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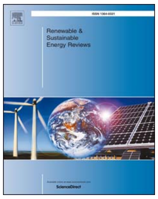

Comprehensive analysis of the relationship between thermal comfort and building control research - A data-driven literature review

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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 between the two (i.e., number of publications cited by others). To visualize the citation network, we extract citation information by VOSviewer, and visualize a citation chord diagram using R [29]. Of particular interest are publications that appear in both the thermal comfort and the building control search, because these are the best candidates to understand the interaction between the fields. We review these publications thematically and chronologically in detail, and investigate the reason why these publications appeared in both search results.

3. Results

3.1. Publication overview

Using the methodology described in Section 2, we identified 3707 articles for thermal comfort (result set $\mathbf{P}_1$), 1951 for building control research (result set $\mathbf{P}_2$), from a total of 5536 publications ($\mathbf{P}_1 \cup \mathbf{P}_2$). Only 122 papers appear in both search results ($\mathbf{P}_1 \cap \mathbf{P}_2$). Fig. 1 shows the distribution of all the publications over the years, from 1970 to 2016. In general, the total number of publications has continuously increased. This increase has been significant in the last decade, as the research published after 2006 constitutes 84%, of all the publications. The relative importance of the two research fields has changed during the investigated period. While until about 1985, building control research was predominant (albeit on a generally small number), since 1991, thermal comfort related research has been prevailing.

In total, we identified 1978 different publication sources (journals and conferences). We found that the fields are mainly advanced through journals, and that the top 15 sources are responsible for 34% of all the publications, while 1963 sources are responsible for the remaining 66%. Fig. 2 indicates the chronological development of the top 15 publication sources. We can observe that most sources have had steady and continuous publication numbers. However, the top-left corner of Fig. 2 represents that the significant quantitive increase is mainly due to recent publications from the two journals, ENERGY & BUILDINGS, and BUILDING & ENVIRONMENT.

In Fig. 3, we show the proportion of the research topics and the number of publication grouped according to these top 15 sources. In the left chart, we can observe that thermal comfort research is predominant over building control research in all but one source, the IEEE INDUSTRIAL ELECTRONICS SOCIETY. In two journals, the ASHRAE TRANSACTIONS, and APPLIED MECHANICS & MATERIALS, the proportion of building control research is about 40%, making them the two most balanced journals with respect to the two research fields. Notice, that the 122 publications that appear in both of our searches, are spread over 10 sources, with their proportion being less than 5%. We can conclude from this Figure that developments are happening independently in the individual research fields, and currently there is no outlet that actively focuses on the interaction between the two. On the right chart of Fig. 3, we can also observe that two specific journals, ENERGY & BUILDINGS, and BUILDING & ENVIRONMENT are the major dissemination sources and responsible for the growth of the fields.

3.2. Scientific landscape of historical developments, (-2010)

To analyze historic developments, we extracted 30,637 terms from the collected publications until 2010 using VOSviewer. From these terms, 361 terms occurred at least 30 times, which were further filtered manually through the thesaurus file to the 85 most relevant keywords (see Appendix A). Fig. 4 illustrates the resulting scientific landscape, clustered by co-occurrences of the keywords in the documents. Four clusters can be identified, and are illustrated by the different colors. Table 1 summarizes the these clusters. We labeled each cluster manually (*Research Topic*) based on the observed keywords in that cluster. For instance, in the red cluster, thermal comfort-related keywords co-occurred, and, consequently, we labeled them as the Thermal Comfort cluster. Similarly, the green, blue, and yellow clusters are labeled as Material, Building control, and Ventilation, respectively.

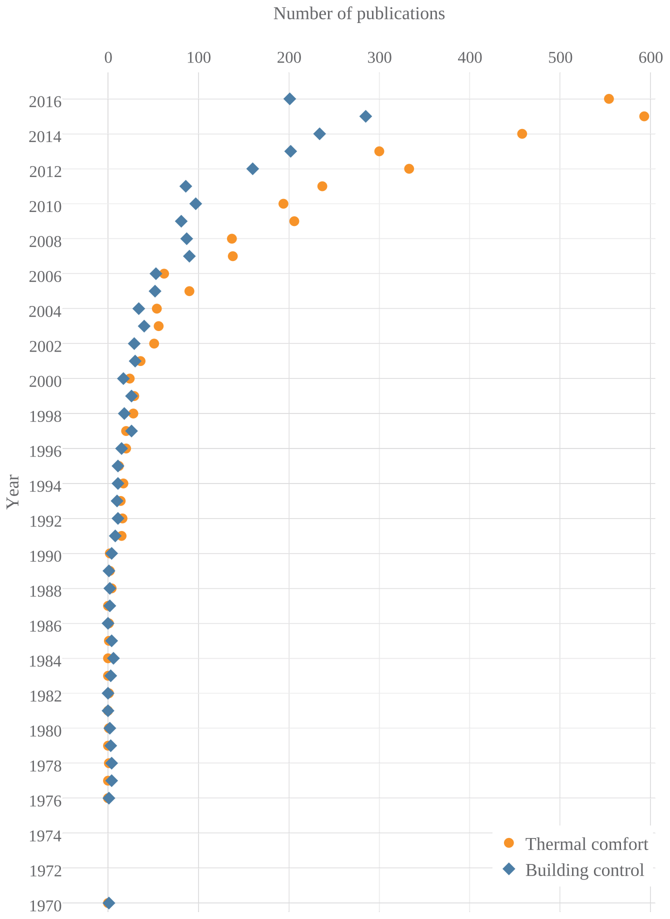

Fig. 1. Number of publications over the years.

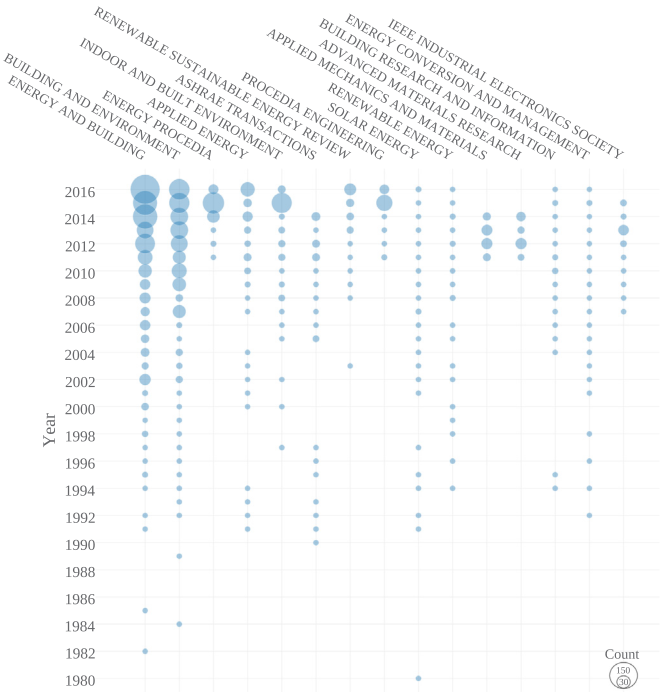

Fig. 2. Chronological development of publication sources.

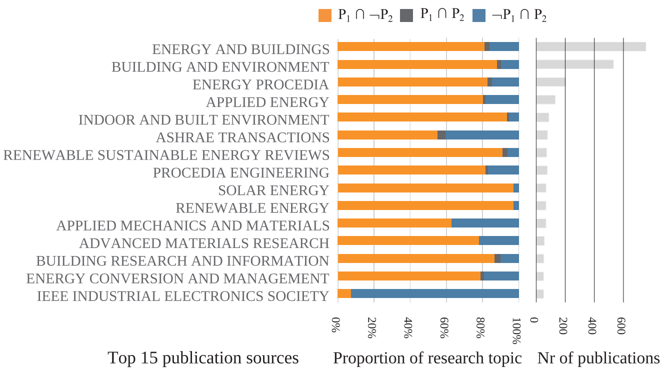

Fig. 3. Publications by source: (left) proportion of research topics, (right) total number of publications. (only thermal comfort: $\mathbf{P}_1 \cap \neg\,\mathbf{P}_2$, only building control: $\neg\mathbf{P}_1 \cap \mathbf{P}_2$ and the intersection: $\mathbf{P}_1 \cap \mathbf{P}_2$).

We can observe in Fig. 4 that the distance between the red and the blue clusters is the largest compared to any other inter-cluster distance. This indicates that the keywords for thermal comfort and building control research are the least co-occurring compared to the others. In other words, building control research papers do not contain thermal comfort-related keywords. We can infer from this that the focus of building control research has not been on thermal comfort. Conversely, thermal comfort researchers concentrated on the principle of thermal comfort rather than on its application in buildings. In addition, except for the blue cluster, the three clusters are close together, and the keyword *thermal comfort* is located center of the three clusters. This shape indicates that research collaborations among thermal comfort, ventilation, and material were conducted, and that these fields, ventilation and material researchers considered thermal comfort more than building control researchers did.

There is a clear opportunity here in bridging these two communities to improve energy efficiency through optimal systems control as well as knowledge gained from the comfort community. Currently, or rather historically, this bridging has been achieved through the adaptive thermal comfort community focused in the yellow cluster, as well as the materials focused research in the green cluster. In the yellow cluster, the keyword *natural ventilation* occurred 202 times, and is located in between thermal comfort and energy-related keywords (e.g., energy efficiency, and energy conservation). In fact, adaptive thermal comfort researchers focused on understanding on naturally ventilated buildings and their relationship to comfortable environments, reducing the need for active HVAC control altogether. On the other hand, the keywords (*Phase Change Material*, and *building envelope*) occured 122 and 137 times, respectively, in the green cluster. These research communities worked on reducing energy consumption through the use of smart materials, and improved integration of systems.

The keywords in the red clusters summarize the developments in the thermal comfort community. First and foremost, the keywords (*Fanger*, and *Predicted Mean Vote (PMV)*) occured 34 and 170 times, respectively. After Fanger's seminal work [6], the PMV-PPD model was selected as standard [8]. Subsequently, several researchers evaluated this model for its suitability. Especially, thermal comfort researchers were particularly interested in *neutral temperature (48)*, *perception (86)*, *clothing (44)*, *adaption (65)*, and *productivity (77)*. Their main findings are as follows: (1) thermal neutrality was not always same as occupant satisfaction, and conversely, high & low PMV index was not indicative of discomfort [30]. (2) more accurate clothing properties and metabolic rates for various furniture materials and activities were needed [31], (3) reliable range for the PMV index was shrunk from its initial values $(-2.0, 2.0)$ to the range of $(-0.5, 0.5)$ to avoid bias error from extreme conditions [32], and (4) it was found that humans accept warmer temperatures in a warm climate zone during the summer season, especially in naturally ventilated buildings [9]. Despite these challenges, the PMV-PPD model has its validity and can be improved through accurate input parameters, in order to be used as productivity evaluation [33,34].

The variation of the neutrality temperature with outdoor temperature in naturally ventilated buildings (point (4) above) gave rise to the adaptive thermal comfort model [7], which is observed mainly in the yellow cluster, and in the overlapping parts of the red and yellow clusters. Many researchers investigated the thermally adaptive behavior with different building locations [9,35–38]. Specifically, these studies were conducted based on field studies, which was made possible due to affordable Information and Communication Technology (ICT) infrastructure (e.g., sensors, computational speed, and database management). Based on the overwhelming evidence of these studies, the

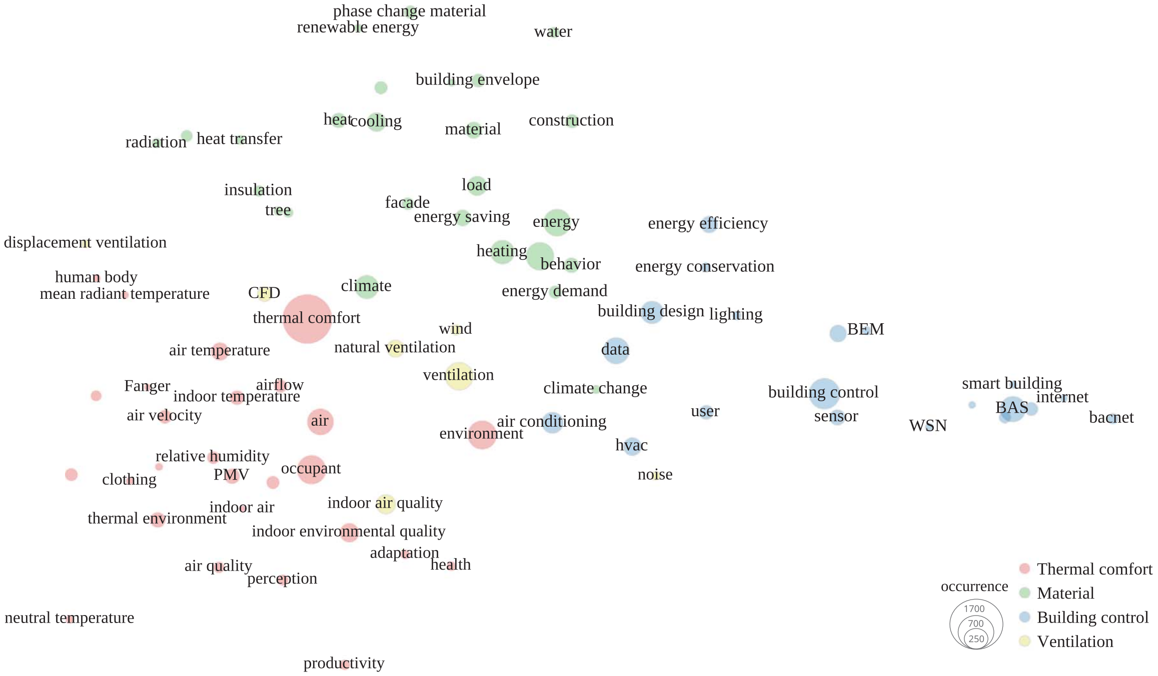

Fig. 4. Scientific landscape by the publications until 2010.

Table 1
Scientific landscape of the publications until 2010.

Cluster color	*Research Topic*	*Observed keywords*	*Nr of keywords*
Red	Thermal comfort	thermal comfort, PMV, occupant	27
Green	Material	material, phase change material, building envelope	26
Blue	Building control	building control, BEM, BAS	20
Yellow	Ventilation	ventilation, natural ventilation, indoor air quality	7

adaptive thermal comfort model has been adopted in standards in the 2000s [10,11,39,40].

Finally, the building control cluster (blue) consists of ICT infrastructures keywords such as *sensor (180)*, *communication (99)*, *data (506)*, and *internet (41)*. In addition, the blue cluster also contains energy-related keywords, for instance, *energy efficiency (210)*, and *energy conservation, (72)*. During the 1980s, building systems were shifted from pneumatic control to direct digital control because of the increasingly available ICT infrastructure. Consequently, this development resulted in building automation systems (BAS), based on the premise that a properly working BAS can save 5–15% of energy [41]. In fact, when combined with advanced analytics methods such as Automated Fault Detection and Diagnosis (AFDD), BAS has the potential to save up to 10–40% of the energy cost [42].

Most of the control research focused on providing and improving the ICT infrastructure from engineering and computer science perspective. Kastner et al. summarized the development of communication standards e.g., *BACnet (84)*, for building automation and control systems [43]. In the center of the blue cluster, the keyword *Wireless Sensor Network (WSN)* occured 48 times together with keywords such as *building control (705)*, *smart building (41)*, *Building Energy Management (BEM) (55)*, and *Building Automation System (BAS) (484)*. In fact, in the late 2000s, the concept of *WSN* was introduced to building applications [44–46]. Dounis & Caraiscos summarized advanced control algorithms based on artificial intelligence for both occupant comfort and energy saving [47]. It should be noted however, that occupant comfort in these research field, i.e., the blue cluster, is typically limited to maintaining a pre-defined set-point, and discomfort is defined as a deviation from this set-point. This is in stark contrast to knowledge in thermal comfort research where it is understood that humans have individual comfort levels, which can vary during the day and/or during seasons.

3.3. *Scientific landscape of recent trends, (2011–2016)*

To investigate recent trends, VOSviewer identified 57,246 terms from the publication of 2011–2016. These were further reduced, using the minimum occurrence of 30 requirement and a thesaurus file, to 172 keywords (see Appendix B). Fig. 5 shows the resulting scientific landscape. Similar to the historical development, there are four clusters, i.e., red, green, blue, and yellow for thermal comfort, material, building control, and ventilation, respectively. In addition to these, two new clusters, cyan and purple, have emerged corresponding to the arising research topics, urban studies, and indoor environmental quality, respectively. Table 2 summarizes the clustering result.

Comparing Figs. 4 and 5, we can observe that the scientific landscape of the recent trends is similar in shape as the one for historical developments. The newly generated purple cluster (indoor environmental quality) is between the red and blue clusters. This indicates that comfort research has increased its focus from thermal comfort to general indoor environmental quality (IEQ) in buildings. In fact, occupant satisfaction and comfort related to IEQ was evaluated in several field studies [12,48–50]. Analyzing IEQ for 400 workstations in 20 office buildings across the U.S., Choi et al. found that the current IEQ standards might result in negative effect on work productivity, occupant health, and excessive energy usage [49]. Lawrence & Keime conducted post-occupancy evaluation for two educational buildings in the UK, and concluded that the degree of environmental control is the key factor to accomplish occupant satisfaction without necessarily consuming more energy [50].

The keyword *adaptation* in the lower left part of Fig. 5, is surrounded by the red, yellow, and purple cluster, and is a key development. It shows that researchers begin to monitor and analyze occupant behavior, in order to understand human adaptation in a broader context. For example, in an eight-month study of 15 dwellings, Andersen et al.

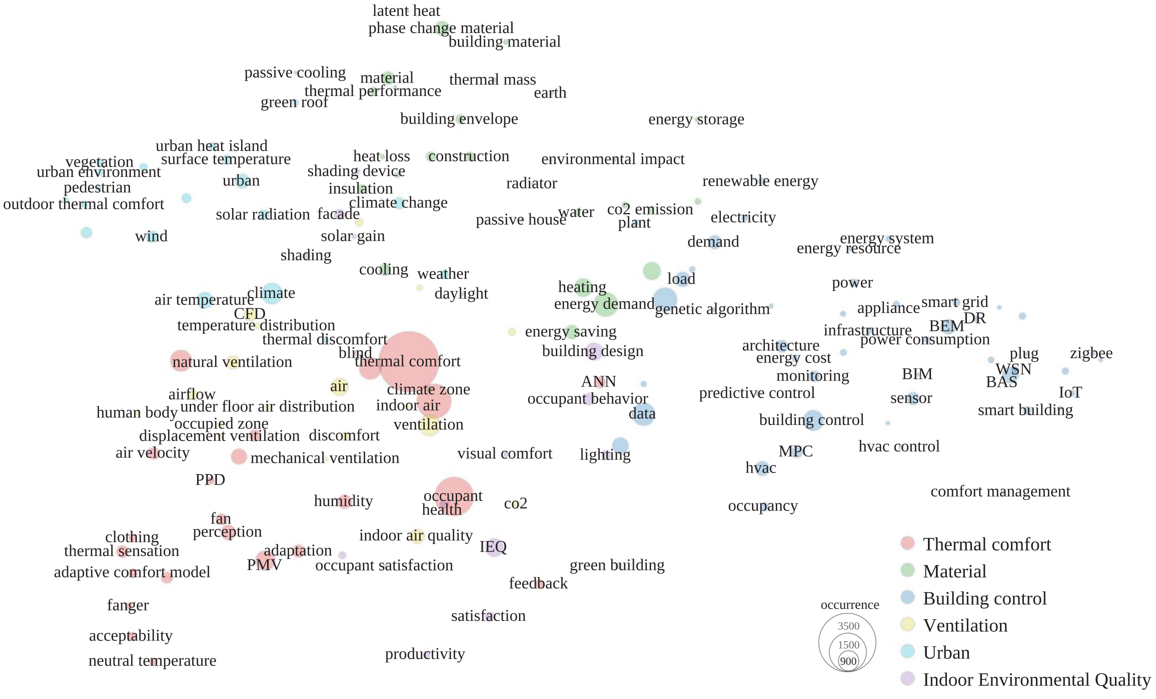

Fig. 5. Scientific landscape by the publications from 2011 to 2016.

Table 2
Keyword clustering result by the publications from 2011 to 2016.

Cluster Color	*Research Topic*	*Observed Keywords*	*Nr of keywords*
Red	Thermal comfort	thermal comfort, PMV, adaptive comfort model	23
Green	Material	material, phase change material, building envelope	30
Blue	Building control	building control, BEM, BAS	48
Yellow	Ventilation	ventilation, natural ventilation, indoor air quality	18
Cyan	Urban	outdoor thermal comfort, urban heat island	19
Purple	Indoor environmental quality	IEQ, productivity, satisfaction	17

verified that occupants window opening and closing behavior has a strong relationship with indoor CO_2 levels and outdoor temperature [51]. Further, simulation, as well as initial experimental results indicate that adaptive occupant-centered set-points of thermal and lighting systems can reduce energy consumption significantly compared to conventional set-points from the automation industry without affecting occupant satisfaction [52–56].

There are a total of 75 new keywords emerging in the recent trends analysis, such as, *artificial neural network (ANN)*, *model predictive control (MPC)*, *internet of things (IoT)*, *demand response (DR)*, and *smart grid*, showing a trend toward highly advanced control approaches. In fact, building control was investigated using various machine learning algorithms. Among them, the *ANN (121)* was the most frequent machine learning related keywords, and it is located in the center of the figure. This implies that the *ANN* was not only famous algorithm in building control research but also in the other fields.

In the blue cluster, the keyword *MPC* occurred 319 times. In fact, we found 105 publications for MPC based HVAC controllers between 2011 and 2016. In contrast, only six papers were published until 2010. Despite this quantitative increase, implementing MPC for application in buildings remain challenging because of the need for detailed building models for successful controller design [57]. However, as with historic developments these building control keywords (e.g., *BAS*, *BEM*, *DR*, and *smart building*) are located far away from human-related keywords (e.g., *thermal sensation*, *adaptation*, *productivity*, and *acceptability*). Thus, we can conclude that advanced control research places significantly more emphasis on energy efficiency rather than being focused on the occupants. Conversely, a clear research opportunity exists in combining the adaptation direction of the human focused research mentioned above, with artificial intelligence based advanced control algorithms capable of identify patterns in data automatically, in order to improve the built environment for both efficiency and human satisfaction.

Another recent trend is the extension of research from smart buildings to smart grids, mainly driven by the electrical engineering community [58,59]. In particular, the focus is on integration of DR approaches into HVAC control [60], appliance load scheduling [61], and electric vehicle charging [62]. In addition, the keyword *IoT* and *WSN* were also found 51 and 122 times, respectively, indicative of further use of these technologies in the built environment for monitoring or determining particular characteristics of buildings [63,64]. *ZigBee* was found as an emerging communication protocol for these devices, mainly because it is a low power protocol, which is beneficial for long term monitoring in building related applications [65].

The cyan cluster, composed of keywords, such as, *urban*, *outdoor thermal comfort*, and *urban heat island effect*, are indicative that in recent years, research has extended from the building to the urban scale. Comfort topics, such as air quality and thermal comfort have been extended from indoors to outdoors. Energy efficiency considerations have shifted from considering isolated buildings toward their potential interaction and their interaction with energy supply systems in the urban fabric [66].

3.4. Interaction between thermal comfort and building control research

Fig. 6 illustrates the citation network of all the publications ($\mathbf{P}_1 \cup \mathbf{P}_2$). The three pie sectors represent each search result or theme. Notice that instead of the inclusive sets $\mathbf{P}_1$ and $\mathbf{P}_2$, we split the results into the three disjoint sets, i.e., $\mathbf{P}_1 \cap \neg\, \mathbf{P}_2$ (only thermal comfort), $\neg\mathbf{P}_1 \cap \mathbf{P}_2$ (only building control), and the intersection $\mathbf{P}_1 \cap \mathbf{P}_2$. The size of the pie sector is the number of citations from all the sectors (including internal citations), and the links between the sectors indicate the citation relationship between them.

We found that 3572 of the total 5536 papers (or 64.5%) actually build a citation relationship, which means that 1964 papers did not cite or were not cited by any other publications in these themes. For the cited thermal comfort publications, 85.9% of papers are cited internally, confirming that thermal comfort research evolved independently from building control research. The intersection result ($\mathbf{P}_1 \cap \mathbf{P}_2$) cited 92 and 21 papers from thermal comfort and building control research, respectively (i.e., the ratio between the two is 4.3). Given that we collected only about 2 times more for papers for $\mathbf{P}_1$ compared to $\mathbf{P}_2$, this disproportional citation ratio indicates that research in $\mathbf{P}_1 \cap \mathbf{P}_2$ is biased toward thermal comfort rather than building control.

We further analyze the relationship between thermal comfort and building control. In Fig. 7, the number of cited publications are plotted by publication year. In addition, in the inset, we highlighted the citation relationship (Fig. 6), particularly for thermal comfort and building control research. Notice that while the first papers were published in the 1970s for both research topics (see Fig. 1), the first cited papers were published after 2000, i.e., 30 years later. In addition, from the 500 cited publications in this analysis, 462 papers (or 92.4%) were published after 2010. Thus, the majority of interactions happened through the most recently published papers.

Consider further that we identified 305 thermal comfort papers cited by building control research. Given that we collected 1951 building control papers in total, this means that only 15.6% of building control papers cited thermal comfort research. This indicates that a

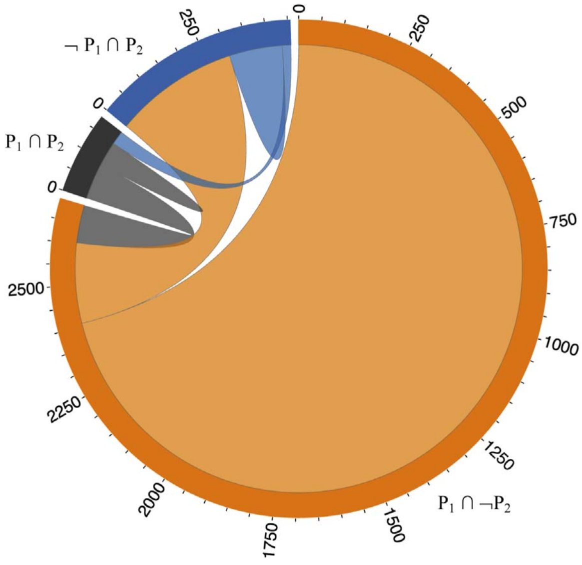

Fig. 6. Citation network for $\mathbf{P}_1 \cup \mathbf{P}_2$.

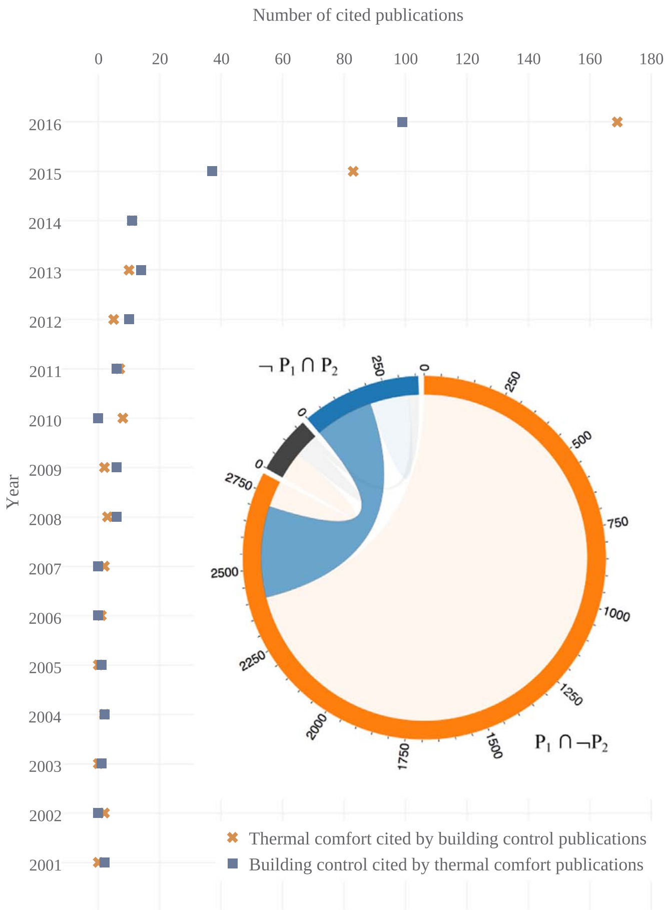

Fig. 7. Number of cited publications over the years.

majority (84.4%) of building control publications may have missed important findings from thermal comfort research. For instance, one of the oldest cited thermal comfort paper explains the origin and development of the adaptive thermal comfort approach [10]. In this paper, Nicol & Humphreys provided informative lessons for building control researchers: (1) poor indication of rational index based comfort measurement, (2) necessity of field evaluation, (3) adaptive mechanism of human behavior, (4) relationship between occupant's controllability and comfort, and (5) relatedness of outdoor temperature for suitable set-point.

As detailed in Section 3.1, there were 122 publications that emerged in both searches (thermal comfort and building control) throughout all years ($\mathbf{P}_1 \cap \mathbf{P}_2$). Since they emerged in both searchers, these publications are of particular interest to study the interaction between the two research fields. We categorized them manually into five research themes: occupant comfort and behavior, building control, building simulation and retrofit, ICT-infrastructure, and review papers. In Fig. 8, the number of publications are shown chronologically and based on the individual themes. We can identify three phases. Phase 1 (1992–2006) is characterized by very few papers (total: 8 papers). In their seminal work in 1992, Dounis et al. firstly suggested for intelligent control system to take occupant comfort into account [67]. Unfortunately, this has not been followed up with further research in this first phase. During Phase 2 (2007–2011), the number of publications increased slightly with about equal importance of the various research topics. In the third phase (2012–2016), a significant increase can be observed.

In the following we review the two major categories, i.e., occupant comfort and behavior, and building control, to analyze interactions. They are also summarized in Tables 3 and 4.

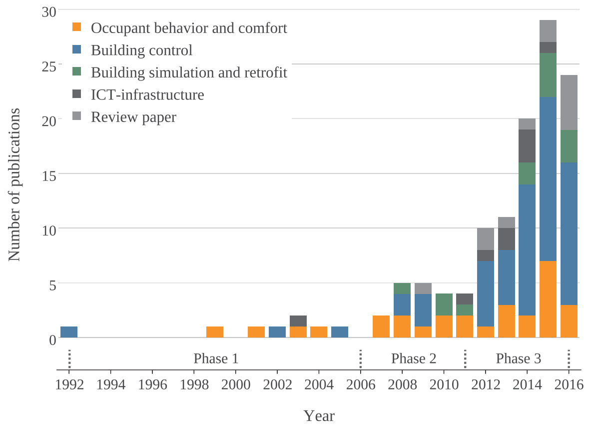

Fig. 8. Number of publications by themes and years.

3.4.1. *Occupant comfort and behavior*

We summarized occupant comfort and behavior research papers in Table 3. The publications are categorized by sub-topic (i.e., thermal comfort, adaptive behavior), and research type (i.e., experiment, simulation, survey). In the last column of the table, we also explained how these studies are related to building control. Since Nicol et al. studied adaptive behavior in 1999 [36], occupant comfort and behavior studies have been conducted through all three phases (Fig. 8).

As described in Sections 3.2 and 3.3, there are two extensions of thermal comfort research, i.e., (1) researchers try to cover overall IEQ for human comfort in a building, and (2) occupant behavior is studied for identifying adaptive behavior in a building. As exact PMV measurements are challenging, researchers evaluated thermal comfort with alternative approaches: Spasokukotskiy conducted an experimental study for model based thermal comfort [68]. Rana et al. developed a simplified thermal comfort index using only temperature and humidity [69]. Songuppakarn et al. evaluated students' thermal comfort in classroom using ANN model [70]. Chen et al. developed state-space Wiener model to investigate the dynamic relationship between ambient temperature and thermal comfort [71], and Zhou et al. analyzed thermal comfort by combining CFD simulation data and K-means clustering techniques [72]. However, these studies dealt with the building control system in a rather general fashion, i.e., using them as motivation for their research or proposing it for future study.

Wilson studied the optimization of thermal preference aggregation from multiple occupants in an open office environment [73]. Even though this study was not applied directly in a building control system, it presented the problem related to building control for multiple occupants. Daum et al. developed a probabilistic measure of thermal comfort using logistic regression from a field survey data [74]. Different from other studies, the probabilistic measure of thermal comfort was directly applied in the building control system, as a case study.

In addition to sole thermal comfort, researchers also evaluated air and acoustic quality [75–77]. Amasyali & El-Gohary analyzed energy-related human behavior by collecting on-line survey data from residential and office building occupants in Illinois (IL), Pennsylvania (PA), and Arizona (AZ) [78]. The results showed that occupants take a top priority on their health among other energy related values (i.e., thermal comfort, visual comfort, indoor air quality, personal productivity, environmental protection, and energy cost saving). These IEQ studies pointed out the importance of integrated approach for occupant comfort. However, there is still a lack of building control applications. Also, considering occupant's psychological aspects, Hellwig discussed the concept of *perceived control*, relating to the fact that occupants tend to be more satisfied with the controller if they have control over their environment [79].

Table 3
Occupant comfort and behavior publications summary.

Ref	Author(s)	Year	Topic	Type	Relation to Control
[36]	Nicol et al.	1999	adaptive behavior	field survey	control related occupant behavior study
[80]	Raja et al.	2001	adaptive behavior	field survey	control related occupant behavior study
[68]	Spasokukotskiy	2003	thermal comfort	lab experiment	future study
[87]	Kulkarni & Hong	2004	thermal comfort	lab experiment	motivation of study
[81]	Rijal et al.	2007	adaptive behavior	field survey	control related occupant behavior study
[82]	Rijal et al.	2007	adaptive behavior	field survey	control related occupant behavior study
[88]	Rijal et al.	2008	adaptive behavior	field survey	control related occupant behavior study
[89]	Haldi & Robinson	2008	adaptive behavior	field survey	control related occupant behavior study
[90]	Rijal et al.	2009	adaptive behavior	field survey	control related occupant behavior study
[75]	Tiller et al.	2010	acoustical quality, thermal comfort	lab experiment	motivation of study
[91]	Indraganti	2010	adaptive behavior	field survey	control related occupant behavior study
[74]	Daum et al.	2011	thermal comfort	field experiment	case study for blind controller
[83]	Rijal et al.	2011	adaptive behavior	field survey	control related occupant behavior study
[84]	Rijal et al.	2012	adaptive behavior	field survey	control related occupant behavior study
[69]	Rana et al.	2013	thermal comfort	field experiment	motivation of study
[92]	Sahari et al.	2013	thermal comfort	simulation	motivation of study
[51]	Andersen et al.	2013	adaptive behavior	field survey	control related occupant behavior study
[70]	Songuppakarn et al.	2014	thermal comfort	field experiment	future study
[93]	Shih	2014	occupancy, activity detection	field experiment	future study
[73]	Wilson	2015	thermal comfort	theoretical	motivation of study
[71]	Chen et al.	2015	thermal comfort	lab experiment	future study
[76]	Montgomery et al.	2015	thermal comfort, air quality	field experiment	comparison between natural and mechanical ventilation
[72]	Zhou et al.	2015	thermal comfort	lab experiment	future study
[79]	Hellwig	2015	thermal comfort	theoretical	conceptual framework for perceived control
[77]	Chen et al.	2015	thermal comfort, air quality	simulation	pollutant control effect on thermal comfort
[94]	Rana et al.	2015	occupancy, activity detection	field experiment	motivation of study
[95]	Yao et al.	2016	thermal comfort	simulation	shading control effect on thermal comfort
[78]	Amasyali & El-Gohary	2016	energy related behavior	field survey	control related occupant behavior study
[85]	Langevin et al.	2016	adaptive behavior	simulation	control related occupant behavior study

On the other hand, we also found that most of these publications in this group, shown in Table 3, are part of adaptive thermal comfort. Nicol et al. observed thermally adaptive behaviors (e.g., windows, fans, air-conditioners, heatings, activity, and clothing) for workers in Pakistan, and their result was not explained by Fanger's PMV model [36]. Raja et al. emphasized thermally adaptive behavior in a naturally ventilated building, and that the occupants felt more comfortable when they were able to control their environment [80]. Subsequently, adaptive behavior research continued with more data, and window opening behavior models were applied as simulation inputs [51,81–84]. Recently, agent-based occupant behavior modeling was developed [85]. Given the importance of occupant behavior, a group of researchers has studied occupant behavior under the International Energy Agency's Energy in Buildings and Communities Program [86]. Historically, occupant behavior research contributed to the establishment of the adaptive thermal comfort model [7]. However, implementing occupant behavior models in actual building control system remains an open research direction.

3.4.2. Building control

Table 4 summarizes the publications for building control research. We sub-grouped the publications according to their control method (e.g., rule-based control, optimization, intelligent control, and model predictive control (MPC)), verification type (e.g., simulation, experiment), and metric for thermal comfort (i.e., temperature, temperature range, PMV-PPD, actual vote). As Fig. 8 indicates, more than half of the papers in this group were published from 2014 to 2016, which means only recently have building control researchers actively begun to consider thermal comfort criteria.

For building controllers there is no established criterion which is used to evaluate how well thermal comfort has been achieved. In fact, several different meanings of thermal comfort exist concurrently. Within the building control researches verified by simulation results, the majority of studies (21 papers) evaluated thermal comfort by indoor air temperature alone, and thermal comfort was considered achieved if the controller maintained the room temperature within a certain range. In nine publications, the PMV-PPD index was calculated to evaluate thermal comfort, and only two studies evaluated thermal comfort by actual interaction with occupants through voting: McCartney & Nicol proposed a calculation method for adaptive set-points based on outdoor conditions and verified these using a survey from occupants [96]. Zhao et al. pre-collected thermal comfort using a web-based dashboard, and utilized the preference of the occupants as input to their MPC [55]. Finally, researchers considered not only thermal comfort but also additional IEQ criteria (i.e., visual comfort and CO_2 level) [97–100]. These other IEQ criteria are evaluated with predefined ranges for illuminance and CO_2 level. Considering the adaptive human behavior, Hoyt et al. suggested dead bands based on different climate zones [101].

We identified 24 control publications based on experimental work. These have been made possible mainly due to the recent development of ICT infrastructure as identified in Fig. 5. Similarly to the simulation based control papers, the majority (17 papers) were published in the past three years. However, much fewer MPC based control algorithms (only six papers vs 21) have been investigated. This is because, it is challenging, time-consuming and expensive to deploy MPC based controllers in real building environments due to the need for detailed model development, and computational requirements. Since these studies were verified by experiment, the system scopes were typically limited to single zone or multiple zones within a single floor. As an exception, Bengea et al. evaluated their MPC algorithm in two identical large-size buildings. Using the proposed controller, they proved energy saving of 20% in the transition period, and 70% in the heating season, compared to conventional rule based schedule controller [102]. However, this MPC algorithm has a limitation in that it considers thermal comfort by temperature range alone. With larger scale perspective, the integration of ten buildings in a smart grid, e.g., demand response, scenario was evaluated [103,104].

Table 4
Building control publications summary.

Ref	Author(s)	Year	Method	Verification	Comfort metric
[67]	Dounis et al.	1992	intelligent control	simulation	PMV-PPD
[96]	McCartney & Nicol	2002	rule based	experiment	actual vote
[109]	Nassif et al.	2005	intelligent control	simulation	PMV-PPD
	Zeiler et al.	2008		simulation	
[110]	Nassif & Moujaes	2008	optimization	simulation	temperature range
	Zeiler et al.	2009		simulation	
[97]	Mitsios et al.	2009	rule based	experiment	temperature range
[111]	Sourbron et al.	2009	rule based	experiment	temperature range
	Trandabat et al.	2012		simulation	
[112]	Ma et al.	2012	MPC	experiment	temperature range
[113]	Wallace et al.	2012	MPC	experiment	temperature
[114]	Klein et al.	2012	intelligent control	experiment	PMV-PPD
[115]	Hazyuk et al.	2012	MPC	experiment	temperature range
[116]	Nouvel & Alessi	2012	rule based	experiment	PMV-PPD
[105]	Purdon et al.	2013	model free	simulation	actual vote
[117]	Counsell et al.	2013	intelligent control	experiment	temperature
[118]	Drgona & Kvasnica	2013	MPC	experiment	temperature range
[119]	Sourbron et al.	2013	MPC	experiment	temperature range
[98]	Sun et al.	2013	MPC	experiment	temperature range
[120]	Bengea et al.	2014	MPC	simulation	temperature range
[121]	Jazizadeh et al.	2014	intelligent control	simulation	actual vote
[53]	Jazizadeh et al.	2014	intelligent control	simulation	actual vote
[52]	West et al.	2014	MPC	simulation	actual vote
[122]	Hazyuk et al.	2014	MPC	simulation	PMV-PPD
[106]	Ghahramani et al.	2014	intelligent control	simulation	actual vote
[123]	Klauco & Kvasnica	2014	MPC	experiment	PMV-PPD
[60]	Yoon et al.	2014	rule based	experiment	temperature range
[124]	Scherer et al.	2014	MPC	experiment	temperature
[125]	Mokhtar et al.	2014	intelligent control	experiment	temperature
[99]	Gruber et al.	2014	intelligent control	experiment	temperature range
[126]	Hussain et al.	2014	intelligent control	experiment	PMV-PPD
[127]	Ciabattoni et al.	2015	intelligent control	simulation	PMV-PPD
[107]	Anand et al.	2015	rule based	simulation	PMV-PPD
[103]	Fanti et al.	2015	optimization	simulation	temperature range
[128]	Revel et al.	2015	rule based	simulation	PMV-PPD
[102]	Bengea et al.	2015	MPC	simulation	temperature range
[129]	Michailidis et al.	2015	intelligent control	simulation	temperature
[104]	Fanti et al.	2015	optimization	simulation	PMV-PPD
[130]	Mansur et al.	2015	intelligent control	experiment	actual vote
[131]	Behrooz et al.	2015	intelligent control	experiment	temperature
[132]	Lee et al.	2015	MPC	experiment	temperature
[133]	Ruano et al.	2015	MPC	experiment	PMV-PPD
[134]	Miletic et al.	2015	MPC	experiment	temperature range
[101]	Hoyt et al.	2015	rule based	experiment	PMV-PPD
[135]	Gupta et al.	2015	optimization	experiment	temperature
[136]	Kirubakaran et al.	2015	MPC	experiment	temperature
[137]	Sturzenegger et al.	2016	MPC	simulation	temperature range
[138]	Katsigarakis et al.	2016	MPC	simulation	PMV-PPD
[139]	Lim et al.	2016	intelligent control	simulation	temperature range
[108]	Salamone et al.	2016	rule based	simulation	PMV-PPD
[140]	Ascione et al.	2016	MPC	experiment	PMV-PPD
[141]	Hilliard et al.	2016	MPC	experiment	temperature range
[142]	Nowak & Urbaniak	2016	MPC	experiment	PMV-PPD
	Popescu & Borza	2016		experiment	
	Popescu & Borza	2016		experiment	
[143]	Killian et al.	2016	MPC	experiment	temperature
[55]	Zhao et al.	2016	MPC	experiment	actual vote
[144]	Castilla et al.	2016	MPC	experiment	PMV-PPD
[100]	Mofidi & Akbari	2016	optimization	experiment	temperature range

From the thermal comfort perspective, we found four control algorithms actively engaging the users to vote in the loop: Purdon et al. suggested a model-free controller which collects binary opinion (hot or cold) from occupants. This controller saved up to 60% of energy and showed a relatively small increase of discomfort in 12 offices over a 3-week period [105]. West et al. installed an online occupant survey tool based on the ASHRAE 7-point scale to constrain their optimized supervisory MPC system and proved 19% and 32% of energy saving in two office buildings without considerably affecting occupant satisfaction [52]. Jazizadeh et al. developed a fuzzy algorithm by direct preference feedback from the user interface, and this controller reduced 39% of air-flow rate while the HVAC system providing occupants' desired temperature [53]. With a similar experiment condition, Ghahramani et al. achieved 12.08% airflow reduction in three targeted zones [106]. In addition, with a simple rule based algorithm, open source controllers for retrofit were suggested for saving building energy consumption [107,108]. Notably, Salamone et al. developed a custom automatic HVAC control system, which, compared to the existing controller, saved 7% of energy consumption and improved occupant comfort from 35% to 65% [108]. This strongly suggests that it may not be necessary to consider advanced controllers.

4. Discussion

4.1. Research gap and opportunities

The two research areas (i.e., thermal comfort, and building control) published their first papers in the 1970s and developed rather independently. The scientific landscapes for both historical development (until 2010) and recent trends (2011–2016) indicate a discrepancy between thermal comfort and building control (see Figs. 4 and 5). Historically, the building control research keywords were not co-occurred with other research keywords (i.e., thermal comfort, material, and ventilation). In fact, the distance between the thermal comfort and building control clusters is the largest of any two clusters, indicating that they have the least in common. In addition, analyzing the citation network for the whole 5536 publications ($\mathbf{P}_1 \cup \mathbf{P}_2$), we found that only 5.2% and 15.6% of thermal comfort and building control publications cited each other, respectively, and this interaction mainly happened during recent publication years (2015–2016).

Adaptive comfort research attempts to bridge thermal comfort and building control by understanding the adaptive behavior of occupants in naturally ventilated buildings. In recent trends, this research community extended the scope of interest from just thermal comfort to overall indoor environmental quality and models the adaptive occupant behavior in a building. In particular, understanding how occupants use building system is a critical step toward building energy saving [145]. However, most of the previous occupant behavior studies rather focused on windows and blind opening behaviors. There is an opportunity to explore other types of occupant behavior further (e.g., thermostat usage pattern) [146]. On the other side, beyond environmental quality, control researchers should also embrace the opportunity to consider human factors (i.e., psychological and physiological aspects) to understand thermal sensation comprehensively [147–149].

To promote a collaborative environment and effective knowledge transfer, thermal comfort related works should be published in control publication sources and vice versa. In addition, there are numerous organizations participating in these research fields, e.g., ACM,[1] ASCE,[2] ASHRAE,[3] IEEE,[4] and USGBC[5] to name a few. There are several joint conferences by ACM and IEEE [150], as well as IEEE and ASCE [151]. However, they are not related to neither thermal comfort or building control. Notable examples are the development of ASHRAE 189.9 [152] code for high-performance building code developed by ASHRAE, USGBC, and Illumination engineering society. Also, IEEE and ASHRAE communities established standards for ventilation and thermal management of battery [153]. However, none of them have fully related to thermal comfort and building control altogether. More collaboration and communication between the societies is required to ensure that buildings are operated both efficiently and comfortably.

Recently, the emergence of *smart buildings* has prompted a re-evaluation of the purpose of building control. While the keyword itself appears in the far right of Fig. 5, indicating its focus on energy management, some researchers argue that, there is a need to [154]

> strike a balance between allowing users to have control of their environment, and […] allow the building systems to manage the energy consumption efficiently.

Thus, building control should more actively incorporate the large amounts of knowledge generated by the thermal comfort community to achieve truly smart buildings. From the citation network analysis, it is clear that there is an opportunity to increase the interaction between the fields. Thus, collaborative conference or organizations should be inaugurated for the sake of knowledge transition of thermal comfort and building control research.

There are more keywords about ICT-infrastructure and novel control algorithms in Fig. 5. Indeed, low-cost ICT infrastructures enabled researchers to acquire building operation data with higher resolution, and manage a large stream of data efficiently. Specifically, occupant behavior was monitored due to the development of sensor technology. With abundant data, researchers developed building control algorithms, attempting to fulfill simultaneously occupant satisfaction and energy saving. However, for most of the control studies, occupant satisfaction with the environment is reduced to a temperature range, rather than the multiple dimensions and psychological aspects identified by thermal comfort researchers. Therefore, future research should focus on establishing procedures to determine occupant comfort comprehensively, e.g., from objective measurements and/or subjective surveys, and integrate it with the control algorithm. Due to the adaptive nature of the behavior of occupants in a building, control algorithms should also be adaptive and responsive to the desired indoor environment of the occupants [53,54,56,155]. With low-cost and easy-deployable ICT infrastructures, the experiment based control studies should increase their scale from single zones or floors to multiple zones and eventually to the building scale.

In Fig. 5, the cyan cluster includes urban scale related keywords. On the other hand, the keywords *smart grid*, and *DR* indicating energy related urban scale research, occurred in the blue cluster. Similar to the discussion above for *smart buildings*, there is a significant discrepancy between the two indicated by the large distance between the keywords. However, research toward the *smart city* should carefully balance the two in the future. The development of ICT-infrastructure will further facilitate this by providing IoT environment for cities [156]. There is a research opportunity to leverage urban spatio-temporal data, i.e., from transportation, power grid, and weather conditions, in order to adapt the building, its occupants and its control system to the surrounding urban context.

4.2. Limitations

In the following, we discuss the limitations of our study. Certainly, a data-driven approach is highly dependent on the quality of data collection. Even though we collected publications by logical combinations of selected search terms, it is challenging to assure that we collected all relevant papers because of possible alternative research terms. For instance, some researchers might use thermal satisfaction instead of thermal comfort. Considering further non-English publications, the number of possible search terms would increase significantly.

Also, the study is limited in that the WebOfScience (WoS) database search engine finds search terms only in the title, abstract and author's keyword part, rather than the main text as well. Further, the WoS database indexes SCI-EXPANDED, SSCI, A & HCI, CPCI-S, AND SPCI-SSH. Because of this, the publication collection excludes some important papers e.g., Fanger's early work [6], and Mozer's neural network house [157]. A more systematic and inclusive publication collection approach is required to derive more accurate results. We do not anticipate, however, a significant change in our conclusions.

In addition, VOSviewer clustered and visualized the keywords based on their co-occurrences in the publications, and we defined each cluster as a specific research topic. Most of the keywords are correctly matched with the research themes of the clusters. However, it is likely that certain keywords may belong to other topics as well, especially when the topics are related. For instance, the keyword *thermal discomfort* is clustered in the urban studies (cyan) topic, rather than thermal comfort (red). This shows the sensitivity of the data to the number of clusters chosen during the process. A small number (one or two clusters) does not allow to identify sufficient variation of the research topics, whereas a large number creates too many artificial and potentially overlapping clusters.

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[1] Association for Computing Machinery.

[2] American Society of Civil Engineers.

[3] American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[4] Institute of Electrical and Electronics Engineers.

[5] U.S. Green Building Council.

5. Conclusion

In this review, we employed a data-driven method to search and analyze scientific literature, in order to identify historical development and recent trends of thermal comfort and building control. The relationship between the two research fields is visualized through scientific landscapes and a citation chord diagram. We find that building control focuses pre-dominantly on energy-savings rather than incorporating results from thermal comfort, especially when it comes to occupant satisfaction. In between thermal comfort and building control, there were ventilation-related keywords and indoor environmental quality-related keywords. These two research fields study adaptive occupant behavior as an attempt to bridge thermal comfort and building control.

Various ICT related keywords emerged in the recent trend analysis. In addition artificial intelligence algorithms arose in the center of the scientific landscape. Thus, there is an increased activity to explore adaptive occupant behavior with ICT-infrastructure using machine learning algorithms. It is important, however, that these explorations are based on previous knowledge generated by the thermal comfort and building control communities and address opportunities to bridge them.

Successful bridging the disciplines on multiple scales, from building to urban scale, by balancing human requirements (comfort, satisfaction) on the one hand, with energy conservation goals on the other hand, will contribute to a sustainable and comfortable transformation of the building stock, leading to smart building and cities.

Appendix A. Keywords 1970–2010

Table A.5

Table A.5
List of keywords for Fig. 4.

Thermal comfort (red)		**Material (green)**	
Keywords	*Nr of occurance*	*Keywords*	*Nr of occurance*
Thermal comfort	1746	Energy consumption	609
Occupant	606	Energy	576
Environment	602	Heating	448
Air	506	Climate	434
Indoor environmental quality	267	Load	292
Air temperature	228	Cooling	277
Predicted mean vote	170	Material	209
Thermal environment	168	Energy saving	202
Indoor temperature	150	Behavior	173
Air velocity	134	Heat	169
Airflow	119	Construction	140
Humidity	119	Building envelope	137
Thermal sensation	118	Energy demand	125
Relative humidity	110	Thermal performance	124
Air quality	90	Phase change material	122
Perception	86	Facade	112
Indoor thermal environment	84	Solar radiation	100
Productivity	77	Insulation	93
Adaptation	65	Water	89
Health	63	Radiation	73
Neutral temperature	48	Urban	73
Clothing	44	Heat transfer	62
Outdoor temperature	44	Tree	60
Human body	43	Climate change	58
Mean radiant temperature	41	Renewable energy	50
Fanger	34	Thermal mass	44
Indoor air	33		

Building control (blue)		**Ventilation (yellow)**	
Keywords	*Nr of occurance*	*Keywords*	*Nr of occurance*
Building control	705	Ventilation	532
Data	506	Indoor air quality	255
Building automation system	484	Natural ventilation	202
Building design	382	Computational fluid dynamic	146
Air conditioning	334	Wind	73
hvac	238	Noise	52
Architecture	210	Displacement ventilation	41
Energy efficiency	210		
Sensor	180		
User	146		
Control network	131		
Communication	99		
Bacnet	84		
Energy conservation	72		
Lighting	56		

(*continued on next page*)

Table A.5 (*continued*)

Building control (blue)		Ventilation (yellow)	
Keywords	*Nr of occurance*	*Keywords*	*Nr of occurance*
Building energy management	55		
Wireless sensor network	48		
Internet	41		
Smart building	41		
Actuator	36		

Appendix B. Keywords 2010–2016

Table B.6

Table B.6
List of keywords for Fig. 5.

Thermal comfort (red)		Ventilation (yellow)	
Keywords	*Nr of occurance*	*Keywords*	*Nr of occurance*
Thermal comfort	3403	Ventilation	821
Occupant	1414	Air	548
Environment	1112	Indoor air quality	374
Indoor temperature	460	Natural ventilation	330
Thermal environment	436	Computational fluid dynamic	303
Predicted mean vote	358	Airflow	166
Relative humidity	227	Heat transfer	119
Perception	208	Discomfort	113
Humidity	184	Energy simulation	96
Adaptation	156	CO2	92
Thermal sensation	140	Temperature distribution	71
Air velocity	138	Under floor air distribution	65
Outdoor temperature	128	Heat source	58
Sensation	125	Displacement ventilation	44
Fan	124	Indoor air	43
Artificial neural network	121	Human body	40
Adaptive comfort model	80	Occupied zone	39
Feedback	77	Mechanical ventilation	36
Acceptability	70		
Clothing	58		
Neutral temperature	57		
Predicted percentage of dissatisfied	55		
Fanger	46		

Building control (blue)		Material (green)	
Keywords	*Nr of occurance*	*Keywords*	*Nr of occurance*
Energy	1398	Energy demand	1692
Data	1250	Heating	964
Building control	1005	Building energy efficiency	888
Building automation system	642	Phase change material	596
Air conditioning	635	Energy saving	568
Load	541	Material	479
Building energy management	533	Cooling	428
hvac	507	Heat	287
Demand	455	Construction	269
Sensor	396	Building envelope	253
Architecture	369	Insulation	229
Model predictive control	319	Thermal performance	215
Monitoring	294	Water	145
Smart building	182	Emission	125
Occupancy	176	CO2 emission	123
Power	167	Heat pump	120
Grid	150	Heat gain	97
Renewable energy	132	Thermal mass	97
Wireless sensor network	122	Energy storage	88
Communication	119	Building material	83
Smart grid	118	Climate zone	76
Plant	115	Heat loss	67
Energy cost	109	Environmental impact	57
Appliance	108	Radiator	52
Policy	107	Earth	46

(*continued on next page*)

Table B.6 (*continued*)

Building control (blue)

Keywords	*Nr of occurance*
Infrastructure	106
Power consumption	106
Electricity	102
Energy system	97
Internet	97
Control network	95
Demand response	95
Sustainability	91
Energy conservation	87
Electricity consumption	77
Energy resource	63
Chiller	56
Genetic algorithm	51
Internet of things	51
Hvac control	48
Predictive control	48
Battery	46
Building information modeling	44
Bacnet	43
Optimal control	42
Zigbee	41
Comfort management	34
Plug	34

Material (green)

Keywords	*Nr of occurance*
Passive cooling	42
Passive house	40
Heating load	38
Latent heat	38
Night ventilation	37

Urban (cyan)

Keywords	*Nr of occurance*
Climate	689
Air temperature	400
Urban	313
Wind	215
Climate change	208
Mean radiant temperature	184
Solar radiation	159
Microclimate	136
Surface temperature	135
Weather	121
Urban heat island	104
Vegetation	100
Tree	98
Outdoor thermal comfort	72
Urban environment	66
Green roof	65
Thermal discomfort	64
Heat stress	55
Pedestrian	47

IEQ (purple)

Keywords	*Nr of occurance*
Indoor environmental quality	612
Building design	576
Occupant behavior	269
Facade	211
Lighting	182
Satisfaction	180
Health	162
Productivity	108
Air quality	105
Shading	105
Green building	65
Blind	63
Shading device	59
Visual comfort	59
Solar gain	46
Daylight	38
Occupant satisfaction	35

References

[1] U.S Department of Labor, Bureau of Labor Statistics, Occupational Outlook Handbook, 2012–13 Edition, Medical Assistants.

[2] Janssen JE. The history of ventilation and temperature control. ASHRAE J 1999;41(10):48–70.

[3] Tredgold T. Principles of warming and ventilating public buildings. London: Dwelling Houses, Josiah Taylor; 1824https://catalog.hathitrust.org/Record/012241658.

[4] Department of Energy, Buildings energy databook, Office of Energy Efficiency & Renewable Energy.

[5] IPCC. Climate change 2014: mitigation of climate change. 3. Cambridge University Press; 2015http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.

[6] Fanger PO. Thermal comfort analysis and applications in environment engineering (1972).

[7] ASHRAE, Standard 55-2010, Thermal Environmental Conditions for Human Occupancy.

[8] ISO, Standard 7730:2005. ergonomics of the thermal environment., Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[9] De Dear RJ, Brager GS, Reardon J, Nicol F, et al. Developing an adaptive model of thermal comfort and preference/discussion. ASHRAE Trans 1998;104:145.

[10] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 2002;34(6):563–72. http://dx.doi.org/10.1016/S0378-7788(02)00006-3.

[11] Nicol F. Adaptive thermal comfort standards in the hot-humid tropics. Energy Build 2004;36(7):628–37. http://dx.doi.org/10.1016/j.enbuild.2004.01.016.

[12] Frontczak M, Schiavon S, Goins J, Arens E, Zhang H, Wargocki P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air 2012;22(2):119–31.

[13] Healthy Heating, ⟨http://healthyheating.com/⟩, [accessed 18 March 2017].

[14] Tom S. Managing energy and comfort: don't sacrify comfort when managing energy. ASHRAE J 2008;50(6):18–26.

[15] Hong T, Yan D, D'Oca S, Chen C-f. Ten questions concerning occupant behavior in buildings: the big picture. Build Environ 2016;114:518–30. http://dx.doi.org/10.1016/j.buildenv.2016.12.006.

[16] Djongyang N, Tchinda R, Njomo D. Thermal comfort: a review paper. Renew Sustain Energy Rev 2010;14(9):2626–40. http://dx.doi.org/10.1016/j.rser.2010.07.040.

[17] Brager GS, Dear RJDe. Thermal adaptation in the built environment: a literature review. Energy Build 1998;27(1):83–96.

[18] Halawa E, Van Hoof J. The adaptive approach to thermal comfort: a critical overview. Energy Build 2012;51:101–10.

[19] Cook DJ, Das SK. How smart are our environments? An updated look at the state of

the art. Pervasive Mob Comput 2007;3(2):53–73. http://dx.doi.org/10.1016/j.pmcj.2006.12.001.

[20] Afram A, Janabi-Sharifi F. Theory and applications of HVAC control systems - a review of model predictive control (MPC). Build Environ 2014;72:343–55. http://dx.doi.org/10.1016/j.buildenv.2013.11.016.

[21] Wang Y, Kuckelkorn J, Liu Y. A state of art review on methodologies for control strategies in low energy buildings in the period from 2006 to 2016. Energy Build 2017;147:27–40.

[22] Vesely M, Zeiler W. Personalized conditioning and its impact on thermal comfort and energy performance - a review. Renew Sustain Energy Rev 2014;34:401–8. http://dx.doi.org/10.1016/j.rser.2014.03.024.

[23] Shaikh PH, Nor NBM, Nallagownden P, Elamvazuthi I, Ibrahim T. A review on optimized control systems for building energy and comfort management of smart sustainable buildings. Renew Sustain Energy Rev 2014;34:409–29. http://dx.doi.org/10.1016/j.rser.2014.03.027.

[24] Enescu D. A review of thermal comfort models and indicators for indoor environments. Renew Sustain Energy Rev 2017;79:1353–79.

[25] van Eck NJ, Waltman L. VOSviewer manual, Leiden: Univeristeit Leiden.

[26] Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 2010;84(2):523–38.

[27] Web of science, 〈https://apps.webofknowledge.com/〉, [accessed 8 April 2017].

[28] Park JY, Nagy Z. Relationship between thermal comfort and building control research by analyzing 5,536 articles, Data in Brief in Press.

[29] Team RC. R language definition, Vienna, Austria: R foundation for statistical computing.

[30] Humphreys MA, Hancock M. Do people like to feel ‘neutral’?. Exploring the variation of the desired thermal sensation on the ASHRAE scale. Energy Build 2007;39(7):867–74. http://dx.doi.org/10.1016/j.enbuild.2007.02.014.

[31] Havenith G, Holmér I, Parsons K. Personal factors in thermal comfort assessment: clothing properties and metabolic heat production. Energy Build 2002;34(6):581–91. http://dx.doi.org/10.1016/S0378-7788(02)00008-7.

[32] Humphreys MA, Fergus Nicol J. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy Build 2002;34(6):667–84. http://dx.doi.org/10.1016/S0378-7788(02)00018-X.

[33] Van Hoof J. Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 2008;18(3):182–201. http://dx.doi.org/10.1111/j.1600-0668.2007.00516.x.

[34] Kosonen R, Tan F. Assessment of productivity loss in air-conditioned buildings using PMV index. Energy Build 2004;36(10 SPEC. ISS.):987–93. http://dx.doi.org/10.1016/j.enbuild.2004.06.021.

[35] Baker N, Standeven M. Thermal comfort for free-running buildings. Energy Build 1996;23(3):175–82. http://dx.doi.org/10.1016/0378-7788(95)00942-6.

[36] Nicol JF, Raja IA, Allaudin A, Jamy GN. Climatic variations in comfortable temperatures: the Pakistan projects. Energy Build 1999;30(3):261–79. http://dx.doi.org/10.1016/S0378-7788(99)00011-0.

[37] Mui KWH, Chan WTD. Adaptive comfort temperature model of air-conditioned building in Hong Kong. Build Environ 2003;38(6):837–52. http://dx.doi.org/10.1016/S0360-1323(03)00020-9.

[38] Bouden C, Ghrab N. An adaptive thermal comfort model for the Tunisian context: a field study results. Energy Build 2005;37(9):952–63. http://dx.doi.org/10.1016/j.enbuild.2004.12.003.

[39] De Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy Build 2002;34(6):549–61. http://dx.doi.org/10.1016/S0378-7788(02)00005-1.

[40] Nicol F, Humphreys M. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Build Environ 2010;45(1):11–7. http://dx.doi.org/10.1016/j.buildenv.2008.12.013.

[41] Brambley MR, Hansen D, Haves P, Holmberg D, McDonald S, Roth K, Torcellini P. Advanced sensors and controls for building applications: Market assessment and potential r & d pathways, Pacific Northwest National Laboratory.

[42] Schein J, Bushby ST, Castro NS, House JM. A rule-based fault detection method for air handling units. Energy Build 2006;38(12):1485–92. http://dx.doi.org/10.1016/j.enbuild.2006.04.014.

[43] Kastner W, Neugschwandtner G, Soucek S, Newman HM. Communication systems for building automation and control. Proc IEEE 2005;93(6):1178–203. http://dx.doi.org/10.1109/JPROC.2005.849726.

[44] Zhang JZJ, Orlik P, Sahinoglu Z, Molisch A, Kinney P. UWB systems for wireless sensor networks. Proc IEEE 2009;97(2):313–31. http://dx.doi.org/10.1109/JPROC.2008.2008786.

[45] Shelby Z. Embedded web services. IEEE Wirel Commun 2010;17(6):52–7. http://dx.doi.org/10.1109/MWC.2010.5675778.

[46] Han D-M, Lim J-H. Design and implementation of smart home energy management systems based on zigbee. IEEE Trans Consum Electron 2010;56(3):1417–25. http://dx.doi.org/10.1109/TCE.2010.5606278.

[47] Dounis AI, Caraiscos C. Advanced control systems engineering for energy and comfort management in a building environment-a review. Renew Sustain Energy Rev 2009;13(6–7):1246–61. http://dx.doi.org/10.1016/j.rser.2008.09.015.

[48] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Build Environ 2011;46(4):922–37. http://dx.doi.org/10.1016/j.buildenv.2010.10.021.

[49] Choi JH, Loftness V, Aziz A. Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. Energy Build 2012;46:167–75. http://dx.doi.org/10.1016/j.enbuild.2011.08.009.

[50] Lawrence R, Keime C. Bridging the gap between energy and comfort: post-occupancy evaluation of two higher-education buildings in sheffield. Energy Build 2016;130:651–66.

[51] Andersen R, Fabi V, Toftum J, Corgnati SP, Olesen BW. Window opening behaviour modelled from measurements in Danish dwellings. Build Environ 2013;69:101–13. http://dx.doi.org/10.1016/j.buildenv.2013.07.005.

[52] West SR, Ward JK, Wall J. Trial results from a model predictive control and optimisation system for commercial building HVAC. Energy Build 2014;72:271–9. http://dx.doi.org/10.1016/j.enbuild.2013.12.037.

[53] Jazizadeh F, Ghahramani A, Becerik-Gerber B, Kichkaylo T, Orosz M. User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings. Energy Build 2014;70:398–410. http://dx.doi.org/10.1016/j.enbuild.2013.11.066.

[54] Gunay HB, O'Brien W, Beausoleil-Morrison I, Huchuk B. On adaptive occupant-learning window blind and lighting controls. Build Res Inf 2014;42(6):739–56. http://dx.doi.org/10.1080/09613218.2014.895248.

[55] Zhao J, Lam KP, Ydstie BE, Loftness V. Occupant-oriented mixed-mode EnergyPlus predictive control simulation. Energy Build 2016;117:362–71. http://dx.doi.org/10.1016/j.enbuild.2015.09.027.

[56] Nagy Z, Yong FY, Schlueter A. Occupant centered lighting control: a user study on balancing comfort, acceptance, and energy consumption. Energy Build 2016;126:310–22. http://dx.doi.org/10.1016/j.enbuild.2016.05.075.

[57] Prívara S, Cigler J, Váňa Z, Oldewurtel F, Sagerschnig C, Žáčeková E. Building modeling as a crucial part for building predictive control. Energy Build 2013;56:8–22. http://dx.doi.org/10.1016/j.enbuild.2012.10.024.

[58] Palensky P, Dietrich D. Demand side management: demand response, intelligent energy systems, and smart loads. IEEE Trans Ind Inform 2011;7(3):381–8. http://dx.doi.org/10.1109/TII.2011.2158841.

[59] El-hawary ME. The Smart Grid—state-of-the-art and future trends. Electr Power Compon Syst 2014;42(3–4):239–50. http://dx.doi.org/10.1080/15325008.2013.868558.

[60] Yoon JH, Baldick R, Novoselac A. Dynamic demand response controller based on real-time retail price for residential buildings. IEEE Trans Smart Grid 2014;5(1):121–9. http://dx.doi.org/10.1109/TSG.2013.2264970.

[61] Du P, Lu N. Appliance commitment for household load scheduling. IEEE Trans Smart Grid 2011;2(2):411–9. http://dx.doi.org/10.1109/TSG.2011.2140344.

[62] Nguyen HK, Song JB. Optimal charging and discharging for multiple PHEVs with Demand side management in Vehicle-to-Building. J Commun Netw 2012;14(6):662–71. http://dx.doi.org/10.1109/JCN.2012.00032.

[63] Nagy Z, Rossi D, Hersberger C, Irigoyen SD, Miller C, Schlueter A. Balancing envelope and heating system parameters for zero emissions retrofit using building sensor data. Appl Energy 2014;131:56–66. http://dx.doi.org/10.1016/j.apenergy.2014.06.024.

[64] Ali AS, Zanzinger Z, Debose D, Stephens B. Open Source Building Science Sensors (OSBSS): a low-cost Arduino-based platform for long-term indoor environmental data collection. Build Environ 2016;100:114–26. http://dx.doi.org/10.1016/j.buildenv.2016.02.010.

[65] Yi P, Iwayemi A, Zhou C. Developing ZigBee deployment guideline under WiFi interference for smart grid applications. IEEE Trans Smart Grid 2011;2(1):98–108. http://dx.doi.org/10.1109/TSG.2010.2091655.

[66] Krüger EL, Minella FO, Rasia F. Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil. Build Environ 2011;46(3):621–34. http://dx.doi.org/10.1016/j.buildenv.2010.09.006.

[67] Dounis AI, Santamouris MJ, Lefas CC. Implementation of artificial intelligence techniques in thermal comfort control for passive solar buildings. Energy Convers Manag 1992;33(3):175–82. http://dx.doi.org/10.1016/0196-8904(92)90123-E.

[68] Spasokukotskiy K, Trankler HR, Lukasheva K. Model-based methodto measure thermal comfort in buildings. In: Proceedings of the Second IEEE International Workshopon Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, 2003, IEEE; 2003, pp. 154–158.

[69] Rana R, Kusy B, Jurdak R, Wall J, Hu W. Feasibility analysis of using humidex as an indoor thermal comfort predictor. Energy Build 2013;64:17–25.

[70] Songuppakarn T. Artificial neural networks based prediction for thermal comfort in an academic classroom. In: Proceedings of the 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE); 2014, p. 1-8.

[71] Chen X, Wang Q, Srebric J. A data-driven state-space model of indoor thermal sensation using occupant feedback for low-energy buildings. Energy Build 2015;91:187–98. http://dx.doi.org/10.1016/j.enbuild.2015.01.038.

[72] Zhou H, Soh YC, Wu X. Integrated analysis of CFD data with K-means clustering algorithm and extreme learning machine for localized HVAC control. Appl Therm Eng 2015;76:98–104. http://dx.doi.org/10.1016/j.applthermaleng.2014.10.004.

[73] Wilson N. Approaches and properties for aggregating occupant preferences. In: Proceedings of the 2015 IEEE 27th International Conference on Tools with Artificial Intelligence (ICTAI), IEEE; 2015, pp. 558–565.

[74] Daum D, Haldi F, Morel N. A personalized measure of thermal comfort for building controls. Build Environ 2011;46(1):3–11. http://dx.doi.org/10.1016/j.buildenv.2010.06.011.

[75] Tiller DK, Wang LM, Musser A, Radik MJ. Combined effects of noise and temperature on human comfort and performance. ASHRAE Trans 2010;116(PART 2):522–40.

[76] Montgomery JF, Storey S, Bartlett K. Comparison of the indoor air quality in an office operating with natural or mechanical ventilation using short-term intensive pollutant monitoring. Indoor Built Environ 2014;0(0):1–11. http://dx.doi.org/10.1177/1420326X14530999.

[77] Chen Y, Gu L. CHAMPS-Multizone co-simulation for energy and indoor air quality analysis. Build Simul 2015;8(4):371–80. http://dx.doi.org/10.1007/s12273-015-0211-1.

[78] Amasyali K, El-Gohary NM. Energy-related values and satisfaction levels of

residential and office building occupants. Build Environ 2016;95:251–63. http://dx.doi.org/10.1016/j.buildenv.2015.08.005.

[79] Hellwig RT. Perceived control in indoor environments: a conceptual approach. Build Res Inf 2015;43:302–15. http://dx.doi.org/10.1080/09613218.2015.1004150.

[80] Raja IA, Nicol JF, McCartney KJ, Humphreys MA. Thermal comfort: use of controls in naturally ventilated buildings. Energy Build 2001;33(3):235–44. http://dx.doi.org/10.1016/S0378-7788(00)00087-6.

[81] Rijal HB, Tuohy P, Nicol F, Humphreys Ma, Clarke J. A window opening algorithm and UK office temperature: field results and thermal simulation. Syst Res 2007:709–16.

[82] Rijal HB, Tuohy P, Humphreys MA, Nicol JF, Samuel A, Clarke J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy Build 2007;39(7):823–36. http://dx.doi.org/10.1016/j.enbuild.2007.02.003.

[83] Rijal HB, Tuohy P, Humphreys MA, Nicol JF, Samuel A. An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints. Build Simul 2011;4(2):117–34. http://dx.doi.org/10.1007/s12273-011-0037-4.

[84] Bahadur Rijal H, Tuohy P, Humphreys MA, Nicol JF, Samuel A. Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings. Archit Sci Rev 2012;55(1):35–48. http://dx.doi.org/10.1080/00038628.2011.641734.

[85] Langevin J, Wen J, Gurian PL. Quantifying the human-building interaction: considering the active, adaptive occupant in building performance simulation. Energy Build 2016;117:372–86. http://dx.doi.org/10.1016/j.enbuild.2015.09.026.

[86] Yan D, Hong T. International Energy Agency EBC, Annex 66.

[87] Kulkarni MR, Hong F. An experimental technique for thermal comfort comparison in a transient pull down. Build Environ 2004;39(2):189–93. http://dx.doi.org/10.1016/j.buildenv.2003.08.008.

[88] Rijal HB, Tuohy PG, Humphreys MA, Nicol JF, Samuel A, Clarke JA, et al. Development of adaptive algorithms for the operation of windows, fans, and doors to predict thermal comfort and energy use in pakistani buildings. Am Soc Heat Refrig Air Cond Eng (ASHRAE) Trans 2008;114(2):555–73.

[89] Haldi F, Robinson D. On the behaviour and adaptation of office occupants. Build Environ 2008;43(12):2163–77. http://dx.doi.org/10.1016/j.buildenv.2008.01.003.

[90] Rijal HB, Humphreys Ma, Nicol JF. Understanding occupant behaviour: the use of controls in mixed-mode office buildings. Build Res Inf 2009;37(4):381–96. http://dx.doi.org/10.1080/09613210902904221.

[91] Indraganti M. Adaptive use of natural ventilation for thermal comfort in Indian apartments. Build Environ 2010;45(6):1490–507. http://dx.doi.org/10.1016/j.buildenv.2009.12.013.

[92] Sahari KSM, Jalal MFA, Homod RZ, Eng YK. Dynamic indoor thermal comfort model identification based on neural computing PMV index, IOP Conference Series: Earth and Environmental Science 16; 2013, 012113. doi:10.1088/1755-1315/16/1/012113.

[93] Shih HC. A robust occupancy detection and tracking algorithm for the automatic monitoring and commissioning of a building. Energy Build 2014;77:270–80. http://dx.doi.org/10.1016/j.enbuild.2014.03.069.

[94] Rana R, Kusy B, Wall J, Hu W. Novel activity classification and occupancy estimation methods for intelligent HVAC (heating, ventilation and air conditioning) systems. Energy 2015;93:245–55. http://dx.doi.org/10.1016/j.energy.2015.09.002.

[95] Yao J, Chow DHC, Zheng R-Y, Yan C-W. Occupants' impact on indoor thermal comfort: a co-simulation study on stochastic control of solar shades. J Build Perform Simul 2015;1493(February):1–16. http://dx.doi.org/10.1080/19401493.2015.1046492.

[96] McCartney KJ, Fergus Nicol J. Developing an adaptive control algorithm for Europe. Energy Build 2002;34(6):623–35. http://dx.doi.org/10.1016/S0378-7788(02)00013-0.

[97] Mitsios I, Kolokotsa D, Stavrakakis G, Kalaitzakis K, Pouliezos A. Developing a control algorithm for CEN indoor environmental criteria - Addressing air quality, thermal comfort and lighting. In: Proceedings of the 2009 17th Mediterranean Conference on Control and Automation; 2009. p. 976–981 http://dx.doi.org/10.1109/MED.2009.5164672.

[98] Sun B, Luh PB, Jia Q-S, Jiang Z, Wang F, Song C. Building energy management: integrated control of active and passive heating, cooling, lighting, shading, and ventilation systems. IEEE Trans Autom Sci Eng 2013;10(3):588–602.

[99] Gruber M, Truschel A, Dalenback JO. Alternative strategies for supply air temperature control in office buildings. Energy Build 2014;82:406–15. http://dx.doi.org/10.1016/j.enbuild.2014.06.056.

[100] Mofidi F, Akbari H. Integrated optimization of energy costs and occupants' productivity in commercial buildings. Energy Build 2016;129:247–60. http://dx.doi.org/10.1016/j.enbuild.2016.07.059.

[101] Hoyt T, Arens E, Zhang H. Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings. Build Environ 2015;88:89–96. http://dx.doi.org/10.1016/j.buildenv.2014.09.010.

[102] Bengea SC, Li P, Sarkar S, Vichik S, Adetola V, Kang K, Lovett T, et al. Fault-tolerant optimal control of a building HVAC system. Sci Technol Built Environ 2015;21(6):734–51. http://dx.doi.org/10.1080/23744731.2015.1057085.

[103] Fanti MP, Ieee S, Mangini AM, Roccotelli M, Ukovich W, Ieee M, Pizzuti S. A Control Strategy for District Energy Management. In: Proceedings of the 2015 IEEE International Conference on Automation Science and Engineering (CASE); 2015. p. 432–437 http://dx.doi.org/10.1109/CoASE.2015.7294117.

[104] Fanti MP, Member S, Mangini AM, Roccotelli M, Ukovich W. A district energy management based on thermal comfort satisfaction and real-time power balancing. IEEE Trans Autom Sci Eng 2015;12(4):1271–84. http://dx.doi.org/10.1109/TASE.2015.2472956.

[105] Purdon S, Kusy B, Jurdak R, Challen G. Model-free HVAC control using occupant feedback. In: Proceedings of the - Conference on Local Computer Networks, LCN (2013) 84-92 http://dx.doi.org/10.1109/LCNW.2013.6758502.

[106] Ghahramani A, Jazizadeh F, Becerik-Gerber B. A knowledge based approach for selecting energy- aware and comfort-driven HVAC temperature set points. J Energy Build 2014;85:536–48. http://dx.doi.org/10.1016/j.enbuild.2014.09.055.

[107] Anand A, Vasudevan R, Bhattacharya S, Arun R, Sivanantham A. Retrofit control solutions for old buildings using WSN. In: Proceedings of the 2015 International Conference on Computer, Communications, and Control Technology (I4CT); 2015, pp. 59–63. http://dx.doi.org/10.1109/I4CT.2015.7219537.

[108] Salamone F, Belussi L, Danza L, Ghellere M, Meroni I. An open source smart lamp for the optimization of plant systems and thermal comfort of offices, Sensors (Switzerland) 16 (3). http://dx.doi.org/10.3390/s16030338.

[109] Nassif N, Kajl S, Sabourin R. Optimization of hvac control system strategy using two-objective genetic algorithm. HVAC R Res 2005;11(3):459–86.

[110] Nassif N, Moujaes S. A cost-effective operating strategy to reduce energy consumption in a hvac system. Int J Energy Res 2008;32(6):543–58.

[111] Sourbron M, De Herdt R, Van Reet T, Van Passel W, Baelmans M, Helsen L. Efficiently produced heat and cold is squandered by inappropriate control strategies: a case study. Energy Build 2009;41(10):1091–8. http://dx.doi.org/10.1016/j.enbuild.2009.05.015.

[112] Ma Y, Vichik S, Borrelli F. Fast stochastic MPC with optimal risk allocation applied to building control systems. In: Proceedings of the IEEE Conference on Decision and Control; 2012. p. 7559–7564 http://dx.doi.org/10.1109/CDC.2012.6426251.

[113] Wallace M, McBride R, Aumi S, Mhaskar P, House J, Salsbury T. Energy efficient model predictive building temperature control. Chem Eng Sci 2012;69(1):45–58. http://dx.doi.org/10.1016/j.ces.2011.07.023.

[114] Klein L, Kwak JY, Kavulya G, Jazizadeh F, Becerik-Gerber B, Varakantham P, et al. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. Autom Constr 2012;22:525–36. http://dx.doi.org/10.1016/j.autcon.2011.11.012.

[115] Hazyuk I, Ghiaus C, Penhouet D. Optimal temperature control of intermittently heated buildings using Model Predictive Control: Part II - control algorithm. Build Environ 2012;51:388–94. http://dx.doi.org/10.1016/j.buildenv.2011.11.008.

[116] Nouvel R, Alessi F. A novel personalized thermal comfort control, responding to user sensation feedbacks. Build Simul 2012;5:191–202. http://dx.doi.org/10.1007/s12273-012-0076-5.

[117] Counsell J, Zaher O, Brindley J, Murphy G. Robust nonlinear HVAC systems control with evolutionary optimisation. Eng Comput 2013;30(8):1147–69. http://dx.doi.org/10.1108/EC-04-2012-0079.

[118] Drgona J, Kvasnica M. Comparison of MPC strategies for building control. In: Proceedings of the 2013 International Conference on Process Control, PC 2013 (2013) 401-406 http://dx.doi.org/10.1109/PC.2013.6581444.

[119] Sourbron M, Verhelst C, Helsen L. Building models for model predictive control of office buildings with concrete core activation. J Build Perform Simul 2013;1493:1–24.

[120] Bengea SC, Kelman AD, Borrelli F, Taylor R, Narayanan S. Implementation of model predictive control for an HVAC system in a mid-size commercial building, HVAC & R Research 20 (February 2014) (2014) 121-135. http://dx.doi.org/10.1080/10789669.2013.834781.

[121] Jazizadeh F, Ghahramani A, Becerik-Gerber B, Kichkaylo T, Orosz M. Human-building interaction framework for personalized thermal comfort-driven systems in office buildings. J Comput Civ Eng 2013;28(1):2–16. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000300. [http://arxiv.org/abs/arXiv:1011.1669v3arXiv:arXiv:1011.1669v3.].

[122] Hazyuk I, Ghiaus C, Penhouet D. Model Predictive Control of thermal comfort as a benchmark for controller performance. Autom Constr 2014;43:98–109. http://dx.doi.org/10.1016/j.autcon.2014.03.016.

[123] Klauco M, Kvasnica M. Explicit MPC approach to PMV-based thermal comfort control. In: Proceedings of the IEEE Conference on Decision and Control 2015-Febru (February); 2014. p. 4856–4861. http://dx.doi.org/10.1109/CDC.2014.7040147.

[124] Scherer HF, Pasamontes M, Guzmán JL, Álvarez JD, Camponogara E, Normey-Rico JE. Efficient building energy management using distributed model predictive control. J Process Control 2014;24(6):740–9. http://dx.doi.org/10.1016/j.jprocont.2013.09.024.

[125] Mokhtar M, Liu X, Howe J. Multi-agent Gaussian Adaptive Resonance Theory Map for building energy control and thermal comfort management of UCLan's WestLakes Samuel Lindow Building. Energy Build 2014;80:504–16. http://dx.doi.org/10.1016/j.enbuild.2014.05.045.

[126] Hussain S, Gabbar HA, Bondarenko D, Musharavati F, Pokharel S. Comfort-based fuzzy control optimization for energy conservation in HVAC systems. Control Eng Pract 2014;32:172–82. http://dx.doi.org/10.1016/j.conengprac.2014.08.007.

[127] Ciabattoni L, Cimini G, Ferracuti F, Grisostomi M, Ippoliti Pirro GM, Politecnica U. Indoor thermal comfort control through fuzzy logic PMV optimization. In: Proceedings of the 2015 International Joint Conference on Neural Networks (IJCNN); 2015, pp. 1–6. http://dx.doi.org/10.1109/IJCNN.2015.7280698.

[128] Revel GM, Arnesano M, Pietroni F, Frick J, Reichert M, Schmitt K, et al. Cost-effective technologies to control indoor air quality and comfort in energy efficient building retrofitting. Environ Eng Manag J 2015;14(7):1487–94.

[129] Michailidis IT, Baldi S, Pichler MF, Kosmatopoulos EB, Santiago JR. Proactive control for solar energy exploitation: a German high-inertia building case study. Appl Energy 2015;155:409–20. http://dx.doi.org/10.1016/j.apenergy.2015.06.

033.
[130] Mansur V, Carreira P, Arsenio A. A learning approach for energy efficiency optimization by occupancy detection. In: Internet of Things. User-Centric IoT, Springer, 2015, pp. 9–15.
[131] Behrooz F, Mariun NB, Marhaban H, Amran M, Radzi M.s New design Approach to MIMO Nonlinear Controller for Direct Expansion Air Conditioning System in Building Automation System. In: Proceedings of the 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC); 2015, pp. 1706–1712.
[132] Lee YM, Horesh R, Liberti L. Optimal HVAC control as demand response with on-site energy storage and generation system. Energy Procedia 2015;78:2106–11. http://dx.doi.org/10.1016/j.egypro.2015.11.253.
[133] Ruano AE, Silva S, Pesteh S, Ferreira PM, Duarte H, Mestre G, Khosravani H, Horta R. Improving a neural networks based HVAC predictive control approach. In: Proceedings of the 2015 IEEE 9th International Symposium on Intelligent Signal Processing (WISP) Proceedings; 2015, pp. 1–6.
[134] Miletic M, Schirrer A, Kozek M. Load management in smart grids with utilization of load-shifting potential in building climate control. In: Proceedings of the 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST 2015; 2015. p. 468–474 http://dx.doi.org/10.1109/SEDST.2015.7315254.
[135] Gupta SK, Kar K, Mishra S, Wen JT. Collaborative energy and thermal comfort management through distributed consensus algorithms. IEEE Trans Autom Sci Eng 2015;12(4):1285–96. http://dx.doi.org/10.1109/TASE.2015.2468730.
[136] Kirubakaran V. SCRTKSN. Energy efficient model based algorithm for control of building HVAC systems. Ecotoxicol Environ Saf 2015;121:236–43.
[137] Sturzenegger D, Gyalistras D, Morari M, Smith RS. Model predictive climate control of a Swiss Office Building: implementation, results, and cost-benefit analysis. IEEE Trans Control Syst Technol 2016;24(1):1–12. http://dx.doi.org/10.1109/TCST.2015.2415411.
[138] Katsigarakis K, Kontes G, Giannakis G, Rovas D. Sense-think-act framework for intelligent building energy management. Comput-Aided Civ Infrastruct Eng 2016;31. http://dx.doi.org/10.1111/mice.12173. [n/a-n/a].
[139] Lim B, Hijazi H, Thiébaux S, van den Briel M. Online hvac-aware occupancy scheduling with adaptive temperature control. In: Proceedings of the International Conference on Principles and Practice of Constraint Programming, Springer; 2016, pp. 683–700.
[140] Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort. Energy Build 2016;111:131–44. http://dx.doi.org/10.1016/j.enbuild.2015.11.033.
[141] Hilliard T, Swan L, Kavgic M, Qin Z, Lingras P. Development of a whole building model predictive control strategy for a LEED silver community college. Energy Build 2016;111:224–32. http://dx.doi.org/10.1016/j.enbuild.2015.11.051.
[142] Nowak M, Urbaniak A. Application of predictive control algorithms for thermal comfort and energy saving in the classroom. In: Proceedings of the 2016 17th International Carpathian Control Conference (ICCC); 2016. p.527–532 http://dx.doi.org/10.1109/carpathiancc.2016.7501154.
[143] Killian M, Mayer B, Kozek M. Cooperative fuzzy model predictive control for heating and cooling of buildings. Energy Build 2016;112:130–40. http://dx.doi.org/10.1016/j.enbuild.2015.12.017.
[144] Castilla M, Bonilla J, Álvarez J, Rodríguez F. A room simulation tool for thermal comfort control in a bioclimatic building: A real example of use with an optimal controller, Optimal Control Applications and Methods.
[145] Janda K. Buildings don't use energy - People do!. Planet Earth 2011;8628(WINTER):12–3. http://dx.doi.org/10.3763/asre.2009.0050.
[146] Pritoni M, Woolley JM, Modera MP. Do occupancy-responsive learning thermostats save energy? A field study in university residence halls. Energy Build 2016;127:469–78.
[147] de Dear R. Revisiting an old hypothesis of human thermal perception: alliesthesia. Build Res Inf 2011;39(2):108–17. http://dx.doi.org/10.1080/09613218.2011.552269.
[148] Choi J-H, Loftness V. Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. Build Environ 2012;58:258–69.
[149] Choi J-H, Moon J. Impacts of human and spatial factors on user satisfaction in office environments. Build Environ 2017;114:23–35.
[150] ACM / IEEE-CS jointly sponsored conferences, 〈http://www.acm.org/acm-ieeecs-coop/conferences〉, [accessed 21 March 2017].
[151] Tedesco PA. IEEE/ASCE Transmission structure foundation design guide, in: Innovations in the Design of Electrical Transmission Structures:, ASCE, 1986, pp. 96–105.
[152] ASHRAE/USGBC, Standard 189.9, High Performance Building Codes.
[153] IEEE/ASHRAE, Standard 1636–2012, Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications.
[154] Buckman A, Mayfield M, Beck SBM. What is a smart building? Smart Sustain Built Environ 2014;3(2):92–109. http://dx.doi.org/10.1108/SASBE-01-2014-0003.
[155] Nagy Z, Yong FY, Frei M, Schlueter A. Occupant centered lighting control for comfort and energy efficient building operation. Energy Build 2015;94:100–8.
[156] Jin J, Gubbi J, Marusic S, Palaniswami M. An information framework for creating a smart city through internet of things. IEEE Internet Things J 2014;1(2):112–21.
[157] Mozer MC. Lessons from an Adaptive Home. in: Smart Environments, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2005, pp. 271–294. http://dx.doi.org/10.1002/047168659X.ch12.