792 were exported in CSV format in Scopus. These created the input of the scientometric analysis phase. Several analyses were conducted on the bibliometric data, such as publications and citations per year, publication sources and origin of publications. VOS-viewer was used to produce the scientometric links and maps between the various bibliometric parameters, including keywords co-occurrence and software used (van Eck and Waltman, 2013).

Phase four: Systematic literature review

Systemic literature review helped to outline thirteen critical areas of research. These topics were grouped into five main categories. A structured representation of the main areas of thermal comfort research was presented, identifying research gaps, findings and conclusions.

Scientometric analysis

This section presents a scientometric analysis of the 792 research papers revealing the current state and development of knowledge surrounding thermal comfort in indoor environments. (Nalimov and Mul'chenko, 1971) were the first to use the term scientometric and define it as “a quantitative study of the research on the development of science”.

Number of publications and citations

Figure 2 shows the distribution of the 792 articles published on thermal comfort between 1962 and 2021. An upward trend in research associated with thermal comfort started in 2008, with 18 publications increasing to 111 in October 2021 (the date the research analysis was conducted). . This increase in publications coincided with the acceptance of the ASHRAE standard 55 for the adaptive thermal approach in 2004. It can be concluded that the subject field is critical among scholars in the scientific field.

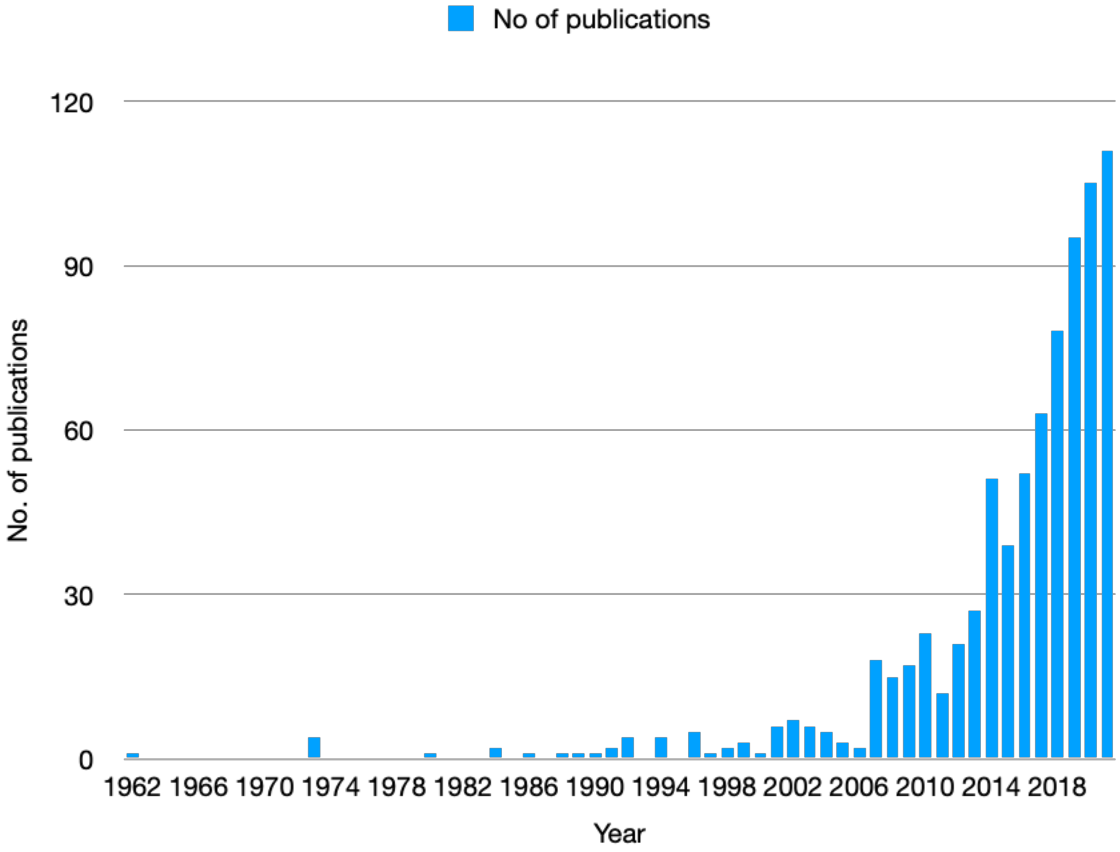

Figure 2- Evolution of the number of publications

Publication source

Publication sources used in this scientometric analysis were limited to journal articles to increase the quality of analysis done in this paper. 116 scientific journals were identified; however, considering the high number of journals, figure 3 displays the top 15 journals published with nine or more articles. It was observed through this analysis that almost 60% of the articles were published in two journals; Building and Environment have 196 publications, followed by Energy and Buildings with 149 publications. It indicates the leadership of these two journals in thermal comfort.

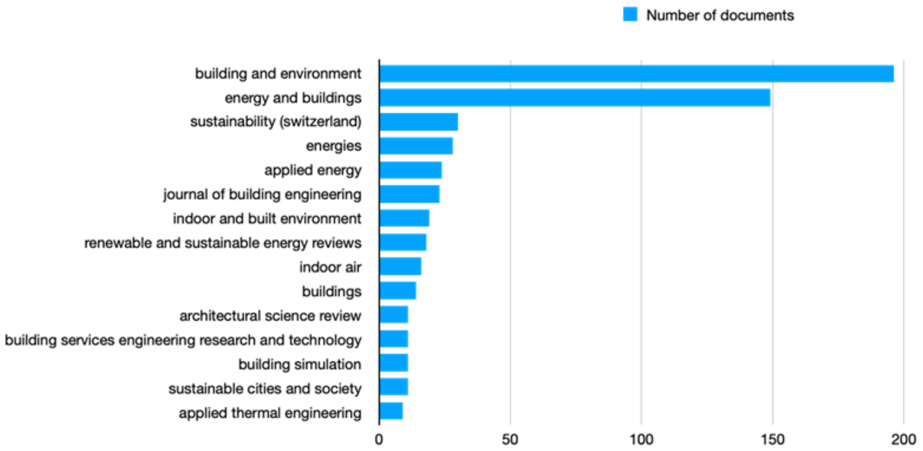

Figure 3- publication sources

Origin of publications

This research analysed the origin of publications through VOSViewer software. A total of 85 countries were identified and presented in figure 3. The leading countries are China (152 articles), the United Kingdom (96 articles), and the United States of America (84 articles), respectively. The United States of America and the United Kingdom have a long history of thermal comfort research. However, China has significantly increased research on thermal comfort in the last 20 years.

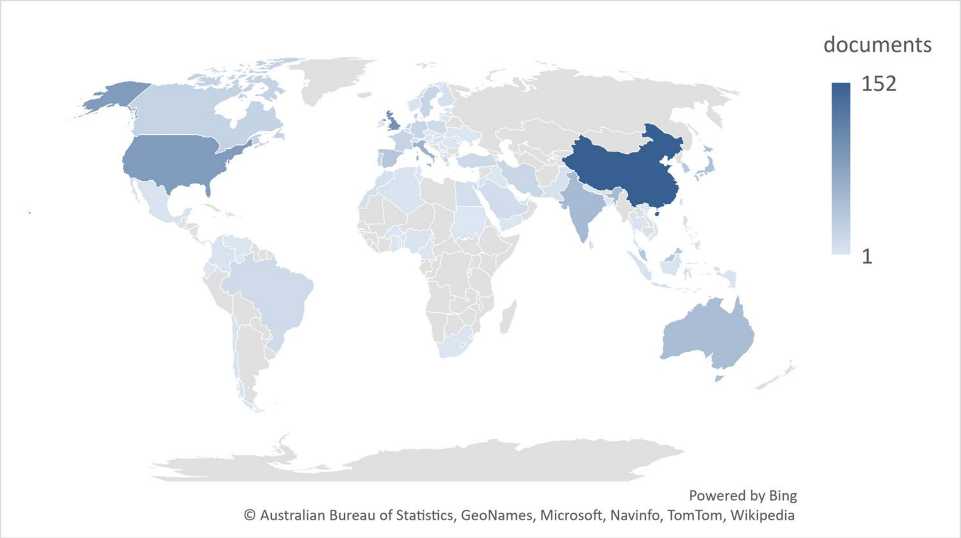

Figure 4- Distribution of publications by country

Most cited publications

Global citations have recognised the top ten distinguished and highly regarded articles. These are presented in table1. It includes three literature reviews of thermal comfort (Liu Yang, Yan and Lam, 2014; and building energy consumption implications (Crawley *et al.*, 2008), a review of optimised control systems for building energy (Shaikh *et al.*, 2014)and comfort management of innovative, sustainable buildings Rijal *et al.*, 2007 and a review of human thermal comfort in the built environment (Rupp, Vásquez and Lamberts, 2015).

Table 1- Top 10 cited publication

Order	**Citations**	**Title**	**Reference**
1	1197	Developing an adaptive model of thermal comfort and preference	(De Dear and Brager, 1998)
2	1095	Adaptive thermal comfort and sustainable thermal standards for buildings	(Nicol and Humphreys, 2002a)
3	1013	Contrasting the capabilities of building energy performance simulation programs	(Crawley *et al.*, 2008)
4	845	Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55	(De Dear and Brager, 2002)
5	665	Thermal comfort and building energy consumption implications - A review	(Liu Yang, Yan and Lam, 2014)
6	485	A review on optimized control systems for building energy and comfort management of smart sustainable buildings	(Shaikh *et al.*, 2014)
7	403	Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings	(Rijal *et al.*, 2007)
8	396	A review of human thermal comfort in the built environment	(Rupp, Vásquez and Lamberts, 2015)
9	394	Forty years of Fanger's model of thermal comfort: Comfort for all?	(Van Hoof, 2008)
10	363	Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251	(Nicol and Humphreys, 2010)

Keywords’ co-occurrence

Keywords’ analysis signifies the themes of knowledge in thermal comfort research. This study had 4345 keywords across the 792 publications included in this research. Due to many keywords, a normalisation method was used through the thesaurus file accumulating repeated keywords. Irrelevant keywords, such as country names, were removed. Figure 5 represents the number of co-occurrence of keywords. The larger node size indicates increased occurrence. The link strength is shown through the thickness of the lines between keywords relevant to the concept. As expected, “thermal comfort” has the largest central node in the network. The co-occurrence mapping displays strong direct links between “thermal comfort” and keywords such as “energy efficiency in buildings”, “indoor air quality”, “ventilation”, “architectural design”, “climate conditions”, and “HVAC”. It indicates the direct effect of those concepts on indoor thermal comfort. Regarding the keyword “building”, it has direct links with “air temperature”, “carbon dioxide”, “air quality”, “operative temperature”, and “airspeed”. These keywords pinpoint the factors affecting thermal comfort in buildings.

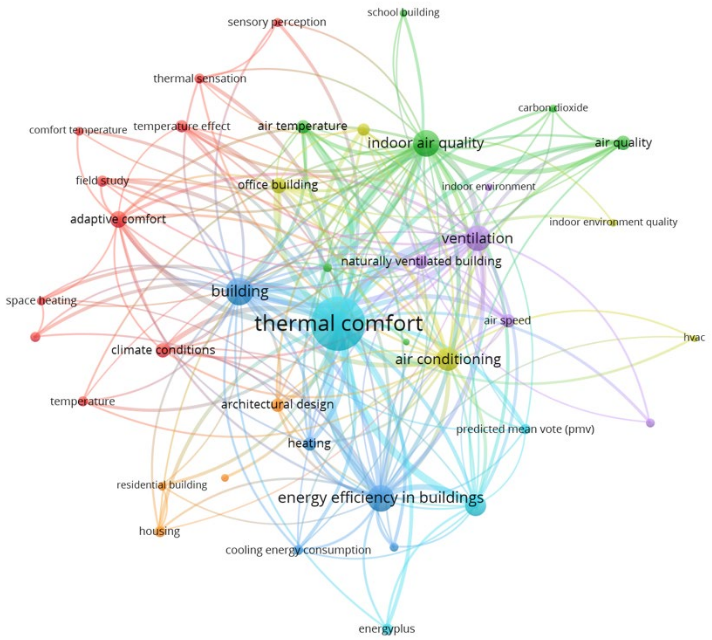

Figure 5- Keyword co-occurrence network

Software

A total of 23 software tools were identified within the literature on thermal comfort. Figure 6 displays the identified software. The node size represents the number of times the software has been included in a publication. The link thickness represents the number of occurrences of both software tools in a specific publication. Table 2 presents the top

10 software tools used for energy simulation, building design and data collection. They are also used specifically for thermal comfort research. EnergyPlus is the most used by designers and validated by the most significant number of research articles. DesignBuilder is one of the interfaces of EnergyPlus software, and it can be seen in second place in the analysis. Figure 6 shows the vital link between these two software tools. EnergyPlus software has strong links with four other tools, namely CBE, DesignBuilder and IDA-ICE, and MATLAB©.

Table 2- Thermal comfort software in the publications

No.	**Software**	**Total Link Strength**	**References**
1	EnergyPlus	23	(Chowdhury, Rasul and Khan, 2008; Xu *et al.*, 2010; Hwang and Shu, 2011; Attia *et al.*, 2012; Buratti *et al.*, 2013a; Evola, Marletta and Sicurella, 2013a; Gon Kim *et al.*, 2013; Cappelletti *et al.*, 2014; Dias *et al.*, 2014; K.H. Lee and Schiavo, 2014; Nguyen and Reiter, 2014; Petersen, Momme and Hviid, 2014; Sage-Lauck and Sailor, 2014; Stazi *et al.*, 2014; Attia and Carlucci, 2015; Hilliaho, Lahdensivu and Vinha, 2015a; Liao, Cheng and Hwang, 2015; Vanhoutteghem *et al.*, 2015; Wang *et al.*, 2015a, 2020; Zhang and De Dear, 2015; Cetin, Manuel and Novoselac, 2016a, 2016b; Delgarm, Sajadi and Delgarm, 2016a; Jamil *et al.*, 2016a; Kim *et al.*, 2016a; Li, Lee and Jia, 2016; Muñoz-González, León-Rodríguez and Navarro-Casas, 2016; Nghana and Tariku, 2016; Requena-Ruiz, 2016; Samani *et al.*, 2016; Figueiredo *et al.*, 2017a; He *et al.*, 2017; Kim, Yang and Moon, 2017; Kontes *et al.*, 2017a; Kwok *et al.*, 2017; Pastore, Corrao and Heiselberg, 2017; Zhang *et al.*, 2017a; Abuelnuor *et al.*, 2018a; Beccali *et al.*, 2018; Costanzo *et al.*, 2018; de Abreu-Harbich, Chaves and Brandstetter, 2018; Hong *et al.*, 2018a; Ibrahim *et al.*, 2018; Jazizadeh and Jung, 2018; Martinopoulos *et al.*, 2018; Ruz, Garrido and Vázquez, 2018; S. Gou *et al.*, 2018; S. Yang *et al.*, 2018a; Yao *et al.*, 2018; Ahangari and Maerefat, 2019; Amoruso, Dietrich and Schuetze, 2019a; Ardiyanto, Hamid and Sutopo, 2019; Escandón, Ascione, *et al.*, 2019a; Escandón, Suárez, *et al.*, 2019; Kwak and Huh, 2019; Lotfabadi and Hançer, 2019; Mahar *et al.*, 2019; Robledo-Fava *et al.*, 2019a; Salehi *et al.*, 2019; Zamani *et al.*, 2019; Deng and Tan, 2020; Grygierek and Sarna, 2020a; Luo *et al.*, 2020; Muñoz González *et al.*, 2020; Sadeghi *et al.*, 2020; Shan and Lu, 2020; Tuck *et al.*, 2020; Vella *et al.*, 2020; Xu, Li and Zhang, 2020; Zhao and Du, 2020;

			Al-Absi *et al.*, 2021; Aliakbari, Ebrahimi-Moghadam and Ildarabadi, 2021; Conejo-Fernández, Cappelletti and Gasparella, 2021a; Elnaklah *et al.*, 2021; Elshafei *et al.*, 2021; Ghaderian and Veysi, 2021a; Goudarzi *et al.*, 2021; Hagentoft and Pallin, 2021; Halhoul Merabet *et al.*, 2021; Heibati, Maref and Saber, 2021a; K. Qu *et al.*, 2021; Kükrer and Eskin, 2021a; Mabdeh, Radaideh and Hiyari, 2021; Nie *et al.*, 2021; Rangaswamy and Ramamurthy, 2021; Saif *et al.*, 2021a; Yılmaz and Yılmaz, 2021; Y. Qu *et al.*, 2021a)
2	DesignBuilder	10	(Chowdhury, Rasul and Khan, 2008; Shastry, Mani and Tenorio, 2014, 2016; Adekunle and Nikolopoulou, 2016; Braulio-Gonzalo *et al.*, 2016; Kwok *et al.*, 2017; Martinez-Molina *et al.*, 2017a; Stazi, Tomassoni and Di Perna, 2017; Beccali *et al.*, 2018; Shaeri, Yaghoubi and Habibi, 2018; Lotfabadi and Hançer, 2019; Zamani *et al.*, 2019; Muñoz González *et al.*, 2020; Sadeghi *et al.*, 2020; Shao and Jin, 2020; Zhao and Du, 2020; Al-Absi *et al.*, 2021; Albatayneh *et al.*, 2021a; Cao *et al.*, 2021; Diler *et al.*, 2021; Elshafei *et al.*, 2021; Kükrer and Eskin, 2021a; Mabdeh, Radaideh and Hiyari, 2021; Saif *et al.*, 2021a)
3	Trnsys	1	(Theluer, Cordier and Monchoux, 1994; Nikolaou *et al.*, 2009; Buratti *et al.*, 2013b; Wang, Tian and Ding, 2013; Cappelletti *et al.*, 2014; Wang *et al.*, 2015b; Yu *et al.*, 2015a; Delgarm, Sajadi and Delgarm, 2016b; Kim *et al.*, 2016b; Kotopouleas and Nikolopoulou, 2016; Medjelekh *et al.*, 2016; Mirrahimi *et al.*, 2016; Moon and Jung, 2016; Kontes *et al.*, 2017b; Lebon *et al.*, 2017; Mousa, Lang and Auer, 2017; Zhang *et al.*, 2017b; Abuelnuor *et al.*, 2018b; Cho and Jeong, 2018; Martinopoulos *et al.*, 2018; Mora and Bean, 2018a; Potočnik *et al.*, 2018; S. Gou *et al.*, 2018; S. Yang *et al.*, 2018a; Escandón, Ascione, *et al.*, 2019b; Escandón, Suárez, *et al.*, 2019; Robledo-Fava *et al.*, 2019b; Yang *et al.*, 2019; Evola *et al.*, 2020)
4	CBE	7	(Mora and Bean, 2018b; Kwag *et al.*, 2019; W.W. Che *et al.*, 2019; Zhou *et al.*, 2019; Balbis-Morejón *et al.*, 2020; Fu *et al.*, 2020; Kiki *et al.*, 2020; Konis *et al.*, 2020; Tartarini *et al.*, 2020; de Oliveira, Rupp and Ghisi, 2021; Goudarzi *et al.*, 2021; Oh and Song, 2021a; Shahinmoghadam, Natephra and Motamedi, 2021)
5	Equest	4	(Attia *et al.*, 2012; Leung and Ge, 2013; Charoenkit and Yiemwattana, 2016; Pastore, Corrao and Heiselberg, 2017; Galagoda *et al.*, 2018; Martinopoulos *et al.*, 2018; Z. Gou *et al.*, 2018; Tang and Wang, 2019; Sokkar and Alibaba, 2020; Utkucu and Sözer, 2020; Ghilardi *et al.*, 2021; Heibati, Maref and Saber, 2021b; Saif *et al.*, 2021b)
6	Exergy	3	(Saber *et al.*, 2014a; Li, Lee and Jia, 2016; Buyak, Deshko and Sukhodub, 2017; Feng *et al.*, 2018;

			Turhan and Gokcen Akkurt, 2018; Draganova *et al.*, 2021; Indraganti and Humphreys, 2021; Kim *et al.*, 2021; Lamberti *et al.*, 2021; Yüksel *et al.*, 2021)
7	Ecotect	9	(Altan *et al.*, 2009; Attia *et al.*, 2012; Yao, 2013; Latha, Darshana and Venugopal, 2015; Anand, Deb and Alur, 2017; Vitale and Salerno, 2017; Ibrahim *et al.*, 2018; Kwon, Lee and Cho, 2019; Jin and Zhang, 2021)
8	IES-VE	4	(Lomas and Giridharan, 2012; Spentzou, Cook and Emmitt, 2018; Amir *et al.*, 2019; Oleiwi *et al.*, 2019; Ghaddar *et al.*, 2021)
9	OpenStudio	5	(Attia *et al.*, 2012; Cetin, Manuel and Novoselac, 2016a; Amoruso, Dietrich and Schuetze, 2019b; Grygierek and Sarna, 2020b; Guo and Bart, 2020)
10	IDA-ICE	3	(M Hamdy, Hasan and Siren, 2011; Hilliaho, Lahdensivu and Vinha, 2015b; Simson, Kurnitski and Maivel, 2017; Dodoo and Ayarkwa, 2019)

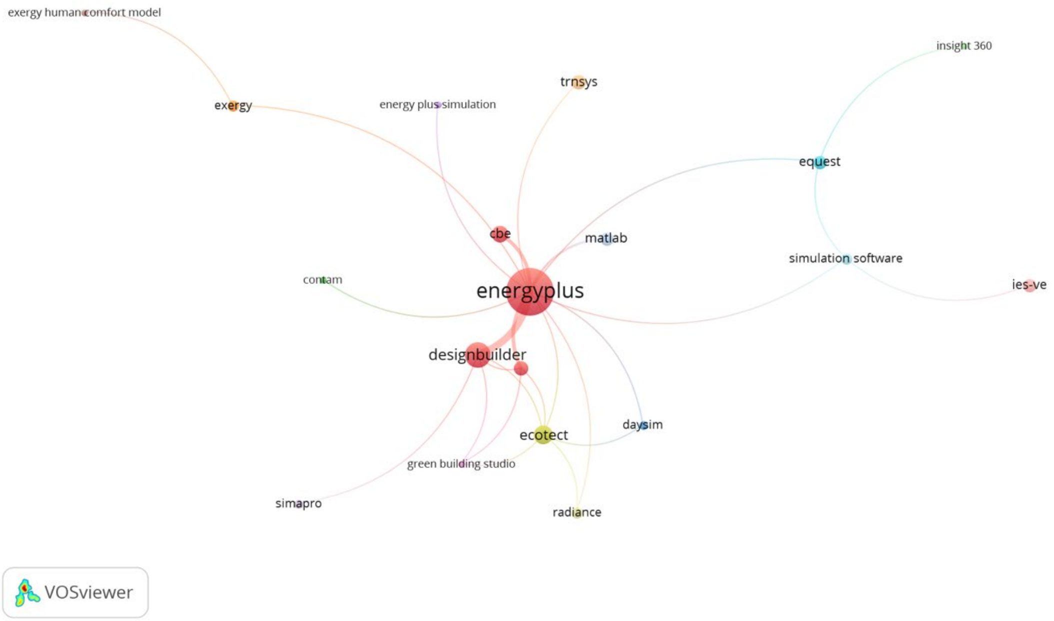

Figure 6 - Thermal comfort software network

Systematic literature review

A systematic literature review was conducted in this section, critically appraising the selected research articles. Key focus areas of thermal comfort research were identified and grouped into main research categories as presented in table 3. The review starts from the thermal comfort background, initial works and development of various models.

It includes thermal comfort parameters and standards. It is followed by a review of thermal comfort simulation work, which CFD and software usage. The third sub-section discusses energy efficiency in buildings. It is followed by a fourth sub-section continuing the review of energy efficiency. Sub-section four focuses on heating and cooling systems. The fifth sub-section presents occupant and building interaction, and it presents a review of occupant productivity and occupant behaviour.

Table 3- Main research areas of thermal comfort

Category	Topic	Publications
Thermal Comfort Development	Thermal Comfort Model Development	(Fanger, 1970; de Dear and Brager, 1998; Haghighat *et al.*, 2000; ISO, 2005; La Gennusa *et al.*, 2007; Hoof, 2008; ASHRAE, 2010; De Dear, 2011; Orosa and Oliveira, 2011; Chen and Chang, 2012; Halawa and Van Hoof, 2012; Li, Yu and Li, 2012; Langevin, Wen and Gurian, 2013; Maiti, 2014; Wang *et al.*, 2014; Martínez *et al.*, 2015; Gangisetti *et al.*, 2016; Moon and Jung, 2016; Martinez-Molina *et al.*, 2017b; Alzahrani *et al.*, 2018; B. Yang *et al.*, 2018; Deng and Chen, 2018; Elizabeth Amudhini Stephen, 2018; Hang and Kim, 2018; Hong *et al.*, 2018b; Jiang *et al.*, 2018a; Zhang *et al.*, 2018, 2020; Escandón, Ascione, *et al.*, 2019b; Haddad, Osmond and King, 2019; Hellwig *et al.*, 2019; Jindal, 2019; Kwak and Huh, 2019; Ma, Liu and Shang, 2019; Piasecki *et al.*, 2019; Tewari *et al.*, 2019; Xu, Li and Zhang, 2019; Ali *et al.*, 2020; Gładyszewska-Fiedoruk and Sulewska, 2020; Heracleous and Michael, 2020; Huang and Zhai, 2020; Karyono *et al.*, 2020; Ma *et al.*, 2020, 2021; Mui, Tsang and Wong, 2020; Palladino, Nardi and Buratti, 2020; Sung and Hsiao, 2020; Yang *et al.*, 2020; Zhao, Genovese and Li, 2020; Alonso *et al.*, 2021; Aparicio-Ruiz *et al.*, 2021; Bagheri Moghaddam *et al.*, 2021; B. Chegari *et al.*, 2021; Bouzidi *et al.*, 2021; Brik *et al.*, 2021; Conejo-Fernández, Cappelletti and Gasparella, 2021b; de Oliveira, Rupp and Ghisi, 2021; Forcada *et al.*, 2021; Kükrer and Eskin, 2021a; Lamberti *et al.*, 2021; Nie *et al.*, 2021; Oh and Song, 2021b; Ozarisoy and Altan, 2021; Rijal *et al.*, 2021; Rodríguez, Coronado and Medina, 2021; Shrestha *et al.*, 2021; Staveckis and Borodinecs, 2021; Taylor, Brown and Rim, 2021a; Valinejadshoubi *et al.*, 2021; Vella *et al.*, 2021; Xu and Li, 2021; Zahid, Elmansoury and Yaagoubi, 2021)
	Thermal Comfort Parameters	(Macpherson, 1962; Nicol and Humphreys, 2002b; Morgan and de Dear, 2003; Marincic, Ochoa and Del Río, 2012; Chen, Moshfegh and Cehlin, 2013; Jing *et al.*, 2013; Wang, Tian and Ding, 2013; Adunola, 2014; Kwang Ho Lee and Schiavo, 2014; Saber *et al.*, 2014b; Song, Wang and Wei, 2016; Djamila, 2017; Vellei *et al.*, 2017; Zhang *et al.*, 2017a;

		Kalmár, 2018; S. Yang *et al.*, 2018b; Cao and Deng, 2019; Gautam *et al.*, 2019; Kong *et al.*, 2019; Kwag *et al.*, 2019; Van Craenendonck *et al.*, 2019; Wang *et al.*, 2019; Wang, Kang and Zhou, 2019; Sansaniwal *et al.*, 2020; Deng and Chen, 2021; Jiang *et al.*, 2021; Kim, Shin and Cho, 2021; Rupp, Kazanci and Toftum, 2021; Sharma, Kumar and Kulkarni, 2021; Zuo, Luo and Liu, 2021)
	Thermal Comfort Standards	(de Dear and Brager, 1998; Olesen and Parsons, 2002; Olesen and Brager, 2004; Li *et al.*, 2014; Carlucci *et al.*, 2018; Gautam *et al.*, 2019; Elnaklah *et al.*, 2021; Rupp, Kazanci and Toftum, 2021)
Thermal Comfort Simulation	CFD	(Catalina, Virgone and Kuznik, 2009; Wang and Wong, 2009; Chiang, Wang and Huang, 2012; Woo O., 2012; G. Kim *et al.*, 2013; Hajdukiewicz, Geron and Keane, 2013; Schellen *et al.*, 2013; Fathollahzadeh, Heidarinejad and Pasdarshahri, 2015; Horikiri, Yao and Yao, 2015; Naboni, Lee and Fabbri, 2017; van Hooff, Blocken and Tominaga, 2017; Liu *et al.*, 2019; Utkucu and Sözer, 2020; Xie *et al.*, 2020; Calzolari and Liu, 2021; Gan *et al.*, 2021)
	Thermal Comfort Software	(Lee and Strand, 2001; Crawley *et al.*, 2008; Attia *et al.*, 2011; Jamaludin *et al.*, 2015; Felix and Elsamahy, 2017; Morsy *et al.*, 2018; de Wilde, 2019; Tartarini *et al.*, 2020)
Energy Efficiency in Buildings	Energy Use and Optimisation	(M. Hamdy, Hasan and Siren, 2011; L. Yang, Yan and Lam, 2014; Shaikh *et al.*, 2014; Stazi *et al.*, 2014; Méndez Echenagucia *et al.*, 2015; Yu *et al.*, 2015b; Delgarm, Sajadi and Delgarm, 2016b; Mao *et al.*, 2017; Martinopoulos *et al.*, 2018; Lotfabadi and Hançer, 2019; Wang and Fukuda, 2019; Kuczyński and Staszczuk, 2020; Panraluk and Sreshthaputra, 2020; Acar, Kaska and Tokgoz, 2021; B Chegari *et al.*, 2021; Ghaderian and Veysi, 2021b; Ghilardi *et al.*, 2021; Homod *et al.*, 2021; Lakhdari, Sriti and Painter, 2021; Rana, 2021; Taylor, Brown and Rim, 2021b; Yılmaz and Yılmaz, 2021; Y. Qu *et al.*, 2021b)
	Phase Change Materials	(Evola, Marletta and Sicurella, 2013b; Sage-Lauck and Sailor, 2014; Jamil *et al.*, 2016b; Nghana and Tariku, 2016; Socaciu *et al.*, 2016; Feng *et al.*, 2017; Figueiredo *et al.*, 2017b; Afolabi *et al.*, 2019; Ahangari and Maerefat, 2019; Alizadeh and Sadrameli, 2019; Nada, Alshaer and Saleh, 2019; Bagheri-Esfeh, Safikhani and Motahar, 2020; Kerroumi, Touati and Virgone, 2020; Ye, Wang and Qian, 2020; Yun *et al.*, 2020; Al-Absi *et al.*, 2021; Al-Yasiri and Szabó, 2021; Ortega Del Rosario *et al.*, 2021; Y. Qu *et al.*, 2021b; Zhu *et al.*, 2021)
Heating and Cooling Systems	Naturally Ventilated	(De Dear and Brager, 2002; Wong *et al.*, 2002, 2003; Liping and Hien, 2007; Zhang *et al.*, 2007, 2016; Stavrakakis *et al.*, 2008; Yang and Zhang, 2008; Wang *et al.*, 2010, 2021; Ai *et al.*, 2011; Dong, Soebarto and Griffith, 2014; Lei *et al.*, 2017; Omrani *et al.*, 2017; Singh *et al.*, 2018; Heracleous and

		Michael, 2019; Kumar *et al.*, 2019; Abdullah and Alibaba, 2020; Izadyar *et al.*, 2020; Ahmed, Kumar and Mottet, 2021; Luo, Hong and Pantelic, 2021)
	Air Conditioned	(de Dear, Leow and Foo, 1991; Dounis *et al.*, 1994; Kavgic *et al.*, 2008; Karjalainen, 2009; ASHRAE, 2010; Daum, Haldi and Morel, 2011; Mardiana-Idayu and Riffat, 2012; Indraganti *et al.*, 2014; Chenari *et al.*, 2016; Wei *et al.*, 2019; Zhang, Zhang and Khan, 2020; Guevara, Soriano and Mino-Rodriguez, 2021)
	Personal Comfort Systems	(Madsen and Saxhof, 1980; Bogdan and Chludzinska, 2010; Jazizadeh *et al.*, 2014; Parkinson and Dear, 2015; Conceição *et al.*, 2018; Godithi *et al.*, 2019; W.W. Che *et al.*, 2019; Rawal *et al.*, 2020)
Occupant Building Interactions	Productivity and Task Performance	(Wargocki *et al.*, 1999; Edwards and Torcellini, 2002; Akimoto *et al.*, 2010; Bakó-Biró *et al.*, 2012; De Giuli, Da Pos and De Carli, 2012; Boerstra *et al.*, 2015; De Dear *et al.*, 2015; Al Horr, Arif, *et al.*, 2016b; Al Horr, Katafygiotou, *et al.*, 2016; Arif *et al.*, 2016; Hoque and Weil, 2016; Mustapa *et al.*, 2016; Kang, Ou and Mak, 2017; Rijal, Humphreys and Nicol, 2017; Tarantini, Pernigotto and Gasparella, 2017; Jiang *et al.*, 2018b; Liu *et al.*, 2018; Lau, Zhang and Tao, 2019; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019; A. Kaushik *et al.*, 2020; Amit Kaushik *et al.*, 2020; Alzahrani *et al.*, 2021; Bueno, de Paula Xavier and Broday, 2021; Kükrer and Eskin, 2021a; Tuniki, Jurelionis and Fokaides, 2021; Hu *et al.*, 2022)
	Monitoring Occupant Behaviour	(Branco *et al.*, 2004; Tohoku University, 2013; De Wilde, 2014; Tam, Almeida and Le, 2018; Causone *et al.*, 2019)
	Occupant Perception of Thermal Comfort	(Lutzenhiser, 1993; Baker and Standeven, 2007; Karjalainen, 2012; Mishra and Ramgopal, 2013; Veselý and Zeiler, 2014; Tuniki, Jurelionis and Fokaides, 2021)

Thermal Comfort development

This category brings together topics associated with thermal comfort development relating to the fundamental models used in the literature, the parameters incorporated in these models and the standards they are included.

Thermal Comfort model development

Thermal Comfort models prevailing in the literature are the steady-state and adaptive models. P.O. Fanger developed the first thermal comfort model in the 1970s (Fanger, 1970). This steady-state model calculates the Predicted Mean Vote (PMV) of thermal comfort as well as the Predicted Percentage of Dissatisfied (PPD) (Fanger, 1970). This model has become the base of thermal comfort standards such as ASHRAE 55 (Hoof, 2008; ASHRAE, 2010) and ISO 7730 (ISO, 2005). However, the PMV-PPD model is based on controlled laboratory experiments, assuming that the human body passively accepts surrounding thermal conditions without adapting to temperature changes. Thus, it is usually most suitable to be used in air-conditioned spaces with mostly seated occupants, such as office buildings (Chen and Chang, 2012; Langevin, Wen and Gurian, 2013; Wang *et al.*, 2014; Martínez *et al.*, 2015; Gangisetti *et al.*, 2016; Elizabeth Amudhini Stephen, 2018; Kwak and Huh, 2019; Tewari *et al.*, 2019; Ali *et al.*, 2020; Bagheri Moghaddam *et al.*, 2021; de Oliveira, Rupp and Ghisi, 2021; Staveckis and Borodinecs, 2021). Previous research has established that the difficulty of applying PMV models is estimating occupants' clothing insulation and metabolic rate (Ma *et al.*, 2021).

Moreover, there are some discrepancies in PMV and subjective Thermal Sensation Value (TSV). While some researchers found that the latter is always higher than objective PMV, reflecting thermal adaptation (B. Yang et al., 2018), others found that PMV overestimated TSV responses (Maiti, 2014). Thus, many researchers have debated the accuracy of the PMV-PPD results (Orosa and Oliveira, 2011) and recommended several solutions to correct it (Martinez-Molina *et al.*, 2017b; Piasecki *et al.*, 2019; Mui, Tsang and Wong, 2020; Nie *et al.*, 2021). One of the reasons for the imprecision of Fanger's model is that it neglects the influence of solar radiation on human thermal comfort (La Gennusa et al., 2007; Huang and Zhai, 2020; Conejo-Fernández, Cappelletti and Gasparilla, 2021b). A Corrected Predicted Mean Vote (CPMV) model was developed to consider the solar radiation in the original heat balance equation (Zhang *et al.*, 2018).

The acceptability of this model has been studied by several researchers (Xu, Li and Zhang, 2019; Yang *et al.*, 2020; Zhang *et al.*, 2020; Xu and Li, 2021). Another concern surrounding the PMV-PPD model is that it neglects the differences in occupants' perception of thermal comfort depending on their gender, age and metabolic rate, among other personal differences in multi-occupancy environments (Hong *et al.*, 2018b).

De Dear and Brager developed the adaptive Thermal Comfort model as the basis of standards for the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) (de Dear and Brager, 1998; ASHRAE, 2010). In contrast to the steady-state model, the adaptive model expresses the indoor comfort temperature about the outdoor temperature and determines acceptable thermal comfort conditions in naturally ventilated environments. It is deducted from the idea that the range of thermally acceptable temperature in naturally ventilated buildings is more extensive than in air-conditioned buildings. Those models are applied in naturally ventilated buildings. They have been extensively researched in the literature in different types of buildings, such as nursing homes (Forcada *et al.*, 2021) and educational buildings (B. Yang *et al.*, 2018; Jiang *et al.*, 2018a; Haddad, Osmond and King, 2019; Jindal, 2019; Heracleous and Michael, 2020; Ma *et al.*, 2020; Alonso *et al.*, 2021; Aparicio-Ruiz *et al.*, 2021; Kükrer and Eskin, 2021a; Lamberti *et al.*, 2021; Oh and Song, 2021b; Rodríguez, Coronado and Medina, 2021; Shrestha *et al.*, 2021; Taylor, Brown and Rim, 2021a) health care buildings (Bouzidi *et al.*, 2021) and places of worship (Vella *et al.*, 2021). Although this adaptive approach works better in naturally ventilated buildings, it fails to include some important aspects of the traditional thermal comfort model (Halawa and Van Hoof, 2012). As the adaptive method is concerned with human behaviour, the former focuses on thermal physiology (Karyono *et al.*, 2020). It has been previously observed that thermal comfort models are constructed for young adults and are unsuitable for estimating children and the elderly (Aparicio-Ruiz *et al.*, 2021). Some studies highlighted the use of the adaptive approach in estimating the comfort standards for those vulnerable groups of people (such as young, elderly, ill and disabled) (Haghighat *et al.*, 2000). The adaptive thermal comfort model has also been used to save energy and cost compared to other strategies for retrofitting buildings (Albatayneh *et al.*, 2021b). However, there remains a need to explore the correlation between adaptive principles and building energy use (Hellwig *et al.*, 2019). Research also suggests the need to question the applicability of existing adaptive thermal comfort models in naturally ventilated buildings (Ozarisoy and Altan, 2021). The literature has confirmed that adaptive building design and adaptive thermal comfort of people are essential for energy-saving building design (De Dear, 2011; Rijal *et al.*, 2021). Other models, such as a two-node and multi-node model, also calculate thermal comfort.

Latest developments in technology and computing have influenced the data collection and analysis of indoor environmental quality and its effect on the occupant. Several studies have incorporated industry 4.0 technologies into the thermal comfort models to cope with the various factors influencing both models of thermal comfort. Artificial Intelligence, for examplethe use of Artificial Neural Network (ANN) methods, has been incorporated into several studies (Li, Yu and Li, 2012; Moon and Jung, 2016; Alzahrani *et al.*, 2018; Deng and Chen, 2018; Escandón, Ascione, *et al.*, 2019b; Ma, Liu and Shang, 2019; Gładyszewska-Fiedoruk and Sulewska, 2020; Palladino, Nardi and Buratti, 2020; B. Chegari *et al.*, 2021). ANN can provide the personalisation of thermal comfort settings (Karyono *et al.*, 2020). Another use of technology has been highlighted by (Zahid, Elmansoury and Yaagoubi, 2021), who developed the “Dynamic PMV”. This method uses real-time visualisation of thermal comfort using the PMV index to calculate the optimal temperature for indoor thermal comfort. This emerging technology of using a Digital Twin by combining BIM (Building Information and Modeling) and IoT sensors (Internet of Things) has been investigated by several other thermal comfort scholars (Hang and Kim, 2018; Sung and Hsiao, 2020; Zhao, Genovese and Li, 2020; Brik *et al.*, 2021; Valinejadshoubi *et al.*, 2021).

Thermal Comfort parameters

PMV model is a heat-balance model that incorporates six parameters in identifying acceptable thermal conditions for the number of occupants. Those parameters are environmental and personal. The environmental parameters are indoor air temperature (Adunola, 2014; Zhang *et al.*, 2017a; Cao and Deng, 2019; Wang *et al.*, 2019; Jiang *et al.*, 2021), radiant temperature (Saber *et al.*, 2014b), relative humidity(Marincic, Ochoa and Del Río, 2012; Jing *et al.*, 2013; Vellei *et al.*, 2017; S. Yang *et al.*, 2018b; Kong *et al.*, 2019; Kwag *et al.*, 2019; Deng and Chen, 2021; Zuo, Luo and Liu, 2021) and air velocity (Kalmár, 2018; Van Craenendonck *et al.*, 2019; Sansaniwal *et al.*, 2020). At the same time, the personall parameters are personal activity and clothing insulation levels (Chen, Moshfegh and Cehlin, 2013; Wang, Tian and Ding, 2013; Kwang Ho Lee and Schiavo, 2014; Song, Wang and Wei, 2016; Gautam *et al.*, 2019; Wang, Kang and Zhou, 2019; Kim, Shin and Cho, 2021; Rupp, Kazanci and Toftum, 2021). It is suggested that PMV predictions can improve by considering chair and clothing insulation (Rupp, Kazanci and Toftum, 2021) and the effects of adding the age parameter to the thermal comfort investigations (Djamila, 2017).

On the other hand, an adaptive model depends on the relationship between outdoor temperature and its effect on indoor temperature (Morgan and de Dear, 2003). This model does not consider personal parameters. They are implicitly considered by including the outdoor temperature (as the level of clothing insulation and human movement depends on outdoor temperature) (Nicol and Humphreys, 2002b). Nevertheless, disregarding the influence of relative humidity and air velocity that does not strongly depend on outdoor temperature has been debated amongst several scholars (Vellei *et al.*, 2017). The research on thermal comfort has continuously evolved since Macpherson introduced thermal comfort parameters in 1962 (Macpherson, 1962),Click or tap here to enter text.They have not resolved to the debate of accurately evaluating thermal comfort (Sharma, Kumar and Kulkarni, 2021). Latest addition to the research is the data driven thermal comfort to improve the accuracy of the comfort prediction for the elderly(Zhao, 2021).

Thermal Comfort standards

P.O. Fanger's model has been the base of thermal comfort standards; it is included in international standards ISO 7730 (Olesen and Parsons, 2002), American standards (Olesen and Brager, 2004) and Chinese standards (Li *et al.*, 2014). One major issue in the PMV-PPD model is building ventilation, as this model overestimates occupant discomfort in naturally ventilated buildings (de Dear and Brager, 1998). Some minor issues include other insulation factors, such as chair insulation, as suggested by (Rupp, Kazanci and Toftum, 2021), who have argued that this impacts the indoor environment classification according to the European standard EN 16798-1. It also has significant limitations in incorporating and adapting to the individual users' preferences that can be resolved using Bayesian Comfort Model (BCM) (Auffenberg, 2017).

The adaptive model has been included in American, European, Dutch and Chinese standards and reviewed in the body of literature. (Carlucci *et al.*, 2018) Compared the adaptive thermal comfort models in five different standards (ANSI/ASHRAE 55, EN 15251, prEN 16798-1, ISSO 74 and GB/T 50784), the review concluded discrepancies in results when applying those standards as well as a need to resolve the issue of applying adaptive models in mixed-mode buildings. Another study points out that comfort temperature in cold regions is significantly lower than the ASHRAE and CEN standards limit (Gautam *et al.*, 2019). They are indicating the need to recommend adaptive standards suitable for freezing climates. In the same vein (Elnaklah *et al.*, 2021) highlights the necessity of having localised thermal comfort standards in the Middle East region as the thermal comfort in buildings changes according to the surrounding climates.

Thermal Comfort simulations development

Thermal comfort analysis and simulation software tools allow designers to explore thermal performance and create several design options. We only considered specialist software and not self-developed tools implemented in general-purpose or domain-specific programming languages. This category focuses on using those software tools and their role in providing occupant comfort while enhancing energy efficiency in buildings.

Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) simulation techniques predict thermal comfort in complex indoor environments (Catalina, Virgone and Kuznik, 2009; Chiang, Wang and Huang, 2012; Hajdukiewicz, Geron and Keane, 2013). CFD is mainly used as an inverse design technique for thermal comfort analysis. Inverse design is a method of setting an aim in thermal performance and using an automated technique to search for a system that satisfies this aim (Calzolari and Liu, 2021). They have been used to predict thermal comfort in a single space or room (Wang and Wong, 2009; G. Kim *et al.*, 2013; Schellen *et al.*, 2013; Fathollahzadeh, Heidarinejad and Pasdarshahri, 2015; Horikiri, Yao and Yao, 2015), as well as thermal comfort-CFD mapping to assist in the design of thermally comfortable buildings (Naboni, Lee and Fabbri, 2017). CFD is widely used to analyse the performance of HVAC systems in different spaces, it includes the efficiency of system, their layout and occupant response based on thermal comfort models (Buratti, 2017; Catalina, 2009). Although CFD has not substituted theoretical analysis and experimental data, it has been used to supplement them (Liu *et al.*, 2019). A primary concern of CFD numerical simulation tools is in the accuracy and reliability of those predictions (van Hooff, Blocken and Tominaga, 2017), as using simulated data for predicting thermal comfort without enhancing it with accurate measurements might lead to errors in real applications (Xie *et al.*, 2020). Another issue is their computational expensiveness (Woo O., 2012; Calzolari and Liu, 2021). Some researchers have incorporated CFD in 3D Building Information Models (BIM) (Utkucu and Sözer, 2020; Gan *et al.*, 2021). However, interoperability limitations remain a significant concern in such analyses.

Thermal Comfort software

Building Performance Simulation (BPS) software replicates aspects of a building related to design, construction, and operation (de Wilde, 2019). Several software tools have evaluated thermal comfort conditions at the early design stages. EnergyPlus is one of the most widely used open-source energy simulation software (Crawley *et al.*, 2008). It allows access from various simulation tools and third-party user interfaces. EnergyPlus is suitable for thermal analysis for two reasons. First, for its ability to address surface temperature effect on thermal comfort. Secondly, it incorporates thermal comfort models into its simulation algorithm (Lee and Strand, 2001). DesignBuilder is a graphical user interface for the EnergyPlus simulation engine. BIM models can be imported into the DesignBuilder interface through gbXML formats. It can assist designers and architects in all design stages (Attia *et al.*, 2011). One of the uses is in choosing the most appropriate thicknesses of insulation materials that will reflect the best thermal comfort conditions for the occupants (Morsy *et al.*, 2018). Another tool used by designers is the CBE thermal comfort tool. Like EnergyPlus, it incorporates the main thermal comfort models into its computations (Tartarini *et al.*, 2020). Ecotect and GBS can be used as plugins for Autodesk Revit 3D modelling software and are suitable for early design stages (Jamaludin *et al.*, 2015; Felix and Elsamahy, 2017).

Energy efficiency in buildings

This category brings together topics associated with maintaining acceptable indoor thermal comfort while enhancing building energy efficiency. It also sheds light on Phase Change Material (PCM) and its role in reaching optimal thermal comfort conditions by incorporating them in building envelopes.

Energy use and optimisation

One of the most significant challenges in thermal comfort studies is increasing energy efficiency while maintaining acceptable thermal comfort conditions for building occupants. A large amount of energy usage in buildings goes directly towards thermal comfort. It involves fulfilling thermal comfort parameters such as keeping the proper range of temperatures, relative humidity, and air velocity (L. Yang, Yan and Lam, 2014). Several studies have explored passive strategies to minimise energy use, namely; building orientation (Rana, 2021), thermal mass (Kuczyński and Staszczuk, 2020), advanced building envelope (Mao *et al.*, 2017; Lotfabadi and Hançer, 2019; Acar, Kaska and Tokgoz, 2021; Homod *et al.*, 2021), window to wall ratio (Lakhdari, Sriti and Painter, 2021) and shading equipment (Stazi *et al.*, 2014; Martinopoulos *et al.*, 2018). These factors are determined in the preliminary design stage (Méndez Echenagucia *et al.*, 2015). The multi-objective optimisation method can equally consider both objectives of raising efficiency and thermal comfort while incorporating the study with different algorithms (M. Hamdy, Hasan and Siren, 2011; Yu *et al.*, 2015b; Delgarm, Sajadi and Delgarm, 2016b; Wang and Fukuda, 2019; Panraluk and Sreshthaputra, 2020; Acar, Kaska and Tokgoz, 2021; B Chegari *et al.*, 2021; Ghaderian and Veysi, 2021b; Ghilardi *et al.*, 2021; Yılmaz and Yılmaz, 2021; Y. Qu *et al.*, 2021b). Algorithms enable comparing multiple scenarios and variables to find the optimised solution (Taylor, Brown and Rim, 2021b). Another aspect that familiar scholars have gained interest in has been balancing energy and thermal comfort using optimisation and building controls in real-time environments (Shaikh *et al.*, 2014). However, there is still a paucity of research that combines air temperature, relative humidity and air velocity using the optimisation approach (Taylor, Brown and Rim, 2021b).

Phase Change Materials (PCM)

Building envelope plays a significant role in building efficiency (Feng *et al.*, 2017). Integrating Phase Change Materials (PCM) into building envelopes has improved thermal comfort in buildings (Sage-Lauck and Sailor, 2014). PCMs have a high thermal storage capacity with moderate temperature variations, increasing energy efficiency while maintaining good thermal comfort. (Socaciu *et al.*, 2016). It is an emergent research area, attracting scholars to testing new types of PCM to reach optimal thermal comfort conditions by incorporating them into building envelopes (Evola, Marletta and Sicurella, 2013b; Sage-Lauck and Sailor, 2014; Jamil *et al.*, 2016b; Nghana and Tariku, 2016; Figueiredo *et al.*, 2017b; Afolabi *et al.*, 2019; Ahangari and Maerefat, 2019; Alizadeh and Sadrameli, 2019; Nada, Alshaer and Saleh, 2019; Bagheri-Esfeh, Safikhani and Motahar, 2020; Kerroumi, Touati and Virgone, 2020; Ye, Wang and Qian, 2020; Yun *et al.*, 2020; Al-Absi *et al.*, 2021; Ortega Del Rosario *et al.*, 2021; Y. Qu *et al.*, 2021b; Zhu *et al.*, 2021). However, one of the main challenges of PCM, according to (Al-Yasiri and Szabó, 2021), is their poor thermal conductivity, and this area needs further experimental research.

Heating and cooling system control

This topic explores the role of heating and cooling systems in constructing more thermally accepted and efficient buildings. Factors influencing thermal comfort levels in naturally ventilated structures and air-conditioned/ mechanically ventilated systems will be discussed along with thermal comfort modelling approach used in each case

Naturally ventilated systems

Before the implemention of Heating, Ventilating, and Air-Conditioning (HVAC) systems, natural ventilation was used to manage thermal comfort in buildings. The application of the adaptive thermal comfort model in determining thermal conditions in naturally ventilated spaces has attracted considerable attention from scholars (Ai *et al.*, 2011; Singh *et al.*, 2018; Heracleous and Michael, 2019; Abdullah and Alibaba, 2020; Izadyar *et al.*, 2020; Ahmed, Kumar and Mottet, 2021). Those studies calculate the thermal adaptability of occupants because outdoor temperatures influence indoor thermal preferences. It engages wind and buoyancy to bring outdoor air into indoor spaces without mechanical systems. Based on buildings' proper design, natural ventilation provides higher ventilation rates than mechanical ventilation (De Dear and Brager, 2002). However, other factors should be taken into consideration, such as shading of windows (Abdullah and Alibaba, 2020), presence of balconies (Ai *et al.*, 2011), and types of buildings (Wong *et al.*, 2002; Liping and Hien, 2007; Dong, Soebarto and Griffith, 2014; Wang *et al.*, 2021), seasons (Lei *et al.*, 2017; Kumar *et al.*, 2019) and climatic zones (Wong *et al.*, 2003; Zhang *et al.*, 2007, 2016; Yang and Zhang, 2008; Wang *et al.*, 2010). Occupant behaviour in opening and closing windows also influences natural ventilation performance, improving indoor thermal comfort and air quality. Natural cross ventilation outperforms single-sided ventilation to attain a suitable thermal comfort level (Stavrakakis *et al.*, 2008; Omrani *et al.*, 2017).

Recent research trends have focused on employing industry 4.0 technologies such as IoT technology, which has been used to determine natural ventilation potential and utilisation (Luo, Hong and Pantelic, 2021).

Heating and Ventilation and Air Conditioning

Designing an HVAC system is essential for enhancing indoor environmental quality and energy efficiency (Mardiana-Idayu and Riffat, 2012). Several studies have developed advanced systems to achieve greater comfort for occupants (Dounis *et al.*, 1994; Kavgic *et al.*, 2008). ASHRAE standards have specified that 80% of occupants should find thermal conditions satisfactory for the thermal environment to be acceptable (ASHRAE, 2010). This standard uses the PMV model to specify comfort zones. However, although those systems have vastly advanced, thermal comfort and indoor air quality are sometimes inadequate (Chenari *et al.*, 2016). The PMV model does not represent occupants' diversity, thus making it challenging to apply it unanimously (Daum, Haldi and Morel, 2011). Secondly, limited occupant building control interaction leads to lower thermal comfort. A study highlighted lower thermal comfort in offices as compared to homes due to less control over thermal environment (Karjalainen, 2009).

Several studies investigated the indoor environments and occupants' comfort in hot, humid conditions (de Dear, Leow and Foo, 1991; Indraganti *et al.*, 2014; Wei *et al.*, 2019), as Air-Conditioning systems are primarily used in those climates. Some scholars have noted that the PMV model overestimates occupant thermal sensation in centrally air-conditioned buildings in hot, humid areas (Zhang, Zhang and Khan, 2020). However, it underestimates occupants' satisfaction in tropical climates in some other cases (Guevara, Soriano and Mino-Rodriguez, 2021).

Personal comfort systems

Personal Comfort Systems (PCS) are used to attain thermal comfort at a personal level (Bogdan and Chludzinska, 2010; Godithi *et al.*, 2019). It can possibly improve air quality (Conceição *et al.*, 2018; W.W. Che *et al.*, 2019) and offers occupants of buildings psychological satisfaction of having personal control over their indoor thermal environment (Jazizadeh *et al.*, 2014; Parkinson and Dear, 2015). They were first introduced to reduce energy consumption in buildings (Madsen and Saxhof, 1980). Despite numerous studies in the literature around this topic, further investigation in evaluating thermal comfort and energy savings of PCS devices is recommended, and research concerning extreme indoor air temperature in heating or cooling-dominated environments (Rawal *et al.*, 2020).

Occupant building interactions

This category displays thermal energy's influence on building occupants’ health and productivity. It highlights occupant building interactions and their role in improving the predicted energy consumption of buildings during the design phase.

Productivity and task performance

Thermal Comfort conditions affect occupants' productivity (Wargocki *et al.*, 1999; Edwards and Torcellini, 2002; De Giuli, Da Pos and De Carli, 2012; Boerstra *et al.*, 2015; Al Horr, Katafygiotou, *et al.*, 2016; Arif *et al.*, 2016; Kang, Ou and Mak, 2017) and task performance (Akimoto *et al.*, 2010; Hoque and Weil, 2016; Liu *et al.*, 2018; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). Researchers in the field have focused on studies in a single zone, such as offices (Al Horr, Arif, *et al.*, 2016b; Mustapa *et al.*, 2016; Rijal, Humphreys and Nicol, 2017; Tarantini, Pernigotto and Gasparella, 2017; A. Kaushik *et al.*, 2020; Amit Kaushik *et al.*, 2020) or classrooms (Bakó-Biró et al., 2012; De Dear et al., 2015; Hoque and Weil, 2016; Jiang et al., 2018b; Lau, Zhang and Tao, 2019; Alzahrani et al., 2021; Kükrer and Eskin, 2021a). However, far too little attention has been paid to multipurpose buildings (Kükrer and Eskin, 2021b). A limited number of studies also discuss all the IEQ factors combined with personal factors necessary to calculate productivity. There have been limited studies detailing occupant profiles, including ethnicity, age (Kükrer and Eskin, 2021a) and gender (Hu et al., 2022), as well as emotional states and cognitive abilities (Bueno, de Paula Xavier and Broday, 2021). (Tuniki, Jurelionis and Fokaides, 2021) suggests linking occupant productivity studies with energy consumption to conducting a cost-benefit analysis for decision-making purposes.

Monitoring occupant behaviour

Studies indicate a significant inconsistency between designed and actual energy consumption in buildings. Occupant behaviour plays a significant role in this discrepancy (Branco *et al.*, 2004; Tohoku University, 2013; De Wilde, 2014). The main reason for consuming energy in buildings is to maintain the comfort conditions of occupants. Occupant behaviour depends on several objective and subjective factors. These factors include climate, indoor temperature, airspeed, and accessibility to energy control features, whereas the subjective factors include gender, age, social interaction, and thermal comfort perception (Tam, Almeida and Le, 2018).

Although guidelines and laws on energy performance promote high-performance buildings (e.g., Net Zero Energy Buildings), very little research is published on operational data of building performance and occupant behaviour monitoring in real-time (Causone *et al.*, 2019).

Occupant perception of thermal comfort

Previous research has established that the thermal comfort perception of occupants depends on various factors; Occupant related factors, Building related factors and Indoor Environmental Quality (IEQ) factors. Occupant-related metrics can be personal aspects such as the occupant’s lifestyle (Lutzenhiser, 1993), equipment control (such as windows doors and shading), and ability to adjust clothing and gender. Females, for example, display higher sensitivity and dissatisfaction than males, specifically in colder atmospheres (Karjalainen, 2012). It is also suggested that females should be used as test subjects when investigating indoor thermal comfort needs. If females are content, likely, males will also be content. (Karjalainen, 2012). Some studies (Mishra and Ramgopal, 2013) indicate that people above 60 prefer warmer environments (Veselý and Zeiler, 2014). Another aspect that influences occupants’ thermal perception is the building type. Most studies are conducted in the residential, office and educational buildings. However, few studies compare occupants' thermal behaviours in homes and offices (Tuniki, Jurelionis and Fokaides, 2021). IEQ factors influence the thermal perception of occupants, including Indoor Air Quality (IAQ), Visual Comfort, and Acoustic Comfort. Those factors influence their adaptive behaviours and cognitive tolerance (Baker and Standeven, 2007).

Conclusion

Statistics indicate that people spend more than 80% of their time indoors. Enhancing comfort in the built environment is vital for occupants' health and work efficiency. However, one of the most significant challenges in thermal comfort studies is increasing energy efficiency while maintaining acceptable indoor thermal comfort conditions. The foundation of achieving a balance between decreasing energy consumption of buildings and a comfortable environment for people can only be done by correctly evaluating the surrounding environment of occupants and understanding all the factors influencing human thermal comfort conditions. This paper provides an overview of the current state of thermal comfort research and its efforts to improve the comfort of buildings while decreasing energy consumption's economic and environmental effects. From this work, the following conclusions can be drawn:

Scientometric analysis conclusions

- There is a high interest among scholars in the indoor thermal comfort topic. It is evident in the exponential growth in the number of published research papers and the 116 journals identified with publications on this topic. The increase in publications in 2008 coincided with the acceptance of the ASHRAE standard 55 for the adaptive thermal approach in 2004.
- The main keywords identified were "thermal comfort", "ventilation", "energy efficiency", and "indoor air". These keywords reveal that research into thermal comfort is connected directly with indoor air quality and ventilation, respectively. These indoor factors can have a direct influence on energy efficiency in buildings.
- "EnergyPlus" is the most used software tool for thermal comfort. It represents strong links with all the other thermal comfort software as it allows access from various simulation tools and third-party user interfaces.

Systematic literature review conclusions

- Since Macpherson introduced thermal comfort parameters in 1962, discrepancies between the two fundamental thermal comfort models have remained. On this front, some researchers suggested considering chair and clothing insulation to improve PMV predictions, while others suggested adding the age parameter to thermal comfort investigations. Fanger's thermal comfort model can also be improved by considering solar radiation's influence on human thermal comfort. Studies combining the adaptive approach with the PMV-PPD model can combine all parameters concerning human behaviours and thermal physiology to overcome some of the challenges these models face when evaluating the thermal comfort of occupants.
- New technologies to analyse thermal comfort levels have been increasingly used, such as incorporating IoT sensors with BIM models to enable real-time visualisation of thermal comfort. Artificial Intelligence has also played a significant role in designing more innovative solutions for thermal comfort. A future survey paper regarding the use of industry 4.0 technologies in enhancing the thermal comfort of occupants would be beneficial to understanding the extent of their current incorporation into this research area.
- In thermal comfort standards, it was observed that those international standards do not apply to some regions, such as the Middle East or icy regions. It necessitates having local thermal standards targeted for specific areas, imposing a need to conduct more field studies demonstrating the levels of thermal comfort sensations in those regions.
- CFD tools and simulation software have been increasingly used to optimise thermal comfort in buildings in the early design stages. However, the lack of interoperability between BIM 3D modelling and energy simulation tools remains an obstacle.
- Considering natural ventilation is one of the most energy-efficient ways to enhance thermal comfort, many studies have surrounded the topic. Thus, employing IoT

sensors technology to determine ventilation potential and utilisation in buildings is potentially a fruitful avenue for future research.

- HVAC systems are a significant source of energy consumption in buildings. The PMV model fails to accurately estimate occupant thermal sensations in some areas, such as hot, humid, and tropical climates. The genericapplication of HVAC systems does not necessarily satisfy the recommended number of occupants and their preferences; thus, personal comfort systems are used to attain thermal comfort at a personal level. It contributes to improving air quality and offering occupants of buildings the psychological satisfaction of having personal control over their indoor thermal environment. In the future, further investigation in evaluating thermal comfort and energy savings of PCS devices is recommended, and research concerning extreme indoor air temperature in heating or cooling dominated environments.
- The effects of occupant behaviour on building energy performance are mostly undervalued and generalised in the literature, resulting in a gap between buildings' design and energy consumption. Despite the importance of factors influencing occupant behaviour, such as socioeconomic aspects, lifestyle, and occupants' habits, there remains a paucity of research. Currently, some researchers focus their work on the impact of thermal comfort on occupant productivity. However, it would be beneficial to link this with the energy consumption of buildings to conduct a cost-benefit analysis for decision-making purposes.
- One of the most significant challenges in thermal comfort studies is increasing energy efficiency while maintaining acceptable thermal comfort conditions for building occupants. A large amount of energy usage in buildings goes directly towards thermal comfort, which involves fulfilling thermal comfort parameters such as temperatures, relative humidity, and air velocity. Hence, more research is needed to address the combined parameters influencing thermal comfort while balancing energy consumption.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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