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A multi-domain data collection strategy for capturing relationships between occupant behaviour, comfort, indoor environment, and energy use in offices

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Abstract: A significant corpus of research has shown that occupant behaviour is a key factor of uncertainty when predicting building energy use. Building occupants affect energy use directly and indirectly by regulating their indoor environment according to their comfort criteria and a wide range of contextual, psychological or social factors. Increasing research efforts are being dedicated on developing models able to capture the stochastic nature of the human-building interaction in dynamic simulation programs. However, existing models oftentimes do not include information on multi-domain variables and the global environment. The foundation for the investigation and data-driven modelling of occupant behaviour in the built environment remains measured data, and an effective and extensive data collection remains a key challenge towards gaining a better understanding and modelling of occupant behaviour. This paper provides a structured overview of a monitoring framework for open space offices, eCOMBINE (*"Interaction between **e**nergy use, **COM**fort, **B**ehaviour and the **IN**door **E**nvironment in office buildings")*, aimed at capturing an extensive set of subjective and objective multi-domain variables likely to drive building occupants to perform actions on environmental controls. Towards this end, this paper presents a survey framework and an ad-hoc mobile application developed to capture motivations behind actions in real-time. Finally, we highlight lessons learned and research opportunities one might envision once the collection of such comprehensive datasets will become more mainstream.

Keywords: occupant behaviour; open space office; user interface; global environmental comfort; energy use

1. Introduction

Improving energy efficiency has become a challenge of primary importance for the building sector, which nowadays accounts for approximately 40% of the global energy demand and generated annual global GHG emissions (European Commission 2010). Increasing effort is put on designing high performing and adaptive buildings that can hit energy performance targets while considering comfort preferences of the occupants. Dynamic Building Performance Simulation (BPS) tools are increasingly used by researchers and practitioners to gain a more precise understanding of the underlying processes of energy flows and to optimize building design and energy use. Despite advances in the field of BPS tools, simulation outcomes are still prone to errors due to a variety of factors such as non-linearity, discreteness, and uncertainty (Hopfe and Hensen 2011). ASHRAE (2007) states that neither the proposed building performance nor the baseline building performance represent actual energy consumption after construction, but that the key items from the listed sources of uncertainty are strictly related to occupancy and building operation. Hence, nowadays, the building energy research community is aware of the pivotal role that occupant behaviour has on impacting both building energy demand and the quality of the indoor environment (Masoso and Grobler 2010; Mahdavi 2011). To reduce current inconsistencies in building energy simulation, several probabilistic and data-driven modelling approaches have been developed, and integrated into advanced simulation programs to account for uncertainties related to human factors when predicting building energy consumption (Hong et al. 2018). These approaches include models for occupancy patterns, occupants' activities, adjustment of thermostat settings, or usage of plug-in appliances, and sometimes also aim to anticipate the operation of windows and lighting controls or the regulation of window blinds/shades as functions of various environmental and contextual drivers (Gaetani et al. 2016).

1.1 State-of-the-art

Yan et al. (2015) have attempted to describe the current state and future challenges in occupant behaviour modelling, where they emphasized the many remaining knowledge gaps and the limitations of current methodologies. The same authors also highlighted the importance of moving towards more comprehensive modelling procedures of occupant behaviour, acknowledging that the latter might be influenced by multiple contextual and personal factors. Oftentimes existing models do not yet accurately cover an extensive set of potential drivers and/or do not include qualitative model inputs (e.g. individual characteristics and preferences over the indoor environment). Indeed, individuals tend to perceive the indoor environment in different ways based on multiple factors to which they give a variable importance, to have different motivations and habits, and/or to sometimes be conditioned by certain constraints (e.g. social or technical) when it comes to adjusting their own environment to their liking. While many studies have linked human factor to single comfort-related stimuli, a comprehensive understanding and, therefore, evaluation of environmental comfort, addressing thermal comfort, visual comfort, acoustic comfort and indoor air quality together, seems to be necessary before being able to establish causal relationships with occupant behaviour. The new IEA-EBC Annex 79 "Occupant-Centric Building Design and Operation" (IEA 2019) represents an international effort towards understanding the exposure of the occupant to a multi-dimensional environment and its impact on behaviour and comfort. A key challenge in this endeavour will be to better understand how multiple, interdependent indoor environmental factors may trigger occupant actions.

A number of researchers have put effort on developing more comprehensive IEQ monitoring systems to assess the quality of buildings (Parkinson et al. 2019, Heinzerling et al. 2013, Alavi et al. 2017). However, despite the advancements in our understanding in separate fields of comfort (visual, thermal, indoor air quality (IAQ), acoustics), the question of how the combined effect of IEQ factors affects the ultimate users' perception and behaviour in real buildings has not yet been answered (Schweiker 2017). For example, while a large number of studies addresses the relationship between behaviour and thermal, IAQ, and visual aspects, the acoustic dimension has been mostly overlooked. This gap might also be due to the fact that researchers focus on their own area of expertise and priority is not given to analyse the global environment as such, neither in direct relation to human-building interactions. Multidimensional comfort studies would ideally require a collaboration between experts in different areas to achieve high quality results. Furthermore, multi-dimensional monitoring campaigns can turn out to be costly, leading to restrictions in the feasibility of this type of studies (Parkinson et al. 2019). The high cost of such complex monitoring campaigns can also limit the type and the number of buildings or space typologies (small private vs. open space offices) that can realistically be selected as case studies, the number of observed occupants, and/or the duration of the study, which in turn will limit the generalisation potential of the gathered datasets. To develop more reliable models, we need comprehensive datasets, that capture key variables both related to the environment and to the occupants (Wagner et al. 2017). And to be able to rely on different datasets – each one having its own limitations – to build a more comprehensive understanding, they must be comparable and thus be collected with a consistent data collection strategy (Yan and Hong, 2018), so that they can be replicable.

1.2 Towards a multi-dimensional approach

The newly-developed eCOMBINE framework (*"Interaction between* ***e****nergy use,* ***COM****fort,* ***B****ehaviour and the* ***IN****door* ***E****nvironment in office buildings"*) aims at contributing to new knowledge on the human-building interactions in office environments, with a dedicated focus on open plan offices, by developing an integrated approach to study the cause-effect relationships between occupant behaviour and combined indoor environmental factors (thermal, visual, air quality and noise). The data collection involves environmental variables, including the 4 IEQ categories (thermal, IAQ, visual, and acoustics), occupant's input (personal characteristics, comfort perception and actions) through point-in-time and long-term surveys. Surveys indeed remain important to understand the experience and motivation of users, while physical measurements of the occupants' environment provide an objective characterization of the indoor and outdoor conditions that they are exposed to.

The objective of this paper is to provide insights on the multi-dimensional eCOMBINE data collection framework. This framework includes a monitoring of the four key dimensions of the indoor environment (thermal, IAQ, visual, acoustic) performed simultaneously with a survey of the occupants' preferences and action triggers. To conduct the latter, an ad-hoc mobile application named OBdrive was developed, that captures the perceived motivations behind interactions with building controls.

2. The eCOMBINE monitoring framework

The eCOMBINE data collection framework aims to capture relevant variables to describe the relationship between the indoor and outdoor environment, global environmental comfort, occupant behaviour and energy use, as illustrated in Figure 1. With the term "global environmental comfort" the authors refer to an overall comfort estimation based on occupant's subjective votes from four IEQ categories, namely: thermal, visual, olfactory, and acoustical comfort. The data in this research project consists of newly collected and falls into four key categories: (i) environmental factors, (ii) occupant behaviour indicators, (iii) energy consumption, and (iv) answers to a survey. The objective is to highlight key influencing factors and the most relevant motivations behind the interaction occupants have with controls, in relation to their perception of comfort and physical measurements of the environment. To be able to reveal potential seasonal effects, the study was carried out in different seasons for a minimum of two weeks in selected open space office buildings with a minimum of 40 participants in total for each monitoring campaign.

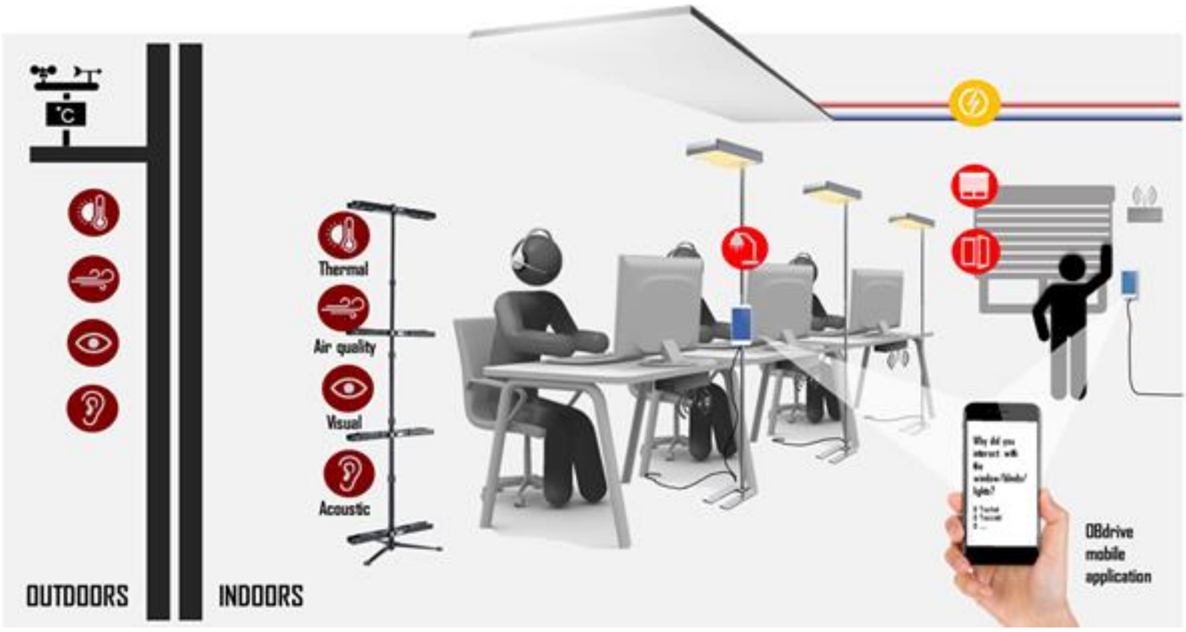

Figure 1. Simplified rendering of the eCOMBINE campaign used to inform occupants on the environmental, behavioural and energy monitoring (burgundy, red and yellow logos). Occupants are triggered to report comfort and motivation via desktop and app surveys.

2.1. Environmental data

The detailed list of measured physical variables (and their associated sensors) can be found in Table 1. The variables are classified by IEQ categories: thermal comfort, indoor air quality, lighting and acoustics.

2.1.1. Thermal environment

Data on a wide range of thermal variables were collected in order to capture global microclimate and local discomfort parameters. Air and globe temperature, relative humidity, and air speed were measured at the desk level of occupants (between 0.7 and 1.2 m height). Draft rate, vertical air temperature difference between the ankle and head level, and radiant temperature asymmetry (in vertical and horizontal plane) were measured to evaluate local thermal discomfort. In addition, outdoor environmental measurements were taken with a dedicated weather station installed on-site, that monitored outdoor air temperature, relative humidity, precipitation, wind speed, wind direction, and solar radiation.

2.1.2. Indoor Air Quality

In order to better understand whether and to what extent office workers were exposed to various airborne pollutants, the eCOMBINE project monitored the temporal and spatial variation of gaseous and particulate air pollutants at multiple locations in the office environment. Specifically, five types of sensors were used for monitoring seven major air pollutants indoors and outdoors, including carbon dioxide (CO_2), total volatile organic compounds (TVOC), formaldehyde, ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter smaller than 2.5 microns ($PM_{2.5}$).

2.1.3. Visual environment

Visual comfort, views and lighting conditions play a fundamental role in ensuring a satisfying and healthy occupant experience in buildings. Discomfort glare is known to be one of the major sources of complaints in offices and was thus part of the key factors to monitor. On the other hand, we have in the last 20 years become increasingly aware of the critical role played by light in synchronizing our internal clock. The so-called non-image forming effects of light, mediated by the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs), have a demonstrated impact on human health and well-being, and must thus be carefully taken into account when discussing the environmental quality of the workplace (Amundadottir et al. 2017). Of particular importance to those effects are the intensity, spectrum and timing of the light exposure, as it may trigger both phase-shifting (circadian, e.g. impacting sleep quality) and acute effects (e.g. impacting alertness). This project offered the first opportunity to continuously measure both light spectrum and intensity in a Post-Occupancy Evaluation (POE).

2.1.4. Acoustic environment

Workspace noise can cause stress or fatigue and be distracting, resulting in a decrease of productivity. Despite its importance in the perceived quality of a workspace, acoustic quality remains a difficult parameter to assess in the context of post-occupancy evaluations, mostly because of the evaluation method. As measurements typically require some form of recording, they are often perceived as intrusive. In this project, it became a priority to address privacy concerns through a careful selection of the measurement device: the chosen approach was to record sound pressure level integrated over time as well as at the different octave bands without recording people's conversations while they work.

Table 1. Summary table of the physical measurements for the four IEQ categories.

	I/O[1]	**Parameter[2] (unit)**	**Accuracy**	**Sensor**	**Frequency/Location**
Thermal environment	I	T_a (°C)	±0.15°C	Digital thermometer	every 5'/every 2-3 workstation
		T_{globe} (°C)	±0.15°C	Digital thermometer	
		RH(%)	± 2.5%	RH sensor embedded in the datalogger	
		Radiant temperature asymmetry	±0.20°C	Thermocouples (T-type)	
		Air velocity (m/s)	±0.02 m/s ± 1.5% of reading	Omnidirectional anemometers	every 0.2'/every 2-3 workstation
	O	Ta (°C)	±0.60°C	Digital weather station	every 5'/roof
		RH (%)	±3%		
		Solar radiation (W/m^2)	±5% of measurement		
		Wind speed (m/s)	±0.3 m/s		
		Wind direction (°)	±5°		
		Precipitation (mm/h)	±5% of measurement		
Air quality	I	CO_2 (ppm)	±50 ppm ±5% of reading	Nondispersive infrared (NDIR) CO2 logger	every 5'/every 2-3 workstation
		CO (ppm)	±2 ppm	Multigas sensor	every 5'/every 2-3 workstation

		SO_2 (ppm)	±2 ppm		
		O_3 (ppm)	±2 ppm		
		CO_2 (ppm)	±3% of reading (ppm)		
		Formaldehyde (ppb)	LOD[(3)] < 5 ppb		
		TVOC (ppb)	LOD[(3)] < 5 ppb		
		CO_2 (ppm)	±7% of reading (ppm)	Air quality sensing module	every 15'/every 2-3 workstation
		TVOC (ppb)	±14% of reading (ppb)		
		NO_2 (ppb)	±30 ppb		
		$PM_{2.5}$ mass (µg/m3)	±10 µg/m^3 ($PM_{2.5}$)		
	O	CO_2 (ppm)	±7% of reading (ppm)	Air quality sensing module	every 15'/roof
		NO_2 (ppb)	±30 ppb		
		TVOC (ppb)	±14% of reading (ppb)		
		$PM_{2.5}$ mass (µg/m3)	±10 µg/m^3 ($PM_{2.5}$)		
Visual environment	I	Illuminance meter (lux)	±10% of reading (lux)	Photodiode sensor connected to a data logger	every 5'/every 2-3 workstation (horizontally-mounted)
		Spectral intensity (W/m^2/nm)	±25nm resolution	Optical spectrometer sensor with embedded data logger	every 5'/near each façade and near the core (vertically- / horizontally-mounted)
		High Dynamic Range (HDR) image	-	Digital single-lens reflex camera	1x per season (spot measure)/every 2-3 workstation
		Luminance meter (handheld) (cd/m^2)	±2% ±1 digit of reading (cd/m^2)	Luminance Meter	1x per season (spot measure)/every 2-3 workstation
		Illuminance meter (handheld) (lux)	7% of reading (lux)	Photodiode sensor (hand held device)	1x per season (spot measure)/every 2-3 workstation
	O	Global (Total) and Diffuse irradiance (W/m^2)	5% ±10 W/m^2	Pyranometer	every 5'/roof
Acoustical environment	I	SPL across the octaves (dB)		Integrating averaging sound level meter	every 1'/every 2-3 workstation

[(1)] I/O = indoor/outdoor

[(2)] Acronyms used for the parameters: Ta = indoor air temperature, Tglobe = globe temperature, RH = relative humidity, CO = Carbon monoxide, CO_2 = Carbon dioxide, TVOCs = Total Volatile Organic Compounds, NO_2 = Nitrogen dioxide, SO_2 = Sulfur dioxide, O_3= Ozone, PM=Particulate matter, SPL = Sound pressure level

[(3)] LOD = limit of detection

2.2. Occupant Behaviour

In the eCOMBINE pilot study, four different types of occupant behaviours were tracked: window control, window blinds control, light switching and occupancy (Table 2). Thermostat and mechanical ventilation controls were neglected since occupants in the planned pilot case studies did not have direct control over the space heating and cooling system. If in future case study buildings such kinds of controls were to be available, these types of human-building interactions should also be tracked through the building management system or a dedicated sensor network. If employees have no control over space heating, cooling, and mechanical ventilation systems, operating windows and blinds remain the only possible (human-building) actions that allow for improving thermal comfort. The impact on energy use of these not automatically controlled interactions needs to be carefully evaluated and is a main point of investigation of the eCOMBINE project.

Table 2. Summary table of measurements for occupant behaviour tracking.

Behaviour	Parameter	Sensor	Frequency/Location
Window control behaviour	Window state position	Bluetooth enabled low energy contact sensors	Event-based/on window frame
Window blinds control behaviour	Window blinds position	Wireless window blinds	Event-based/on slats
Light switch behaviour	Instant power	Wireless smart plug load meter	1'/on desk light plugs
Occupancy	Presence at desk	Wireless occupancy sensor	5'/under each desk

2.3. Energy metering

The monitoring of energy use by HVAC systems, one of the main energy users in office buildings, is essential for bridging the gap between the real performance with predicted values from building energy simulation outcomes. Monitoring approach and instruments to measure energy use should be selected based on the specifics of the BMS system and HVAC system installed in the case study building. If energy metering is pre-installed in the case study building, it is possible to get direct measurements. However, in some cases, no direct metering of the energy usage by the HVAC system is possible either because of no energy metering pre-installed or no possibility to retrieve energy use for conditioning and ventilation of a particular zone. It was the case in the COMBINE pilot study, where studied office areas were in large office buildings. The energy use by the HVAC system was indirectly measured by recording thermal energy removed or supplied to space by the thermal conditioning system and required pre-conditioning of fresh air for adequate ventilation. Heating and cooling in one case study office were provided by radiant ceiling panels, while only radiators for heating were used in the second case study office. Heat supplied/removed from the space was measured using heat flux sensors placed directly on each heating/cooling surfaces. Supplied fresh air for ventilation was pre-conditioned in one of the case study spaces, and thermal energy provided for pre-conditioning was estimated by knowing the volumetric air flow rate and the temperature difference between the outdoor air and air supplied into office space. The volumetric air flow rate was measured at the air supply diffusers by means of a ventilation hood and dedicated read-out device, while hourly air temperature difference was taken from the BMS system.

2.4. Survey framework

The eCOMBINE project relies on a mixed experimental approach that combines environmental measurements with subjective responses of the occupants. The study involves two types of long-term (LT) questionnaires and three types of point-in-time (PIT) questionnaires, as detailed in Table 3 and 4, respectively.

The LT surveys were designed to gather occupant's background information and general comfort perception. They fall into two categories:

- **LT-A** captures employees' general personal data and information not sensitive to seasonal variations (e.g., personal characteristics, work routines, global personal preferences). It occurs only one time over the entire study.
- **LT-B** captures the occupant's general comfort preferences, perception, satisfaction, knowledge of control, and usual group dynamics in the office. As these responses might change with seasons, this survey was conducted at the end of each seasonal monitoring campaign.

Table 3: Detail of the eCOMBINE long-term surveys.

Survey type / name	**Contents**	**Timing (duration)**	**Tool**
LT-A: Background information of the participants	• Background (gender, age, height, weight, eye colour, use of glasses or lenses, origin, time spent in the country/at this office space) • Workstation & working routines (position, location on floor plan, working days / week, type of office work) • Personal comfort perception: sensitivity (5-pt scale) and preferences (5-pt scale) to temperature, air freshness and air movement, light, noise. • Perception and satisfaction (7-pt scale) of control (perceived control related to the thermostat, windows, window blinds, desk lights, ceiling lights, and mechanical ventilation; level of difficulty to interact with controls; satisfaction (7-pt scale) with controls, preferences in terms of manual or automatic controls) • Control and group dynamics (environmental control decision-makers, most important reasons when taking an action, (dis)agreement with energy- and action-related statements)	once (at the start of the study) (10')	PC (triggered by e-mail)
LT-B: Seasonal perception of global (dis)comfort	• Workstation & working routines (position, location on floor plan, working days / week, type of office work) • Satisfaction with the indoor environment over the past two weeks (satisfaction with the thermal, IAQ, visual, acoustic environment; investigation of causes for dissatisfaction and discomfort) • Control and interaction (frequency of reporting the action on the app, frequency of discussions/negotiation with co-workers, causes for not interacting with controls) • Adaptive opportunities (selection and ranking of actions taken when feeling too hot/cold)	1x /season (5-10')	PC (triggered by e-mail)

PIT surveys were designed to gather direct feedback on comfort perception and on motivations behind occupants' interactions with controls over the two weeks of monitoring that were run during each season. They fall into 3 categories:

- **PIT-A** captures occupants' general perception of experience comfort 'right-now'. It touches all 4 IEQ categories. It occurs twice a day, at specific times of the day. Occupants are invited via an email to complete the survey on their desktop.
- **PIT-B and PIT-C** capture the occupants' actions, motivation behind these actions and group dynamics (social interactions). PIT-B covers window and window blinds control (opening/closing), and PIT-C desk lights controls (switch on/off, dim up/down). These surveys occur when specific actions are completed. They are administrated via mobile phones installed right next to controls (windows and light switch). The *OBdrive* app was developed for the purpose of the eCOMBINE project (see Figure 2).
- **PIT-D** captures occupants' glare perception. It occurs towards the end of each seasonal monitoring campaign, when direct sun enters the workspace. It is supplemented by High Dynamic Range (HDR) photographs and spot luminance measurements (taken at the workstations) to inform on the luminance distribution in the field of view.

These subjective responses of the occupants were matched with the environmental measurements of the indoor environment to allow for a comparison. Conducting qualitative and quantitative analyses in parallel enabled to offer a better understanding of cause-effect relationships between drivers and actions.

A general prerequisite for the design of all point-in-time surveys was the minimization of number of questions and input needed in order to allow for a simple and fast compilation of the questionnaires. Therefore, the drop of response rates due to survey fatigue is to be reduced as much as possible, while still gathering all information necessary to answer the selected research questions. As an example, daily surveys (PIT-A, B, C) were designed to take under 1 minute to be completed.

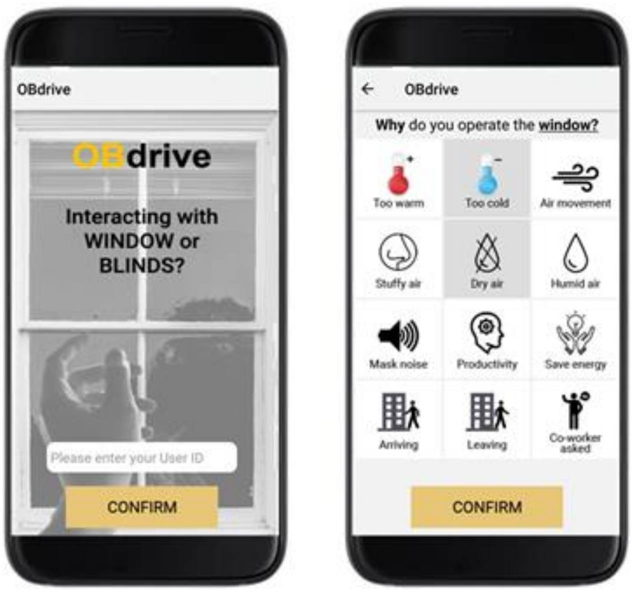

Figure 2: Selected screenshots from the *OBdrive* application: PIT-B on window control motivations.

Table 4: Detail of the eCOMBINE point-in-time surveys.

Survey type / name	**Contents**	**Timing (duration)**	**Tool**
PIT-A: Perception of global (dis)comfort in the workspace	● Metabolic rate, clothing insulation, ● Perception of the global environment (thermal, IAQ, visual, acoustic) on a 5-pt scale (extremely uncomfortable to comfortable) ● Preferred or desired changes of: ○ temperature (colder/no change/warmer) ○ air movement (less/no change/more) ○ air (no change/fresher air) ○ humidity (less /no change/more) ○ light (less /no change/more) ○ contrasts (less/no change/more) ○ noise (less/no change/more) ● Branching question on the sources of discomfort related to the thermal environment (e.g. hot/cold surfaces, hot/cold body parts, drafts), the indoor air quality (e.g. strong odours), the visual environment (e.g. glare, reflection on screen), and the acoustic environment (e.g. outdoor noise, indoor noise)	2x /day (1')	PC (triggered by e-mail)
PIT-B: Motivations behind window/window blinds control behaviour	Indication of the action, motivation and interactions: ● Type of action: ○ opening/closing windows ○ opening/closing window blinds ● Motivation behind: ○ *window operation*: too warm, too cold, air movement, stuffy air, dry air, humid air, mask noise, productivity, save energy, arriving, leaving, co-worker asked ○ *window blinds operation*: too warm, too cold, prevent overheating, too bright, too dim, glare, reflection, view outside, save energy, arriving, leaving, co-worker asked ● Report on consultation with co-worker(s) before interacting with controls (gain understanding on the social norms and dynamics in the work environment)	Every time an action is performed (1')	OBdrive app
PIT-C: Motivations behind light switching behaviour	● Type of action: turn on/off light, dim up/down light ● Motivation behind: ○ *lighting operation*: too bright, too dim, glare, reflection on screen, reflection on desk, save energy, arriving, leaving, co-worker asked ● Report on consultation with co-worker(s) before interacting with controls (gain understanding on the social norms and dynamics in the work environment)	Every time an action is performed (1')	OBdrive app
PIT-D: glare perception	● Overall comfort on a 5-pt scale (extremely uncomfortable to comfortable) ● Glare perception (4-pt scale from imperceptible to intolerable) and reflexions on screen (yes/no) ● Satisfaction with view out (7-pt scale) and obstruction rating of the shading device (4-pt scale)	1x /season, (right before glare measures) (5')	PC or paper form

3. Lessons learned: challenges and opportunities of the chosen approach

This section is aimed at providing first insights into the challenges and opportunities of the developed framework and the in situ monitoring study.

Finding case-study buildings

The preparatory planning phase involved the selection of suitable case study buildings that meet the requirements of an open space office and in which employees have the possibility to interact with controls (windows, blinds, lights). However, the increasing number of automatization processes of environmental control through BMS (e.g. not openable windows and automatic lighting or window blinds controls) made many office spaces unsuitable. Communication protocols with existing building systems shall be accurately verified to ease the retrieving of valuable data (e.g., energy use). Further, our protocol requires the consent of both the building manager and the occupants to a dense monitoring strategy. Employers might be concerned by the involvement of their employees in the study (e.g. time needed to fill the surveys). Finally, privacy issues (e.g. concerns of having microphones and phones in the space) needs to be clarified carefully. It is hence of primary importance to clearly outline expectations and implications of the study from the start in order to avoid that case-study buildings renounce to participate during the course of the project.

Occupant's involvement

The active involvement of occupants is a key to a successful implementation of the proposed eCOMBINE framework. Gathering direct feedback from the occupants allows to gain insights on the motivations behind their actions. However, it is not realistic that all employees agree to participate in the study. It is hence possible that participating and non-participating employees sit side-by-side and that the latter feel disturbed by the neighbours' sensors. We also experienced that the tolerance of participating employees varied significantly. Some occupants were concerned about having sensors near them (e.g. fear that sensors may emit a signal that has negative impact on their health) or had privacy issues related to reporting personal or monitored data to their employers. A comprehensive information session at the start of the project is therefore essential to detail the functionalities (and safety) of the sensors and the precautions taken for data protection. Further, to maximize the participation rate, occupants were motivated to participate in the study with the provision of a gift at the end of each monitoring campaign. Additional incentives and motivation strategies (e.g. peer comparison, social or monetary rewards) should be investigated, but might conflict with privacy concerns or the willingness to share personal attitudes and data with co-workers.

During the monitoring phase, ideally, the employees should pursue their normal habits and everyday activities in their usual work environment. However, a comprehensive monitoring campaign (like eCOMBINE) has the down-side to increase the *Hawthorne effect*, which means that occupant's knowledge of being studied might affect their natural behaviour (Adair 2000). It is therefore preferable that researchers avoid invading the studied spaces (Wagner et al. 2017) and we planned our site visits and installation of the sensors during non-working hours. When this was not possible, we made sure to assemble multiple sensors on stands beforehand to ensure a quick set-up and minimize the disturbance of employees. Since the campaign stretches over four seasons, it is expected that occupants eventually notice the presence of the sensors less and less and this type of study therefore presents an interesting opportunity to evaluate the Hawthorne effect analytically.

Finally, we noticed that occupants who were particularly dissatisfied with their work environment provided extensive feedback (comparable to a "complain log") with the hope that somebody intervenes to improve their situation. It is therefore essential to clarify the researcher's role in order to manage expectations.

Sensors deployment

The monitoring framework foresees the installation of a wide range of sensors (multiple dimensions with high spatial resolution), and is more cost-intensive than more classical one-dimensional campaigns. Since measurements are taken at different resolutions (workstation vs. office level), the study provides the opportunity to identify the minimum set/kit of sensors that would be needed to usefully describe occupant behaviour, so as to move towards cost-effective solutions with maximum information.

In order to measure many parameters at one location, different sensors had to be assembled on stands. Setting up a neat and non-invasive sensor environment is not a trivial task and needs to be planned carefully so that sensors do not interfere with each other. Occupants shall be made aware of the functionality of the sensors in order to not alter it (e.g. by covering them). Further, data acquisition from many different sensors implies possible redundancy and time-stamp misalignments. These issues should be tackled in advance to save storage space and ease the post-processing of the data. The development and deployment of integrated Internet-of-Things solutions might be useful to further optimize the data acquisition. On the other hand, we noticed that having a large number of wireless sensors in the open space could lead to connectivity issues with important data loss. It should finally be noted that the installation and maintenance of sensors, as well as the analysis of gathered data considering the their data and diversity, requires research manpower and knowledge from sometimes very different fields, best handled through interdisciplinary collaborations.

Replicability of the approach

Each case study building represents its own challenges due to different limitations related to the building envelope and system characteristics, space layout, and available controls. The eCOMBINE framework provided an opportunity to move closer to a unified multi-dimensional approach for investigating the cause-effect relationships between the indoor environment, energy use and occupant behaviour.

4. Conclusions and research opportunities

This paper introduced the eCOMBINE monitoring framework that aims to collect and synthesize an extensive dataset that will permit a deeper understanding on the cause-effect relationships between human-building interactions, global environmental comfort, the indoor environment, and energy use. Detailed monitoring strategies for the collection of objective (indoor and outdoor environment, occupant behaviour and energy metering) and subjective data (survey framework) were described, including the challenges and lessons learned. Such data is the starting point for a wide range of research opportunities towards a more comprehensive analysis of the human factor in the built environment, especially in terms of how the latter may influence both energy use and the indoor environment.

The large number of data collected together with their variety allowed us to engage in a multitude of prospective research paths, such as:

- Studying the combined effect of IEQ (multi-dimensional) and determining interactions between IEQ parameters on human perception of comfort and on behavioural actions. This would also include (non exclusively): (1) determining the importance of the different dimensions studied; (2) investigating what are the key drivers within one dimension; (3) investigating of the trade-off between sources of discomfort and interactions (e.g., occupants accept discomfort glare to enjoy the view outside (forgiveness factor)).
- Studying the impact of occupant's personal characteristics and preferences on adaptive actions.
- Studying the impact of behavioural actions on indoor conditions and on energy use.
- Analysing human-human interaction in terms of impact of group dynamics and social norms on occupant behaviour in open-space offices, especially as they pertain to agreement/disagreement on comfort and on control of the environment
- Developing a model of occupant behaviour (OB) able to capture and predict human-building interactions in open-space offices. This model would have the potential to further bridge the gap between measured and predicted energy use.
- Comparing subjective responses (in particular motivations for action captured via *OBdrive*) with existing comfort and behavioural models.
- Investigating impact on human health: the multi-dimensional sensing strategy would allow us to determine long-term exposure to air pollutants, noise and daylight for each occupant.
- Developing a fully-calibrated simulation model. Such a model can then be used to analyse indoor scenarios (e.g., desk-positioning) and improve indoor building design in regard to IEQ and energy.

The aim is to extend this study to other office buildings, ideally in different geographical locations, and make the datasets openly accessible. It is hoped that fully anonymized open access datasets will be made available by other groups so they can be shared amongst researchers to further advance our understanding of the complex inter-relationships between comfort, energy and behavioural aspects.

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