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Comprehensive analysis of the relationship between thermal comfort and building control research - A data-driven literature review

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ABSTRACT

Buildings are responsible for about 30–40% of global energy demand. At the same time, we humans spend almost our entire life, up to 80–90% of the time, inside of buildings. Reducing energy demand through optimal operation is the subject of building control research, while human satisfaction in buildings is studied in the thermal comfort community. Thus, balancing the two is necessary for a sustainable and comfortable building stock. We review both research fields and their relationship using a data-driven approach. Based on specific search terms, all relevant abstracts from the Web Of Science database are downloaded and analyzed using the text mining software VOSviewer. We visualize the scientific landscapes of historic and recent trends, and analyze the citation network to investigate the interaction between thermal comfort and building control research. We find that building control focuses predominantly on energy savings rather than incorporating results from thermal comfort, especially when it comes to occupant satisfaction. We identify potential research directions in terms of bridging the two fields.

1. Introduction

Because humans spend 80–90% of the day indoors [1], it is necessary that buildings be designed such that sufficient comfort is provided. In the 19th century, thermal comfort in a building was equivalent to disease prevention through proper ventilation [2]. In fact, one of the first publications that uses the term *thermal comfort* was published in 1824. In this book, Tregold mentions that [3]

> It is important to study the art of heat in order to find a combination between an equal degree of safety, cleanliness, and comfort, along with more healthiness and economy of a space.

In the early 20th century, building systems, i.e., heating, ventilation, air-conditioning (HVAC) and lighting have been developed to provide and maintain a comfortable environment. As a consequence, today, the energy required for this contributes to about 30–40% of the total energy consumption of buildings [4]. In addition, the built environment contributes to about 19% to global greenhouse gas emissions [5]. Thus, buildings constitute a large leverage for reducing global greenhouse gas emissions.

In 1972, Fanger developed the Predicted Mean Vote (PMV) model of thermal comfort based on the heat balance equation on the human skin [6]. This model requires asking large groups of people about their thermal sensations on a seven point scale, and correlating it to air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing level. The PMV model is complemented with the Predicted Percentage of Dissatisfied (PPD) people model [6], and the combined PMV-PPD model is currently used in standards, such as ASHRAE-55 [7] and ISO 7730 [8]. Finally, in the 1990s the adaptive thermal comfort model, which correlates thermal neutrality to outdoor conditions in naturally ventilated buildings [9–11], has been also included in the ASHRAE-55 standard [7].

Despite this progress, providing a comfortable environment is not a trivial task. In 2012, a post occupancy survey in 351 office buildings (52,980 occupants) found that over 50% of the occupants are dissatisfied with their indoor environment [12]. Among 17 parameters, occupants were dissatisfied with sound privacy, temperature, noise level, and air quality. In fact, anecdotal evidence suggests that in Northern America, 97% of people working in the HVAC industry are unaware of and/or cannot cite the ASHRAE Standard which addresses thermal comfort [13]. In addition, monitoring building energy consumption is relatively common and widespread in practice, while investigating occupant satisfaction is not [14]. Finally, it is challenging to generalize occupant behavior for building systems operation, which would be a prerequisite for developing good standards [15].

One way to reduce energy consumption and increase efficiency is

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through optimal operation of the building systems. This is the subject of the research field of building or HVAC control. Conversely, understanding occupant comfort and behavior is studied in the thermal comfort research community. Balancing building operation with occupant comfort, on the other hand, requires that the two fields transfer knowledge between each other to improve. In particular, building control should incorporate knowledge on occupant comfort. However, as has been pointed out above, this does not seem to be the case to date.

1.1. Previous reviews

Both research fields are inherently multidisciplinary, and have been extensively reviewed independently. For example, Djongyang et al. reviewed physiological aspect of thermal comfort of the human body [16], Brager & deDear explained the development of adaptive thermal comfort in the built environment in 1998 [17], and Halawa & van Hoof discussed the adaptive approach to thermal comfort in recent years [18].

Building control, on the other hand, is a compound of multiple engineering fields, i.e., architectural, mechanical, electrical, and computer science. Cook & Das discussed smart building technology in terms of pervasive computing [19], Afram & Janabi-Sharifi reviewed the main HVAC control methods [20], and Wang et al. summarized more recent control strategies in low energy buildings from 2006 to 2016 [21].

Existing review articles that consider both topics focus on specific applications. For example, Vesely et al. discussed how personalized conditioning can be applied for optimal thermal comfort and energy performance [22], while Shaikh et al. reviewed smart building publications in terms of comfort management and building energy consumption [23]. Recently, Enescu reviewed thermal comfort models, and their integrations with artificial intelligence control methods such as Artificial Neural Networks (ANNs), fuzzy control or hybrid control [24]. However, a comprehensive review of the fields and their relationship is not available.

1.2. This review

Previous reviews analyzed the individual research fields independently, or focused on specific examples. However, as has been highlighted above, energy efficient operation cannot be achieved without considering human comfort, which in itself is a complex topic. Therefore, the purpose of this review is to provide a holistic overview by (1) analyzing historical developments and recent trends, (2) investigating through citation networks how both areas have interacted with each other, and ultimately, (3) identifying gaps in the literature on thermal comfort and building control.

The remainder of the paper is organized as follows. Section 2 describes the methodology of the data-driven literature survey. In Section 3, we first analyze the publications quantitatively, and then we describe historical developments and recent trends using scientific landscapes and citation networks. We discuss our findings in Section 4, and conclude the paper in Section 5.

2. Data-driven literature survey

Since thermal comfort and building control are studied in large communities with a long history, it is challenging to conduct our holistic review manually. Instead, we leveraged bibliographical data, i.e., *keywords* and *citations*, and used VOSviewer, a freely available text-mining software to generate bibliometric maps of scientific fields [25,26]. Essentially, we used four functions of this software: (1) importing the publication information, (2) calculating the co-occurrence of terms, (3) extracting the citation relationship among publications, and (4) clustering and visualizing the terms by co-occurrences. This approach allows for a systematic and automatic analysis of an almost arbitrarily large amount of publications, and the relationships between them.

2.1. Publication collection

We selected Thomson Reuters' Web of Science (WoS) bibliographic database for the collection of the publications [27]. We used the following logical combinations of search terms to collect relevant articles: For thermal comfort research related to buildings, we used the search term

(*thermal comfort*) AND (*building**)

On the other hand, the search term for building control research related to energy efficiency was

(*building* automation**) OR (*building* energy management**)
OR (*building* control**)
OR (*HVAC control**),

owing to the fact that building control research can be found under several alternative terms.

Using these search terms, we downloaded the publication information, i.e., title, abstract, author, citation, publication year, as a tab-delimited text file, suitable for further processing with VOSviewer. The download procedure to reproduce our results, as well as the downloaded files are available in [28].

2.2. Publication analysis

We employed two analysis techniques to generate our results. The first method is a keyword analysis, and results in scientific landscapes that we use to analyze historic development and recent trends. As a second method, we used the citation information to analyze the interaction between thermal comfort and building control research. We now describe both methods.

2.2.1. Keyword analysis

For the selection of keywords in a scientific landscape, all the words were extracted from the title and abstract of the publication collections and they were filtered for a minimum of 30 occurrences. With filtered words, the most relevant keywords were extracted through a VOSviewer built-in text mining function [26]. Subsequently, we eliminated unrelated words (i.e., regional words, organization names, generic terms) and merged repetitive words (i.e., singular and plural forms, and abbreviation and full name) by applying the pre-defined thesaurus files.

With the list of keywords, VOSviewer generated the co-occurrence map and clustered the keywords based on the co-occurrences. Two words are defined as *co-occured* if they appear in the same document. In addition, the cluster names were manually labeled based on the observed keywords. Finally, the scientific landscape of thermal comfort and building control research is generated. In this figure, the size and color of the circle represents the frequency of occurrence and cluster type of the individual keyword, respectively. Lastly, the distance between the keywords is representative of their relative co-occurrence, e.g., two keywords that are close to each other co-occur more frequently, whereas a large distance between two keywords indicates that they do not co-occur.

For the keyword analysis, we split the dataset into two parts by dates. The first part contains all the publications until 2010 and allows us to understand the historical developments. The second part is for the publications from 2011 to 2016 in order to analyze and identify recent trends.

2.2.2. Citation analysis

To identify the interaction between thermal comfort and building control research, we investigate citations of the whole publications. Analyzing citation information specifies quantitative interactions