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Modeling and spatial visualization of indoor micro-climates for personalized thermal comfort

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ABSTRACT

The indoor thermal environment is conventionally considered homogeneous as anchored on a universal thermal comfort paradigm, although occupants' experience is often diversified and influenced by several physio-cognitive factors. Personal comfort devices aim to enhance thermal comfort acceptance through localized heating and cooling while reducing overall energy consumption as temperature set-points of centralized HVAC systems can be relaxed. To further incentivize the adoption of distributed HVAC systems, it is critical to examine the energy benefits and the spatial characteristics of heterogeneous thermal environments.

Here we developed a parametric framework based on building energy modeling coupled with a spatial visualization of micro-climatic thermal fields, which respond to a variable space occupation. HVAC system loads and indoor environmental conditions, extracted from the energy model, are integrated with an analysis of the human thermal balance. As a case study, a thermoelectric-based system for personalized thermal comfort was considered in an office space, based on a specific layout of workstations and meeting rooms. The contribution of distributed heating and cooling systems to the overall HVAC energy consumption was analyzed for the office, and the micro-climatic variability was visualized based on transient occupation patterns.

Understanding the impact of variable occupation for the building energy balance is significant for developing performative metrics for next-generation distributed HVAC systems. At the same time, it can inform novel design strategies based on micro-climatic controls to maximize personalized thermal comfort and enhance the quality of indoor environments.

KEYWORDS

indoor micro-climates, energy modeling, responsive environments, personalized thermal comfort, thermal field visualization.

INTRODUCTION

Expanding the temperature set-points of Heating, Ventilation and Air Conditioning (HVAC) systems may unravel new strategies to reduce building energy consumption and incentivize the adoption of distributed systems for enhanced thermal comfort. Energy savings up to 73% were projected when extending the temperature setpoints of conventional Variable Air Volume (VAV) system to near 30ºC for cooling and 17ºC for heating (Hoyt, Arens, & Zhang, 2015). Under these conditions, Personalized Comfort Systems (PCS) may provide maximum thermal comfort to occupants and hypothetically utilize less energy than centralized HVAC systems (Amai, Tanabe, Akimoto, & Genma, 2007; Bauman et al., 2015; Kong, Dang, Zhang, & Khalifa, 2017). However, the relationship between PCS and ambient conditions is still largely unexplored, particularly throughout an entire year. The objective of this study is to examine the potential benefits of localized heating and cooling systems for energy savings and occupants' comfort, and provide means of spatial visualization of micro-climatic conditions indoors. As post-occupancy evaluation shows, thermal comfort acceptance in office spaces is a critical aspect to be considered because it has an impact on building operational energy and indoor environmental quality (Huizenga, Abbaszadeh, Zagreus, & Arens, 2006). Providing means of modeling and visualization of indoor micro-climates has the potential to facilitate the adoption of distributed HVAC systems beyond the strive for system efficiency for a more human-centric design approach.

METHODS

An energy model was developed to examine HVAC system loads, indoor environmental conditions, and determine human heat balance within an occupied space. An 800m^2 multi-zoned office space with 75% window-to-wall ratio was modeled in *OpenStudio*, a validated energy modeling software. The New York City typical meteorological year was utilized for calculations under ASHRAE 90.1 2013 construction assemblies, schedules, and internal loads. A Variable Air Volume (VAV) HVAC system type was considered for the simulation for typical baseline and expanded temperature set-point ranges. Ladybug plugin allowed for a direct integration of energy modeling from *OpenStudio* into the *Rhinoceros-Grasshopper* environment (Roudsari, Pak, & Smith, 2013). In this study, indoor air temperature, relative humidity, air flow rates, surface temperatures, and HVAC energy loads were examined in *Rhinoceros-Grasshopper* to determine the human energy balance and energy consumption parameters. Finally, the efficacy of the supplemental heating and cooling was assumed at 0.5, implying that for example, 50W of power would provide 25W of active localized heating or cooling to each occupant (Kong et al., 2017). A Coefficient Of Performance (COP) of 2.5 was also assumed for the supplemental HVAC system, which refers to current targets aimed by the authors on a solid-state HVAC system under research. The *Modular Indoor Micro-Climate* (MIMiC) system is based on a modular thermoelectric heat pump coupled with a temperature-optimized thermal storage for reversible, localized heating and cooling which may also be deployed in office environments. The detailed workflow, including the variables and procedural steps described in this study, is illustrated in Figure 1.

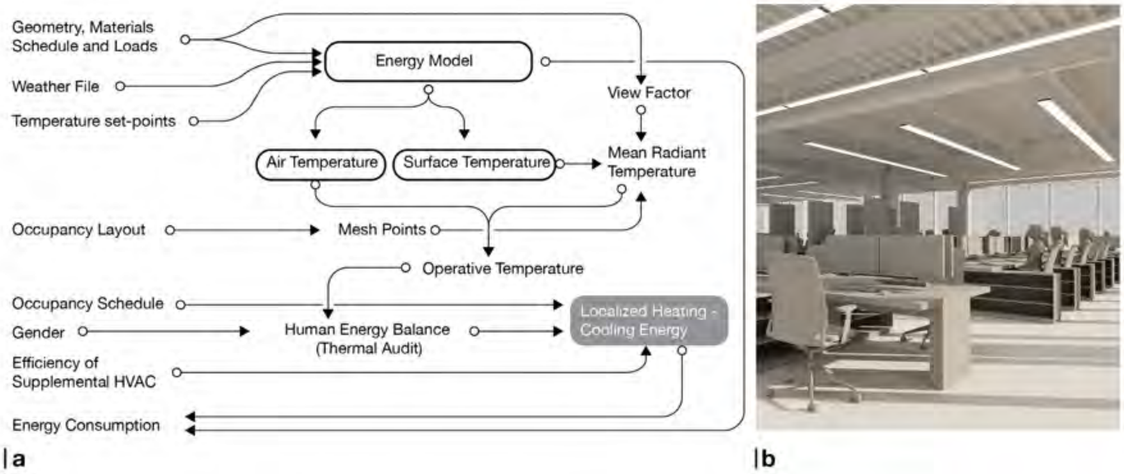

Figure 1. Diagram of the energy model workflow (left) and partial rendering of the office space considered for energy modeling (right).

Human Heat Balance

In current standards, thermal comfort is primarily assessed using the Predicted Mean Vote or the Adaptive Comfort ranges, for which there is no explicit gender differentiation (ASHRAE, 2004; Kingma & van Marken Lichtenbelt, 2015). Thereby, the thermal audit process was utilized to determine the human heat balance with the environment (Parsons, 2014). Assuming a relaxed temperature set-point, it is possible to characterize the resulting heat to be supplied or removed (*S*) using the following equation:

$$S = (M - W) - ((C + R + E_{sk}) + (C_{res} + E_{res})) \tag{1}$$

Where *M* represents the rate of heat generated by the body or metabolic activity, *W* is the rate of any mechanical work, *R* is radiation, *C* is convection, E_{sk} is the rate of total evaporative heat losses from the skin, C_{res} is the rate of convective heat losses from respiration, and E_{res} is the rate of evaporative heat losses from respiration. In this study, beside the radiant portion of the thermal balance, the environmental conditions are assumed to be homogeneous within the thermal zones but varying over time. The mechanical work (*W*) component was considered null and thermal conduction neglected. The metabolic activity (*M*), a critical factor in the determination of the energy balance, was gender-specific (Kingma & van Marken Lichtenbelt, 2015). In particular, the female metabolic rate was considered as 48 Wm^{-2} when performing light work. Male metabolic activity was derived from ASHRAE (2004), being at 60 Wm^{-2} under light work in office environments.

Mean Radiant Temperature

As radiant thermal exchanges constitute a large component of the human thermal balance (Parsons, 2014), this studied focused on calculating the Mean Radiant Temperature (MRT) for a specific occupation layout within an office space. The equation for the MRT is assumed as (La Gennusa, Nucara, Rizzo, & Scaccianoce, 2005):

$$T_r = \sqrt[4]{\sum_{i=1}^{N} F_{S\to i} T_i^4} \tag{2}$$

Where $F_{S\to i}$ represents the view factor between the receiving geometry, here a person, and a building internal enclosure (i), for which the surface temperature (T_i) is derived from the energy model. Although the calculation of the view factor is computationally expensive, this study utilized the following, validated approximation (Walton, 2002):

$$F_{S\to i} \approx \frac{-1}{\pi A_S} \sum_S \sum_i \frac{(\vec{r} \cdot \overrightarrow{n_S})(\vec{r} \cdot \overrightarrow{n_i})}{(\vec{r} \cdot \vec{r})} \Delta A_S \Delta A_i \tag{3}$$

Where $\vec{r}$ is the vector connecting the centers of the finite areas ΔA_S and ΔA_i; $\overrightarrow{n_S}$ and $\overrightarrow{n_i}$ are their normal vectors at the center point, and the dot product indicated scalar multiplication between vectors. A recursive calculation was coded in Python within the Grasshopper platform, to better interface with the results coming from the energy model as depicted in Figure 2.

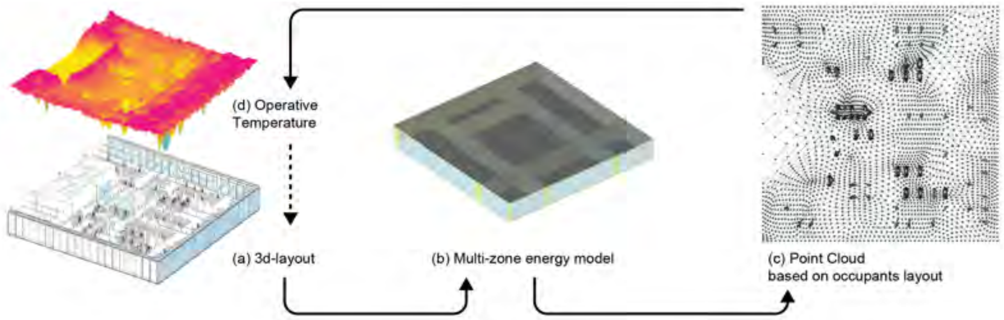

Figure 2. Approach for calculation of MRT and micro-climatic visualization: (a) office layout determining occupants position in space; (b) multi-zone energy model provides surface temperatures on hourly basis; (c) point cloud definition for view factor; (d) visualization of the operative temperature.

RESULTS

The overall HVAC energy saving are projected in 14% relative to baseline conditions when the temperature set-points are extended from 22ºC to 26ºC for cooling and from 21ºC to 19ºC for heating (Table 1). The HVAC energy savings account for the supplemental heating and cooling for each occupant based on the satisfaction of their specific human thermal balance. The energy expenditure for the MIMiC supplemental system accounts for about 1/5 of the overall energy consumption under expanded temperature set-points. However, different behaviors were observed when considering heat loads on an hourly basis. For a typical summer day such as June 21st (Figure 3, a), the energy expenditure associated with expanded temperature set-points and the supplemental system were consistently lower than baseline condition. Conversely, for a typical winter day, such as December 21st (Figure 3, b), no substantial energy savings during heating demands were observed. Also, the energy expenditures for regaining comfort almost nullified the benefits given by expanded heating temperature set-point. Mainly, from mid-morning to early afternoon, the expansion of temperature set-point did not produce any energy savings particularly in the later afternoon. The extreme peaks in heating demand around 5AM (Figure 3,b) were observed only for some days and not consistent in terms of intensity, although a more detailed investigation is required.

Table 1. Summary of the HVAC energy consumption for baseline and experimental conditions.

	a. Baseline	b. Relaxed Temp. Set-Pt	c. MIMiC	Total (b+c)	Energy Savings (%)
HVAC Energy Consumption (kWh/yr)	64,069	46,547	8,288	54,835	-14%
HVAC Energy Density (kWh/m2 - yr)	80.2	58.3	10.4	68.7	

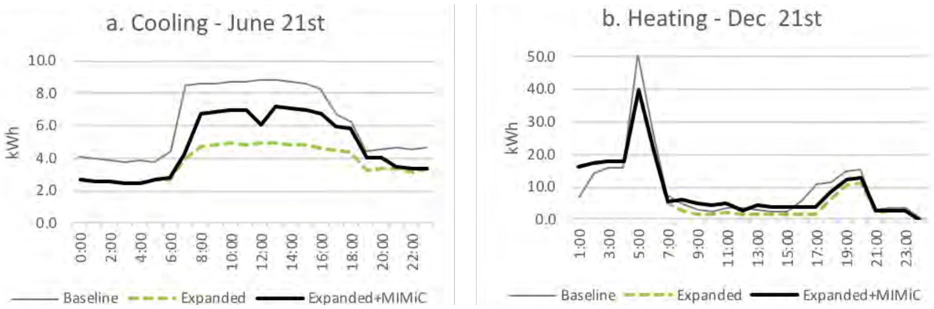

Figure 3. HVAC energy consumption for a typical cooling (a) and typical heating (b) day.

The micro-climatic maps of the operative temperature are represented for a typical summer and winter day at 1PM (Figure 4). The maps, resulting from the integrated computation of the mean radiant temperature and heat balance, suggest that the operative temperature is generally higher than relative air-temperature set-points. Such discrepancy is more pronounced during the summer day (Figure 4,a) where occupants closers to the envelope and the core may experience higher operative temperature than near the core. Instead, on winter time (Figure 4,b), the benefit of the solar exposure can be inferred from the micro-climatic map, for which shout-west portion of the floor plate has 2ºC higher operative temperature than central and north-east exposed spaces. Finally, gender differences in operative temperatures can be observed from the micro-climatic maps, where blue-colored areas are indicative of males with typical preferences for colder air temperature set-points (Kingma & van Marken Lichtenbelt, 2015).

Figure 4. Synthetic visualization of localized cooling (a) and heating (b), and associated energy consumptions for a typical summer day

DISCUSSIONS

The energy savings observed herein align with previous studies on the expansions of temperature set-points, although this study project less generous savings (Hoyt et al., 2015). While the energy consumption of the supplemental system for heating and cooling is minimal, it cannot be ignored from the overall building energy balance. The integrated energy model also allows to evaluate the economic feasibility of the supplemental systems for specific cases. In fact, for this study, the simple payback of the MIMiC systems is 8.3 years for a commercial application under NYS energy rate and assuming $80 per system installed in each occupied space. Different paybacks may be obtained when considering the benefits of productivity, however further studies are required. The operative temperature has larger swings than air temperature set-point offset, which may be associated with large glazed areas and their effects on mean radiant temperature. The impact of glazing and partitions on the operative temperature is more pronounced in areas closer to vertical envelopes as shown by the micro-climatic maps. The ability to model and visualize the operative temperature through the refined calculation of the MRT to determine the view factor, represents a key contribution of this study. Two limitations are given by not considering the furniture from the MRT calculation and the uniform distribution of air temperature in the different thermal zones. Future studies can incorporate the methodology presented herein and introduce means to model air temperature and occupation patterns with finer resolution. At the early stage of the design process, which this study targeted, practitioners and architectural scientists may utilize this methodology to evaluate both energy savings, thermal comfort implications, and economic feasibility for different primary and supplemental HVAC options.

CONCLUSIONS

The ability to provide personalized thermal comfort may unleash novel strategies for reducing building energy consumption and address raising concerns on indoor environmental quality, such as gender-specific thermal comfort preferences. This study reported on an integrated modeling and visualization framework for predicting energy savings from expanded temperature set-points and supplemental heating and cooling systems to equalize thermal balance based on different metabolic rates. The application of the modeling approach on a largely-glazed office space showed annual energy savings of 14% relative to a baseline condition. Also, different micro-climatic conditions were observed when calculating the operative temperature using a fine point could as representation of the floorplate occupancy. Integrating energy modeling and spatial visualization may provide useful insights for early-stage decision-making process on HVAC systems and sub-systems, and occupant comfort.

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