مجموعه مقالات پنجمین کنفرانس انرژی و محیط زیست
شماره شابک مقالات: ۸– ۴۵ – ۸۰۴۵ – ۶۰۰ – ۹۷۸
سوم دی ۱۳۹۴، ایران، تهران، مرکز همایش‌های صدا و سیما
(۰۲۱) ۸۸۶۷۱۶۷۶ - ۰۹۱۹۷۵۵۶۴۲۴
مجریان: هم اندیشان انرژی کیمیا و
انجمن علمی مهندسی حرارتی و برودتی ایران
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Personalized Optimization of Energy Costs and Productivity in Commercial Buildings

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Abstract

At the same time that building engineers are targeting reduction of buildings' environmental impact, such as energy consumption and greenhouse emissions, indoor environment of dwellings should also be considered carefully. Indoor environment quality of an office has significant effect on the performance and productivity of its occupants. In order to provide satisfactory indoor environment, timely energy-related decisions should be taken by energy management system. Several inputs that are changing continuously, such as energy prices, indoor and outdoor environment parameters, occupants' presence, activities and preferences are required for decision-making. The main interest of this research is to propose a method which is capable of improving occupants' productivity in commercial buildings, while keeping energy saving objective as a priority. There are differences between thermal preferences of the occupants, as well as their behavior toward energy consumption. Proposed method take into account these differences, by presenting two personalized variables, Maximum Comfort Temperature and Tolerance Range of occupants, and introduced them into energy and comfort management. The operation of proposed method is analyzed by annual energy performance simulation of a single-floor commercial building in Montreal, Canada. Based on the provided results, the proposed method is capable of improving productivity of occupants, by up to $800

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per month, while reaching energy savings' objectives. It is also observed that the potential for productivity improvement is higher during warm season, compared to cold season of Montreal.

Keywords: Energy Intelligent Building, Energy Efficiency, Integrated Building Control, Building Simulation, Productivity, Thermal Comfort, Indoor Air Quality

1 Introduction

Reports show that in Canada, residential, commercial and public buildings consume 46% of total energy generated [1]. *Energy intelligent buildings* are one of the major contributors to the idea of demand engagement into energy supply chain. Early intelligent building research solely focused on the technological aspects, ignoring occupant interactions with the building. These days, productivity, morale and satisfaction of the occupant became crucial parameters, during design and operation of buildings. More recent intelligent buildings emphasis on learning capability and performance adjustment according to occupants' behavior, habits and preferences [2].Within the area of energy intelligent buildings, a building is taken as an independent entity, which is able to manage its operation to ensure occupants' comfort and maximize energy savings. Satisfaction of above requirements demands timely energy-related decisions by energy management system. Several inputs that are changing continuously, such as energy prices, sets of indoor and outdoor environment parameters, occupants' presence, activities and preferences are required for decision-making. Therefore, a well-structured framework, as well as Multi-Objective Optimization (MOOP) techniques are required to reach optimum decisions for energy costs and occupants' Indoor Environment Quality (IEQ). In MOOP problems and especially in the case of MOOP of occupants' comfort and energy costs, there is a huge potential that the two goals of energy savings maximization and occupants' IEQ improvement are in conflict with each other. How MOOP techniques work is like a trade-off between these two or more objectives. The task of optimization techniques is to find the best possible set of compromises between occupants' comfort and energy consumption objectives.

The major difference between MOOP methods can be found in how and when preferences of problem solver or designer of optimization problem, are brought into the process. In methods with *a priori* articulation of preferences, relative importance of two objectives are assigned by problem solver, before running the optimization algorithm. Between all methods with *a priori* articulation of preference, *weighted sum method* is the most popular one. The reason behind this popularity is availability of a single utopia point. How weighted sum method solve MOOP problems is to convert them into a number of single optimization problems [3]. This can be done by aggregating objective functions together, while scaling them. Yang et al. and Wang et al. attempted to optimize energy consumption and overall comfort utilizing weighted sum method to develop objective function [4, 5]. A drawback of weighted sum method is its dependability on the choice of weight factors and the fact that it only leads to one optimal solution, based on the weight factors chosen by its designer. In order to refine this limitation, *Pareto optimality* concept is developed and *Pareto set* is defined. Pareto set can be constitute by optimal points, found by varying weight factors of multi-objective optimization problem [6]. Multi-Objective Genetic Algorithm (MOGA) and Multi-Objective Particle Swarm Optimization (MOPSO) are among the most popular types of Pareto-based approaches or methods with *a posteriori* articulation of preferences. Brownlee et al. and Wright et al. used Genetic Algorithm (GA) for MOOP of energy and comfort for optimal HVAC system design [7, 8]. Yang et al. combined weighted sum method and Particle Swarm Optimization (PSO) to optimize energy and comfort [4]. Wang et al. and Dounis et al. also used PSO algorithm to develop an intelligent energy management system [9, 10].

In order to meet Indoor Air Quality (IAQ) of occupants, fresh air instead of already loaded or polluted air should continuously be provided for them, Moreover, they should be assured that there is no health risks from breathing the indoor air. Thermal comfort is often considered the most important factor of occupant overall comfort. Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment [11, 12, 13]. Thermal comfort is satisfied, when the metabolic rate (heat generated from energy in human body) is in balance with the rate of heat, human body is losing [13]. There are various parameters that influence thermal sensation of building occupants. Humphreys et al. and de Dear et al. find relationships for adaptive thermal comfort with the outdoor temperature, for occupants with different cultural background and different weather conditions. Age, gender, social dimensions and economical background are the other parameters evaluated in multiple studies [15, 16, 17]. *Pro-environmental attitude* of occupant is another factor in accepting immediate indoor environmental conditions. It is observed that people with more environmental-friendly behavior are more forgiving in sacrificing their immediate satisfaction [18, 19, 17]. There is a strong relationship between occupant comfort and his or her productivity. *Productivity* of an occupant is defined as extent to which activities have provided performance in terms of system goals [20]. There have been many studies during the last three decades to find the relationship between occupants' productivity and their level of comfort [21, 22, 23, 24, 25] that confirm the firm bound between productivity and overall comfort of occupants.

The main interest of this research is to develop a MOOP method in Intelligent Energy Management System (IEMS) for automated control of HVAC system, lighting system, blinds and natural ventilation, applicable to commercial buildings. Using this method, a set of Pareto optimal solutions for automated control of indoor air conditions are generated for each hour of simulation. The proposed method has the capability of flexible decision-making, based on energy prices, occupancy information, types of occupant' activities, their attitudes toward energy consumption and their preferences. Energy management system can engage in demand-side management programs, such as Demand Response (Real-Time Pricing); improve IEQ by optimizing occupants' comfort conditions; provide an economic optimum conditions for operation of the building. In previous studies, presented in the literature, occupants' integration into whole energy and comfort management system are weak. Occupants are considered as passive parameters, while their comfort is often secondary to energy savings objectives. Moreover, their interaction and adaptation to the indoor environment are neglected. The MOOP method, proposed in this research is capable of introducing occupants' differences in thermal preferences, attitudes towards energy consumption and their coping potential. This paper is organized as follows. Section 2 consists of the main ideas behind design of proposed MOOP method for IEMSs. In this section, a simplified RC-network thermal model of a commercial building with five zones is developed; the problem formulation of proposed MOOP method for personalized energy and comfort management of the commercial building is described in detail; and the general framework for intelligent decision-making for energy and comfort management is explained. In Section 3, results are provided to observe both single-hour and monthly operation of proposed method. In Section 4, results are discussed and the performance of proposed MOOP method with respect to energy savings and occupants' productivity improvement is analysed. Section 5, provides some final conclusions and directions for future work.

2 Methods

The performance of proposed MOOP method should be studied by simulating its implementation to a building energy and comfort management system. For this purpose, simplified RC-network thermal model of a commercial building, located in Montreal, is developed and operation of IEMS of the commercial building, enhanced with proposed MOOP method is simulated. In this section, problem formulation of proposed MOOP method is described and a technique to add personalized thermal sensation variables to MOOP problem is discussed.

2.1 Building RC-Network Model & Control Systems

A single-floor commercial building located in Montreal, Canada, with 5 zones and 555 m^2 area is chosen for energy performance simulation. Using MATLAB software, simplified RC-network model of this building is developed for energy costs and comfort analysis. In Fig. 1, the whole shape of the building, alongside RC-network model of a sample zone (east zone) are shown.

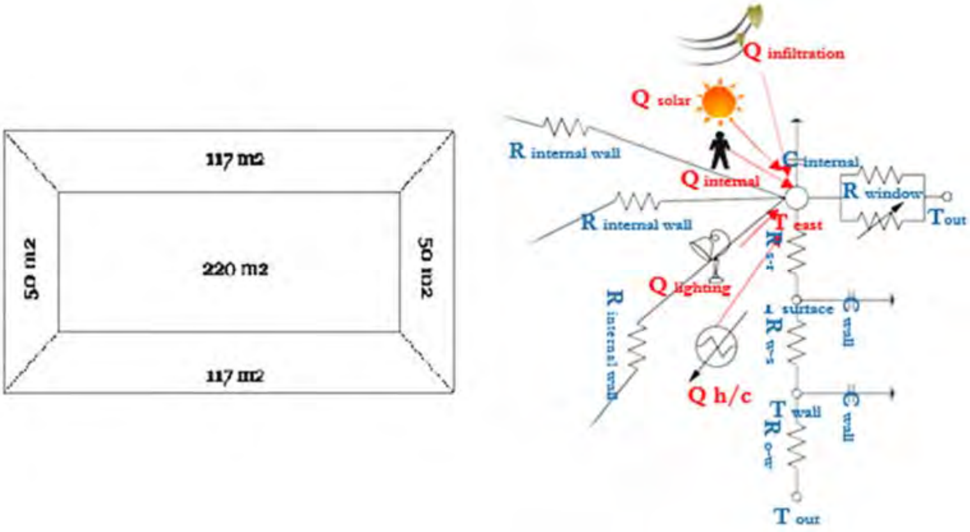

Figure 1: Simulated building in Montreal, Canada (left), RC-network thermal model of east zone (right)

For each zone of the building, there is a particular set of energy balance equations from different types of energy exchanges processes. Internal heat gains from occupants and appliances, solar energy through windows, infiltration and heat exchange with other spaces are among them. Artificial lighting, heating and cooling systems, to provide visual comfort and thermal comfort of occupants, are the other terms of energy balance equation. Energy performance of the whole building, with respect to variable energy costs and comfort conditions, is optimized simultaneously during each cycle of decision-making. *Artificial light ratio*, *blind position*, *inside temperature* and *ventilation rate* are four controllable variables. For each zone, total energy consumption in each cycle of simulation (one hour) is the sum of energy consumption of artificial lighting, chiller, boiler and fan. In Table 1, the values for building parameters and schedules, during occupied and unoccupied hours are given. It is assumed that the commercial building is occupied during weekdays, from 9 am to 5 pm. Energy and comfort management is addressed differently during occupied and unoccupied hours. During unoccupied hours, the optimization problem is single-objective optimization, having only energy costs term in objective function.

Table 1: Building Parameters and Schedules

Building Parameters	Value
Chiller COP	3.5
Electrical heater efficiency (n)	1
Open shade window U value	2.3 W/m^2 K
Close shade window U value	1.4 W/m^2 K
Fluorescent lamp efficacy	70 lumens/W
Exterior wall U value	0.4 W/m^2 K
Exterior wall specific heat	42 kJ/kg K
Exterior wall outdoor surface convection heat coefficient	34 W/m^2 K
Exterior wall indoor surface convection heat coefficient	8.5 W/m^2 K
Interior wall U value	1.53 W/m^2 K
Fan energy consumption	0.88 W per CFM of air
Maximum lamp power	15.8 W/m^2

Schedule	Occupied	Un-occupied
Minimum indoor illuminance	753.5 lux	430 lux
Occupancy heat generation	12.6 W/m^2	1.6 W/m^2
Equipment heat generation	10.7 W/m^2	3 W/m^2
Cooling set-point	-	26.6 °C
Heating set-point	-	18.3 °C
Minimum fresh air flow rate	0.001m^3/s per m^2	0.0003m^3/s per m^2

2.2 Multi-Objective Optimization of Energy Costs & Comfort

According to Marler et al., the process of optimizing systematically and simultaneously a collection of objective functions is called multi-objective optimization [3]. The goal of optimization problem is represented by an objective function or utility function. Solving optimization problem is the process of finding the set of design variables, under design constraints, which suit objective function the best. The general form of MOOP problem is:

$$\begin{aligned}
&Minimize\ F(x) = [F_1(x), F_2(x)\ldots F_k(x)]^T \\
&Subject\ to\ g_i(x) \leq 0, j=1, 2\ldots m, \\
&h_l(x) = 0, l=1, 2\ldots e, \\
&x_{low} \leq x_c \leq x_{high}\ \ c=1, 2\ldots n
\end{aligned} \tag{1}$$

Where; $F(x)$ is a vector of objective functions; $h_l(x)$ and $g_i(x)$ are inequality and equality constraints; $X=X_1, X_2, \ldots X_n$ are design variables, in which n is the number of independent variables; x_{low} and x_{high} are constraints on design variables; k is the number of objective functions; m is the number of inequality constraints. The MOOP objective function consists of two terms: *energy costs* and *productivity losses*. For each zone, total energy consumption for each cycle of simulation (1 hour) is the sum of energy consumption of artificial lighting, chiller, boiler and fan:

$$E_{total} = E_{lighting} + (Q_{cooling})/COP + (Q_{heating})/n + E_{fan} \tag{2}$$

Energy costs term in objective function is the aggregation of energy costs of each energy resource (electricity or gas). For either electricity or gas, the energy cost is the product of its hourly prices and hourly energy consumption.

The easiest way to introduce comfort conditions into optimization problem is taking them as lower or upper bounds of design variables, or treating them as constraints of optimization problem, to constitute single-objective optimization problem. Taking comfort as more important parameter, it is possible to transfer comfort into objective function to construct MOOP problem of energy and comfort. There is a strong relationship between occupant comfort conditions and his or her performances. Here, human performance is introduced in terms of *productivity of occupants ($)* and *Relative Productivity (RP, %)* is expressed as a function of indoor temperature (representing thermal comfort) and ventilation rate (representing IAQ). To construct the MOOP objective function, weighted sum method is used to combine energy costs and occupant comfort objectives. In this manner, both energy costs and comfort conditions are expressed in monetary unit ($).

$$\text{Objective Function} = \text{Energy Costs per hour (\$)} + \text{Productivity Loss per hour (\$)} \tag{3}$$

Productivity loss of occupants per hour ($) is the product of productivity per hour ($), based on occupancy and activity, multiplied by their relative productivity loss (*1- Relative Productivity*).

$$\text{Productivity Loss per hour (\$)} = \text{Productivity per hour (\$)} \,.\, (1 - \text{Relative Productivity}) \tag{4}$$

2.3 Add Personalization & Intelligence into Energy & Comfort Management

In order to consider occupants' thermal preference differences and introduce their adaptive behavior into MOOP problem of energy costs and comfort, two variables of *Maximum Comfort Temperature* and *Tolerance Range* of occupants are introduced into MOOP problem formulation. Thermal comfort of occupants is expressed by their RP. Relative productivity of occupants with respect to indoor temperature is assumed to be in the shape of a Gaussian function, with mean value of their maximum comfort temperature ($T_{maxcomfort}$) and variance of their Tolerance range:

$$e^{\frac{-(T-Tmaxcomfort)^2}{2.(Tolerance)^2}} \qquad (5)$$

At T $_{\text{maxcomfort}}$, RP is equal to 1; it means that at this temperature, occupant has maximum productivity. T $_{\text{maxcomfort}}$ expresses individual occupant satisfaction from environmental condition and accounts for cultural background, seasonal changes, social norms, thermal expectation and previous thermal experiences. For each occupant and at each hour of simulation, T $_{\text{maxcomfort}}$ could be different. Tolerance Range, explains pro-environmental behavior of occupants, their attitudes and beliefs toward environment and possible influence of affective processes. Based on Gaussian function characteristics, higher values of Tolerance Range mean that the level of RP is reducing with slow decline, while moving away from T $_{\text{maxcomfort}}$. On the other hand, having low values of Tolerance Range, mean that the occupant is more sensitive to thermal comfort and has lower RP.

In order to take into account IAQ of occupants, besides their thermal comfort, results of a series of studies by Fisk et al. are used. Fisk et al. derived an equation, which describes the relationship between ventilation rate *(Q, litre/second per person)* and occupants' *RP (%)* [22]:

$$RP\ (\%) = 0.021 \cdot \ln(Q) + 0.960 \qquad (6)$$

Relative productivity with respect to indoor temperature and RP with respect to ventilation rates, are combined with a method suggested by Dai et al.; it was stated that the combined effect of indoor air temperature and ventilation rate on productivity of occupants can be assumed to be in the range of the average of RP values and the larger value between the two [26]:

$$Overall\ Relative\ Productivity\ (\%)=(Average(RPT+RPQ)+Maximum(RPT,RPQ))/2 \qquad (7)$$

Productivity loss per hour of occupants ($) is calculated to be *productivity per hour ($)*, based on occupancy information and types of activities, multiplied by relative productivity loss (*1-Overall Relative Productivity*). Objective function to be minimize is defined by the aggregation of *Productivity loss per hour* to *Energy Costs per hour:*

$$Productivity\ Loss/hour(\$)=Productivity/hour(\$)\ .(1-Overall\ Relative\ Productivity) \qquad (8)$$

$$Objective\ Function=Energy\ Costs\ per\ hour\ (\$)+\ Productivity\ Loss\ per\ hour\ (\$)$$

Multi-objective optimization problem of energy costs and comfort is solved by IEMS to provide an economical optimum solution for automatic control of indoor conditions. Economical optimum solutions are the solutions which consider both energy savings and productivity of occupants. Shading system is controlled with blind actuators to manage the level of solar radiation or natural light entering the room, which has an impact on both thermal and visual comfort. Artificial lighting systems provide additional lighting, if natural light is not enough to fulfill visual comfort of occupants. HVAC systems are controlled to ensure thermal comfort as well as IAQ. Energy management system with the help of MOOP techniques, produces a set of Pareto optimal solutions for each hour of simulation. The final optimal solution can be chosen intelligently, by learning influential factors such as energy prices, occupancy data and occupants' activities.

3 Results

In this section, first, detailed operation of proposed MOOP method, with respect to both energy savings and occupants' comfort and the construction of Pareto optimal solutions are discussed. In order to observe the performance of proposed method with respect to occupants' individual preferences, or personalization of energy and comfort management, five different models of occupants' thermal preference are considered. These *thermal preference models* are differed in $T_{maxcomfort}$ and Tolerance values. Data required for these models are taken from Haldi et al. research, who analysed real occupants' behaviour inside a building, during long-term observation [27]. Performance of proposed MOOP method for personalized energy and comfort management is evaluated, considering different thermal preference models.

3.1 Pareto Optimal Solutions

Occupancy data and occupants' activities can indicate their productivity per hour. Minimum productivity of each employee in the office, during each decision-making cycle is assumed to be $10/hr. Ten values for occupants' productivity per hour, from $10/hr to $100/hr are considered, based on the number of occupants and importance of their activities, to construct Pareto optimal solutions. Within this framework and considering Real-Time Pricing (RTP), electricity prices can also be variable with respect to signals received from utility side. However, for avoiding complexity in analysing the results of simulations, here, electricity and gas prices in Montreal are assumed as fixed rates of 8 cents and 5 cents per kWh, respectively. During energy and comfort management, it is expected that two objectives of energy savings and productivity maximization would be in conflict with each other. Improving one of them would only be viable with the reduction of the other one. This fact is shown in Fig. 2, in which Pareto optimal solutions of a sample zone (east zone) for 1st of January and 1st of July, 10-11 am simulation are provided. It is also observed that costs of discomfort associated with the operation of MOOP method, have negative values in both weather conditions. This negative values for productivity losses, express the level of satisfaction of occupants from better indoor environment quality.

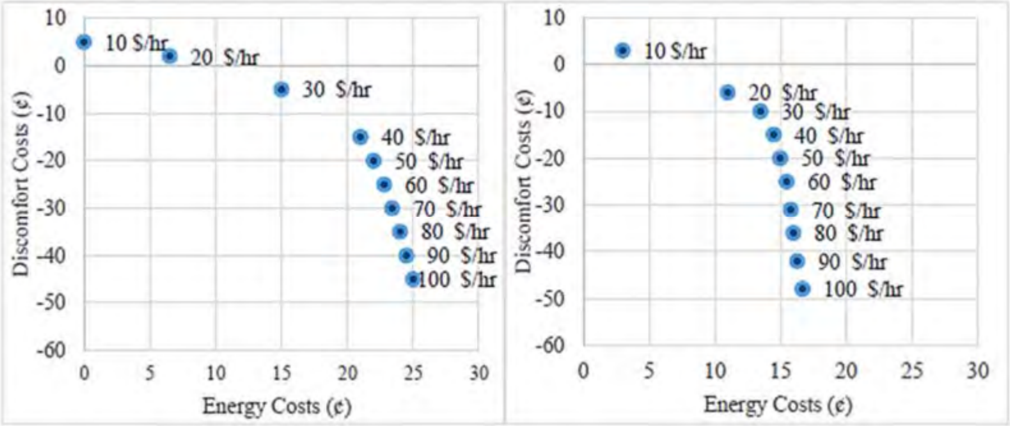

Figure 2: Pareto optimal solutions for 10-11 am simulation in 1st of January (left) and 1st of July (right) - East Zone

3.2 Personalized Energy & Comfort Management

In this part, five thermal preference models with different $T_{maxcomfort}$ and Tolerance values are defined and automated control of indoor environment by MOOP method is analysed, with respect to energy savings and occupants' productivity. The five thermal models are shown in Table 2.

Table 2: Thermal preference models used in the analysis

Thermal Preference Model	**#1**	**#2**	**#3**	**#4**	**#5**
$T_{maxcomfort}$ (°C)	23.86	21.88	22.33	24.35	23.34
Tolerance Range (°C)	6.25	5.11	8.1	6.99	4.35

Two months of January and July, representing two different weather conditions of Montreal, Canada, are chosen for analysis. In order to understand how MOOP method works in case of providing thermal and IAQ, monthly mean indoor temperature and monthly mean ventilation rates, during occupied hours of the building are analysed. Performing MOOP with thermal model #1 for all the occupants inside all zones of the building, the values of monthly mean indoor temperatures during January are shown in Fig. 3. Results are shown inside a polygon, with angles showing each productivity per hour scenario. The scenarios for occupancy are ranged from productivity of 10 dollars per hour to 100 dollars per hour ($10 P/hr to $100 P/hr).

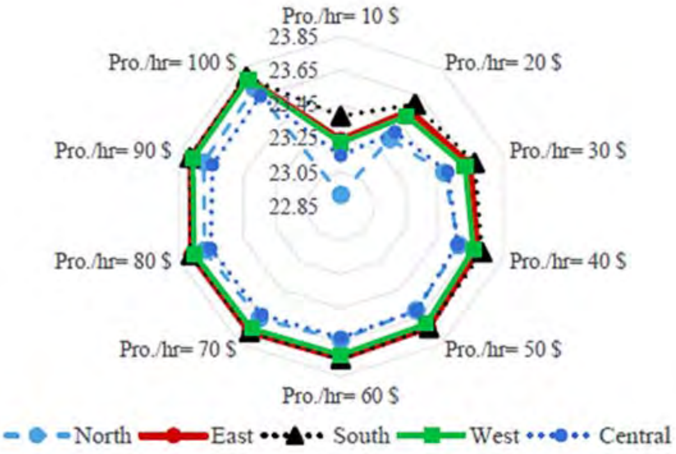

Figure 3: Variation of monthly mean indoor temperature (°C) in different zones for different productivity per hour ($) scenarios – January, thermal model #1

Each point on the corner is representing T $_{\text{maxcomfort}}$ of Thermal model #1 (23.86 °C). Moving through the center of polygon, monthly mean temperatures are moving away from T $_{\text{maxcomfort}}$. The first observation is that, turning clockwise from $10 productivity per hour corner on top, for all zones and for all seasons, values set by MOOP method for indoor temperature are getting closer to the corners of polygon. With the increase in productivity per hour of occupants, proposed MOOP method considers comfort of the occupants as more important factor. Moreover, indoor temperature in south zone is closer to the corners. In contrast, north zone is believed to be least comfortable zone, because of the closer movement of indoor temperature to the center of polygon. These observation are explained as follows. Between all the zones, south zone, has the highest value of monthly solar radiation, with average hourly 382 W/m^2 solar irradiance, east and west zones are second and third with 183 W/m^2 and 158 W/m^2, while north zone only has mean solar irradiance of 83 W/m^2 in January. Therefore, during cold season of January, providing T $_{\text{maxcomfort}}$ of occupants with thermal preference model #1 is easiest in south zone and hardest in north zone.

The importance of the sun and its radiation is not solely associated with thermal and visual comfort of occupants. In Fig. 4, IAQ of occupants with thermal model #1, expressed by mean ventilation rates, during January are analyzed. It is observed, south zone has the best IAQ for most of the occupancy scenarios. Having the highest level of solar irradiance allows MOOP method to insert more fresh air from outside to the inside. The opposite applies to north zone and central zone. IEMS, enhanced by MOOP method, decides not to insert more than minimum required fresh air, because it would be costly to increase indoor temperature level, in order to compensate addition of fresh cold air. Another observation, in Fig. 4 is very important; for January (and all other seasons), with the increase in productivity per hour, the level of ventilation rates would increase. MOOP method is capable of continuously increasing IAQ, when new people are entering the room.

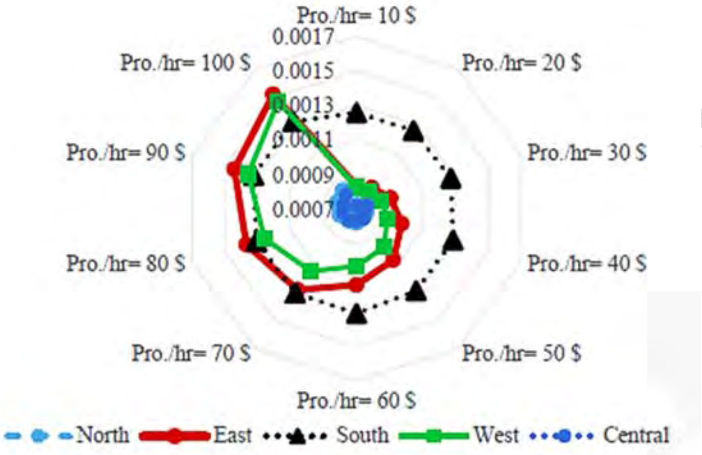

Figure 4: Variation of monthly mean ventilation rates (m^3/s per m^2) in different zones for different productivity per hour ($) scenarios – January, thermal model #1

Now that detailed operation of MOOP method in different zones of the building are observed, it is worthwhile to analyse performance of MOOP method in providing energy savings and occupants' productivity gain objectives. During cold and warm weather conditions of January and July, MOOP method is performed for 5 different thermal models. For each optimization considering particular thermal model, it is assumed that all occupants have that thermal preference. In Fig. 5, monthly energy costs ($) for different productivity per hour ($) scenarios are shown for January (left) and July (right) optimization. $T_{maxcomfort}$ and Variance values of thermal preference models are different. Model #4 and model #1 have the highest $T_{maxcomfort}$ (°C) values. Hence, providing their satisfactory thermal conditions requires higher monthly energy costs during cold season of January. The same reason explains their lower monthly energy costs during warm season of July, which providing warmer indoor air is much easier. This observation shows that MOOP method clearly follows thermal comfort of occupants, as well as energy savings objective. Proposed MOOP method is also capable of inceasing overall productivity of occupants by improving their thermal comfort and IAQ. In Fig. 6 the level of monthly producitivty gains ($) for different scenarios of occupancy are shown for January and July. During both months proposed method improves productivity of any occupants with any thermal preference model. Having larger monthly productivity gains ($), the potential for productivity improvement is genrally higher during July than January. It is also observed that thermal preference model #3 with higher tolerance ranges have lower potential for productivity improvement.

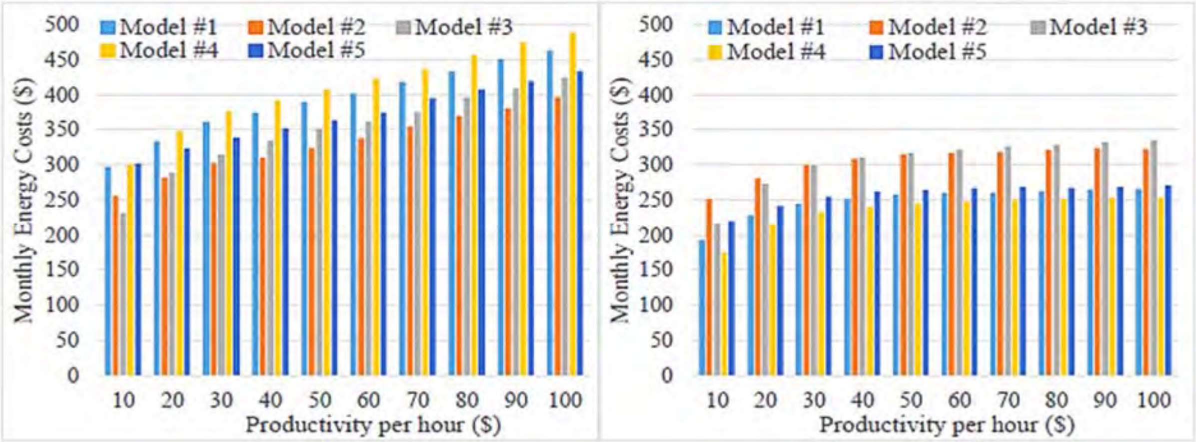

Figure 5: Monthly energy costs ($) for different productivity per hour ($) scenarios considering five different thermal preference model – January (left), July (right)

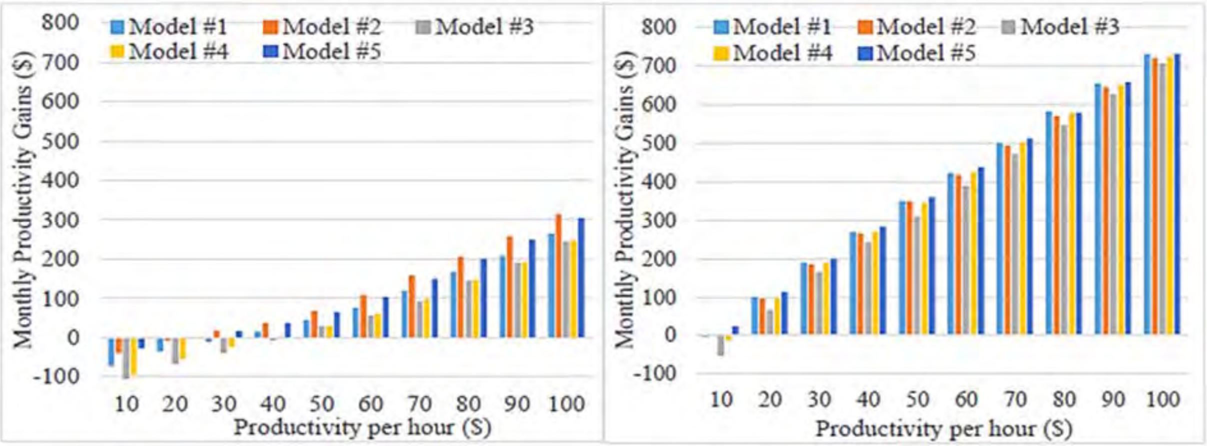

Figure 6: Monthly productivity gains ($) for different productivity per hour ($) scenarios considering five different thermal preference model – January (left), July (right)

4 Discussion

In previous section, results are provided to validate the operation of proposed MOOP method in providing personalized indoor air conditions. It is shown that MOOP method is capable of following occupants' $T_{maxcomfort}$. Moreover, proposed MOOP method can alter indoor air conditions continuously with the change in occupancy. Here, in this section the importance of occupants' attitude toward energy consumption will be stated. As it was discussed in Introduction section, there are various parameters that influence thermal sensation of occupants. People can adapt to the indoor environment. Adjusting cloths to warmer or colder ones, relaxing cultural or social clothing norm, choosing alternative physical activities and drinking beverages are the most common adaptive behavior of pro-environmental occupants. It will be validated that the proposed system can acknowledge occupants' attitude toward energy consumption and perform the automated control of indoor conditions based up on their attitudes, as well as their $T_{maxcomfort}$. For the start, assume that in the east zone and during single-hour optimization in 1st of January, there is a potential of ten occupants' presence inside the zone. All occupants are assumed to have same $T_{maxcomfort}$ of 21.65 °C and same Tolerance. Proposed method has the capability of solving situation-specific optimization problem by presenting $T_{maxcomfort}$ and Tolerance variables into MOOP problem statement. In this way concepts of adaptive thermal comfort can be introduced into IEMS. This is shown in Fig. 7. With different tolerance range (σ) values, MOOP method solve energy and comfort management problem differently and adjust indoor air temperature. Reducing tolerance ranges, would result in indoor temperature values' closer movement towards T $_{maxcomfort}$. On the other hand, if tolerance ranges of occupants are increased, wider range of indoor temperature deviation from T $_{maxcomfort}$ are resulted.

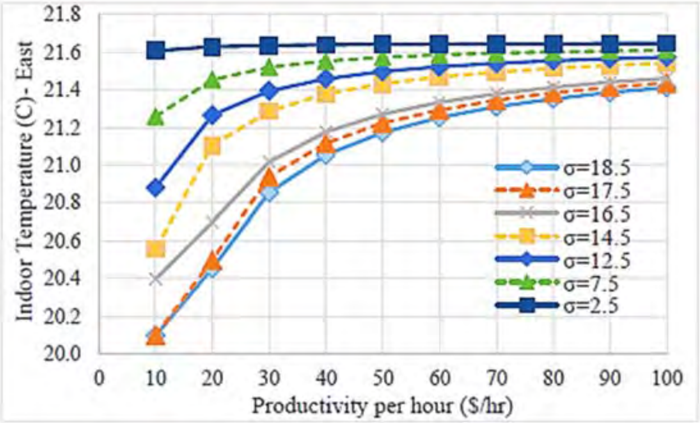

Figure 7: Indoor temperature (°C) variations with the change in Tolerance of occupants (σ) for different productivity per hour ($) scenarios- January 10-11 am simulation- East Zone

Talking about adaptive behavior of occupants and their tolerance ranges, two observation are very important. First, adaptive behavior of occupants clearly influence energy consumption and MOOP method is capable of adjusting itself based on dynamic behavior and attitudes of occupants. In Fig. 7, it is observed that having occupants with lower tolerance range (σ) would result in higher energy costs in the east zone. Otherwise, if there are occupants who are pro-environmental and have higher tolerance ranges (σ), which means that they can adapt themselves to the environment, indoor air temperature and consequently energy costs would reduce. If the number of pro-environmental occupants increase, the system would improve indoor air conditions by increasing indoor temperature and IAQ to boost their overall productivity.

The next subject of discussion is related to the prosperity of MOOP method in providing personalized indoor conditions and avoiding significant amount of productivity losses. To validate that, results of optimization during January and July for different thermal preference models are analyzed. Proposed method performs MOOP for all thermal preference models. For each optimization with particular thermal preference model, the level of productivity losses of occupants having other thermal preferences are calculated. Thermal model #2 and thermal model #4 are chosen for January optimization. The results of MOOP are shown in Fig. 8, for a single scenario of $50 per hour productivity, for model #2 (left) and model #4 (right). No productivity losses are inspected for these models. But, having extra occupant with other thermal preferences, significant amount of productivity losses are observed. As an example, performing personalized MOOP for thermal model #4 (right), if an extra occupant is considered with thermal model #2, its presence in each zone is associated with more than $250 productivity losses during January. This is mainly, because of the large difference between $T_{maxcomfort}$ in model #2 and model #4.

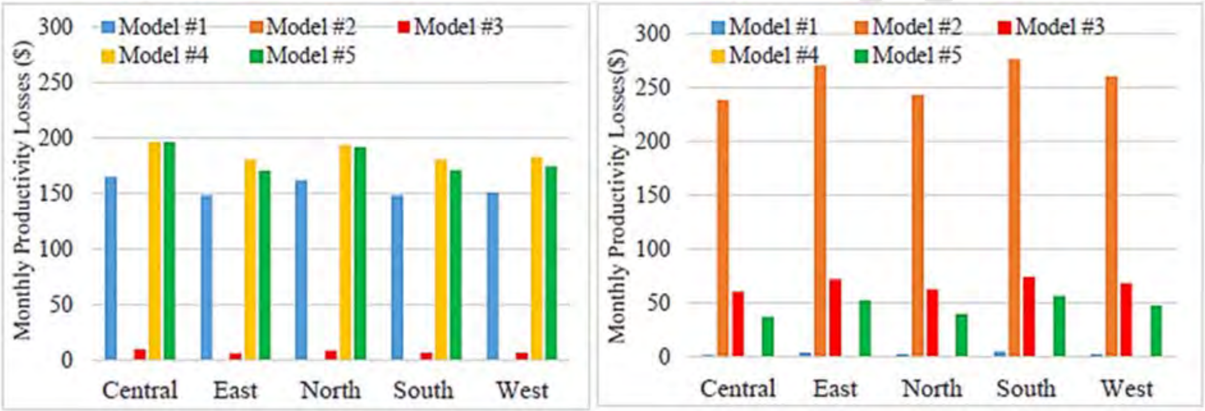

Figure 8: Monthly productivity losses ($) of having occupants with different thermal preferences in the room, doing MOOP with model #2 (left) and model #4 (right) – $50 Productivity per hour of, January simulation

The same analysis is done for single scenario of $50 productivity per hour during July, for thermal preference model #3 and model #5. The results are shown in Fig. 9 for model #3 (left) and model #5 (left). For these two thermal preference models, using proposed MOOP method, no productivity losses are inspected. Because the difference between $T_{maxcomfort}$ of model #3 and model #4 are maximum, in Fig. 9 (left), model #4 occupant has the highest level of productivity losses ($). While, the same explanation is true for occupants with thermal preference model #2 and model #5 in Fig. 9 (right). Large values of productivity losses is observed for an occupant with model #2, when it enters any zone of the building, when proposed method is adjusted to thermal preference model #5. MOOP method is very strong in providing occupants' preferred indoor air conditions and improving their productivity, while keeping energy saving objective as a priority.

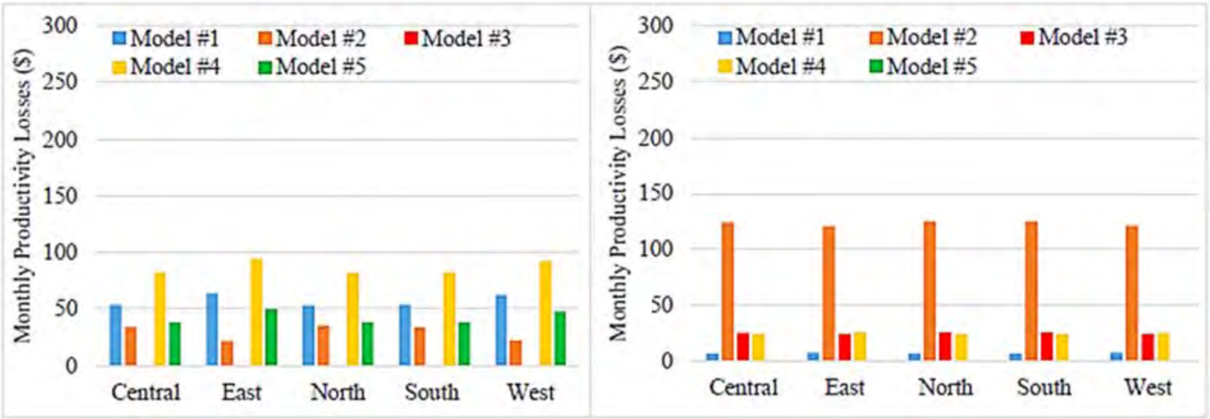

Figure 9: Monthly productivity losses ($) of having occupants with different thermal preferences in the room, doing MOOP with model #3 (left) and model #5 (right) – $50 Productivity per hour of, July simulation

5 Conclusion

Paul Krugman, winner of Nobel Memorial Prize in Economic Sciences in 2008 once quoted “Productivity isn’t everything, but in the long run it is almost everything. A country’s ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker” [24]. The main interest of this research is to propose a method for intelligent energy management systems to improve productivity of occupants inside commercial building, while maintaining energy saving objectives. The results of this research also validate Fisk et al. claim of vast potential for productivity improvement in commercial buildings. Fisk et al. estimate annual economic profit of $700 per person and 17 to 26 billion dollars in U.S. as a result of indoor environment quality improvement in office buildings, across the entire nation [25]. The focus of contemporary studies on adaptive comfort is on differences between thermal sensations and preferences of the occupants. There are various parameters that influence thermal sensation of occupants, such as age, gender, social dimensions, economical background, pro-environmental attitude, previous experiences and their adaptation to the environment; therefore, there is need for intelligent energy management system to provide flexibility in dealing with occupants’ thermal preference differences. This research address the challenge of introducing occupants’ thermal comfort preferences and their adaptive behavior and attitudes toward energy consumption, into energy and comfort management. Occupants’ preferences and behavior inside the same zone could be in conflict with each other. The topic for future work is to present a method for personalized energy and comfort management in which occupants of the same zone are considered to have different preferences, behavior and attitudes toward energy consumption.

Acknowledgements

This work was supported by Natural Sciences & Engineering Research Council of Canada.

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