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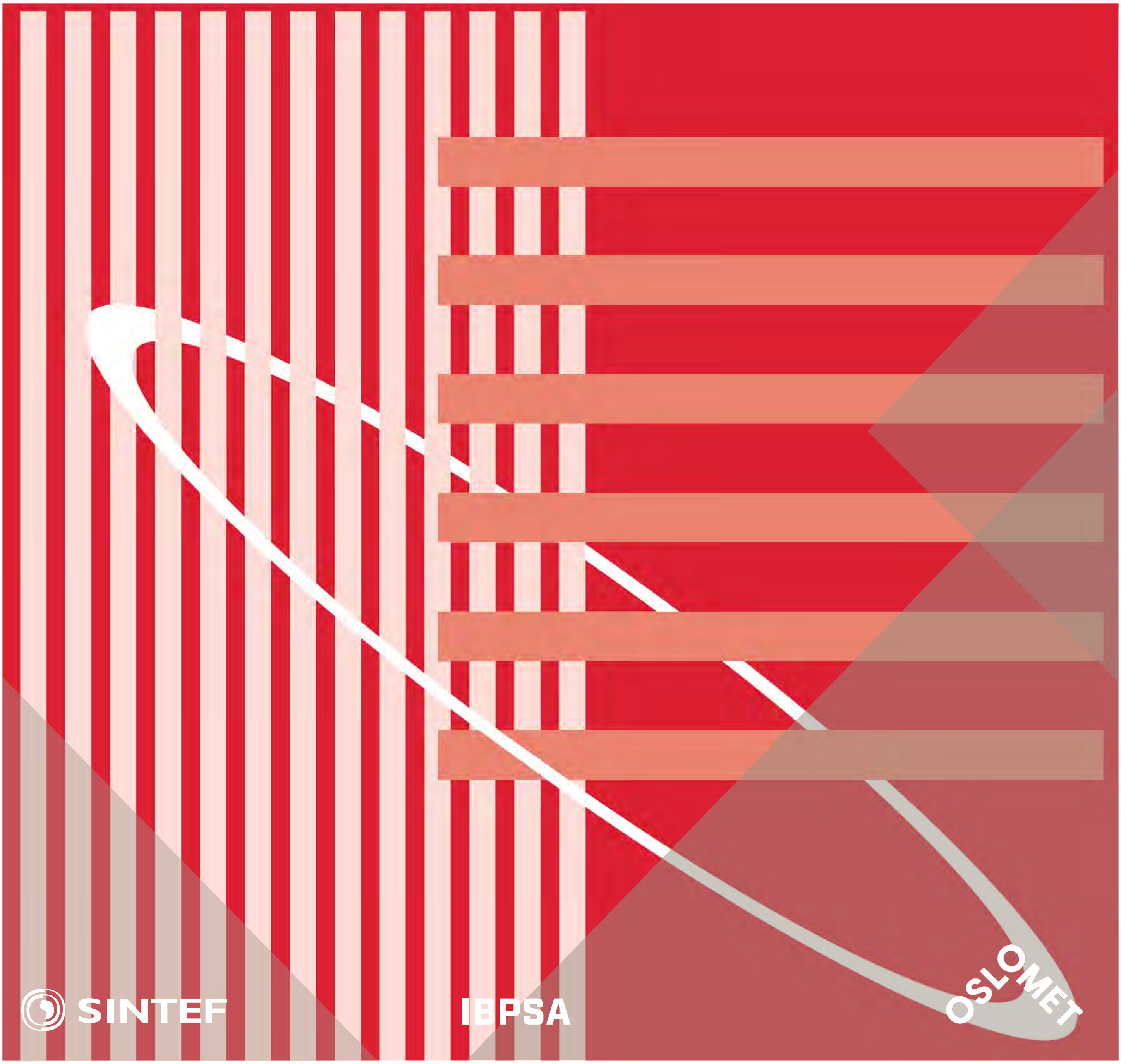

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Energy performance of an office building by using adaptive approach to occupant behaviour and environment control

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Abstract

The predicted percentage of dissatisfied (PPD) value indicates the percentage of people dissatisfied with thermal environment, as it depends not only on the environment itself, but on physical, psychological, or behavioural aspects as well. Flexible and adaptive occupant behaviour provides more opportunities for both reaching higher perceived levels of comfort and energy savings. In this research, the software simulation tool IDA-ICE has been used to analyse the building performance of the office building under two scenarios, an adaptive case, and a non-adaptive case. One pattern was based on standard clothing levels, while the other dealt with the possibility for the occupants to adjust in terms of clothing and window operation with respect to the air temperature. The analysis was based on the concept that coping with dissatisfaction can be linked to lower PPD values, and adaptive models can be incorporated into dynamic building energy performance simulations. The results show that there are noticeable differences in the energy used per m^2, cooling and thermal dissatisfaction, upon adopting adaptive approach with respect to clothing, Predicted Mean Vote (PMV) value and the window opening behaviour. Certain occupant behaviours aimed at maintaining thermal comfort that can both increase the accuracy of energy performance predictions and lead to increased energy savings in office buildings.

Introduction

The energy consumption rates vary depending on the type of building. Specifically, in the case of office buildings, where the consumption is dependent more on comfort than necessity. Importance is to be given to the satisfaction of occupants as it affects their productivity (Mostavi, Asadi, & Ramaji, 2016). The relationship between the occupant satisfaction and the energy consumption has been investigated in various studies. Owing to the subjective nature of these studies, the broader conclusions inferred are limited to those specific studies itself. But the specific conclusions and the commonalities can be understood and applied to other scenarios. Ultimately, it is the mind-set of the occupants and their decision making strategies for achieving comfort that makes a difference in meeting the energy efficiency goals (Nižetić, 2017). The sense of comfort for the occupants is enough to influence their behaviour towards the surroundings. It has been given that the occupants would first take on window operation, changing clothes, etc., as adaptations to cater for thermal comfort needs (KC, Rijal, Shukuya, & Yoshida, 2018). A study has shown that the higher window-to-wall ratio increases occupant satisfaction, but without a provision for window shading or blinds, the satisfaction could decrease owing to the lack of privacy (Hong, Lee, Yeom, & Jeong, 2019). Similarly, there are other factors that affect the occupant comfort variable such as, the activity level, clothing (CLO) value, level of interaction with the temperature controls, etc. Activity level, which is measured in MET, is directly linked to the occupant comfort, and would lead to higher interaction with the building temperature controls. This can be regarded as a form of occupant adaptation. If the choice of interaction is given to them for adjusting controls, i.e., manual temperature adjustment system, a rise in satisfaction can be observed. The complication with an occupant demand driven approach is that, each individuals' thermal adaptation influences their response to comfort which affects the overall predicted percentage of dissatisfied (PPD) rate (Aguilera, Kazanci, & Toftum, 2019). Similar is the case with the occupants' behaviour of adapting to the environment in the form of window operation (Chen, Tong, Samuelson, Wu, & Malkawi, 2019). Hence, higher satisfaction levels can be achieved by imparting a sense of being provided with an option to choose to alter the surroundings. In shared office spaces, there is a higher probability of interaction when the element is closer to the occupant (Marín-Restrepo, Trebilcock, & Gillott, 2020). The clothing level, which is measured in CLO, also has a direct impact on the occupant satisfaction. Usually, office environments have strict dress codes which could impact the interaction with temperature controls, as the clothing adaptation for occupants varies in direct relationship with the indoor temperature (Indraganti & Boussaa, 2017).

The behavioural responses of occupants are merely fuelled by their expectations of thermal comfort, from past experiences of regulation and comfortable indoor environments (Auliciems & de Dear, 1998). The various adaptations that occupants would take on and the implications that these actions have on the energy consumptions have been analysed in this paper. The focus is on the adaptations and the energy consumption rates within an office building, which can help in identifying different ways of saving energy. This can be accomplished by quantifying the energy savings, by the means of IDA ICE software simulations and a questionnaire survey. Various instances of occupant adaptations to the indoor environment are considered. The simulation results from an adaptive case and a non-adaptive case are compared and the results are analysed.

Methods

Case study building

The object of the research is a newly constructed office building in Vilnius, Lithuania (Figure 1). The building has ten floors, premises are rented to various companies and a café is located on the ground floor. All floors of the building are ventilated by mechanical ventilation systems.

Figure 1 Photo of the building

The facade structures of the building are made of painted aluminum profile and glazed with 54-millimeter-thick glass packages. The facade wall constructions are made of painted aluminum profile and filled with thermal insulation filler. The windows of the office building are tilted inwards, made of painted aluminum profile with thermal insulation, glazed with double-glazed units (U value - 1.3 $W/m^2 \cdot K$). The main heat source of the building is district heating. For the ventilation of the premises two ventilation units with rotary heat exchangers are installed. The first is for ventilation of 1 - 5 floors and the second for ventilation of 6 - 10 floors. The units are installed in the technical room on the technical floor. Fresh air is taken through the air intake grille on the north side of the building and removed above the roof. Air cooling units of the variable refrigerant volume (VRV) type are installed for the supply of cold to ventilation equipment. A separate ventilation unit designed to ventilate the cafe is also installed on the technical floor. For the ventilation of other premises, such as toilets, a separate ventilation unit with plate heat exchangers and a heat recovery unit is installed. The air in the premises is cooled by supplying cooled air to the premises through ducts and by cooling the air in the premises with local cooling devices, thus maintaining the necessary room parameters. A separate three-pipe cooling unit of variable refrigerant volume type is designed for each floor. The office rooms are equipped with ducted air conditioners that supply cooled air through air supply distributors. The specific fan energy consumption per air volume unit of the building's HVAC system is 0.000275 kWh/m^3, and the Seasonal Energy Efficiency Ratio (SEER) value is 3.50, for cooling. The HVAC systems design have an 83% heat recovery efficiency.

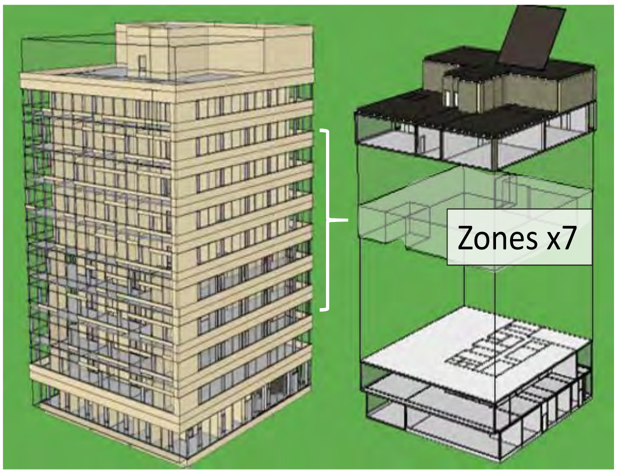

Figure 2 Research building model in IDA ICE environment before and after zone multiplication

Table 1 Building Performance Metrics for 2018

Primary energy consumption of the actual building (kWh/m^2)	175.3
Energy consumption (from simulation) (kWh/m^2)	161.9

IDA ICE Model description

Based on the architectural design of the building a model was created in the IDA ICE environment. The development of the model aims to reproduce the design solutions of the building as accurately as possible. To speed up the simulations a zone multiplier function is used. Buildings often have zones that are identical or very similar. After detailing one zone in this way, the parameters are applied to other zones assigned to the same functional group. This helps to perform simulations faster and to review various options. The object of the research also has identical zones in some floors.

Energy consumption data

The analysis of the energy consumption of a building was performed. Firstly, reports of electricity, heating, and water consumption of the building for the period of 2018 year (Table 1) were received from the company's property manager. Electricity costs include lighting, cooling, and the cost of hot water as it is prepared by electric heaters. Based on the data received, an overall summary of the costs of the building was compiled (Figure 3). The results of the analysis show that the highest costs in terms of the energy consumption of a building are for electricity (28%).

As electricity costs are the biggest part of all building costs, further review of the data was done. It showed that most of the electricity is consumed in autumn and winter when the need for lighting in the premises increases and more hot water is used. Using the Building Management System (BMS), the annual electricity consumption of the building was calculated and spread out according to the need for ventilation, cooling, lighting, and other equipment.

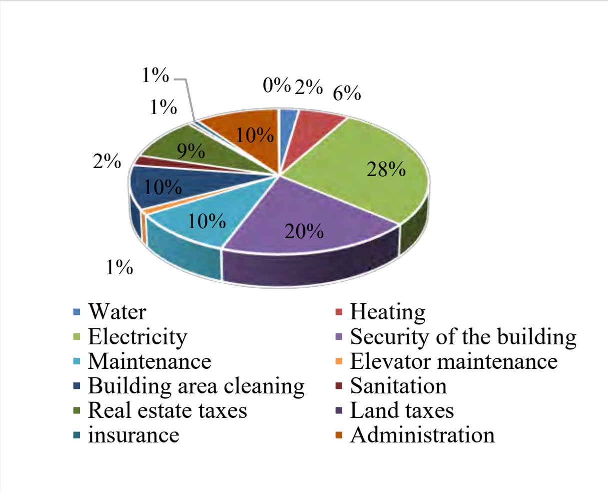

Figure 3 Annual building costs

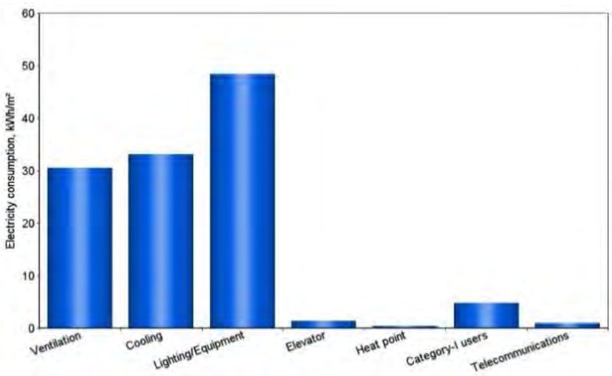

Figure 4 Electricity consumption analysis

It can be seen from Figure 4 that the largest part of electricity consumption is consumed by ventilation, cooling, lighting and equipment systems, which includes not only lighting devices, but also computer equipment, electrical appliances and electric hot water heaters.

Questionnaire survey

The subjects targeted for this questionnaire survey were the occupants in the office building. The survey was designed to gather the data from occupants, regarding the indoor environment and their individual attributes. The survey comprised of 16 questions and was designed using online tools. The survey aims to gather the basic information from the occupants pertaining to their age, gender, duties, physical activities, working hours in office, etc. This is to draw inferences from the survey responders about their backgrounds, which would help in understanding their comfort perceptions and expectations (Derks, Mishra, Loomans, & Kort, 2018; Khalid, Zaki, Rijal, & Yakub, 2019). Further questions focused on their comfort adaptations, i.e., the possibility to modify their clothing, the heating/cooling systems, and the operation of windows. Attempting to modify the surroundings to meet the comfort expectations is the nature of adaptation. Hence, the occupants' adaptations are a precursor to their comfort and satisfaction (Choi & Moon, 2017). The data gathered from the survey, regarding clothing, activity, and window operation, will be necessary to simulate the indoor environment. The CLO and MET values can be noted from the survey responses that could define the occupant behaviour. The hours of operation of the occupants (as received from the survey) can also be fed to the software. This information is intended to be used as the input data for the IDA ICE software simulations.

The software has the option which allows for designing algorithms for the working logic of HVAC components, window opening control, shading control, etc. within the building. Utilizing this feature, the occupant behaviour was linked to the window operation, for the simulation. The first case is the 'Non-Adaptive Case' scenario, which uses the standard values of clothing for summer, winter, autumn, and spring seasons. The activity level and working hours of the occupants are obtained from the survey results. These settings were applied for all the zones in the building and the simulation was run from January 2018 to December 2019. The 'Adaptive Case' is simulated with the window opening control which will be linked to the air temperature, in a way that they are opened when the air temperature is equal to or higher than 24 °C within the indoor environment. This algorithm can be designed through the creation of macro controls for the windows. Within the macro, the zone is linked to a PI controller as a function of air temperature along with a set-point. The output signal from the PI controller is connected to the window opening control. The same algorithm is then used for all the zones in the building with windows. Also, the clothing values of occupants are used as per the results of the survey, which were taken separately for each season. The Predicted Mean Vote (PMV) value for both the adaptive and the non-adaptive cases is different. For the non-adaptive case, the flexibility to change the clothing is lower. Differences in the simulation results are expected when the adaptive case has slightly higher flexibility with clothing. Upon running the simulations for these three scenarios for the years 2018 and 2019, the results are analysed for variations and the PPD values would be observed as to how they change under the two different scenarios. This methodology focuses on analysing the difference in energy consumption rates when adaptive measures are adopted by the building occupants and systems. Thereby, exposing the potential and scope for further energy saving techniques while maintaining the comfort of occupants.

Results

Survey results

The survey received 48 responses from the building occupants, out of which 28 were from women and 20 were from men. Around 77% of them spend 8 to 9 hours a day in the office (Figure 5) and 79% of them spend maximum time of their work sitting in front of a computer (Figure 6), which make their responses dependable and relevant to the study. The MET value for concerned activities is taken as 1.2, which has been used in all the simulations and this value has been derived from the survey results.

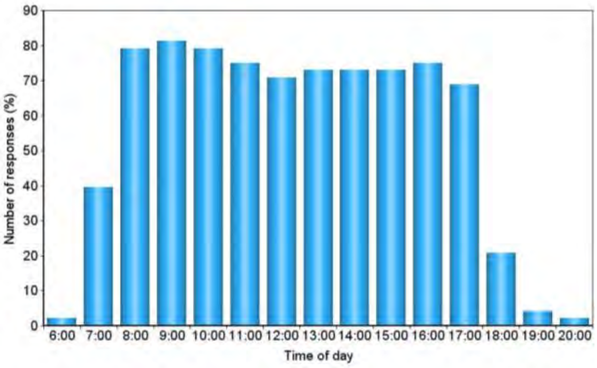

Figure 5 Survey responses for occupants' working hours

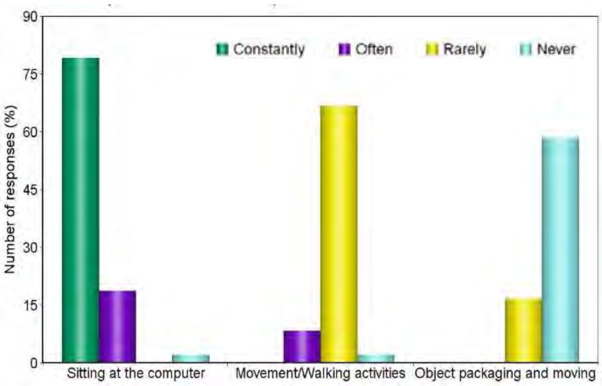

Figure 6 Survey responses for physical activities

The occupants' workplaces were situated on different floors of the building. The maximum number of responses belonging to a single floor were received from the fifth floor which was about 31% while about 22% and 13% of them were from the sixth and second floors, respectively. The remaining respondents were scattered on multiple floors, giving a diverse range of responses covering a significant portion of the building. Focusing on the commonalities among the responses, it has been found that more than half of them had office spaces that had windows facing either southwest or northwest. There is no strict dress code for the employees hence their usual office attire was allowed in the questionnaire. The CLO values were taken from the standard ISO 7730 standard (2005) (International Organisation for Standardisation, 2005) for the base case scenario. Wide range of clothing options were provided within the survey for the respondents to choose their typical office attire. The survey results revealed the choice of attire of the occupants during various seasons in a year and also the level of flexibility they have with altering their clothing (Yao, Yang, Zhuang, Shao, & Yuan, 2018). To achieve the comfort levels, occupants tend to alter their clothing either by taking off their jacket, scarf, etc. when it is hot and putting them on when it is cold. Taking their responses into consideration and allowing for adaptive clothing, the clothing values were taken as shown in Table 2. Since clothing depends on the seasonal variation, the CLO values are different during different times of the year. For the two-year simulation, each season was assigned an appropriate CLO value with the help of rules and schedule options within the software IDA ICE.

Table 2 Clothing values for simulations

	Summer	Winter	Spring/ Autumn
CLO value for Non-Adaptive Case	0.5 ± 0.1	0.9 ± 0.1	0.7 ± 0.1
CLO value for Adaptive Case	0.4 ± 0.2	1.04 ± 0.2	0.76 ± 0.2

The adaptive behaviour of the occupants is heavily influenced by the indoor atmosphere (air temperature, relative humidity, etc.). To obtain these details, the respondents were asked to give their thermal sensation vote pertaining to the indoor atmosphere. A significant number of them responded that the indoor environment in comfortable during the spring/autumn season. Yet, the responses point out that the indoor environment is hotter during summer and colder during winter (Figure 7).

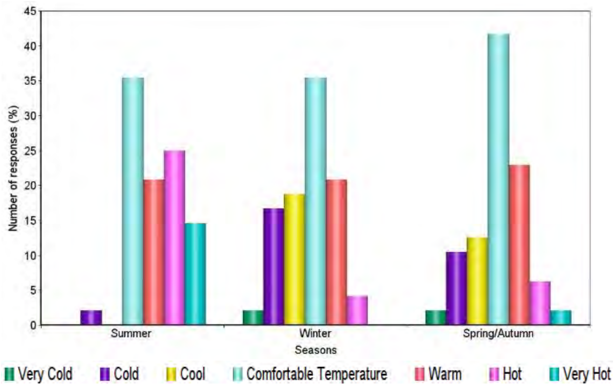

Figure 7 Level of thermal comfort in office during different seasons

Software simulation results

As mentioned earlier, an algorithm was used to run the macros for windows by linking the zone to the opening control as a function of air temperature. This algorithm is used in the adaptive case, where the temperature set point for opening the windows is when the air temperature in the zones is 24°C and above based on the non-adaptive case results. These settings were applied along with the appropriate PMV values and the clothing schedule for both the case scenarios (Table 2). The simulation results show that the differences between both the cases vary by a slight margin. The total energy used by the building per m^2 is reduced for the adaptive case, as shown in Table 4. The overall thermal dissatisfaction of the occupants is reduced upon introducing occupant adaptations. Since the difference in values is not significant, more control over window opening for the occupants, may be given. The results show that they would feel more comfortable with having control over the windows. This could either be the psychological or physiological satisfaction of the occupants. In addition, the air temperature set point for window algorithm, probably if higher, may have resulted in a larger gap between the adaptive and non-adaptive case scenarios. Yet, in the building the occupants are satisfied with the indoor environment just as received through the survey result in Figure 7. The electric cooling and heating results show that the adaptive case has seen a slight reduction.

Table 3 Simulation case scenarios

	Non-Adaptive case	**Adaptive case**
Clothing level	Standard values	From survey results
PMV	-1 to +1	-2 to +2
Window opening	-	Based on air temperature

Table 4 Differences in scenario results from 2018 to 2019

	Non-Adaptive case	**Adaptive case**
Lighting (kWh/m^2)	147.3	147.3
Electric cooling (kWh/m^2)	14.6	13.9
HVAC (kWh/m^2)	58.6	58.6
Electric heating (kWh/m^2)	7.9	7.0
Tenant electric (kWh/m^2)	110.5	110.5
PV production (kWh/m^2)	21.8	21.8
Total used energy (kWh/m^2)	317.2	315.6
Total occupant hours with thermal dissatisfaction (%)	19	18
Mean PPD value of all zones (%)	8.76	8.12

Conclusion

This paper has shown the data collection methods and the energy simulation results of a real office building. The results show that the occupants' adjustments with respect to clothing, do not yield a considerable change in the energy consumption rate. However, the values of PMV and CLO assumed for the simulation could be higher by giving more freedom to the occupants, without compromising energy efficiency of the building. In addition to the different CLO values (Table 3), the adaptive case also included window operation. Results prove that the occupants maybe given more control over HVAC controls with no significant change in the energy consumption. Also, further simulations maybe carried out for each season separately to focus more on the smaller variations between variables. For future research, more variables will be introduced to observe their influence over the occupant comfort levels.

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