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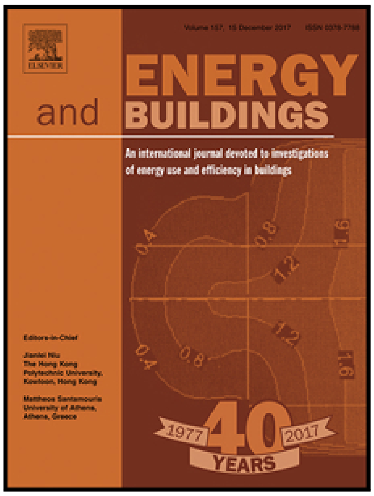

An Integrated Model for Position-based Productivity and Energy Costs Optimization in Offices

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Highlights

- Position-based energy and comfort management, according to occupants' thermal and visual preferences and behavior, and indoor air quality
- Simultaneous optimization of occupants' productivity and energy consumption costs

An Integrated Model for Position-based Productivity and Energy Costs Optimization in Offices

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Abstract

In shared spaces, occupants may have varied thermal and visual preferences for the indoor environmental conditions. Moreover, an occupant's perception of the indoor environment, such as her thermal and visual sensations, depends on her position inside an enclosed space. There is a strong relationship between occupants' comfort conditions and their level of productivity, hence, improving the productivity of occupants in offices offers significant economic benefits. The main interest of this research is to propose a Multi-Objective Optimization (MOOP) method for *position-based* energy and comfort management in offices. The proposed method accounts for personalized thermal and visual preferences of occupants and their *positions* within an office space, and simultaneously optimizes energy consumption costs and collective productivity of office workers, by proposing Pareto optimal solutions for the automated control of the indoor environment. Occupants' thermal and visual preferences and positions, their productivity rates, thermal and visual behavior, Indoor Air Quality (IAQ) of the space, energy exchanges processes across the building, indoor and outdoor environmental parameters, and energy prices, are considered in this optimization. Application of the proposed method under varied occupancy scenarios is analyzed by energy performance simulation of a multi-zone office building, located in Montreal, Canada. The proposed method (1) has the flexibility to account for the diversity among occupants' environmental preferences, (2) manages the indoor environmental conditions based on office workers' positions and preferences, and (3) simultaneously optimizes energy costs and office workers' productivity.

Keywords: Energy Management, Building Simulation, Integrated Building Control, Productivity, Multi-Objective Optimization, Occupant Behavior Modeling

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Nomenclature

English Symbols

a_{cold}, a_{warm}, b_{cold}, b_{warm}	Thermal regression parameter [-]
a_{bright}, a_{dark}, b_{bright}, b_{dark}	Visual regression parameter [-]
A_s	Area of the surface [m^2]
c	Specific heat of the fluid [J/kg.K]
c_{zone}	Average specific heat of the zone [J/kg.K]
E	Energy consumption [kWh]
$ILL_{\text{maxcomfort}}$	The illuminance level of maximum visual comfort [lux]
h_c	Heat transfer coefficient [W/m^2.K]
??	Mass flow rate [kg/s]
$Prob_{\text{Cold}}$	Probability of being cold [-]
$Prob_{\text{Thermal\_Comfort}}$	Probability of being thermally comfortable [-]
$Prob_{\text{Thermal\_Discomfort}}$	Probability of being thermally uncomfortable [-]
$Prob_{\text{Visual\_Comfort}}$	Probability of being visually comfortable [-]
$Prob_{\text{Visual\_Discomfort}}$	Probability of being visually uncomfortable [-]
$Prob_{\text{Warm}}$	Probability of being warm [-]
$q_{\text{in-zone}}$	Heat generated in the zone [W]
Q	Ventilation rate [m^3/s per m^2]
RP_{IAQ}	Relative productivity with respect to indoor air quality [-]
RP_{overall}	Overall relative productivity [-]
RP_{thermal}	Relative productivity with respect to thermal conditions [-]
RP_{visual}	Relative productivity with respect to visual conditions [-]
t	Time [hour]
T	Indoor temperature [°C]
$T_{\text{maxcomfort}}$	Maximum comfort temperature [°C]
T_s	Surface temperature [K]
T_{zone}	Average temperature of the zone [K]
$Tolerance_{\text{thermal}}$	Tolerance range with respect to thermal conditions [K]
$Tolerance_{\text{visual}}$	Tolerance range with respect to visual conditions [lux]
V_{zone}	Volume of the zone [m^3]

Greek Symbols

??$_{\text{zone}}$	Average density of the zone [kg/m^3]

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon Dioxide
COP	Coefficient of Performance
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IoT	Internet of Things
MOGA	Multi-Objective Genetic Algorithm
MOOP	Multi-Objective Optimization
MRT	Mean Radiant Temperature
NSGA-II	Non-dominated Sorting Genetic Algorithm
RP	Relative Productivity
SOOP	Single-Objective Optimization
VAV	Variable Air Volume
WSM	Weighted Sum Method

1 Introduction

The building sector accounts for a large part of global energy demands and can play a major role in mitigating the climate change threat. Reports show that in Canada, residential, commercial, and public buildings consume 46% of total energy produced [1]. Over the recent decades, there has been a continuous development of the building technologies with more efficient energy consumption, while energy efficiency programs and renewable energies have been presented as clean ways to decrease energy consumption [1]. At the same time, during the design and operation of buildings, productivity, morale, and satisfaction of occupants have the same importance as energy conservation [2]. One of the most promising approaches to building energy efficiency is to make buildings *energy intelligent*, by performing intelligent control of building facilities and communicating with occupants. Accordingly, buildings are able to manage their operation to ensure their occupants' comfort and minimize energy consumption, simultaneously. Using computational methods such as Multi-Objective Optimization (MOOP) methods, two conflicting objectives of energy consumption minimization and occupants' comfort maximization can be concurrently achieved.

Paying excessive attention to energy consumption reduction in buildings may have adverse impacts on Indoor Environmental Quality (IEQ), since thermal and visual conditions, and Indoor Air Quality (IAQ) could be influenced consequently. Researchers have developed energy management systems, enhanced with computational intelligence techniques or computational optimization methods to help the system keeping a balance between these two objectives. Dounis et al. [3] generated a set of 23 fuzzy logic rules to regulate building operation and control energy consumption and indoor environmental conditions. Alcala et al. [4] and Kolokotsa et al. [5] tuned and optimized fuzzy logic controllers that controlled Heating, Ventilation and Air Conditioning (HVAC) systems of a building, with respect to energy consumption and occupants' comfort. MOOP techniques are useful to solve problems in which two or more objectives are in conflict with each other, hence, they are effective for energy and comfort management. MOOP techniques consider a trade-off between energy consumption and occupants' comfort conditions and find the best possible set of compromises between them [6]. Weighted Sum Method (WSM) is the most used MOOP method for energy and comfort management [7]. WSM converts MOOP problems into a number of single optimization problems, by aggregating objective functions together while scaling them. Yang et al. [8] and Wang et al. [9] optimized energy consumption and overall comfort using WSM to develop objective function. Dai et al. [10] introduced human performance in terms of productivity of occupants, in MOOP of energy consumption and comfort conditions. The relative productivity of occupants was expressed, as a function of their thermal sensations (thermal comfort) and ventilation rate (IAQ). In Pareto-based MOOP methods, decision-making is performed after running the optimization algorithm, by generating a number of Pareto points (solutions that are optimal points, found by varying weight factors), and selecting a single solution from a set of mathematically equivalent solutions [6]. Multi-Objective Genetic Algorithm (MOGA) and Non-dominated Sorting Genetic Algorithm (NSGA-II) are among the most popular Pareto-based approaches [11]. Ascione et al. [12] and Brownlee et al. [13] used MOGA to optimize HVAC system operation. Carlucci et al. [14] optimized thermal and visual comfort of occupants in a simulated building using NSGA-II.

The overall comfort of an occupant represents her well-being inside an enclosed space. Several factors including the level of thermal comfort, visual comfort, aural comfort, and IAQ influence the quality of life of occupants. Thermal comfort is satisfied, when the metabolic rate, heat generated from energy in the human body, is in balance with the rate of heat human body is losing [15]. Indoor environmental parameters such as indoor temperature, and relative humidity, as well as personal parameters of metabolic rate, and level of clothing are used for thermal comfort assessment [16]. Based on adaptive thermal comfort studies, parameters such as age, gender, outdoor weather conditions, social dimensions, economical background, history of thermal sensations, perceived control over the environment, psychological and physiological adaptation to the environment, and behavioral adjustment, are identified as the parameters that influence the thermal sensations of occupants [15, 17]. This discussion is expandable to visual comfort of occupants. Traditionally, controlling the visual comfort of occupants is based on the types of occupants' tasks and the avoidance of glare [1]. These days, scientists are conducting research on human-centric lighting systems. Within these research studies, the influence of personalized and psychological parameters such as affective processes, mood, environmental appraisal, and perceived control over the visual perception of occupants have been studied [18]. Considering all parameters that shape thermal (and visual) sensation of occupants, it is very probable to have variations among thermal (and visual) preferences of occupants in a shared indoor environment. In order to learn occupants' environmental preferences, longitudinal studies on the comfort sensations of occupants can be performed. Over time, comfort sensation votes of each occupant, in a wide range environmental conditions are collected. Based on the collected data, comfort preference model of each person can be constructed. Indoor environmental parameters and occupants' comfort sensation votes should be continuously collected, through building monitoring systems, to be synchronized with occupants' sensation votes. Jang et al. [19], Noh et al. [20], and Qian et al. [21] proposed wireless sensor networks for building environmental monitoring systems, applicable to comfort studies. Haldi et al. [22] designed a web-based questionnaire, and collected thermal sensation votes of occupants within a long-term observational study, and subsequently, identified their thermal preference models using logistic regression techniques. Jazizadeh et al. [23] suggested collecting occupants' feedback through participatory sensing using smartphones or web-based applications. The *productivity* of an occupant is defined as "the extent to which activities have provided performance in terms of system goals" [24]. During the last three decades, there have been several studies to quantify the relationships between occupants' productivity and their level of comfort [25, 26, 27, 28, 29]. Fisk et al. [30] estimated that annually 17 to 26 billion dollars economic benefits, in terms of office workers' productivity, are achievable by improving IEQ of offices across the United States.

The main interest of this research is to propose a method to simultaneously optimize energy consumption costs and productivity in office buildings, by considering occupants' thermal and visual preferences and their positions inside enclosed spaces. Compared to the previous studies on MOOP of energy and comfort, here, thermal and visual preferences of occupants are introduced in the MOOP problem formulation. For this purpose, each occupant's personalized thermal and visual preferences are modeled (from her sensation votes) in the shape of Gaussian functions. The proposed method combines thermal and visual preferences of each occupant, and IAQ to consider her overall comfort. Occupants' perception of the indoor environmental conditions, such as their thermal and visual sensations, depending on their positions inside enclosed spaces. Compared to the reviewed studies on energy and comfort management, here, positions of occupants are also accounted for thermal and visual comfort evaluations, to achieve *position-based* energy and comfort management. Alongside occupants' comfort conditions, their productivity rates, indoor and outdoor environmental parameters, and energy exchange processes across the building environment are also considered to construct the MOOP problem formulation. Here, occupants' comfort is expressed by their level of productivity. Accordingly, in the objective function of the proposed MOOP method, both occupants' comfort conditions and energy consumption costs are expressed in a same (monetary) unit and aggregated using WSM.

A simplified RC-network thermal model of a single-floor office building, with four zones, located in Montreal, Canada, is developed using MATLAB. Under different scenarios of occupancy, the proposed method optimizes energy consumption costs and productivity of office workers, by optimizing the level of indoor temperature, ventilation rate, natural illumination, and artificial lighting of the zones, on an hourly basis. This paper is organized as follows. In Section 2, the RC-network thermal model of the office and its integrated control system are explained. The techniques for position-based evaluation of the thermal and visual comfort of occupants are described, separately. Subsequently, methods to construct occupants' thermal and visual preference models, from the history of their thermal and visual sensation votes, are discussed. Afterward, the method for MOOP of energy costs and productivity, considering occupants' positions, personalized thermal and visual preferences, and IAQ is proposed. In Section 3, in order to evaluate the capabilities of the position-based method, different parametric simulations are performed, where arbitrary scenarios of occupancy, inside different zones and during varied months of the year, are considered. Accordingly, the flexibility of the position-based method to make energy-related decisions, based on the personalized parameters of occupants' (1) hourly productivity rates, (2) thermal preferences, (3) visual preferences, and (4) positions, are evaluated in different parametric simulations. In Section 4, the sensitivity of the proposed method to occupants' thermal and visual tolerances is analyzed to evaluate the capability of the method to acknowledge thermal and visual behavioral changes of occupants. Section 5, provides conclusions and directions for future work.

2 Methods

A single-floor office with four zones in Montreal, Canada, is assumed. Montreal has a warm, humid summer and a very cold winter, and is located in climate zone 6 in ASHRAE climate zones map [31]. For building energy performance simulation, typical meteorological year weather data of Montreal is used [32]. First, in Section 2.1, the simplified RC-network thermal model of the office building is developed. The position-based method performs automated control of the indoor environment by managing the level of environmental parameters, in different zones of the office. In Section 2.2, the integrated control system in the office is described. The techniques for position-based thermal and visual comfort evaluations are explained in Section 2.3 and Section 2.4, respectively. The proposed method acknowledges each occupant's thermal and visual preferences by constructing her thermal and visual preference models. The approach to constructing thermal and visual preference models from occupants' thermal and visual sensation votes are discussed in Section 2.5 and Section 2.6, respectively. Subsequently, the methodologies used to perform MOOP of energy costs and productivity, according to all personal and environmental parameters are described, in Section 2.7.

2.1 Modeling the Office Building

A single-floor office, located in Montreal, Canada, is considered. The office has four zones, called *north zone*, *east zone*, *south zone*, and *west zone*. In all the zones, the floor area is equal to 139 m^2 (16.66 m x 8.33 m), and the ceiling height is 3 meters. In all four zones, the wall with a connection to the outside has a window-wall ratio of 0.4. Each window (with 20 m^2 area) has the same width as the wall and is located in the middle of the wall. The simplified RC-network thermal model of the office is developed and validated in a previous study [33] and summarized in App. A. The plan of the office and thermal model of one of the zones (east zone) are shown in Fig. 1.

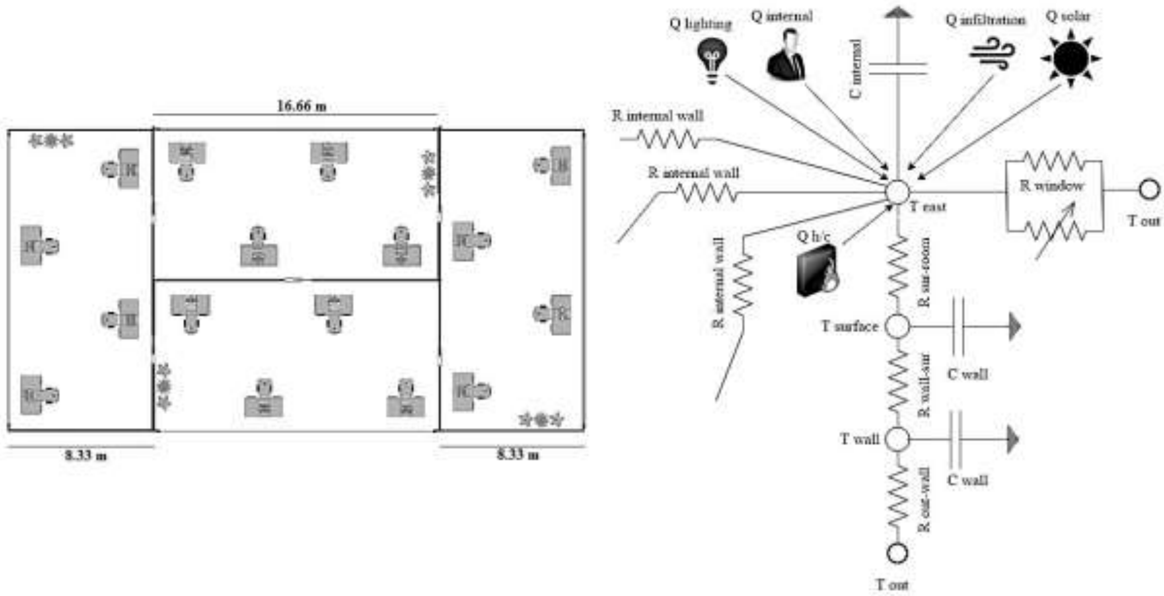

Fig. 1: Office plan (left) and the RC-network thermal model of east zone (right)

Occupants' perceptions of the indoor environment, including their thermal and visual sensations, depending on their positions inside enclosed spaces. In the proposed position-based method, positions of occupants inside the zones, as well as their personalized thermal and visual preferences, are considered for energy and comfort management. By dividing each zone into eight equal parts (4.16 m x 4.16 m), and adjusting the positions of occupants to the middle of four (out of eight) parts, four arbitrary positions inside each zone are considered. In each zone, positions are called; *Position-A, Position-B, Position-C,* and *Position-D*. The positions of occupants inside each zone are illustrated in Fig. 2. For thermal and visual comfort analysis, the operative temperatures (°C) and illuminance levels (lux) in the positions are studied.

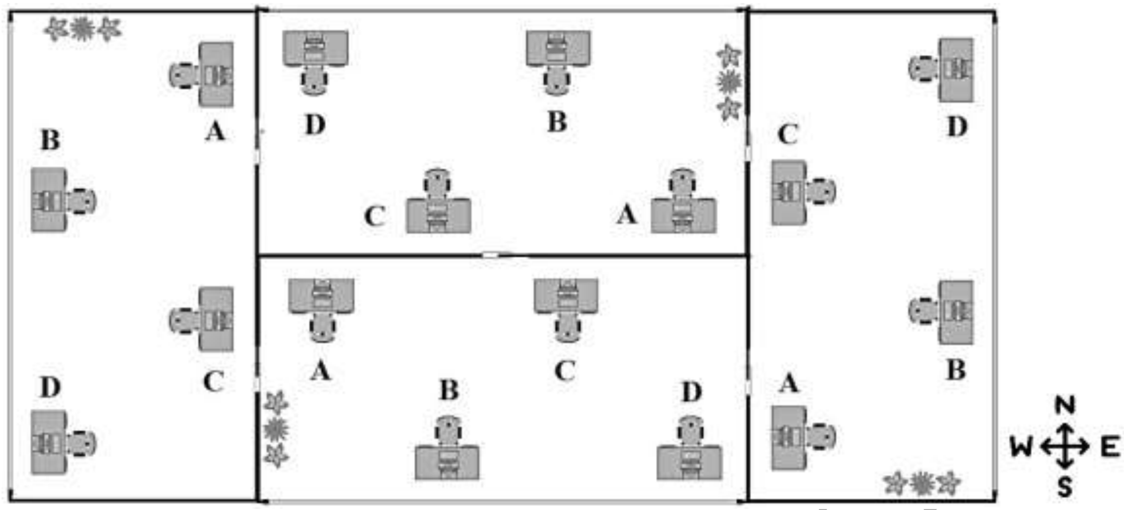

Fig. 2: Positions and their names in each zone of the office

2.2 Integrated Control System

It is assumed that the office is occupied every day, from 9 am to 5 pm, and each zone is equipped with a Variable Air Volume (VAV) system that provides heating, cooling, and air ventilation. In each zone, four indoor environmental parameters of *artificial lighting*, *natural illumination*, *indoor temperature*, and *ventilation rate* are automatically controlled. These four environmental parameters relate to the thermal and visual comfort of occupants and IAQ of the zones. During the unoccupied hours, energy management and integrated control of the zones are based on the Single-Objective Optimization (SOOP) of energy consumption costs. Energy consumption in each zone is the sum of energy consumption of artificial lighting, chiller, boiler, and fan. In the SOOP of energy costs, occupants' comfort conditions are treated as the limits on the indoor environmental parameters [34]. The energy costs term, in the objective function of the SOOP method, is the product of electricity or gas prices and the associated hourly energy consumption. Fixed rates of 8 cents per kWh and 20 cents per m^3 are assumed as electricity and gas prices, respectively. For each hour of simulation, the energy costs term in the objective function is in the form of:

$$Energy\ costs\ = \left[ElecPrice.\sum_{r=1}^{5} E_r^{electricity} + GasPrice.\sum_{r=1}^{5} E_r^{gas}\right], \tag{1}$$

in which E is the energy consumption in kWh; r is the number of the zone; *ElecPrice* and *GasPrice* are electricity and gas prices.

The constraints, related to visual comfort (indoor illuminance), thermal comfort (heating and cooling set-points), and IAQ (conditioned outdoor air flow rate) are demonstrated in Table 1. Building schedules, during the occupied and unoccupied hours, are compared in Table 1. The major difference between the proposed and the SOOP method is the presence of thermal comfort, visual comfort, and IAQ parameters, inside the objective function of the proposed method.

Table 1: Building Schedule

Schedule	***Occupied***	***Unoccupied***
Minimum Indoor Illuminance (lux) [1]	750 (always ≤ 2500 lux)	50
Occupancy Heat Generation (W/m^2)	12.6	1.6
Equipment Heat Generation (W/m^2)	10.7	3
Cooling Set-Point (°C)	-	27
Heating Set-Point (°C)	-	21
Minimum Conditioned Outdoor Air Flow Rate (m^3/s per m^2) [15]	0.0006 + 0.0003 (infiltration)	0.0003 (only infiltration)
Maximum Conditioned Outdoor Air Flow Rate (m^3/s per m^2)	0.002	0.002

During the occupied hours, the position-based method provides economic-optimum conditions for the operation of the building, by managing the level of four mentioned indoor environmental parameters. The method has an energy costs term, as well as an occupants' productivity term, in its objective function. Indoor and outdoor weather conditions, energy prices, occupancy data, occupants' productivity rates, thermal and visual preferences, and positions, are the factors that influence the decision-making of the position-based method.

2.3 Position-Based Thermal Comfort Evaluation

The operative temperature (°C) in each position, is assumed to be the average of indoor temperature and Mean Radiant Temperature (MRT). Indoor temperature in each zone is automatically controlled by the proposed method and is assumed to be uniform throughout the zone. But, MRTs (°C) are varied and depend on the position of each occupant inside the zone. The procedure to find MRTs in different positions is as follows:

1. For each zone, eight surfaces are considered. The wall(s) with the window is divided into three surfaces; a window surface in between (with 1.2 m height), and two top and bottom sides of the window (with 0.9 m height). The other surfaces are interior wall(s), the floor, and the ceiling. South zone and north zone have three interior walls, while east zone and west zone have only one (Fig. 2).
2. Configuration factors between occupants' positions (points) and each surface ($Configuration\ Factor_{\text{point-surface}}$), are calculated from eq. (2), in which x, y, and z are the distances between the center of position and that surface in three-dimensional spaces [35].

$$f(x,y,z) = \frac{1}{2\pi}(\arctan\left(\frac{x}{z}\right) - \frac{z}{\sqrt{y^2+z^2}} \,.\arctan\,(\frac{x}{\sqrt{y^2+z^2}})) \tag{2}$$

3. For all positions, the workplace height is assumed to be 0.9 m.
4. The sum of configuration factors between a single point and all the surfaces is equal to one.
5. Temperatures of all indoor surfaces (T_{surface}) are calculated (except floor and ceiling); T_{surface} is influenced by the level of solar radiation.
6. Floor and ceiling are considered as adiabatic surfaces, in the RC-network thermal modeling of the office, hence, their surface temperatures in each zone are assumed to be the same as the indoor temperature of that zone.
7. In each zone, MRT in Celsius (°C) in each point (position), is calculated from [35]:

$$(273 + MRT_{\text{point}})^4 = \sum_{k=1}^{8} (273 + T_{\text{surface}\,k})^4 .\ Configuration\ Factor_{\text{point-surface}\,k} \tag{3}$$

8. In each zone, for each point, the *Operative Temperature* (°C) is calculated from [15]:

$$Operative\ Temperature_{\text{point}} = \frac{Indoor\ Temperature + MRT_{\text{point}}}{2} \tag{4}$$

2.4 Position-based Visual Comfort Evaluation

One of the zones, south zone, is chosen to describe the position-based visual comfort evaluation in the office. The method used for position-based visual comfort evaluation in north zone and south zone is similar, but slightly different to visual comfort evaluation in west zone and east zone, because of the difference in the number of exterior walls.

From (5), a row number is assigned to each surface (e.g. west wall: one, window: six).

$$Surfaces = [\text{west wall, north wall, east wall, ceiling, floor, window, south wall-top, south wall-bottom}]^T \quad (5)$$

Both position-based thermal comfort and visual comfort evaluations require calculation of configuration factors. Calculating configuration factors is discussed, in the first 4 steps of position-based thermal comfort evaluation (Section 2.3). Configuration factors between each of the four positions and each surface from (5) are calculated using (2):

$$\begin{aligned}
Configuaration\ Factor_{\text{Position-A}} &= [0.129, 0.130, 0.002, 0.310, 0, 0.006, 0.212, 0.212]^T \\
Configuaration\ Factor_{\text{Position-B}} &= [0.016, 0.023, 0.004, 0.402, 0, 0.066, 0.245, 0.245]^T \\
Configuaration\ Factor_{\text{Position-C}} &= [0.004, 0.146, 0.016, 0.410, 0, 0.008, 0.208, 0.208]^T \\
Configuaration\ Factor_{\text{Position-D}} &= [0.002, 0.018, 0.129, 0.412, 0, 0.060, 0.190, 0.190]^T
\end{aligned} \quad (6)$$

For position-based visual comfort evaluation, apart from the configuration factors, the view factors between all surfaces of the zone, as well as each surface reflectance are required. For the wall, the reflectance of 0.7 is assumed, while for the window, floor, and ceiling the reflectances equal to 0.05, 0.3, and 0.8 are considered, respectively:

$$Reflectances = [0.7, 0.7, 0.7, 0.8, 0.3, 0.05, 0.7, 0.7]^T \quad (7)$$

These reflectances are used in (9) to calculate natural illuminance at each position.

Considering south zone's shape and dimensions and the size of the windows, the view factors between all surfaces of south zone are calculated, using the related equations in [35]. The *View Factor*$_{A \rightarrow B}$ is the portion of the radiation that leaves Surface A and strikes Surface B [35]. Considering eight surfaces and their assigned numbers in (5), the *View Factor*$_{i \rightarrow j}$, in which i and j are the surfaces' assigned numbers, is presented:

$$View\ Factor_{\,\mathrm{i\to j}} = \begin{pmatrix} 0 & 0.139 & 0.026 & 0.354 & 0.352 & 0.059 & 0.039 & 0.039 \\ 0.069 & 0 & 0.070 & 0.380 & 0.377 & 0.049 & 0.036 & 0.036 \\ 0.026 & 0.139 & 0 & 0.352 & 0.354 & 0.059 & 0.040 & 0.040 \\ 0.064 & 0.137 & 0.063 & 0 & 0.609 & 0.052 & 0.051 & 0.032 \\ 0.063 & 0.136 & 0.064 & 0.609 & 0 & 0.052 & 0.032 & 0.053 \\ 0.074 & 0.124 & 0.074 & 0.364 & 0.364 & 0 & 0 & 0 \\ 0.066 & 0.121 & 0.066 & 0.475 & 0.296 & 0 & 0 & 0 \\ 0.066 & 0.121 & 0.066 & 0.296 & 0.475 & 0 & 0 & 0 \end{pmatrix} \tag{8}$$

Having the configuration factors in each position, the view factors between the surfaces, the surface reflectances, and the level of natural illumination (lux) entered the room from the window, *Natural Illuminance* (lux), in each of the four selected positions are calculated [35]:

$$Natural\ Illuminance_{\,\mathrm{Position-x}} = Configuaration\ Factor_{\,\mathrm{Position-x}}\ .\ (Identity\ (8) - Reflectances.\ View\ Factor)^{-1}.\ M_{\,0} \tag{9}$$

In which $M_{\,0}$ is:

$$M_{\,0} = [0, 0, 0, 0, 0, \textit{Transmitted light through the window}\ (\mathrm{lux}), 0, 0]^{T} \tag{10}$$

Also, *Identity (8)* is an 8-by-8 square matrix in which all the elements of the principal diagonal are ones and all other elements are zeros. Here, the level of illuminance (lux) in each position, is the parameter to consider in visual comfort evaluation. Moreover, for avoiding glare, the minimum illuminance level (lux) and the maximum illuminance level (lux), should be respected as the constraints on the visual conditions (Table 1). The level of *Illuminance* (lux) in each position is the sum of *Natural Illuminance* (lux) and *Artificial Illuminance* (lux):

$$Illuminance_{\,\mathrm{Position-x}} = Natural\ Illuminance_{\,\mathrm{Position-x}} + Artificial\ Illuminance_{\,\mathrm{Position-x}} \tag{11}$$

It is considered that illuminance from artificial lighting is uniform across the zone.

It is worth mentioning that the above calculations are specific to the office building considered in this paper (Fig. 2). Here, calculations for the comfort evaluation in south zone of the assumed office are demonstrated to provide numerical examples of the required calculations (they are for illustration purposes). The techniques described for position-based thermal and visual comfort evaluations can be applied to any other conditions and any other office building. The position-based comfort calculations for each office building depend on the dimensions and orientation of the office, the location of office desks, and the placement of openings.

2.5 Modeling Thermal Preferences

Occupants' feedback on the thermal and visual conditions of the indoor environment, or their thermal and visual sensation votes, should be collected to learn their preferences. Data from a field study [36] carried out from 2006 to 2009, in a building located in Lausanne, Switzerland is used to construct the thermal and visual preference models of occupants. In the study, the participants were questioned randomly on a daily basis, of their thermal and visual sensations and the type of actions they chose to restore their comfort. Their feedback (their thermal sensation votes) were classified into feeling (1) warm, (2) comfortable, or (3) cold. Over time, each participant's thermal sensation feedback, across a wide range of indoor temperatures were collected.

Each participant's probability of being comfortable ($Prob_{\text{Thermal\_Comfort}}$) or uncomfortable ($Prob_{\text{Thermal\_Discomfort}}$), at a given indoor temperature, were expressed in the form of [37]:

$$Prob_{\text{Thermal\_Discomfort}} = Prob_{\text{Cold}} + Prob_{\text{Warm}} - Prob_{\text{Cold}} . Prob_{\text{Warm}} \quad (12)$$

$$Prob_{\text{Thermal\_Comfort}} = 1 - Prob_{\text{Thermal\_Discomfort}} = (1 - Prob_{\text{Cold}}). (1- Prob_{\text{Warm}})$$

Using multinomial logistic regression techniques in the field study, the probability of a participant comfort ($Prob_{\text{Thermal\_Comfort}}$) from the immediate thermal conditions (indoor temperature (T); °C), was expressed by specific unit-less regression parameters, a_{warm}, b_{warm}, a_{cold}, b_{cold} [36]:

$$Prob_{\text{Thermal\_Comfort}}(T) = \frac{1}{1+\exp(a_{warm} + b_{warm} . T)+\exp(a_{cold}+b_{cold} . T)} \quad (13)$$

From the longitudinal field study, four participants are selected. Thermal regression parameters of four selected participants, alongside the name assigned to them here, are shown in Table 2.

Table 2: Occupants' names in this research and their thermal regression parameters in [36]

Occupant Name	Thermal Regression Parameters			
	a_{cold}	b_{cold}	a_{warm}	b_{warm}
Occupant #1	13.6	-0.6	-11.2	0.4

Occupant #2	20.1	-1	-22.7	0.8
Occupant #3	15.7	-0.8	-13.9	0.5
Occupant #4	11.3	-0.5	-13.2	0.5

In this research, two assumptions are made to model the thermal (and visual) preferences of occupants. First, thermal (and visual) preference models are considered to be in the shape of *Gaussian distribution*. Having each individual's thermal regression parameters, $Prob_{\text{Thermal\_Comfort}}$ (T) from (13), is fitted into a Gaussian function with a mean value of $T_{\text{maxcomfort}}$ and standard deviation of $Tolerance_{\text{thermal}}$:

$$Prob_{\text{Thermal\_Comfort}}\,(T) = \mathrm{e}^{\frac{-(T-T_{\text{maxcomfort}})^2}{2.(Tolerance_{\text{thermal}})^2}} \qquad (14)$$

Second, when optimization is performed, we assume that the relative productivity (RP_{thermal} (T)) is equal to the probability of thermal comfort ($Prob_{\text{Thermal\_Comfort}}$) [10]:

$$RP_{\text{thermal}}\,(T) = Prob_{\text{Thermal\_Comfort}}\,(T) \qquad (15)$$

According to the proposed approach, $T_{\text{maxcomfort}}$ and $Tolerance_{\text{thermal}}$ are two personalized variables that form the personalized thermal preference model (RP_{thermal}) of each occupant [33]. RP_{thermal} (T) of each occupant indicates her immediate satisfaction from the thermal conditions of the indoor environment. For each occupant, the maximum thermal productivity (RP_{thermal}=1) is considered at $T_{\text{maxcomfort}}$. $Tolerance_{\text{thermal}}$ of an occupant expresses her level of sensitivity to the thermal conditions of the indoor environment. Based on the Gaussian function characteristics, higher values of $Tolerance_{\text{thermal}}$ mean that the occupant is less sensitive to the indoor temperature changes. Based on the procedure described, the thermal preferences models of four considered occupants are constructed (Table 3).

Table 3: Occupants' personalized parameters – Thermal comfort

Thermal Preference Model	**Occupant #1**	**Occupant #2**	**Occupant #3**	**Occupant #4**
$T_{\text{maxcomfort}}$ (°C)	25.5	23.4	24.3	23.9
$Tolerance_{\text{thermal}}$ (K)	7.2	4.4	5.8	6.7

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As it was discussed, from equations (13) to (15) and thermal regression parameters (Table 2), occupants' probability of comfort ($Prob_{\text{Thermal\_Comfort}}$) are fitted into Gaussian functions, in order to construct their RP_{thermal} (T). Fig. 3 demonstrates this procedure for two of the occupants. The dotted lines show $Prob_{\text{Thermal\_Comfort}}$ (T) of two occupants, derived from (13), and the solid lines indicate RP_{thermal} (T), derived from (15).

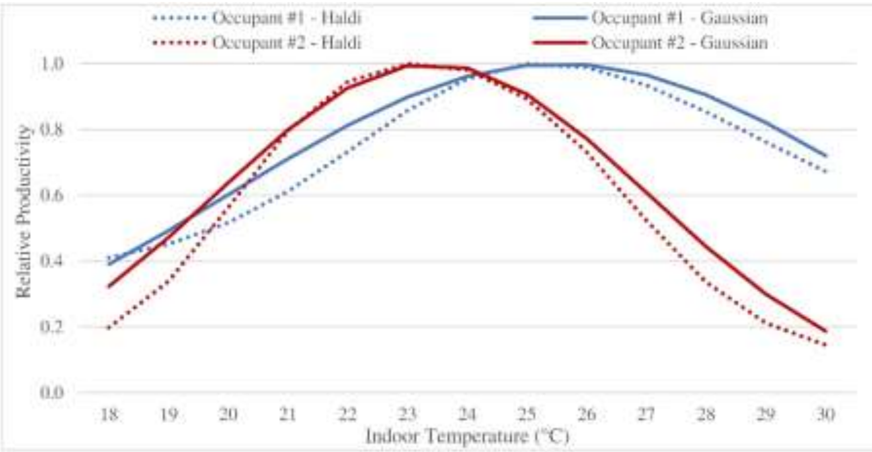

Fig. 3: Fitting the thermal sensation votes of occupants in Haldi research [36] to Gaussian functions

2.6 Modeling Visual Preferences

Through multinomial logistic regression, the regression parameters related to the visual comfort of participants of the field study were derived in [36]. For the same four participants, selected in Section 2.5, the visual regression parameters a_{dark}, a_{bright}, b_{dark}, b_{bright} are presented in Table 4.

Table 4: Occupants and their visual regression parameters [36]

Occupant Name	Visual Regression Parameters			
	a_{dark}	b_{dark}	a_{bright}	b_{bright}
Occupant #1	5.9	-1.3	-10.9	0.006
Occupant #2	3.7	-0.8	-4.3	0.006
Occupant #3	1.6	-0.6	-3.3	0.003
Occupant #4	9.6	-1.8	-4.4	0.001

The *visual preference models* of four occupants, simulated here, are constructed from the visual regression parameters in Table 4. The level of illuminance (lux) is the parameter to evaluate the visual comfort. The probability of an occupant satisfaction ($Prob_{\text{Visual\_Comfort}}$) from the visual conditions of the indoor environment (indoor illuminance (*Illuminance*); lux), can be defined using specific unit-less regression parameters a_{bright}, b_{bright}, a_{dark}, b_{dark} [36]:

$$Prob_{\text{Visual\_Comfort}}(Illuminance) = \frac{1}{1 + \exp(a_{bright} + b_{bright} \,.\, Illuminance) + \exp(a_{dark} + b_{dark} \,.\, Illuminance)} \quad (16)$$

Here, it is suggested that for each occupant, the probability of visual comfort ($Prob_{\text{Visual\_Comfort}}$) with respect to the level of illuminance (lux) is fitted into a Gaussian function with a mean value of $ILL_{\text{maxcomfort}}$ and standard deviation of $Tolerance_{\text{visual}}$:

$$Prob_{\text{Visual\_Comfort}}(Illuminance) = \mathrm{e}^{\frac{-(Illuminance - ILL_{\text{maxcomfort}})^2}{2.(Tolerance_{\text{visual}})^2}} \quad (17)$$

$ILL_{\text{maxcomfort}}$ and $Tolerance_{\text{visual}}$ are two personalized variables, related to the visual comfort of occupants. For each occupant, if her specific $ILL_{\text{maxcomfort}}$ is provided in the occupant's position, he or she has the highest probability of visual comfort (RP_{Visual}=1). Here, it is assumed that the relative productivity from the visual ambient (RP_{Visual}) is equal to the probability of visual comfort ($Prob_{\text{Thermal\_Comfort}}$) [10]:

$$RP_{\text{Visual}}(Illuminance) = Prob_{\text{Visual\_Comfort}}(Illuminance) \quad (18)$$

Accordingly, visual preference models of the simulated occupants are constructed by fitting their visual sensation votes into Gaussian functions. $ILL_{\text{maxcomfort}}$ and $Tolerance_{\text{visual}}$ of four occupants, derived from the fitting process, are demonstrated in Table 5.

Table 5: Occupants' personalized parameters - Visual comfort

Visual Preference Model	Occupant #1	Occupant #2	Occupant #3	Occupant #4
$ILL_{\text{maxcomfort}}$ (*Illuminance*) [lux]	937	1563	1569	1429
$Tolerance_{\text{visual}}$ (*Illuminance*) [lux]	667	1199	1203	1105

Personalization is only applied to the thermal comfort and visual comfort of occupants. However, a general relation between ventilation rate and productivity of occupants is used to consider and improve IAQ of the zones. Relative productivity with respect to IAQ (RP_{IAQ}) is derived from Seppanen et al. meta-analysis of nine field studies, previously conducted on the relationship between ventilation rate and relative productivity [38]. The relationship between ventilation rate (Q, l/s per person) and RP_{IAQ} is presented in (19), and displayed in Fig. 4.

$$RP_{IAQ} = 0.021 \ln Q + 0.960 \qquad 6.5 \text{ l/s per person} \leq Q \leq 45 \text{ l/s per person} \tag{19}$$

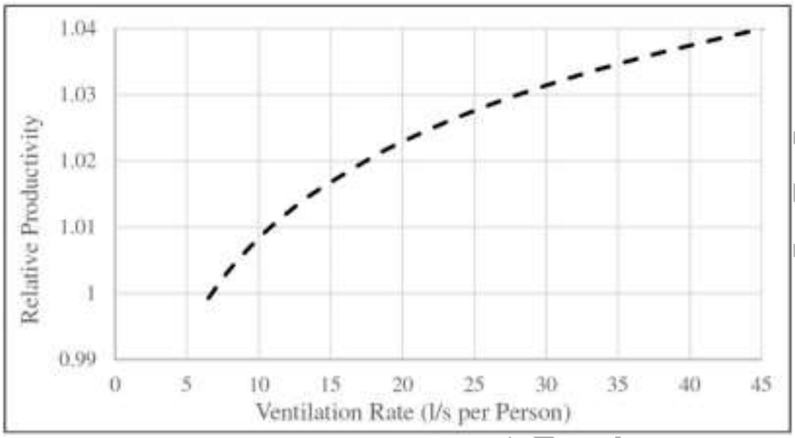

Fig. 4: Relative performance with respect to ventilation rate (l/s per person) [38]

For the proposed method to be applicable to an office building, the first requirement is to have continuous and user-friendly interaction with occupants, to obtain up-to-date information on their environmental preferences. Recently, different smartphone applications have been built to communicate with occupants and receive their preferences for the indoor environment and subsequently act upon [39]. However, additional quantitative studies are required to relate various aspects of occupants' comfort and their performances in different tasks. For this research, certain assumptions are made from the results of previously conducted field studies to relate occupants' comfort conditions and productivity, as well as to model thermal and visual preferences of occupants. However, indoor environmental preferences can be different from place to place and might be varied seasonally. The influence of varied indoor environmental preferences on the indoor environmental control, the productivity of office workers, and energy consumption were previously covered in [33] and [34]. Having information on the indoor environmental preferences, the proposed methods are applicable to any office (or more generally, commercial) building.

For the indoor environmental monitoring, various environmental sensors should be installed, depending on the plan of the office and the positions of occupants inside enclosed spaces. In this research, indoor temperature, mean-radiant temperature, ventilation rate, as well as illuminance level should be continuously measured; hence, in each enclosed space of an office, temperature sensors, light sensors, mean-radiant temperature sensors, and air flow sensors may be required. Moreover, a wireless sensor network is required to transmit environmental data and energy-related decisions (commands) across the office. Recently, the use of Internet of Things (IoT) technologies for smart buildings has become popular. IoT technologies create open software translation layers for data communication, to connect several devices inside a building. For intelligent energy and comfort management of office buildings, the use of IoT technologies facilitates the communication between environmental sensors, the energy management system, controllers and actuators. Moreover, IoT technologies enable cloud-based intelligent energy and comfort management.

2.7 Position-based Multi-Objective Optimization of Energy Costs, Thermal & Visual Comfort & Indoor Air Quality

Overall comfort conditions are the combination of thermal comfort, visual comfort, and IAQ. The strong relationship between occupants' comfort and their performances is already discussed. In the problem formulation of the position-based method, occupants' performances are expressed as their *productivity rates*. Hereby, the objective function consists of two terms: (1) the energy costs term, and (2) the occupants' productivity term. The occupants' productivity term considers the productivity of each occupant, with respect to her overall comfort conditions (RP_{Overall}).

RP_{Overall} is used to compare an occupant productivity with her maximum level of productivity. RP_{Overall} is a dimensionless quantity and can be expressed in percentage, or as a value in the range of 0 to 1. RP_{Overall} equal to 1 is assigned to an occupant's maximum level of productivity [33]. For each occupant, RP_{Overall} is assumed to be in the range of the average of RP_{Thermal}, RP_{Visual}, and RP_{IAQ}, and the maximum value between RP_{Thermal}, RP_{Visual}, and RP_{IAQ} [10]:

$$RP_{\mathrm{Overall}} = [\mathrm{average}\,(RP_{\mathrm{Thermal}}, RP_{\mathrm{Visual}}, RP_{\mathrm{IAQ}}) + \max\,(RP_{\mathrm{Thermal}}, RP_{\mathrm{Visual}}, RP_{\mathrm{IAQ}})] / 2 \qquad (20)$$

Productivity losses of each occupant are equal to occupant's productivity during that hour (*productivity per hour*), multiplied by her overall relative productivity losses (1- RP_{Overall}):

Productivity losses (\$/h) = *productivity per hour* (\$/h). $(1 - RP_{\text{Overall}})$ (21)

Using weighted sum method, the objective function of the position-based MOOP method to be minimized is constructed:

Objective function (\$/h) = *energy costs* $+ \sum_{i=1}^{n} productivity\ losses_{\ i}$ (22)

In which, n is the number of occupants in the office.

To evaluate the performance of the proposed method, different parametric simulations are performed, where varied scenarios of occupancy in different zones of the office, are assumed. The selections of occupancy scenarios are arbitrary. Occupants and their thermal and visual preferences are selected from Table 3 and Table 5, respectively, and their positions are chosen from the assumed positions in Fig. 2. For each parametric simulation, the considered scenario of occupancy is stated at the beginning of the related section. It should be noted that the conclusions derived from the parametric simulations are independent of the choice of occupancy scenario.

3 Results

Occupants' perceptions of the indoor environment (their thermal and visual sensations) depend on their positions inside enclosed spaces, as well as their environmental preferences. In the proposed position-based energy and comfort management, thermal comfort and visual comfort are evaluated accurately, by considering each occupant's position inside a zone. For simulations, four arbitrary positions: *Position-A*, *Position-B*, *Position-C*, and *Position-D* are considered for office workers, inside each zone (Fig. 2). To evaluate the capabilities of the method, different parametric simulations are performed, where arbitrary scenarios of occupancy, inside different zones and during varied months of the year, are considered. The flexibility of the proposed method to make energy-related decisions, based on the personalized parameters of occupants' (1) hourly productivity rates, (2) thermal preferences, (3) visual preferences, and (4) positions, are evaluated in different parametric simulations. January, April, and July represent the cold, the swing, and the warm season of Montreal. Weekly results of simulations, in these three months, are analyzed to have a detailed view of the operation of the method and its decision-making capabilities. Thermal comfort, visual conditions, and indoor air quality in different scenarios are evaluated using indoor operative temperature (˚C), indoor illuminance (lux), and the level of ventilation rates (m^3/s per m^2), respectively, as units. Productivity and energy costs are compared in the monetary unit ($).

3.1 Effect of Occupants' Productivity: Single Occupant

The hourly productivity of each occupant in the office is introduced as a personalized variable in the MOOP problem formulation. To have information on occupants' hourly productivity, occupancy data, and tasks distribution within the office workers are required [40, 41]. The amount of time office workers spend on each task is an important factor to define their productivity rates. The level of hourly productivity influences the method's decision-making. Here, the influence of hourly productivity variation on the thermal and visual comfort of occupants and IAQ are studied.

3.1.1 Thermal Comfort

An arbitrary situation of having a single occupant (Occupant #2 in Position-B) inside south zone is considered. To create varied productivity scenarios, hourly productivity of Occupant #2 is assumed to be (1) 4 $/h, (2) 8 $/h, and (3) 16 $/h. Considering varied hourly productivity scenarios, hourly operative temperatures (°C) in Position-B, during the occupied hours of a week in January (Fig. 5), April (Fig. 6), and July (Fig. 7) are observed.

Fig. 5: The influence of productivity per hour ($/h) on the thermal comfort of occupants– The cold season analysis

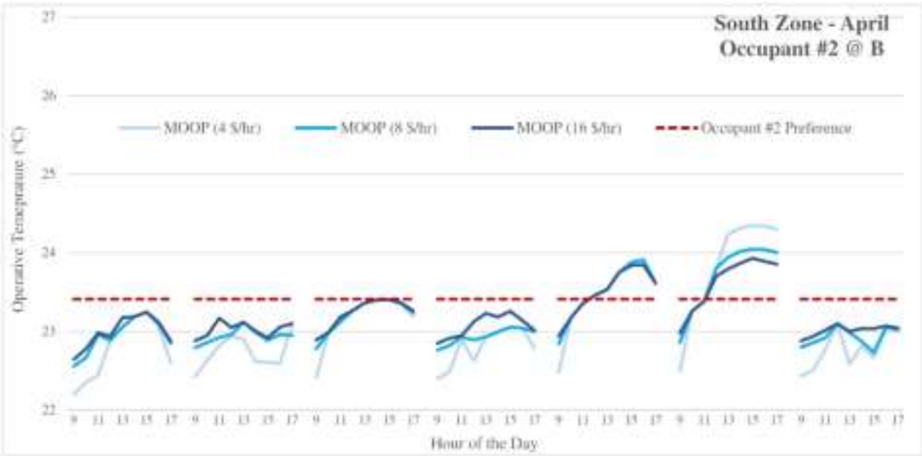

Fig. 6: The influence of productivity per hour ($/h) on the thermal comfort of occupants – The swing season analysis

In all three months, with the increase in hourly productivity ($/h) of Occupant #2, hourly operative temperatures (°C) in Position-B move closer to $T_{\text{maxcomfort}}$ of the occupant (23.4 °C). When the productivity of an occupant increases, the position-based method ascribes a relatively more value to her thermal comfort. Accordingly, the operative temperatures (°C) in the occupant's position approach her $T_{\text{maxcomfort}}$ (Fig. 5, Fig. 6, and Fig. 7).

Fig. 7: The influence of productivity per hour ($/h) on the thermal comfort of occupants – The warm season analysis

3.1.2 Visual Comfort

For the same occupancy scenario, the influence of hourly productivity ($/h) variation on the operation of the position-based method are illustrated (Fig. 8 and Fig. 9). Occupant #2 has $ILL_{\text{maxcomfort}}$ of 1563 lux. For both outdoor weather conditions, with the increase in hourly productivity of Occupant #2, from 4 \$/h to 16 \$/h, provided illuminance levels (lux) in Position-B converge toward $ILL_{\text{maxcomfort}}$ of the occupant.

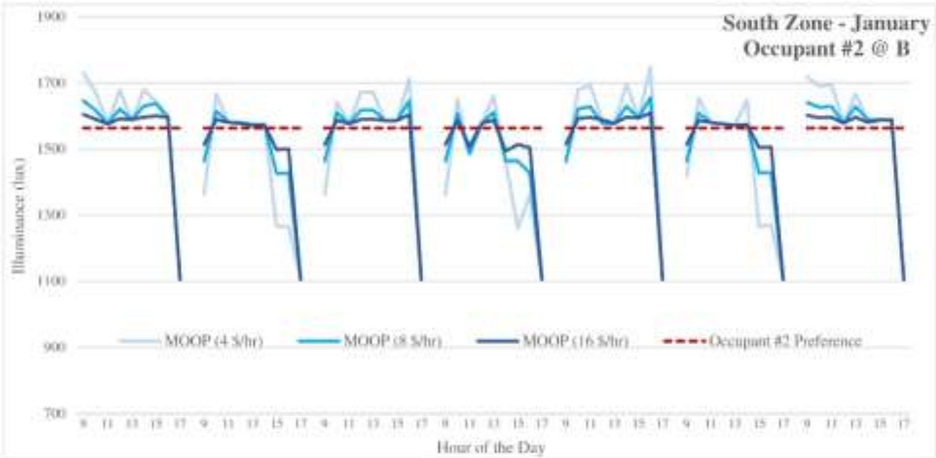

Fig. 8: The influence of productivity per hour (\$/h) on the visual comfort of occupants – The cold season analysis

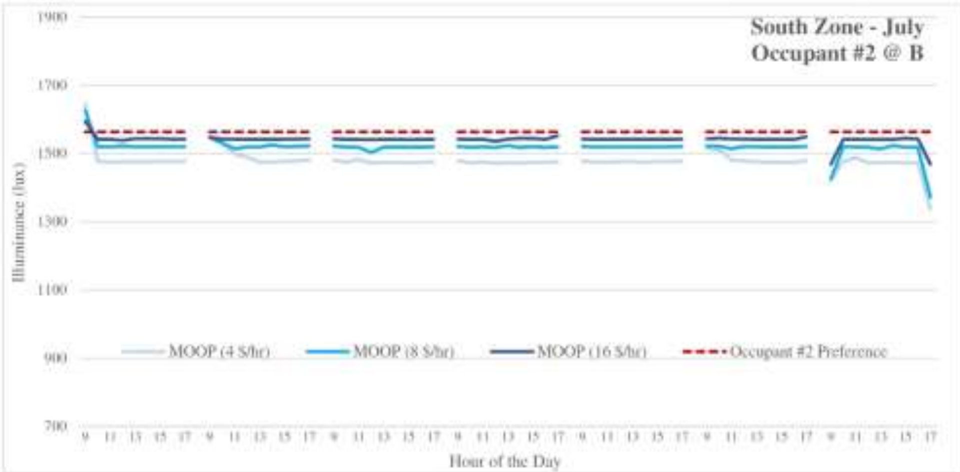

Fig. 9: The influence of productivity per hour (\$/h) on the visual comfort of occupants– The warm season analysis

3.1.3 Indoor Air Quality

In order to study the influence of hourly productivity (\$/h) variations on the IAQ, the same occupancy scenario as the thermal and visual comfort analysis is assumed (Occupant #2 in Position-B of south zone). Results are provided, for a week in January (Fig. 10), and a week in July (Fig. 11). It is observed that with the increase in hourly productivity (\$/h) of the occupant, the level of ventilation rates (m^3/s per m^2) in south zone is also increased (Fig. 10 and Fig. 11).

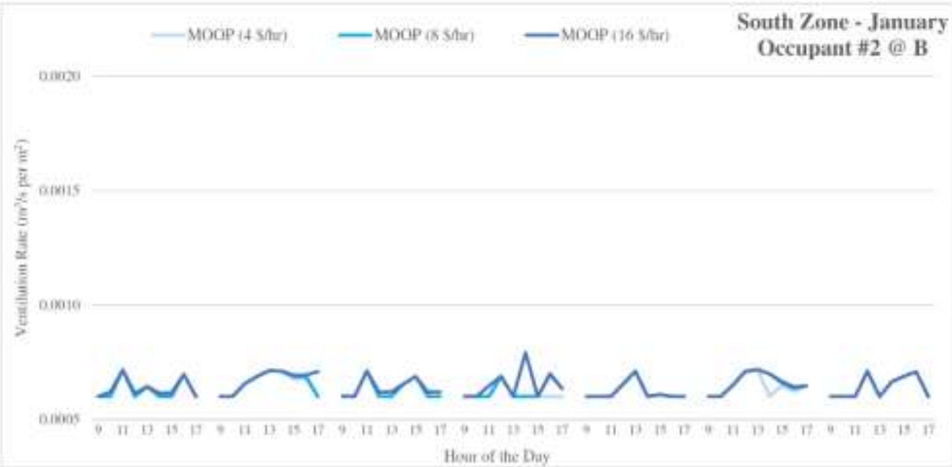

Fig. 10: The influence of productivity per hour ($/h) on the IAQ – The cold season analysis

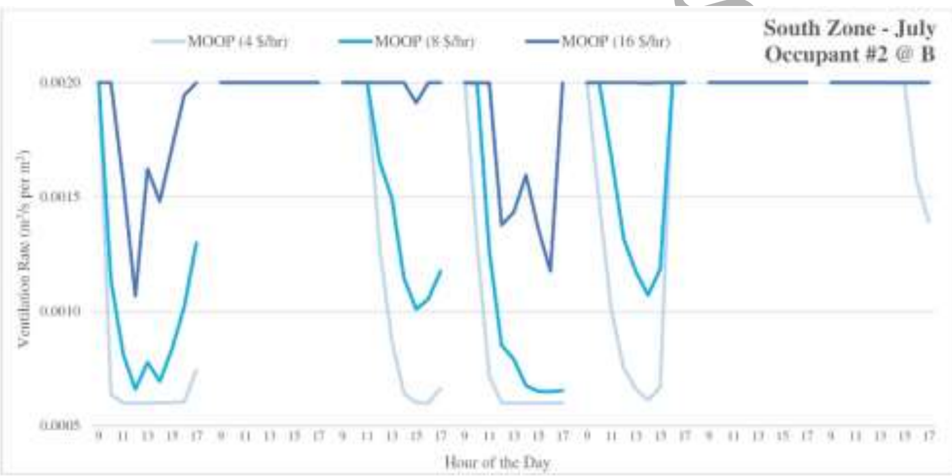

Fig. 11: The influence of productivity per hour ($/h) on the IAQ – The warm season analysis

Based on the results in this section, the proposed method can be applied to office buildings with single-occupancy spaces with personalized control systems and improves the indoor environmental conditions, accordingly.

3.2 Effect of Occupants' Preferences: Single Occupant vs. Multiple Occupants

Considering varied thermal and visual preferences among the occupants, the position-based method should have the capability to provide satisfactory indoor environmental conditions for all the occupants, while minimizing energy costs. To evaluate the capabilities of the method to acknowledge the diversity in preferences of occupants, the weekly energy performance of the office building under different scenarios of occupancy, in varied outdoor weather conditions is studied. In west zone, arbitrary scenarios of having (1) Occupant #1 in Position-A, (2) Occupant #2 in Position-B, and (3) Occupant #1 in Position-A and Occupant #2 in Position-B are considered. Under the third scenario of occupancy, it is assumed that Occupant #1 and Occupant #2 are sharing west zone. It is assumed that each occupant has a constant productivity rate of 8 $/h.

3.2.1 Thermal Preferences

Occupant #1 has $T_{\text{maxcomfort}}$ of 25.5 °C while Occupant #2 has $T_{\text{maxcomfort}}$ of 23.4 °C (Table 3). Hourly operative temperatures (°C) in Position-A and in Position-B, under three occupancy scenarios, are demonstrated for a week in January and April (Fig. 12 and Fig. 13).

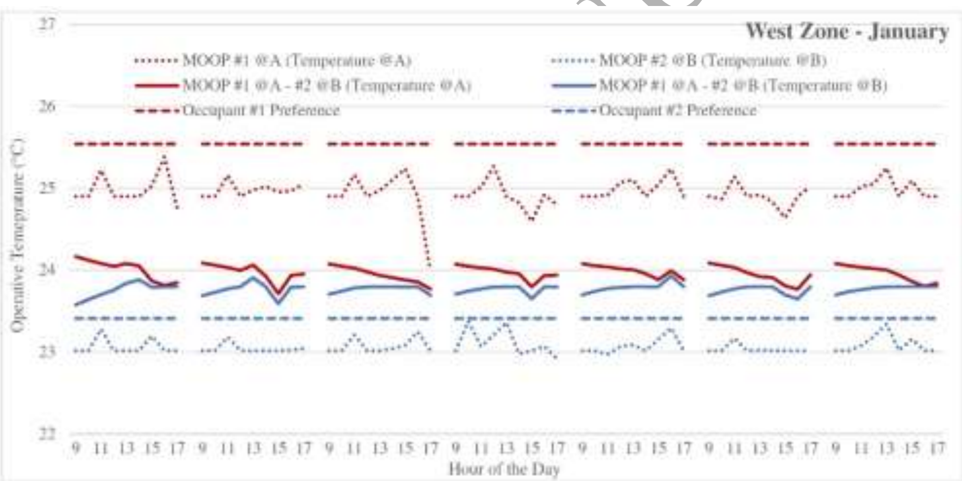

Fig. 12: Acknowledging occupants' thermal preferences – The cold season analysis

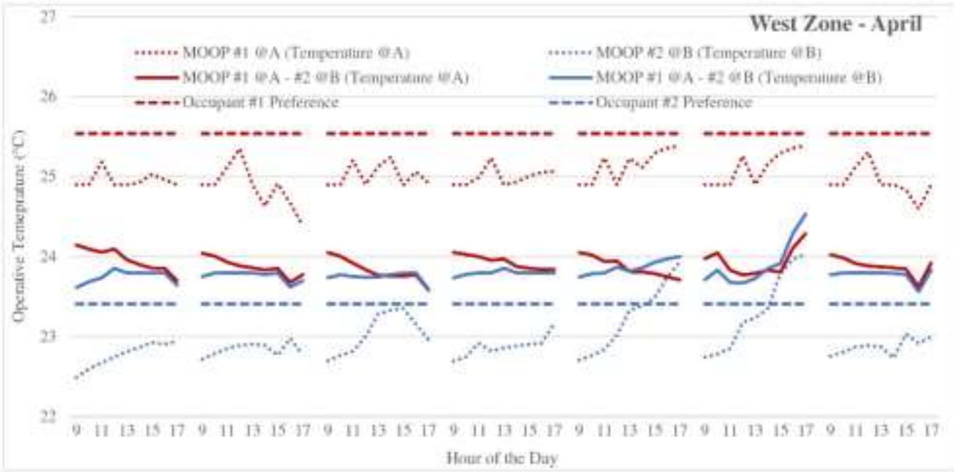

Fig. 13: Acknowledging occupants' thermal preferences – The swing season analysis

For both outdoor weather conditions (January and April), under the two single-occupancy scenarios (Occupant #1 in Position-A or Occupant #2 in Position-B), operative temperatures (°C) in Position-A and Position-B are not far away from the maximum comfort temperatures of the two occupants. These values are slightly lower than the maximum comfort temperatures of the occupants, because of the energy costs minimization objective of the method, during January and April. On the other hand, under the multiple-occupancy scenario, hourly operative temperatures (°C) in Position-A and in Position-B are within the range of Occupant #1's $T_{\text{maxcomfort}}$ (25.5 °C) and Occupant #2's $T_{\text{maxcomfort}}$ (23.4 °C). The position-based method controls the thermal conditions of west zone with the objective of improving the collective productivity of occupants while minimizing the energy costs as much as possible.

Under the multiple-occupancy scenario, operative temperatures (°C) are closer to $T_{\text{maxcomfort}}$ of Occupant #2 (23.4 °C), than $T_{\text{maxcomfort}}$ of Occupant #1 (25.5 °C). There are two reasons for this effect. First, the method also has the energy costs minimization objective. During January and April, having lower indoor temperatures reduces the energy consumption costs. Second, $Tolerance_{\text{thermal}}$ of Occupant #2 (4.4 K) is lower than $Tolerance_{\text{thermal}}$ of Occupant #1 (7.2 K), hence, Occupant #2 is more sensitive to the thermal conditions of the indoor environment, compared to Occupant #1. The method acknowledges the higher sensitivity (the lower thermal tolerance) of Occupant #2 by providing operative temperatures closer to $T_{\text{maxcomfort}}$ of Occupant

#2. During July (Fig. 14), the same discussions can also describe the performance of the position-based method in warm outdoor weather conditions.

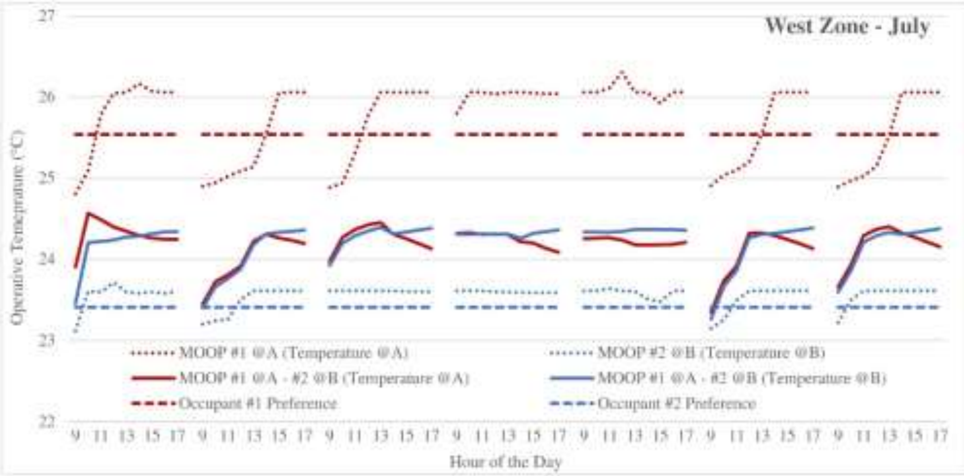

Fig. 14: Acknowledging occupants' thermal preferences – The warm season analysis

3.2.2 Visual Preferences

Under the three considered occupancy scenarios, hourly illuminance levels (lux) in Position-A and Position-B, during a week in January (Fig. 15) and July (Fig. 16), are presented.

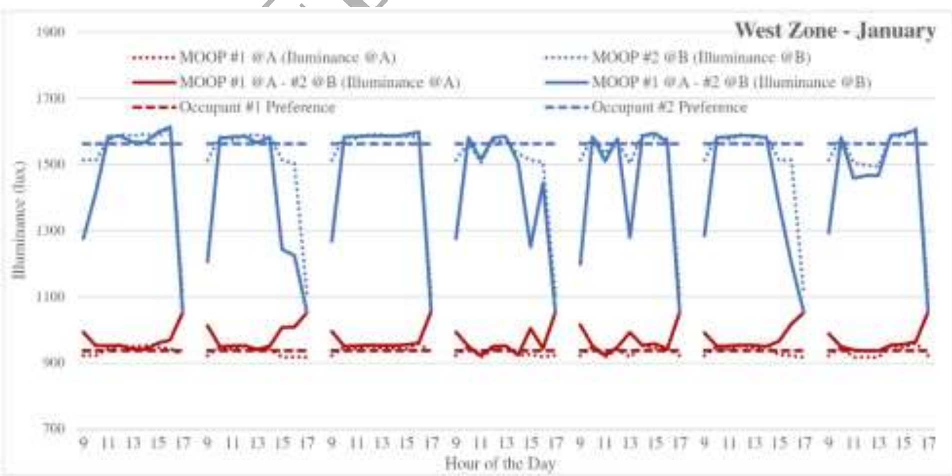

Fig. 15: Acknowledging occupants' visual preferences – The cold season analysis

For both weather conditions, under the two single-occupancy scenarios, the position-based MOOP method manages the level of natural illumination (lux), and artificial lighting (lux) in order to provide satisfactory visual conditions for that specific occupant. Meanwhile, under the scenario of having both Occupant #1 and Occupant #2, the position-based method is still successful in managing the diversity in occupants' visual preferences.

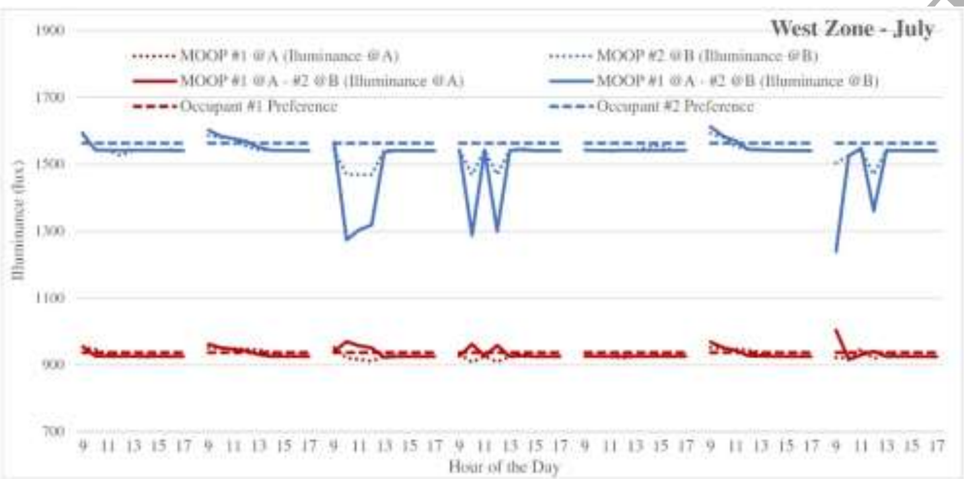

Fig. 16: Acknowledging occupants' visual preferences – The warm season analysis

The position-based method is also helped by the positions of the occupants since the position of Occupant #2 is near the window (Fig. 2). Occupant #2, with the preference of a brighter ambient, receives higher levels of natural illumination (lux), compared to Occupant #1 in Position-A. In the following section, the influence of occupants' positions is discussed in detail.

Results in this section demonstrate the capability of the proposed method to provide preferred indoor environmental conditions for occupants in multiple-occupancy scenarios, while simultaneously optimizing energy costs. It should be noted that for multiple-occupancy scenarios, it is important to consider similar base productivity rates for the office workers that share a space, otherwise, the method would be biased towards the preference of occupant(s) with higher base productivity rate. In the next sections, results are shown to illustrate the influence of occupants' positions in a shared space on the indoor environmental conditions, overall productivity and associated energy consumption.

3.3 Effect of Occupants' Positions on Indoor Visual Conditions: Multiple Occupants

Here, the focus is on the importance of occupants' positions and the effect it has on the performance of the position-based method. Occupants with varied thermal and visual preferences are considered for the simulations. Occupant #1, with a relatively higher $T_{\text{maxcomfort}}$ of 25.5 °C, prefers a warmer indoor environment, while Occupant #2 and Occupant #3 with $ILL_{\text{maxcomfort}}$ of 1563 lux and 1569 lux, respectively, prefer a brighter ambient (Table 3 and Table 5). Two arbitrary occupancy scenarios of having (1) Occupant #1 in Position-A and Occupant #2 in Position-B, and (2) Occupant #2 in Position-A and Occupant #1 in Position-B of west zone, are considered. It is assumed that each occupant has a constant productivity rate of 8 $/h.

Under these two scenarios, the operation of the method with respect to the visual comfort of two occupants is studied for January and July. The level of hourly illuminance (lux) in Position-A and Position-B of west zone, under the two considered scenarios of occupancy, during January (Fig. 17) and July (Fig. 18) are shown. For both outdoor weather conditions, under the 1st scenario of occupancy, the method is successful in providing occupants' preferred indoor visual conditions. However, under the 2nd scenario, hourly illuminance levels (lux) in both positions are very close to each other (Fig. 17 and Fig. 18).

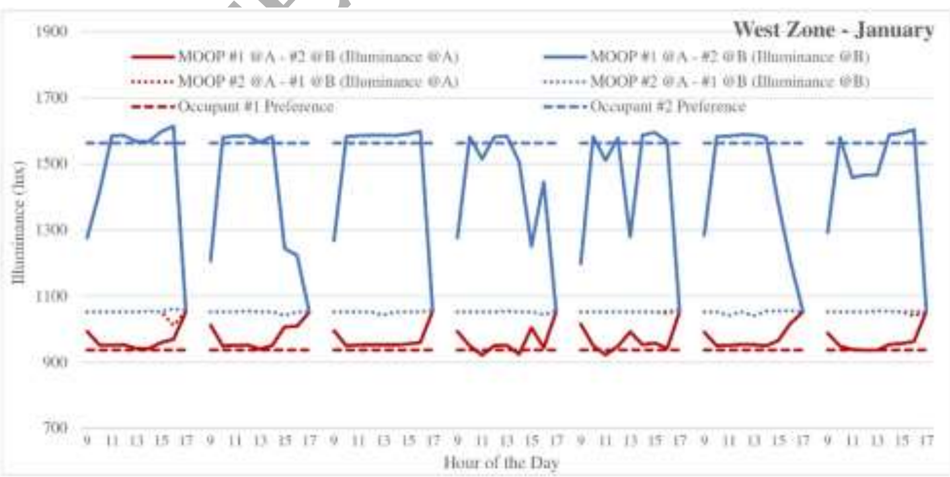

Fig. 17: The importance of occupants' positions for the visual comfort evaluation – The cold season analysis

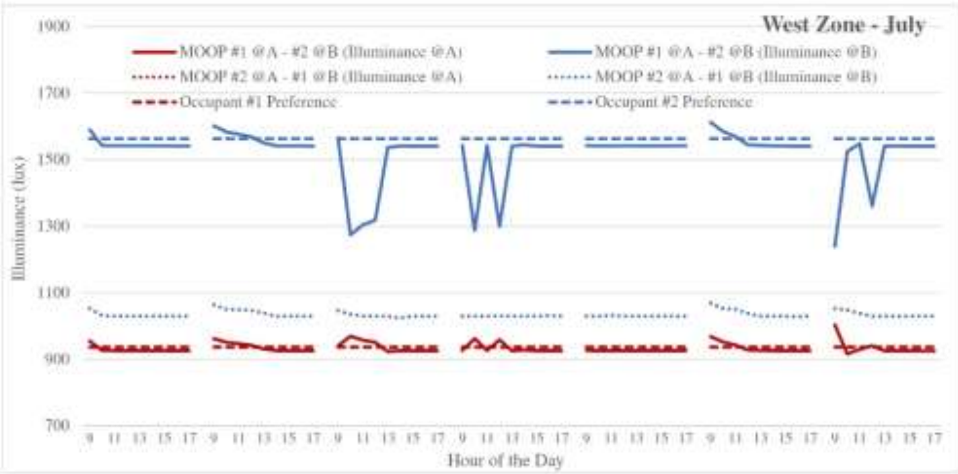

Fig. 18: The importance of occupants' positions for the visual comfort evaluation – The warm season analysis

The level of hourly artificial illuminance (lux) in west zone, under the two considered scenarios of occupancy, are compared for January and July (Fig. 19 and Fig. 20). For both outdoor weather conditions, under the scenario of having Occupant #2 (with a brighter ambient preference) in Position-B (near the window), the position-based method provides a significant portion of lighting demands from natural illumination. In contrast, having Occupant #1 in Position-B and Occupant #2 in Position-A, their visual preferences, and the energy costs minimization objective of the position-based method conflict with each other. Hence, the levels of natural illumination reduce, and consequently, the levels of artificial lighting increase.

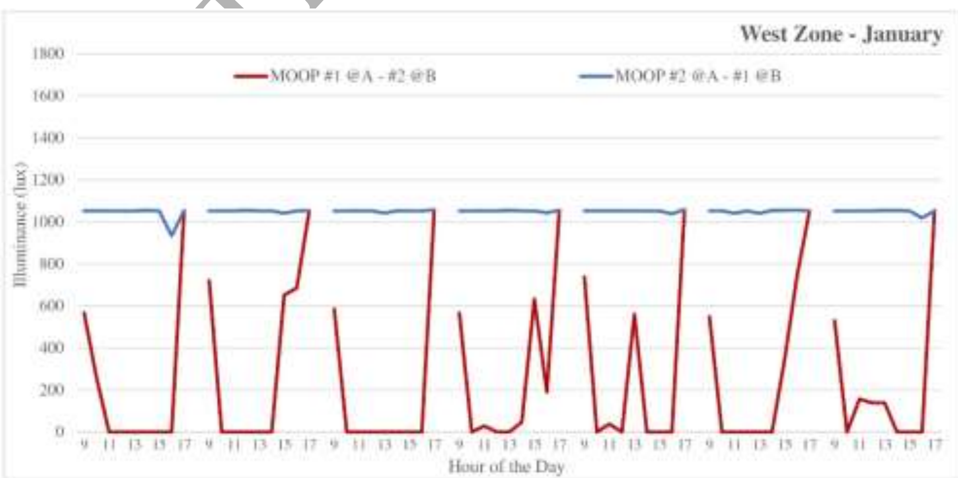

Fig. 19: Different occupancy scenarios and the level of artificial lighting (lux) – The cold season analysis

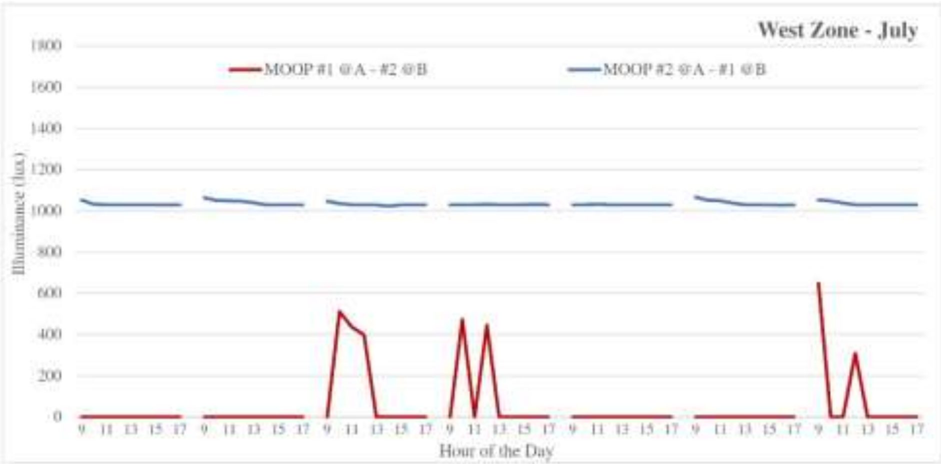

Fig. 20: Different occupancy scenarios and the level of artificial lighting (lux) – The warm season analysis

3.4 Effect of Occupants' Positions on Overall Productivity & Energy Use: Multiple Occupants

The diversity in occupants' preferences and positions have impacts on the automated control of the environment. To observe the influence of occupants' positions on the overall productivity of occupants (considering the combined effect of thermal comfort, visual comfort and indoor air quality from (20)) and the energy costs associated, two previously considered scenarios of occupancy in previous section are expanded to all four zones. In all the zones, two arbitrary scenarios of having (1) an occupant with the same preferences as Occupant #1 in Position-A, and an occupant with similar preferences to Occupant #2 in Position-B; and (2) an occupant with the same preferences as Occupant #2 in Position-A, and an occupant with similar preferences to Occupant #1 in Position-B, are considered.

During January and July, the weekly energy performance of the building with respect to productivity losses ($) and energy costs ($) is analyzed (Fig. 21 and Fig. 22). It is observed that in both months, under the 1st scenario of occupancy, both the weekly productivity losses of occupants ($) and the energy costs of the office ($) are relatively lower, compared to the alternative scenario of occupancy (Fig. 21 and Fig. 22).

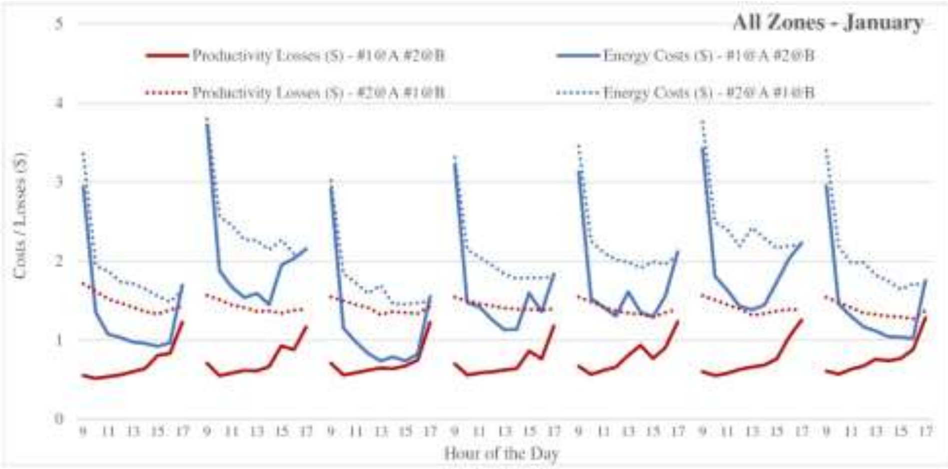

Fig. 21: The importance of occupants' positions for the productivity losses ($) and energy costs ($) - The cold season analysis

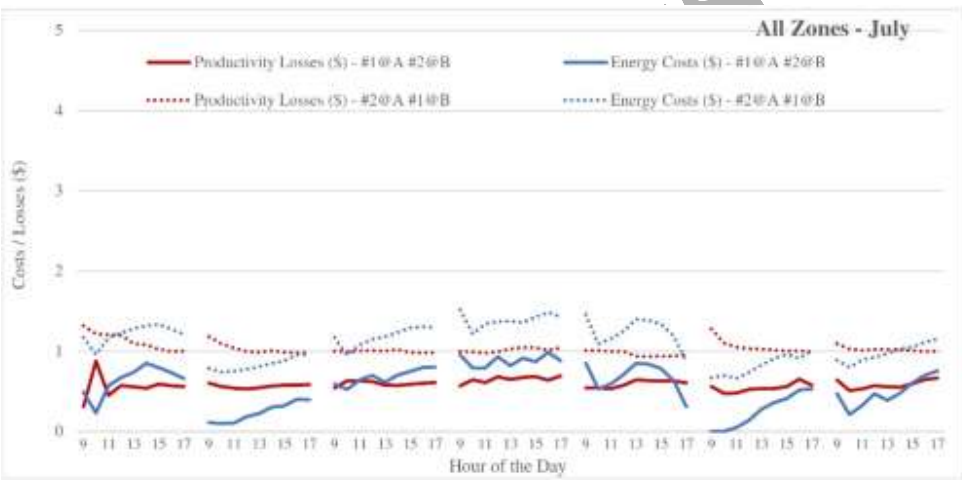

Fig. 22: The importance of occupants' positions for the productivity losses ($) and energy costs ($) - The warm season analysis

4 Discussion

We simulated the position-based method for the automated control of the indoor environment, according to different personalized parameters of (1) productivity rates, (2) thermal preferences, (3) visual preferences, and (4) positions inside the zones. From the Gaussian expressions of RP_{Thermal} and RP_{Visual} (proposed in this paper), each occupant's $T_{\text{maxcomfort}}$, $Tolerance_{\text{thermal}}$, $ILL_{\text{maxcomfort}}$, and $Tolerance_{\text{visual}}$ are extracted as personalized parameters. $Tolerance_{\text{thermal}}$ and $Tolerance_{\text{visual}}$ of each occupant represent her thermal and visual behavior, respectively. Here, the sensitivity of the position-based method to the varied thermal and visual behavior of occupants is analyzed, by considering variations in their $Tolerance_{\text{thermal}}$ and $Tolerance_{\text{visual}}$.

4.1 Thermal Behavior Change

In north zone, during July, an arbitrary occupancy scenario of having Occupant #1 in Position-A, Occupant #2 in Position-B, Occupant #3 in Position-C, and Occupant #4 in Position-D is considered. Variations in the thermal behavior of Occupant #2 are studied. Within the sensitivity analysis, $Tolerance_{\text{thermal}}$ of Occupant #2, during the first week of July is assumed to variate 30%. Accordingly, three arbitrary scenarios of (1) *Less Tolerance* of the occupant, (2) *Normal Behavior* of the occupant, and (3) *More Tolerance* of the occupant are created (Table 6). Under each of the three scenarios, the performance of the method, with respect to the thermal comfort of all occupants is studied. A constant productivity rate of 8 $/h is considered for each occupant.

Table 6: Scenarios for thermal behavior change analysis during July - North zone

Thermal Behavior Variation Scenarios		
Scenario 1	**Scenario 2**	**Scenario 3**
Occupant #2 Less Tolerant $Tolerance_{\text{thermal}}$ = 3.1 K	Occupant #2 Normal $Tolerance_{\text{thermal}}$ = 4.4 K	Occupant #2 More Tolerant $Tolerance_{\text{thermal}}$ = 5.7 K

The variations of hourly operative temperatures (°C), in different positions of the north zone, during the occupied hours of the first week of July, are studied (Fig. 23, Fig. 24, Fig. 25, and Fig. 26). If Occupant #2 has less thermal tolerance, the position-based method provides operative temperatures (°C) relatively closer to $T_{\text{maxcomfort}}$ of Occupant #2, which is 23.4 °C (Fig. 23). It is observed that the thermal behavior variations of Occupant #2 influence the thermal conditions of Occupant #1 (Fig. 24), Occupant #3 (Fig. 25), and Occupant #4 (Fig. 26), as well.

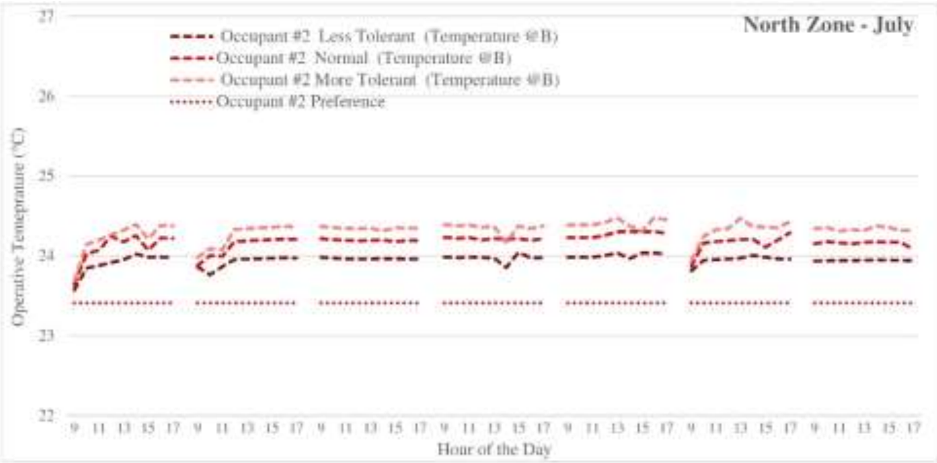

Fig. 23: Thermal conditions of Occupant #2, under thermal behavior change scenarios- The warm season analysis

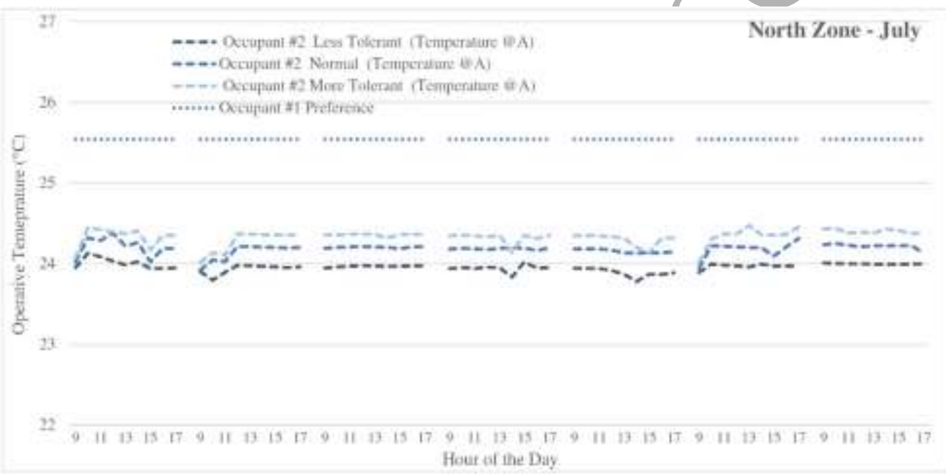

Fig. 24: Thermal conditions of Occupant #1, under thermal behavior change scenarios- The warm season analysis

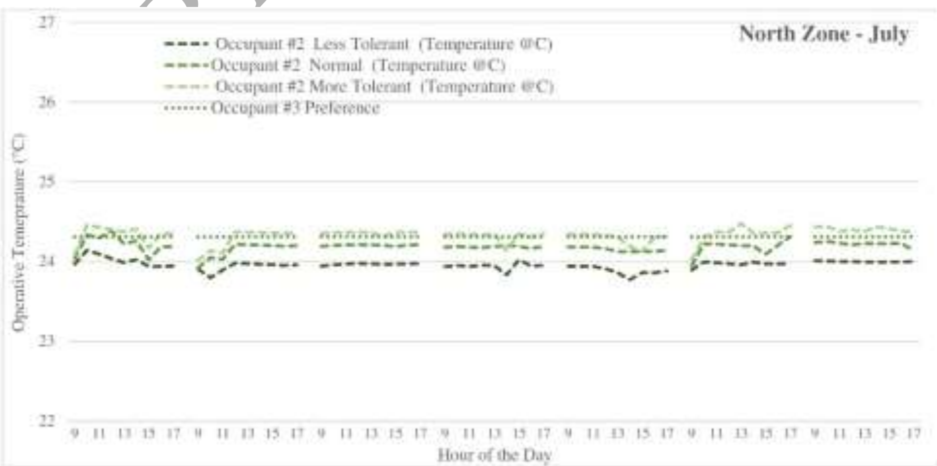

Fig. 25: Thermal conditions of Occupant #3, under thermal behavior change scenarios- The warm season analysis

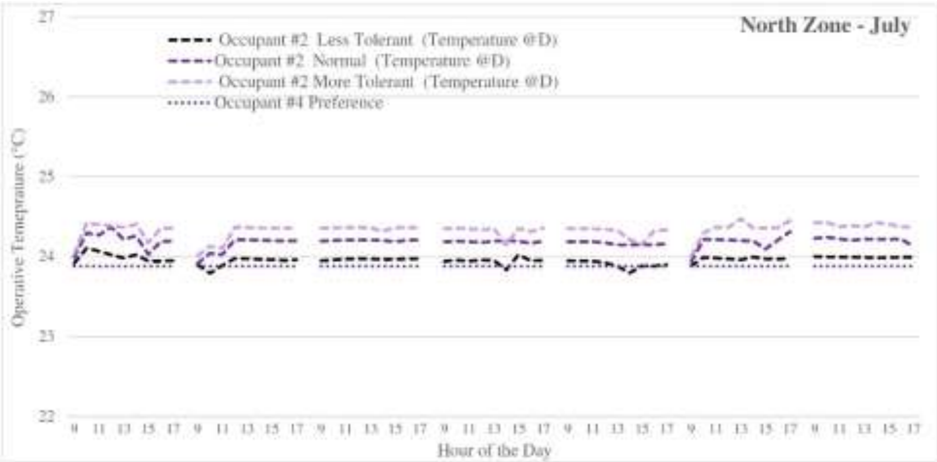

Fig. 26: Thermal conditions of Occupant #4, under thermal behavior change scenarios- The warm season analysis

4.2 Visual Behavioral Change

Here, the sensitivity of the position-based method to the visual behavior of an individual occupant is analyzed. In east zone, an arbitrary occupancy scenario of having Occupant #1 in Position-A, Occupant #2 in Position-B, Occupant #3 in Position-C, and Occupant #4 in Position-D is considered. It is assumed that each occupant has a constant hourly productivity of 8 $/h.

Among four occupants, Occupant #1 has the visual preference of a relatively least bright indoor environment (937 lux). During January, the visual behavior of Occupant #1 is chosen for the sensitivity analysis (Table 7). $Tolerance_{\text{visual}}$ of Occupant #1 is assumed to vary by 20%, from its normal value of 667 lux. Subsequently, the performance of the method with respect to the visual comfort of Occupant #1, as well as the visual comfort of other three occupants is studied.

Table 7: Scenarios for visual behavior change analysis during January – East zone

Visual Behavior Variation Scenarios		
Scenario 1	**Scenario 2**	**Scenario 3**
Occupant #1 Less Tolerant $Tolerance_{\text{visual}}$ = 533 lux	Occupant #1 Normal $Tolerance_{\text{visual}}$ = 667 lux	Occupant #1 More Tolerant $Tolerance_{\text{visual}}$ = 800 lux

The levels of hourly illuminance (lux) in different positions of east zone are demonstrated for January (Fig. 27, Fig. 28, Fig. 29, and Fig. 30). In each hour, the position-based method considers the visual behavior of Occupant #1 and chooses the illuminance levels (lux), accordingly. When Occupant #1 has less visual tolerance, hourly illuminance (lux) in Position-A is relatively closer to $ILL_{maxcomfort}$ of Occupant #1 (937 lux). On the other hand, when Occupant #1 has more $Tolerance_{visual}$, illuminance (lux) in Position-A, can be further away from $ILL_{maxcomfort}$ of Occupant #1 (Fig. 27).

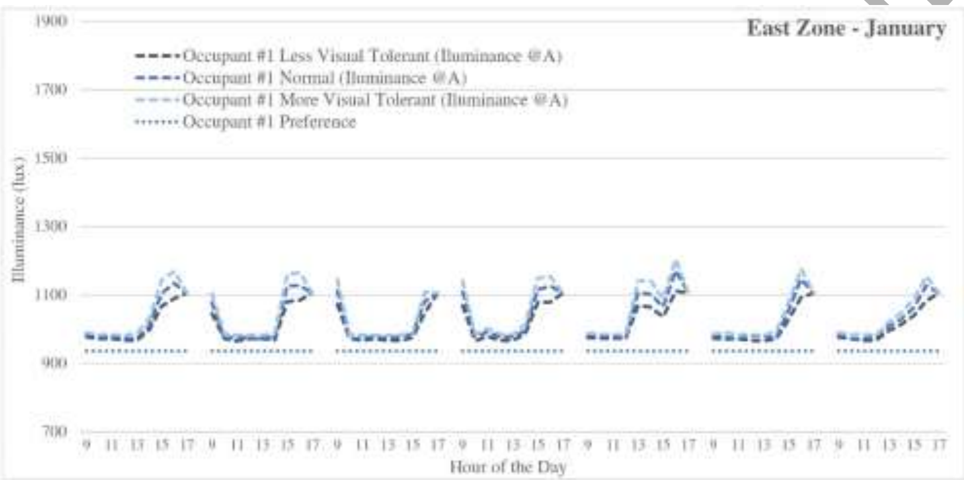

Fig. 27: Visual conditions of Occupant #1, under visual behavior change scenarios - The cold season analysis

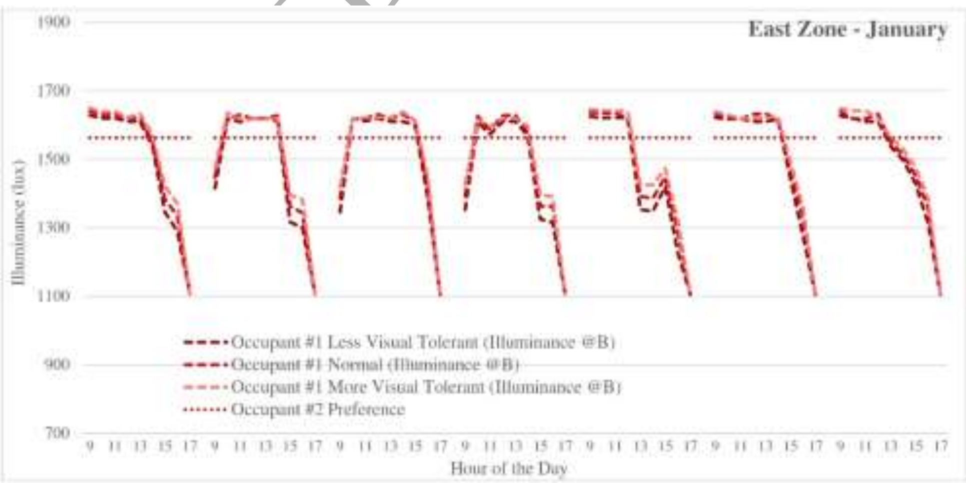

Fig. 28: Visual conditions of Occupant #2, under visual behavior change scenarios - The cold season analysis

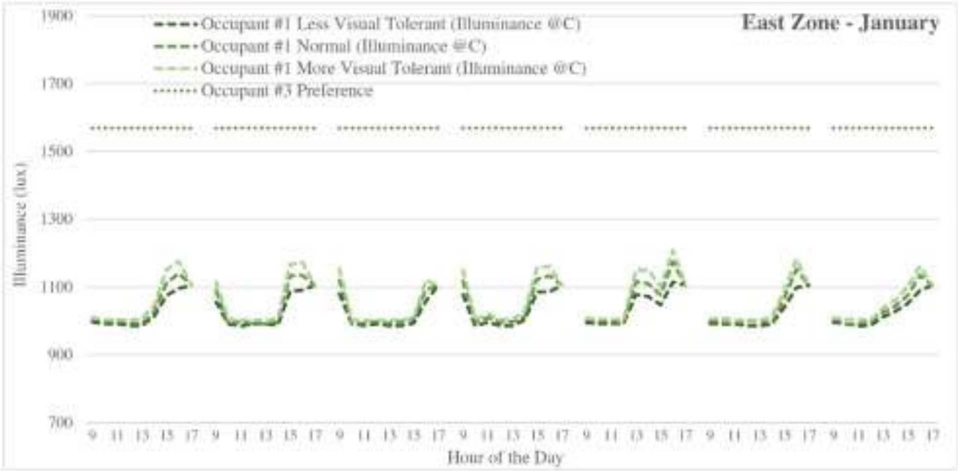

Fig. 29: Visual conditions of Occupant #3, under visual behavior change scenarios - The cold season analysis

Compared to Occupant #1, other three occupants of east zone prefer a brighter visual ambient (Table 5). Hence, they benefit from the higher visual tolerance of Occupant #1. Under the scenario of Occupant #1's higher visual tolerance, levels of hourly illuminance (lux) in Position-B (for Occupant #2), in Position-C (for Occupant #3), and in Position-D (for Occupant #4) are relatively closer to $ILL_{\text{maxcomfort}}$ of the occupants, compared to the alternative scenarios (Fig. 28, Fig. 29, and Fig. 30). The position-based method, wherever possible, can benefit from an individual's or a group of individuals' thermal and/or visual behavior variations, to reduce the associated energy consumption costs of the office building.

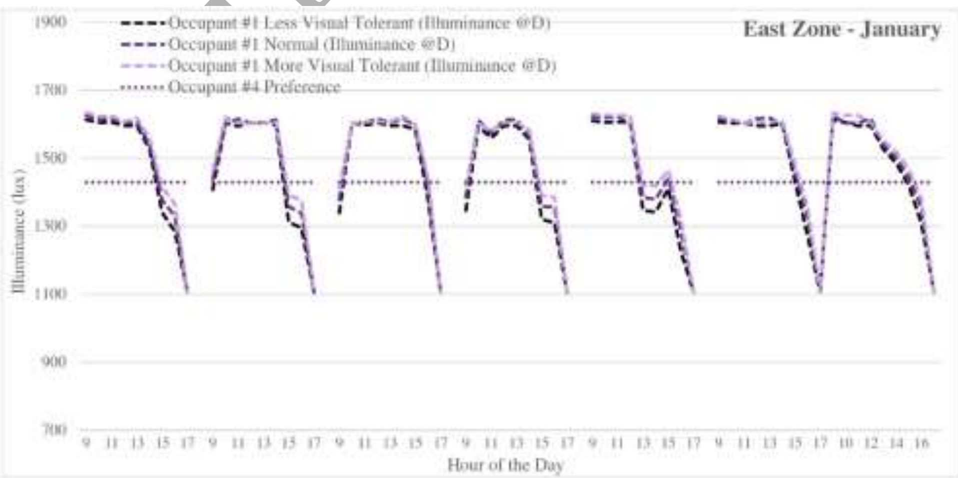

Fig. 30: Visual conditions of Occupant #4, under visual behavior change scenarios - The cold season analysis

There are several parameters that that shape occupants' behavior, in different situations. The additional human-related parameters are included but not limited to occupant's (1) varied behavior in the presence of other occupants, (2) mood and set of emotions, (3) desire and willpower, (4) deprivation of comfort, (5) and short-term adaptation to the environment. These human-related parameters, alongside already considered personalized parameters, can shape a *specific situation*, in an enclosed space.

5 Conclusions

Occupants of buildings, as energy consumers, can significantly benefit from personalized control of the indoor environmental conditions. A position-based personalized method for intelligent energy and comfort management in offices is proposed. The method is applied to the model of an office, located in Montreal, Canada. The proposed method provides optimal control setting of the indoor environment, by managing the level of indoor temperature, ventilation rate, natural illumination, and artificial lighting, in different zones of the considered office. Based on the provided results, the position-based method can manage the indoor environmental conditions according to occupants' (1) thermal preferences, (2) visual preferences, (3) productivity rates, (4) positions, (5) thermal behavior, and (6) visual behavior. Furthermore, it is confirmed that the position-based method is successful in simultaneously improving occupants' productivity and optimizing energy consumption costs.

We observed that the position-based method can make energy-related decisions for the automated control of the indoor environment, according to the varied thermal and visual behavior of occupants. Hence, the proposed method has the potential to acknowledge additional human-related parameters that shape occupants' behavior, in different situations. By acknowledging these parameters while making energy-related decisions, the proposed method can offer *behavioral intelligence*, and perform *situation-specific* energy and comfort management. This is the topic for future work.

Acknowledgments

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Appendix A: Thermal Modeling the Office Building

For each zone, a specific set of energy balance equations is derived from various types of energy exchanges processes including (1) solar gain through windows, (2) internal heat gain from occupants, systems, and equipment, (3) infiltration, (4) heat exchange between the zones, (5) the effect of thermal storage of external walls, (6) the influence of blinds position on the conductive heat transfer of the windows, (7) artificial lighting, (8) heating and cooling systems [33]. For each zone of the office (i), the governing equation, representing energy balances, are in the form of:

$$\rho V_i \, c_p \, \frac{\partial T_i}{\partial t} = \sum_{j=1}^{n} h_{c\,i-j} A_{sj} \, (T_{sj} - T_i) + \sum_{k=1}^{m} \dot{m}_{i-k} \, c_p \, (T_k - T_i) + q_{in} \qquad (23)$$

The term $\rho V_i \, c_p \, \frac{\partial T_i}{\partial t}$ represents the thermal capacitance of the fluid (air) inside the zone, in which ρ is the average density of air (kg/m^3), V_i is the volume of the zone (m^3), c_p is the average specific heat of air (J/kg.K), and T_i is the average temperature of the zone (K). Forward difference scheme is applied to the partial derivative, over some finite time interval (an hour), in hourly building energy performance simulation: $\frac{\partial T_i}{\partial t} = \frac{T_i^{t+\Delta t} - T_i^t}{\Delta t}$. In these calculations, hourly time steps are selected for demonstration of the performance of the MOOP method. In a control application, using an RC-network model, shorter time steps can be selected. During the energy performance simulation, $T_i^{t+\Delta t}$ is the inside temperature of the zone, calculated during that hour, Δt is equal to one hour, and T_i^t is the inside temperature of that zone, calculated in the previous hour.

The term $h_{c\,i-j} A_{sj} \, (T_{sj} - T_i)$ in the governing equation expresses the convective heat transfer rate (W) between the zone (i) and the surrounded surfaces (j). T_{sj} is the surface temperature, A_{sj} is the contact area of the zone with the surface (m^2), and $h_{c\text{-}i\text{-}j}$ is the heat transfer coefficient (W/m^2.K). The term $\sum_{k=1}^{m} \dot{m}_{i-k} \, c_p \, (T_k - T_i)$ describes the rate of energy exchange (W) due to the fluid flow between the zone and other zones, or between the zone and outdoor. In this equation, $\dot{m}_{i-k}$ is the pressure/temperature driven mass flow rate (kg/s) between the two volumes, c_p is the specific heat of air, transferred from another zone or from the outdoor, and T_k is one of the other zone's temperature or outdoor temperature. q_{in} represents the heat generated in the zone from occupants and appliances, or from artificial lighting, or heating/cooling system. It is assumed that the office is on the middle floor of a high-rise commercial building. Accordingly, all ceilings and floors are assumed to be adiabatic [33]. Values of parameters used in the RC-network thermal model of the office are stated in Table 8.

Table 8: Building parameters

Parameter	***Value***	***Parameter***	***Value***
Chiller COP	3.5	Exterior Wall Specific Heat (kJ/kg .K)	42
Electrical Heater Efficiency (n)	1	Exterior Wall Outdoor Surface Convection Heat Coefficient (W/m^2.K)	34
Open Shade Window U-Value (W/m^2.K)	2.3	Exterior Wall Indoor Surface Convection Heat Coefficient (W/m^2.K)	8.5
Close Shade Window U-Value (W/m^2.K)	1.4	Interior Wall U-Value (W/m^2.K)	1.5
Fluorescent Lamp Efficacy (lumens/W)	70	Fan Energy Consumption (W per m^3/s of air)	1760
Exterior Wall U-Value (W/m^2.K)	0.4	Maximum Lamp Power (W/m^2) [1]	15