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Field occupants' behavior monitoring integrated to prediction models: impact on building energy performance

Cristina Piselli[1,*], Ilaria Pigliautile[1] and Anna Laura Pisello[1,2]

[1]CIRIAF – Interuniversity Research Centre, Perugia, Italy
[2]Department of Engineering, University of Perugia, Italy

[*]*Corresponding email: piselli@crbnet.it*

ABSTRACT
Given the massive scientific progress on passive and active solutions to reach near-zero-energy targets, the necessity to consider occupants' behavior as a key variable affecting field energy performance of buildings has become a crucial issue to face. In this panorama, a variety of deterministic and stochastic models, also supported by experimental investigations have been developed in the last decade. This paper builds upon previous contributions to analyze the real occupancy of an office building populated by peers' offices monitored for 2 years by means of microclimate and energy-need field stations. After demonstrating that the peers do not behave the same and do not control in equivalent ways indoors microclimate parameters (e.g. air temperature, desk illuminance, etc.), internationally acknowledged models and field-collected data are compared through dynamic simulation. The estimation of final energy need of different considered scenarios is calculated and the relative difference is highlighted as a possible indicator about the role of building occupancy profiles in affecting energy need prediction. Additionally, EEG experimental test are used to assess the correlation of workers' subjective emotions with external thermal stimuli. Results of final energy need estimation showed to vary by about 20% by only selecting the occupancy simulation scheme, and non-consistent prediction trends are found out while investigating lighting and electric appliances needs. Accordingly, as concerns the human psychological response to the variation of thermal conditions, negligible emotional reactions are found among the different tested workers when suddenly altering comfort conditions indoors.

KEYWORDS
Occupant behavior; Dynamic thermal-energy simulation; Continuous monitoring; Behavior modeling; Scientific Contextual EEG.

INTRODUCTION
Given the acknowledged primary influence of building occupants' behavior on indoor microclimate and energy needs, the understanding of energy related occupant behavior in buildings is a key issue for performance evaluation and optimization at the design stage (Brown and Cole, 2009). In this view, researchers have been working on the understanding and modeling of occupants' behavior in buildings to enable more reliable predictions of building performance (Hong et al. 2016). With the aim of comparing pre- and post-performance of building, Gupta and Gregg (2016) evaluated the actual performance of two low-energy retrofitted buildings in UK. In both buildings, measured annual gas consumption were lower than expected, while electricity consumption was higher as compared to predictions made by energy models, due to occupancy pattern and occupant behavior. In order to face standardized occupancy modeling approach, different stochastic models have been proposed. Such models aim at realistically describing general (Diao et al. 2017) and single energy-related occupancy behaviors, such as people's presence (Mahdavi and Tahmasebi,

2015), windows opening (Fabi et al. 2015), natural ventilation control, and appliances power loads (Zhao et al. 2014). Furthermore, adaptive thermal comfort behaviors have to be understood and taken into account. O'Brien et al. (2016) suggested that the necessary sample size to simulate and exploit occupant diversity between building occupants and uncertainty is dependent on the uniformity of the monitored population. Accordingly, occupants' behavior prediction may become particularly hard in those buildings occupied by a wide variety of users. On the other hand, peer occupants are usually assumed to have identical response to similar environmental conditions and in determining building thermal-energy performance. However, different peer occupants' personal attitudes and habits were found to differently affect the indoor environmental behavior of buildings (Pisello et al. 2016). Therefore, peers' actions homogeneity assumption can involve significant discrepancies in the thermal-energy performance of different areas situated even in the same building position (Kim et al. 2016). In fact, occupants' actions in buildings are related not only to physical stimuli, but also to multi-physics and non-measurable stimuli, in terms of thermal, acoustics, lighting, air quality issues. In this view, further research efforts, in terms of methodologies and simulation tools, are required to elaborate reliable predictive models integrating people energy needy actions into building energy modeling programs (Yan et al. 2015).

In this panorama, the purpose of the present study is to assess the capability of different existing deterministic and stochastic occupancy models for office buildings, usually considered in building dynamic simulation, to comprehensively depict occupants' behavior. To this aim, simulations are compared against real occupancy data continuously monitored in a research office building. Moreover, the discrepancy in terms of final building energy requirements is verified when considering two static standard models, a recent stochastic model, and case-specific models developed based on real monitored data. Additionally, the correlation between occupant's subjective emotions and comfort conditions variation is assessed through neural response tests. Considering the existing literature, the innovative contribution of this research is to compare the performance of different occupancy models in simulating the influence of real offices occupants on total building energy consumption by taking into account the mutual dependence of various occupants' actions. Therefore, different energy-related parameters affected by personal attitudes in office buildings are taken into account. This work builds upon a previous study by the same authors (Pisello et al. 2016) where energy-related peer occupants' behaviors were investigated through field monitoring and peers were found to behave differently based on personal habits and cultural background. Therefore, the capability of a tool based on EEG (Electroencephalography) to assess human perception of discomfort conditions and associated emotional states is evaluated.

METHODS

The research procedure implemented in this study consists of the following steps:

- Experimental continuous monitoring campaign of equivalent office rooms of a building occupied by peer occupants. Analysis of occupancy-related parameters such as energy need, indoor air temperature, illuminance over the working plane, appliances electricity consumption, and windows and door operation;
- Development of the building model and dynamic simulation when considering various occupancy schedules, i.e. static standard, stochastic, real monitored data-based;
- Data analysis and comparison of thermal-energy dynamic simulation results for the different occupancy scenarios in terms of daily trends of occupant related parameters and building total energy consumption;
- Evaluation of models representing the occupants' behavior in the five monitored office rooms against additional monitored data;

- EEG experimental test of selected occupants under different comfort conditions to assess the correlation of workers' emotional response and external thermal stimuli.

Experimental campaign

The experimental monitoring campaign has been carried out in the case study office building, located in Perugia (central Italy) from late spring 2015. The behavior of a group of peer employees working in 5 office rooms has been continuously monitored through dedicated monitoring stations constituting a Wireless Sensors Network (WSN) system. The selected office rooms presents the same characteristics in terms of geometry, energy systems, and each one is equipped with two/three computers according to the number of workers. The monitoring campaign investigates the main parameters related to (i) indoor microclimate and (ii) occupants' activity inside each office room. A more detailed description of the monitoring campaign, setup, and sensors is reported in (Pisello et al. 2016).

Dynamic simulation and occupancy scenarios

Building modeling and thermal-energy dynamic simulation is carried out through EnergyPlus v8.1 simulation engine (Crawley et al. 2000). Different occupancy models are considered for dynamic simulations: two static models, conventionally implemented in building dynamic simulation, i.e. the UK NCM (National Calculation Method for Non Domestic Buildings) standard (UK DCLG, 2004) ("standard" scenario) and the ASHRAE model based on Standard 62.1-2007 and Standard 90.1-2016 ("ASHRAE" scenario); and the stochastic model obtained from the "Occupancy Simulator" tool (LBNL 2011; Luo et al. 2017) ("occ_sim" scenario). Moreover, continuously monitored data in the five offices from June 2015 to January 2016 are considered to develop seasonal, i.e. warm and cold season, occupancy schedules to model five scenarios representative of the different offices occupants ("office_1", "office_2", "office_3", "office_4", and "office_5" scenarios). In particular, heating and cooling set-points, lighting use, and appliances energy use are taken into account. Simulation results with the three reference occupancy scenarios are compared with real monitored occupants' behaviors in terms of daily trend of occupancy-related physical parameters affecting building energy consumption in summer (July) and winter (January). Additionally, the simulation of the five experimental data-based occupancy scenarios is carried out to evaluate the discrepancy with the reference scenarios in terms of total annual building energy requirement (including HVAC, lighting, and appliances). Moreover, occupants' behavior data monitored in the office rooms during summer 2016 and winter 2016/2017, are used for the evaluation of the developed occupancy schedules. Therefore, the developed models are evaluated when compared against the additional experimental data.

EEG experimental tests

To assess the neural response of workers to external thermal stimuli, the EMOTIV EPOC+ neuroheadset (Figure 1) and software are used. In fact, this tool is capable, among other things, to report the real time changes in the subjective emotions experienced by the user, thanks to the *Affectiv* detection tab of the Xavier ControlPanel software. More in detail, the neuroheadset allows to acquire the user's EEG, which is then post-processed through the supplied software. Therefore, the tool is tested to assess the correlation between human emotions and the variation of external physical stimuli. To this aim, tests are performed to the same peer occupants working in similar office rooms ("user_1" to "user_5") when exposed to different thermal conditions, while working at the computer. More in detail, the effect of short-term alteration of the thermal comfort, i.e. by increasing the internal heat gains and, therefore, the air temperature, on the different occupants' emotions is evaluated. Therefore, each occupant is subjected to three test sessions when varying the discomfort time:

- "base": 30 minutes in a thermally comfortable environment;
- "1/2": 15 minutes in a thermally comfortable and 15 in a discomfortable environment;
- "1": 30 minutes in a thermally discomfortable environment.

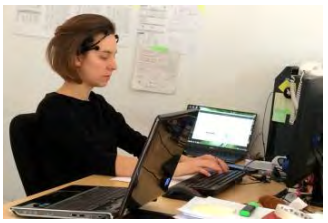


Figure 1. EEG experimental test. Left) Test example, Right) Neuroheadset.

RESULTS

Comparison of occupancy models

Firstly, the trend of occupancy-related simulated parameters in the "standard" and "ASHRAE" scenarios with respect to the monitored data during a summer and a winter day, show that the standardized implemented procedures are neither representative of occupants' individual attitudes nor of their average behavior and tends to overestimate ("standard") and underestimate ("ASHRAE") occupants' energy needs. As concerns the "occ_sim", since only the occupancy presence schedule is changed in this scenario, with respect to the "standard", negligible differences are found in a single-day-term. Switching to the total annual energy consumption for the eight occupancy scenarios, i.e. the three reference and the five experimental data-based, simulation results confirm the high variability of building energy consumption depending on the considered occupancy scenario. In fact, the monitoring-based occupancy scenarios present lower HVAC annual energy consumption with respect to the reference "standard" scenario, up to 19.7% for "office_2". Concerning annual lighting use, all monitoring-based scenarios present lower energy consumption with respect to the three reference scenarios, up to about 13.2 kWh/m^2 per year ("office_4"). Additionally, although considered as peers, the occupants of the five office rooms show notably different electricity energy use and indoor thermal preference, especially in summer. Finally, the simplified occupancy models developed according to the data monitored during year 2015/2016 were evaluated when compared against the experimental data collected during the following year. Figure 2 depicts the trend of simulated parameters with respect to measured data for an average day in summer. The comparison of measured and simulated parameters stresses the higher, yet still not adequate representativeness of experimental data-based occupancy models, compared to standard and stochastic models. However, relevant discrepancies are still noticed, since occupants' behavior is inconstant and influenced by multi-physical and multi-dimensional parameters to be more deeply investigated. Similar results are obtained in winter.

EEG tests results

EEG tests are performed to verify the possibility to correlate the variation of external physical stimuli with worker's subjective emotions. Results (Table 1) show that the analyzed feelings are generally not affected by alteration of thermal conditions. However, some exceptions are noticed: one of the tested occupants experiences focus and excitement reduction in thermally discomfortable conditions, while another one shows excitement increase when increasing the time of exposure to discomfortable conditions. Nevertheless, this singular results cannot be considered representative. Instead, results generally show that non-physical factors, i.e. focus and involvement in the performed tasks, are more significant drivers of personal emotions and behaviors than physical factors, i.e. thermal conditions. In this view, it has to be considered the short test period and the moderate thermal alteration, which may have affected such result.

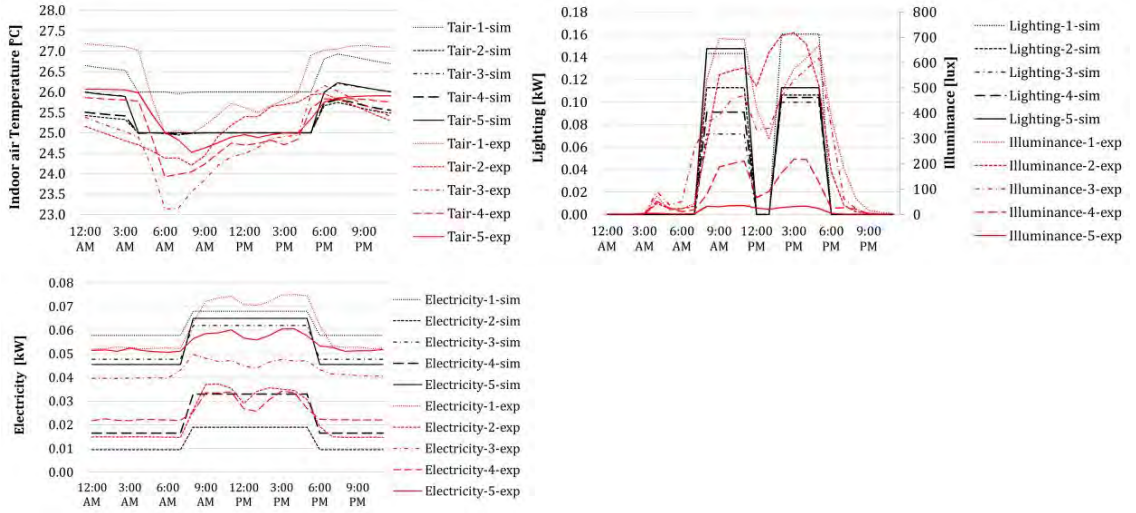

Figure 2. Average trend of data monitored in the five office room with respect to simulated data in a summer day. Up left) Indoor air temperature, Up right) Illuminance over the work plane vs. lighting energy use, Bottom) Appliances electricity use.

Table 1. Variation of occupants' subjective emotions level in different thermal conditions.

		Engagement	Excitement	Interest	Relaxation	Stress	Focus
base	User_1	61%	17%	58%	30%	99%	51%
	User_2	58%	28%	61%	33%	51%	38%
	User_3	57%	8%	55%	30%	54%	26%
	User_4	62%	26%	61%	32%	52%	38%
	User_5	58%	28%	65%	30%	50%	39%
1/2	User_1	61%	24%	60%	31%	99%	55%
	User_2	48%	24%	62%	39%	53%	35%
	User_3	56%	8%	56%	30%	53%	24%
	User_4	62%	25%	60%	30%	52%	41%
	User_5	58%	16%	64%	30%	51%	33%
1	User_1	56%	53%	56%	27%	59%	70%
	User_2	59%	29%	59%	31%	47%	39%
	User_3	56%	8%	62%	30%	59%	31%
	User_4	64%	26%	59%	32%	42%	37%
	User_5	58%	10%	64%	29%	54%	26%

CONCLUSIONS

The purpose of the present study is to verify the capability of different standard static and stochastic occupancy models to predict the behavior of real occupants of an office building. To this aim, occupancy behavior-related environmental and energy parameters were monitored in five rooms of a office building to develop experimental data-based occupancy models. Moreover, an EEG based tool is tested as complementary tool to improve occupant behavior understanding and prediction. Results show that the standard occupancy models are neither representative of specific occupants' preferences and peak energy demand nor of their averaged behavior, both in the short-term and in the long-term. In fact, the standardized existing procedures do not take into account the adaptability of human comfort and energy-saving or -wasting habits of office occupants. Conversely, the occupancy scenarios developed based on the experimental data showed to better represent the real daily occupants' attitudes, yet discrepancies are still noticed, due to inconstant human behavior affected by multi-

physical and non-physical stimuli. In this view, neural response tests are demonstrated to be a reliable tool to improve this multidisciplinary analysis. However, this method requires further investigations, by performing several tests, to provide outstanding results that strengthen the first findings obtained in terms of correlation between subjective emotions and environmental conditions.

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