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Façade impulse: experimental methods for stretching the envelope beyond human comfort

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Abstract
Façades are the primary means of modifying undesirable external conditions to achieve a desirable internal environment. Their energy-efficient performance has often been associated with low-energy buildings. However, the building envelope has a very significant and more direct impact on occupants beyond energy-efficiency. As multisensorial filters, façades have the potential of connecting occupants to the outdoors, while simultaneously moderating the energy and mass flow to positively impact occupant comfort, satisfaction and productivity. In order to understand their impact on human factors, the Façade Impulse research project aims to stretch the intelligent and smart envelopes beyond human comfort, to include their interaction with occupants. This paper presents the methodology and experimental facility developed to assess the transient and multi-sensorial effects of alternative façades technologies. Façade Impulse was conceived as a joint project between the University of Cambridge, Arup and Permasteelisa. A bespoke test cell, called MATELab, has been built in order to validate and quantify the façade effect on office-like environments and occupants in the UK. In parallel, experiments in real offices have been performed with a novel IoT sensor polling station to collect high-frequency occupant feedback. Initial results and future short-term work are presented and discussed in this paper.

1 Introduction

Highly-performance façades have a prominent role in achieving resource-efficient buildings [1], [2]and they are also primarily indoor climate modifiers, strongly affecting occupant satisfaction and productivity in the workplaces [3]. Intelligent façades connect occupants to the outdoors and moderate the energy and mass flow. They therefore provide a largely unexploited potential of providing optimal environmental conditions. These façades represent promising answers to healthy built environments in the austerity of climate change policies and to the challenge of the predicted surge in urban population by 2050 [4]. However, the façade properties and interaction strategies that satisfy occupant demand for a favourable environment are yet to be defined and, often, occupants are unsatisfied with their workplaces [5], despite the larger energy consumed to condition them. This is partly due to the complexity of capturing transient and holistic occupant response [6] and the challenges of including these considerations in the early-design stages. This uncertainty of occupant response becomes even more relevant and acute with adaptive / smart / intelligent façades, which could be beneficial for occupant comfort and productivity if their design and control is tailored to actual occupant preferences. Several researchers have already started to follow a different "fit-for-purpose" approach [7] or to analyse human response with a different experimental and holistic approach [8], however the experimental investigation of occupant response and reaction still presents several challenges [8], namely: (1) Accurate sensors and their calibration are expensive. However, cheaper wireless sensor technologies are becoming widely available and might offer a less accurate but feasible solutions for large scale deployment [8; 9; 10]; (2) The vast amount of data and the time associated with deploying sensors across large buildings can often be impractical. The environmental monitoring through sensors has two main critical factors: a) the choice of the right location to capture the actual effect on occupants b) the choice of the correct sampling frequency for the recording of the environmental value; (3) There is a lack of guidelines for the experimental assessment of IEQ (Indoor Environmental Quality); (4) Capturing actual occupant response and human factors is challenging and it is difficult to gather occupant feedback with a sufficient accuracy and frequency, yet without unduly disrupting occupants.

"Façade Impulse", a joint multi-disciplinary research project between the University of Cambridge (the Departments of Engineering and Psychology), Arup and Permasteelisa, aims to capture the holistic and transient effect of intelligent façades on occupant comfort, satisfaction and productivity. The final objective of this research is the development of an early-design stage tool to assess the holistic effects of façades on occupant comfort and productivity. The research experimentally investigates holistic and transient occupant response to different façade technologies in two different workplace environments: real offices and MATELab (Mobile Adaptive Technologies Experimental Lab), a novel bespoke experimental facility for assessing the holistic effects of façades on occupant comfort, satisfaction and productivity. In parallel, experiments are also performed in real offices in London and in Italy in order to cross-validate the experimental results from MATELab. In this way, results are collected for different seasons and time of the year in order to assess façades in different conditions. The principal novelty of these experimental methodologies is the special focus on capturing subjective, transient and local occupant response in holistic terms whilst developing non-intrusive systems of data collection.
Methods from Engineering and Architecture to monitor the IEQ include experimental quantitative monitoring of environmental conditions through sensors, sometimes integrated with subjective assessment of occupant response, or simulations and theoretical assessment of the environmental conditions.

2 MATELab: a novel Mobile Adaptive Technologies Experimental Lab

Previous studies were often performed in small climatic chambers [11, 12], several examples are reported in Wagner et al. [13]. However, results from climatic chamber tend to be unrealistic or not comprehensive since the environment and the occupant behaviour mutually affect each other and, hence, to capture realistic environmental preferences of occupants it is important to perform investigations, where possible, in real-world office environments in order to capture all relevant data and to avoid experimental bias. The real-world offices, on the other hand, are difficult to control and modify without major disruption. MATELab represents an intermediate step between high precision, but unrealistic lab-scale tests and realistic, but difficult to control real-office environments. MATEALb is designed to capture occupant response in a controlled environment, reducing the bias of highly-controlled laboratory chambers whilst allowing accurate monitoring of the environmental and contextual variables affecting occupant response. An extensive review of the existing experimental facilities to assess human comfort and, especially, with regards to façades, was carried out in order to inform the design process. Existing experimental facilities are primarily intended for the assessment of façades energy performance, such as MoWiTT [14]. Few experimental facilities are currently available to capture the wide range of effects that façades induce on occupants [15] or they are usually equipped to capture one specific aspect of occupant response, such as visual comfort [16] or thermal comfort [17].

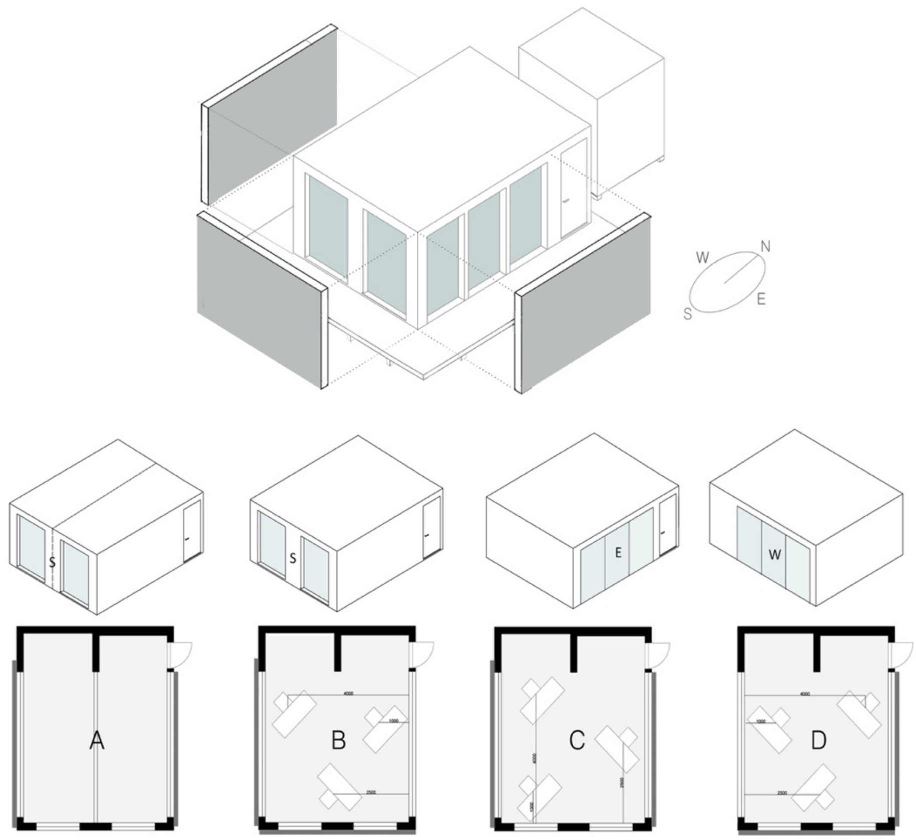

Figure 1 MATELab: design concept and plan of the possible permutations: (A) Configuration with two separate chamber for direct comparison and South orientation; (B) East orientation; (C) South orientation; (D) West orientation.

a)  b) 

Figure 2 (a) a picture of MATELab and (b) a view from the inside of the MATELab.

2.1 General information and design concept

MATELab is an office-like space of approximately 30 square metres with three glazed façades oriented towards south, east and west and designed to host up to three occupants. The location has been chosen to provide an open and green view from indoors (Figure 2). The design concept was to develop a flexible facility for assessing alternative façade technologies, either simultaneously by dividing the chamber in two parts (A in Figure 2), or separately but in three different orientations (B,C and D-Figure 2). MATELab is not rotatable, however the glazed façades can be easily changed and covered with opaque insulated panels in order to test alternative façade technologies in different orientations and according to research needs. MATELab is a flexible facility, also allowing changes in internal desks and furniture layout or to assess the façade effect at different distances.

2.2 Construction process and delivery

The facility has been designed for a rapid construction and assembly process on site (Figure 3). The main structure was manufactured at Permasteelisa offices in Schedelbouvw (Netherlands) from two shipping containers in order to simplify the transportation process and the construction work on site. The envelope is highly insulated with external profiled polyurethane panels and sealed in order to be adiabatic and providing both thermal efficiency and air tightness. In particular, the design and detailing has minimised thermal bridges and air infiltration.

2.3 Artificial services, energy monitoring and sensing technologies

The environmental services, namely artificial lighting, ventilation, heating and cooling, play a key role in the indoor environmental quality. From a research perspective, all the services in MATELab have been designed to avoid any local discomfort for occupants, providing sufficient levels of light when daylight is not available, or providing comfortable appropriate temperatures. MATELab can be transformed into a natural ventilated office, however it has been decided to start the investigations with a mechanically ventilated HVAC system in order to provide larger control on the environmental parameters. Due to the limited dimensions of MATELab, the main challenge of the design was to avoid any local discomfort effect due to asymmetries, proximity to ventilation grilles or inefficient artificial lighting. Hence, a careful design of the air flow velocities and temperature and of the lamp position and intensity was conducted to minimise building services impact on occupants.
The artificial lights are a LED technology suitable for computer work, complying with EN-12464 [18] and with tunable white for adjustable colour temperature in relation to the time of the day.
In terms of occupant control of the services, a personal control protocol was decided. Artificial lighting is always allowed when needed, but its use is monitored in order to compare the capability of the façades of allowing natural daylight while preventing discomfort glare or overheating. The control of artificial lights is then shared among all the occupants in order to reproduce real office

environments. However, specific central control strategies can be implemented according to the research needs. Lastly, MATELab can be separated in two chambers and the relative building services isolated in order to allow a direct and simultaneous comparisons of alternative façades energy consumption. Hence, the energy consumption can be monitored by either considering the entire MATELab or only half the facility, when divided in two chambers.

Sensors setup and logging system play a fundamental role in ensuring all the environmental and contextual variables are monitored, however their presence is also a bias factor towards occupants. The choice of environmental parameters to be monitored was informed from the extensive literature regarding the environmental effects on human comfort [19; 20]. MATELab has been equipped with a wide range of sensors in order to capture the holistic effect of façades on thermal, visual, acoustic, air quality comfort and, additionally, the interaction of the occupant with the intelligent or static façades (Table 1). There are three ways of capturing the occupant's interaction and usage of dynamic façades: 1) time-lapse photography of the exterior of the building façade (external dynamic shading devices), 2) sensors or control systems that can directly record occupant interaction with the façade, such as shade position or 3) behavioural observations [21]. A combination of all of them will be applied to MATELab. Time-lapse photography is less effective for venetian blinds, since precise slat angles are often not readable from photographs [22]. In MATELab, intelligent / dynamic façades are controlled by a Permasteelisa in-house control strategy system, which can also provide data on blind positions and occupant overrides.

Figure 3 Construction and delivery process on site of the MATELab

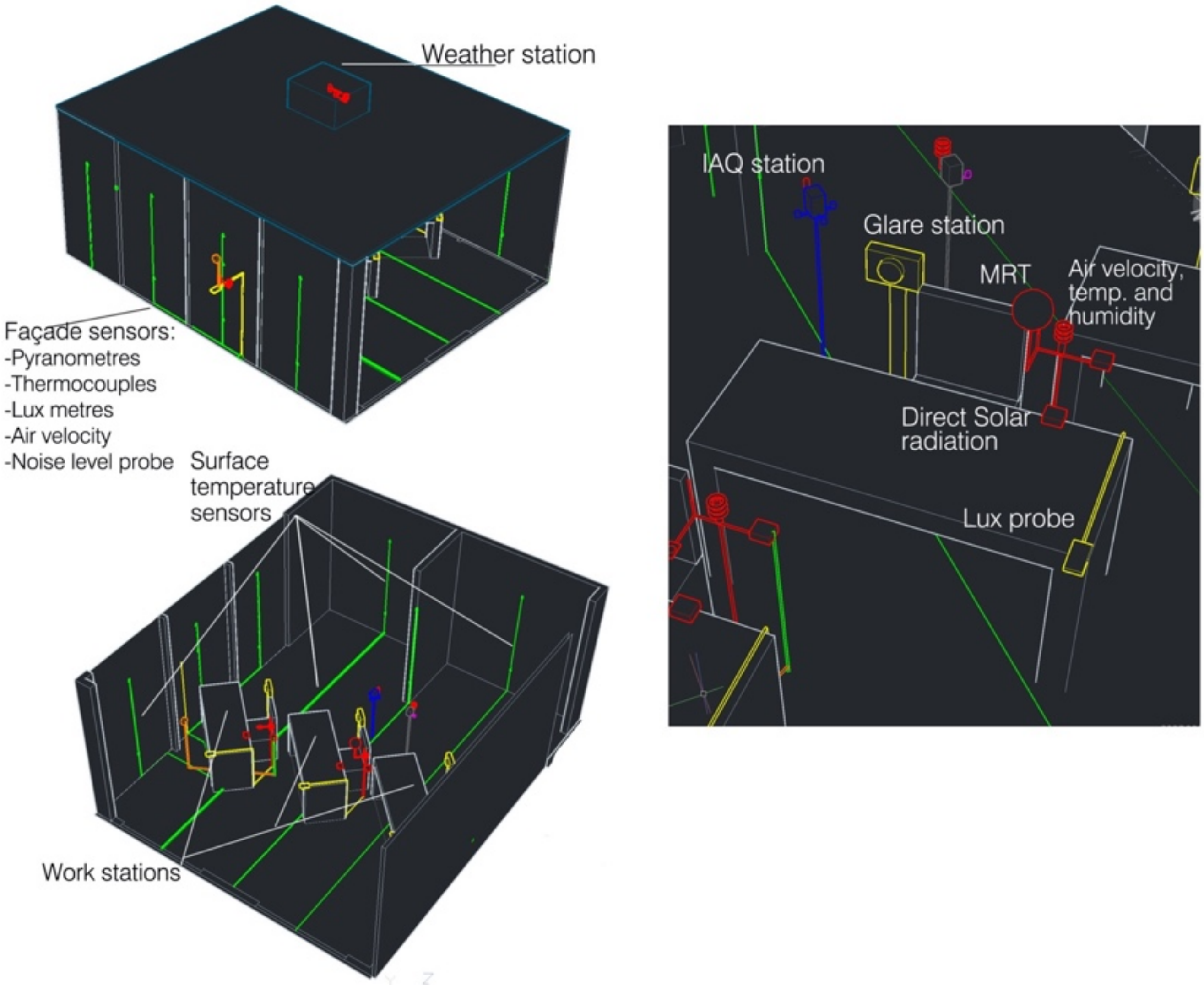

Figure 4 Sensor setup inside the MATELab

Table 1 Environmental parameters monitored in MATELab

Group of parameters	Environmental parameter	Sensor type	Sampling frequency	Location
Façade level	Solar irradiance	Pyranometer	10 minutes	Outer and inner façade surface
	Surface temperature	Thermocouples	10 minutes	Outer and inner façade surface in multiple positions
	Illuminance	Lux meter	10 minutes	Inner and outer surface
	Air temperature	Thermocouple	10 minutes	Inner façade surface at different location
	Air velocity	Hot wire anemometer	10 minutes	Inner surface at different heights at the center of the façade
	Radiant asymmetry	Net radiometer	10 minutes	1 meter from the façade
Local occupant comfort level	Noise levels	Noise level meter	10 minutes	Center of the room
	CO_2 levels	CO_2 meter	10 minutes	Center of the room
	VOC levels	VOC meter	10 minutes	Center of the room
	CO levels	CO meter	10 minutes	Center of the room
	Air temperature	Thermistor	10 minutes	Center of the room and at each workstation
	Air velocity	Hot wire anemometer	10 minutes	At each workstation
	MRT	Black Globe temperature sensor	10 minutes	At each workstation
	Illuminance	Lux meter	10 minutes	At each workstation
	Solar radiation	Pyranometer	10 minutes	At each workstation
	Humidity	Humidity probe	10 minutes	Center of the room
	Luminance levels	Glare station with DSLR and Vertical Illuminance sensors	10 minutes	At each workstation
	View clarity	HDR Images	10 minutes	At each workstation
	View occlusion	Time-lapse photography with DSLR	10 minutes	At each workstation
Building services level	Air temperature at the AC inlets	Thermocouple	10 minutes	At each inlet
	Air velocity at the AC inlets	Hot wire anemometer	10 minutes	At each inlet
	Artificial light colour	Colorimeter	60 minutes	Through the lamp control system and sensors
	Artificial light lux levels	Lux meter	60 minutes	Through the lamp control system and sensors

2.4 Experimental procedures

The experimental procedure in terms of sampling frequency and methodology has been devised to allow a constant and dynamic monitoring of both the environment and the occupant response. The façade technologies to be tested in MATELab during the first experimental cycle have been chosen and correspond to façades of the real-world offices in order to facilitate the cross-validation of experimental results.
The environmental and occupant response monitoring will be performed at three different distances from the façade, (1 m, 2.5 m and 4 metres) to capture the influence of the façade with increasing distance. In order to gain statistical significance on the experimental results, a large number of occupants are tested. The experimental procedure has been defined in collaboration with the Department of Psychology, and aims to minimise experimental biases. Occupants are asked to follow a pre-defined set of behavioural rules in order to guarantee a similar work environment across the experiments. Occupants are asked to work in MATELab for long periods in order to reduce the Hawthorne effect.

Occupant feedback is collected through traditional methods from behavioural science, such as surveys, and through a novel bespoke polling station, developed in order to maximise the sampling frequency in a non-imtrusive manner. The polling stations provide a valuable means for occupants to provide their (dis)satisfaction instantly and outside the pre-determined sampling times. In addition, novel methods for capturing indirectly occupant feedback, such as those based on facial recognition or physiological readings, will also be trialled. Lastly, the environmental and façade effect on productivity is assessed through periodical occupant self-assessments.

3 Experiments in real office environment

3.1 General description and experimental procedures

In parallel with experiments in MATELab, Façade impulse includes experiments in real-world offices. Consequently, the façade technologies tested in MATELab for the first experimental cycle correspond to those in the real-world offices façades. The two offices earmarked for investigation are located one in London (UK) and the other in Vittorio Veneto (Italy). The first office has a curtain wall with static double-glazed units with solar control coatings and manual internal venetian blinds (Figure 5). The second office has a double skin façade with an open cavity (Interactive wall by Permasteelisa) and dynamic automated venetian blinds. Similar experimental procedures will be followed in both locations, in order to collect comparable experimental results. In both workplaces, different user-façade interaction scenarios will be investigated in order to assess the effect of different levels of personal control and to isolate the effect of view on overall occupant satisfaction.

a)

b)

Figure 5 a) Arup office in London, Fitzroy street. b) Permasteelisa office building in Vittorio Veneto, Italy.

3.2 Sensing technologies and role of buidling services

For the experiment in real-world offices, a bespoke sensor setup has been developed for both the environmental monitoring and the collection of occupant feedback. The polling stations are similar to the ones deployed in MATELab, but the frequency of sampling and occupant involvement have been defined differently. In order to minimise any disruption to the daily office work, volunteers have been divided in groups and asked to perform the assessment only at alternative week days. The environmental monitoring is performed at both façade level and at several workstations, located at different distances from the façades (approximately 1, 2 and 4 metres) within the same open space.

Both office buildings have a central mechanical ventilation, where occupant overriding is not possible. Similarly, the artificial lighting system is centrally controlled, however occupants can use task lighting to improve their visual comfort.

4 Data collection, post-process and expected results: digitalising human comfort and connecting intelligences

The most novel aspect of this research is the experimental methodology, which has been specifically developed for collecting transient and holistic occupant response to alternative façade technologies, considering also the effect of distance from façades on occupant comfort and satisfaction. The first step was to understanding the most appropriate method to digitise data from occupant response and environmental conditions. In this sense, the main objective was to correlate transient changes in façade properties, including frequency, level and velocity of change, to occupant holistic levels of comfort and productivity in order to identify: 1) the main façade properties that trigger occupant environmental satisfaction and productivity in the workplace; 2) the optimal velocity and frequency of change in façade properties 3) the interaction strategies between occupants and façades that ensure satisfactory conditions in the workplace; 4) the optimal balance in multi-objective control strategies, particularly when the individual objectives are in conflict e.g. glare vs view and daylight vs overheating to maximise occupant satisfaction and productivity in the workplace.

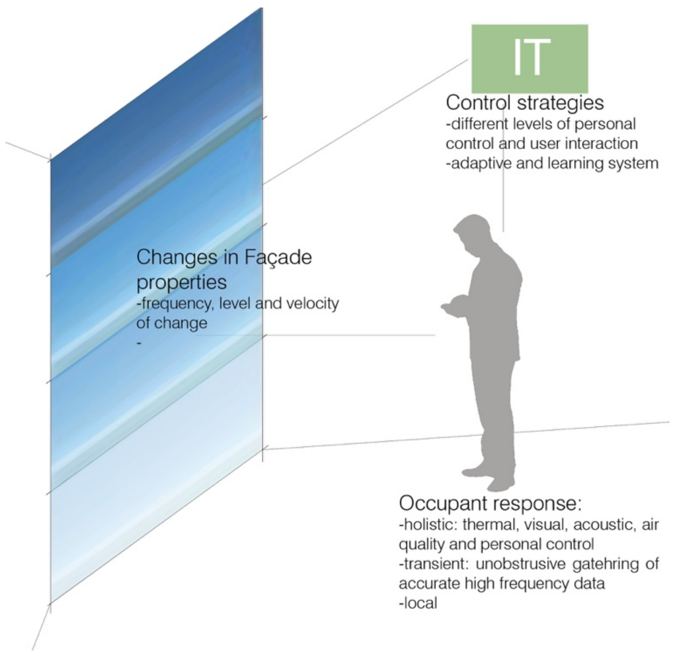

Figure 6 Diagram of variables captured by the experimental methodology

Continuous objective environmental monitoring of façades is currently feasible since high accuracy sensors technologies exist, which allow for high frequency sampling and efficient storage of digital data on environmental conditions. Consequently, the experimental methodology has been focused on capturing all the environmental parameters of façades that are believed to influence occupants with appropriate sampling frequency and granularity in space, in order to capture also façades not-uniform effect in space. However, continuous data gathering from occupants in order to digitise holistic and transient occupant response and preferences is a challenging task, since the risk of facing the Hawthorne effect or of being disruptive is relatively high. For this reason, novel polling stations a have been developed for this project, capable; of capturing high frequency occupant response and coupling them with long-term surveys and physiological readings. Lastly, the experiments allow occupants to have different levels and modes of personal control in order to assess the optimal satisfactory interaction strategy between occupants and control strategies for façades. Occupant response to different level of interaction with façades is captured through polling stations, while particular attention has been put to allow occupants for habituation when the interactive scenarios change. Habituation is then assessed through surveys and brief daily messages prompted by the polling stations.

The second step was to design a post-processing method able to connect those different intelligences (occupants, façades and IT systems) with machine learning algorithms in order to identify statistical correlations across large number of variables and data. Once, these algorithms are set, they could potentially be applied to train and adapt control strategies to actual occupants demands.

The data collected from occupant surveys, polling and environmental monitoring stations in both real offices and MATELab is then stored in a single shared server, accessible online.

5 Future outcomes of the research and applications

Initial results are expected to inform novel control strategies for intelligent façades and gain understanding on the holistic effect of façades on occupants, which potentially could also be applied in early-design stages. For instance, if thresholds of discomfort and main comfort triggers in façades are identified, the data could then be implemented for early design stage tools that consider holistically and transiently façade effect. Additionally, Façade Impulse represents the initial research step towards novel intelligent façade technologies. The next steps would incorporate indirect means of gathering occupant response and predict occupants' preferences. Lastly, the methodology could be applied to inform policy makers on the optimal design criteria for healthy, productive and comfortable workplaces.

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