Challenges and Future Directions of Smart Sensing and Control Technology for Adaptive Facades Monitoring

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Smart sensors with embedded microprocessors and wireless communication links have the potential to fundamentally change the way dynamic façade systems are monitored, controlled, and maintained. According to our review presented in this paper the use of networked systems of embedded computers and sensors throughout society could well dwarf all previous milestones in the information revolution and improve the work place experience, user interaction and empower building occupants. However, a framework does not yet exist that can allow the distributed computing and automation paradigm offered by smart sensors to be employed for dynamic facades monitoring and control systems. Such an approach does not scale to user interactions, smart grid interaction and monitoring systems with densely instrumented arrays of sensors that will be required for the next generation of adaptive facades monitoring and control systems. This paper provides a brief introduction on automated control and users' interaction of smart sensing technology for adaptive facades and identifies some of the opportunities and associated challenges.

Keywords: advanced facades, smart sensing, automation, user interaction, building control, framework

1 Introduction

The classical way to monitor adaptive facades (AF) is based on ad-hoc measuring approaches that are not integrated within the façade (Attia et al. 2018a and 2018b). Traditionally, introducing measuring devices and sensors to assess AF's performance happens after construction. Based on our investigation of several cases studies, we found that building systems are not networked and the performance of most buildings in relation to the adaptive façade performed is rarely actively monitored (Attia and Bashandy 2016, Attia 2017 and Bilir et al. 2018). Even in the case of centralized control the automation systems are not integrated and user interaction is neglected. The abundance of data and sensors can overwhelm any facility manager leading to simple control rules that overrides users' preferences. The complication of automation and building management systems (BMS) leads to poor performance and conflicts between occupants' satisfaction, energy efficiency and cost effective maintenance. The interaction between the smart grid and the building management systems requires connecting, monitoring and controlling all active building services and elements including AF elements and components. In this context, the acceleration of market uptake of smart buildings and modernization of grids can lead to an increase of AF to benefit from cost signals or well-being signals. Consequently, the monitoring and assessment of AF will become much easier and accessible due to optimized and predictive control of smart buildings.

Therefore, there is a strong need to develop environmental BMSs that empower building occupants and allow user interaction. As we enter the era of smart and connected facades, much more interaction between users and their living, working or learning environment is emerging (Attia et al. 2018a and Stanza 2009). Providing occupants with control over the office indoor environment increases productivity and satisfaction. With the modernization of grids and buildings towards smart interaction AF can benefit from the building users as sensors next to the embedded sensors and abundant devices that became part of any smart building. The Internet of Things IoT and signals oriented communication between appliances, building systems, building services, users and grids will make it easier to monitor and assess AF. Understanding the dynamics of façade operation, BMS and programs for building occupants is an operational challenge that grows more continuously important. The workplace experience is the key to the market penetration of AF (Attia 2018a).

This paper is part of the COST Action TU 1403 on AF and aims to share the experience learned from analyzing several case studies regarding smart sensing and control technology. Therefore, in this paper we present a short introduction on smart sensing and control technology for AF. Then, we propose an initial framework for smart sensing and control technology for AF and identify some of the opportunities and associated challenges.

2 Methodology

The research methodology builds up on previous work that has been introduced in COST Action TU 1403 on adaptive facades systems assessment (Attia et al. 2015, Attia 2018a and Attia et al. 2018b) and reviewed case studies (Attia and Bashandy 2016, Attia 2017 and Bilir et al. 2018) of AF where experts where interviewed (Attia et al. 2019). The concept of this study was built around three axes in the context of developing an initial framework to combine smart sensing with control technologies for adaptive facades and identify the challenges and opportunities for future directions. The study concept adapted in this research borrowed from the review continuum that will be presented in Section 3. The study concept focused on three key approaches for data collection and validation of the proposed assessment framework. The earliest step of the methodology comprised a literature review, passing by the analysis of the literature and identification of challenges and opportunities until the articulation of a framework for AF that groups the operation system components and connects the façade's operation stakeholders.

3 Background of adaptive facades operation conflicts

There are three types of conflicts related to AF. The first conflict is related to the individual nature of the façade delivery and operation stakeholders. The second conflict is related to the conventional delivery process of buildings. The third conflict is related to the conflict of interest between owners, users and operators. In the following paragraphs, we will elaborate on each type of conflict in detail.

The first conflict related to adaptive facades operation in related to the linear and chopped project delivery process. Over the whole life cycle of AF, design and construction stages are considered as too short compared to the operation stage. As shown in Figure 1, the operation stage for a continuously maintained AF last in average between 20 to 40 years. In the same time, the complexity and duration of operation stage requires the integration of several disciplines and stakeholders to make sure the building is smartly connected and managed. As shown in Figure 2, building automation involves 8 aspects and requires the communication between installers, operators and users. This brings a complexity to building management and makes the automation for building performance optimization and user satisfaction a serious challenge.

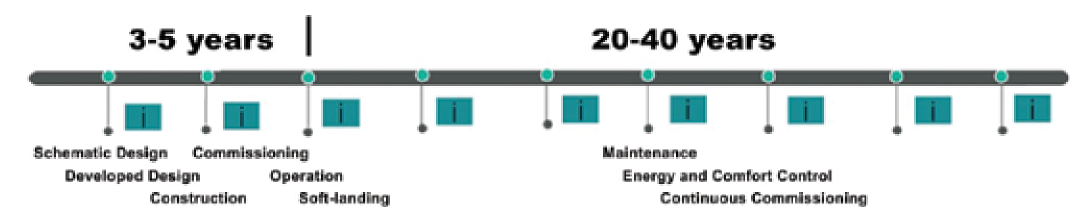

Fig. 1 Adaptive Façade life cycle

Early on during the concept development, owners and design team focus on the aesthetical and architectural value of the building and often neglect the operation stage of the façade. There is a serious disconnect between architects and facades subcontractors. As shown in Figure 2, we developed a generic performance process map that could be used as a visual guideline support by companies in the building industry based on our analysis of three case studies of AF (Attia and Bashandy 2016, Attia 2017 and Bilir et al. 2018). The map was validated and tested through interviews with different project stakeholders. To realize global and specific maps of the project delivery we drew hierarchical scales, task charges suite and information flows. To limit the scope of the process map we focused on the identification and modeling of generic processes that was associated with adaptive facades project delivery. Creating a process map involved systematic data-based interviews. Interviewees where asked to explain exactly what they did during the construction and operation stage, as well as share their technical challenges and express their expectations. We conducted several interviews with architects, façade engineer, façade contractors as well as facility managers and electrical engineers. As seen in Figure 2, the process is linear and does not allow architects, builders, occupants and operators to communicate in an iterative and integral way. The design-bid-build process shifts the responsibility and disconnects users from designers and builders from operators. As a result, we can identify a serious conflict related to the façade delivery and operation process.

The second conflict is directly related to separate actions of the design team, builders and operators. As shown in Figure 3, there are several performance requirements for AFs that requires different types of expertise. There are too many players involved in the value chain of AF. Façade designers do not collaborate with façade builders. More importantly, building operators cannot empower building occupants. A major challenge of AF is to monitor their responsiveness and empower the building occupants. The limited interaction between the user (demand the façade (response) and the overriding control models of black box BMS systems are serious barriers that hinders the market uptake of AF. Already, the management of building systems became increasingly complex in the recent years with the new dynamic and variable controls features of high performance buildings (Attia 2018b). Facility managers do not have the knowledge and means to meet occupants' expectations regarding comfort and satisfaction, which requires a high flexibility of the response. In most investigated cases of AF, there was a conflict of interest between owners and occupants regarding the operation of the AF.

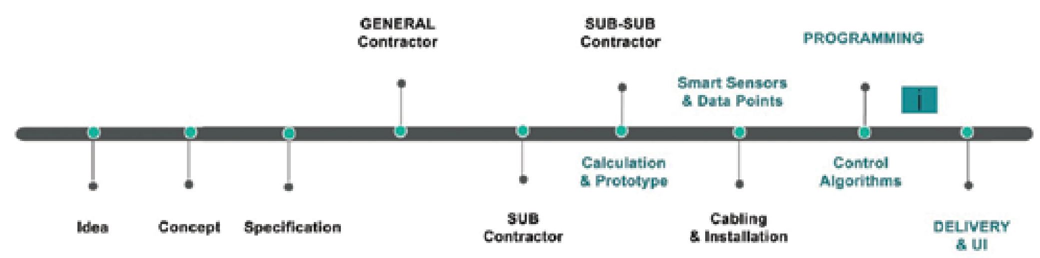

Fig. 2 a schematic process map of conventional AF delivery

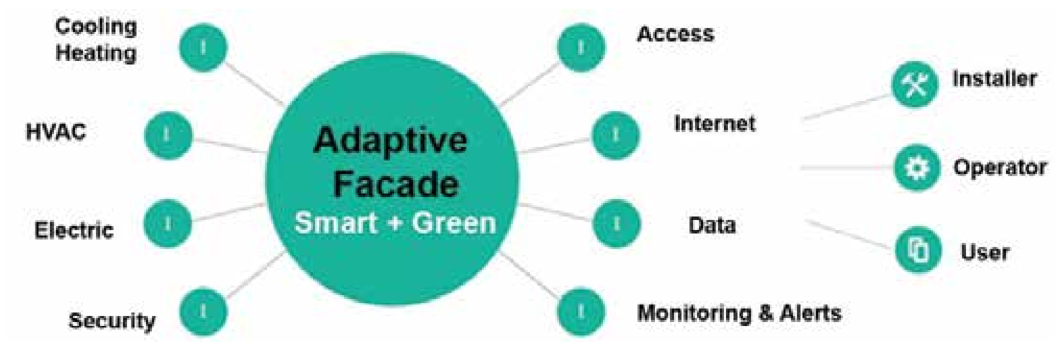

Fig. 3 Adaptive Façade performance requirements and the involved stakeholders

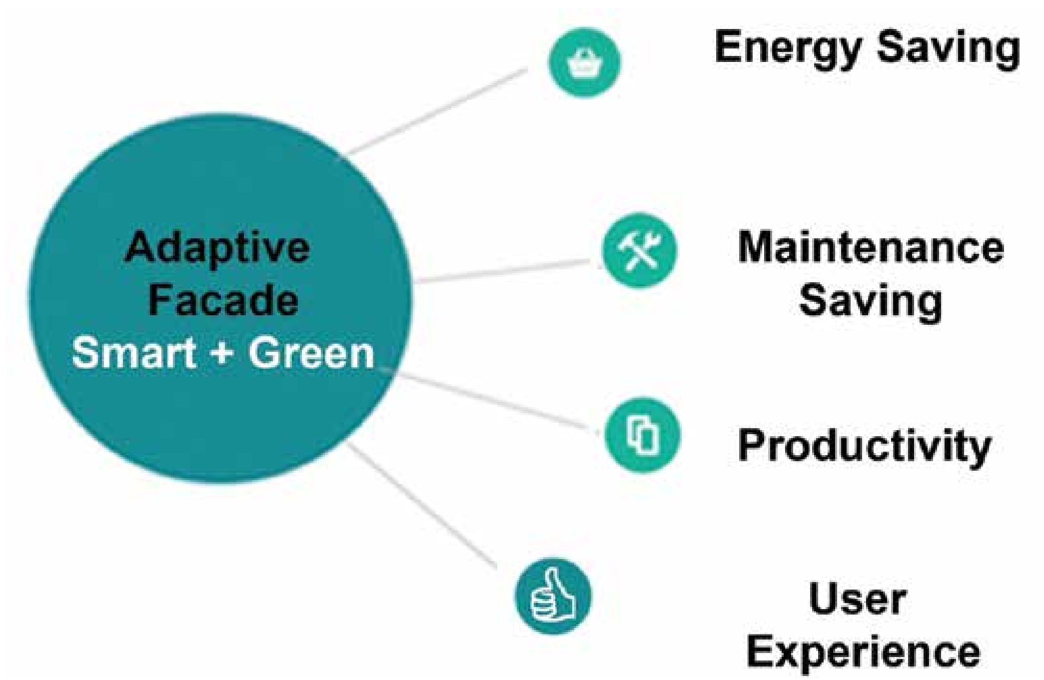

Fig. 4 Adaptive Facades multiple operation objectives

The third conflict is related to the different interests of stakeholders. Historically, operators are responsible to control building systems. Building operators want to save on running cost and reduce the stress of equipment maintenance. However, in most investigated cases (Attia et al. 2018a) operators alienate occupants by make the building too uncomfortable. This case gets magnified in workspaces with AF where adaptive responses of building occupants are not addressed. In the same time, the awareness about well-being and occupant's feedback and the proliferation of low-cost sensors and interactions devices changed the game rules and allowed to empower occupants. As shown in Figure 4, there are different aims and actions required in relation to the operation of

a building with an AF. In most investigated cases of AF projects, owners and building operators focus in most of the time on the energy savings and the cost effectiveness of maintenance. On the other hand, occupants are concerned with their satisfaction, productivity or experience in the case of being customers. With the increase of awareness about the importance of productivity there is serious need to empower and enable occupants and make sure they gain greater control over their desk environments (Attia 2018b).

To sum up, the three previously mentioned conflicts require a modern approach to manage this complex problem. This conflict requires allowing continuous feedback and flexible building management systems and control software. There is a need to create a balance between running the facades actuators and responding to user's needs. Operating AF requires making users central and requires that BMS should not only respond to operators.

4 Smart Sensing and Control Technology for Adaptive Facades Monitoring

Following the background section on adaptive facades operation conflicts we identify in this section the components of smart sensing and building control technology. Building controls are normally instigated with mechanical and electrical and plumbing (MEP) system controls. Additionally, the AF automation components are part of the overall regulation of the building environment. Therefore, we wanted to answer two research questions here:

- What are the components of an integrated system of smart sensing and control technology for adaptive facades monitoring?
- What is the architecture/framework of such a system?

In the following section we present the soft and hard components and present an initial proposition for a framework for smart sensing and control.

1. Data Collection

The data collection for smart sensing of AF is mainly based on conventional or smart sensors.

Smart Sensors (Measuring): Smart Sensors can be grouped into three parts: (i) the sensing element (e.g. resistors, capacitor, transistor, piezo-electric materials, photodiode, etc.), (ii) signal conditioning and preprocessing (e.g. amplifications, linearization, compensation and filtering), and (iii) a sensor microprocessor (e.g. on-board microprocessor, wires, plugs and sockets to communicate with other electronic components) (Kirianaki 2002 and De Paola et al. 2009). Microelectromechanical systems (MEMS) sensor devices (i) can embody both mechanical and electrical functions. MEMS can be used to sense and actuate as a reaction to physical or chemical phenomenon and convert actions into electrical signal for display, processing, transmission and recording. The sensors' microprocessor (iii) is used to signals code conversions, calculations and interfacing functions, which can facilitate decision making functions. Smart sensors are wireless, with data transmission based on radio frequency (RF) communication.

2. Connection to the Network

Various transmission protocols such as an on/off switching controller, i.e., thermostats, proportional-integral and proportional-integral-derivative, have been used in BMS (Bernard et al. 1982, Levenmore 1992, Mathews et al. 2000, Salsbury 1998 and Kasahara et al. 1999).

Transmission Protocol (Communication): There exist several protocols for transmitting data. These protocols are typically met by appropriate requirements. There are many variable requirements of different sensor data streams and applications. But there are also some basic functionality that are common, such as registering sensors at a receiver, time stamping of sensor data as well as synchronization of all nodes. The transmission involves signal conditioning, filtering, sampling, quantization and processing.

5 Processing and Visualization of Data

Building control systems and control models are basic components for AF management.

Actuator (Control): An actuator is a component of a device that is responsible for controlling a mechanism or system. An actuator requires a control signal and a source of energy. The control signal is relatively low energy and may be electric voltage or current, pneumatic or hydraulic pressure. The control system can be simple (a fixed mechanical or electronic system), software-based, a human, or any other input (Jang et al. 2013).

Control Algorithms (Computation): The control models are based on preprogrammed decision algorithms and user-defined algorithms. The control model can have a learning component or predictive component to control the façade system. The purposed of algorithms is to monitor and control AF. In closed loop control, the control action from the controller is dependent on feedback from the process in the form of the value of the process variable (Figure 5). Control algorithms deals with the control of continuously operating of dynamic facade in engineered processes and machines. Control algorithms are based on models for controlling AF using a control action in an optimum manner without delay or overshoot and ensuring control stability.

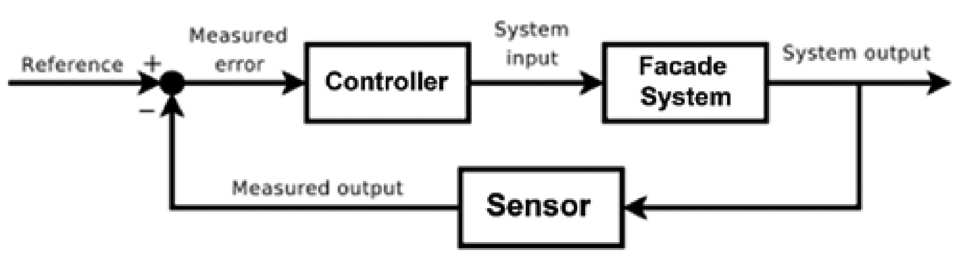

Fig. 5 a block diagram of a feedback control system using a feedback loop to control the process variable

Voiceover Technology (Control): Voiceover technology is based on control algorithms that can better control the amount of redundancy and allow users to react and override the automated operation program.

6 Interaction with Data

As shown in Figure 6, AF smart sensing and control require the collection of data from various sources, from metering information to contextual data sets (weather, building usage, energy prices …) as well the interaction of users and operators. The following components are essential to achieve that.

Building Management System (Processing and Control): A building management system (BMS), is a computer-based control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, and shading louvers. A BMS consists of software and hardware; the software program, usually configured in a hierarchical manner, can be proprietary, using such modeling protocols.

User Interface and Dashboards: User interfaces are screens that show and interpret the data to inform the decision making of users and operators. Training and continuous coaching is recommended for the occupant to make sure they will be able to engage with the façade system. Investment in soft-landing and educational briefing regarding the operation and interaction with the operation system are essential (Attia 2018b).

To answer the two questions mentioned earlier, we propose a framework that groups the four work components and sub-components mention above in one scheme. As shown in Figure 6, the framework identifies the basic components of AF operation and connects them through an opportune construct. The significance of this framework compared to others is that it can operate the exchange through a set of sensors and actuators while involving users through direct interaction. The user involves facility managers and occupants who both provide implicit feedback that guide the operation and allows predictive control. The suggested framework benefits from the presence of specialized sensors for monitoring and operating users interactions with the actuators. The ultimate purpose of such framework is to provide explicit feedback to users about environmental conditions and allows to facilitate the interaction between the user and the indoor and outdoor environment and achieve the expected energy saving and carbon reduction.

7 Challenges and future directions

In this section, we present a framework for future POE for AF and suggest a User Interface (UI) for a dynamic online. Also, we suggest some key recommendations for future POE for AF.

The industry is not ready for adopting AFs. There are successes with smart sensing and control of dynamic solar shading solution. However, there is a lack of proven systems that live up to their expected performance promises. The serious conflicts during operation in relation to overheating, glare and personal control make many users and architects don't trust the automation of AF. The control solutions are limited to shading control but there is no established solution that goes beyond shading. Control strategies do not consider the comfort factors and users interactions and are more concerned with energy consumption savings. Ensuring thermal comfort and limit set-point overshoots with energy savings has been investigated in the 1980s on predictive (Chen 2001, Henze et al. 1997), adaptive (Curtis et al. 1996 and Nesler 1986) and optimal controllers (Zaheer-Udin et al. 2000 and Dounis et al. 2001). There has been no industrial development of optimal and user interaction based controllers followed with the introduction of AF (Shaikh et al. 2014).

The complexity of AF solutions and smart sensing and control technologies is another challenge that hinders AF for market penetration. Each building with an AF possesses non-linear thermal behavior related to its dynamic façade technology, construction material, location operation and climatic conditions. The capability of the self-regulation and adaption of the environmental conditions in many adaptive facades buildings is non-linear and highly uncertain. Therefore, there is a need for adaptive and intelligent control techniques to maintain a constant performance of AF under continuous variations of MEP and occupants control parameters. Additionally, many stakeholders in the AEC industry are not used to deliver and operate complex solutions such as AF. The segmented project delivery process and the multiple stakeholder approach is creating a serious complexity. The low awareness about smart sensing and control technology for adaptive facades monitoring among operators reduce their market uptake significantly. The steep learning curve that operators have to go through is part of this problem.

The main challenge of the AF community is to come up with a holistic smart sensing and intelligent control concepts for adaptive control properties and make the full use of the environmental and energy management potential.

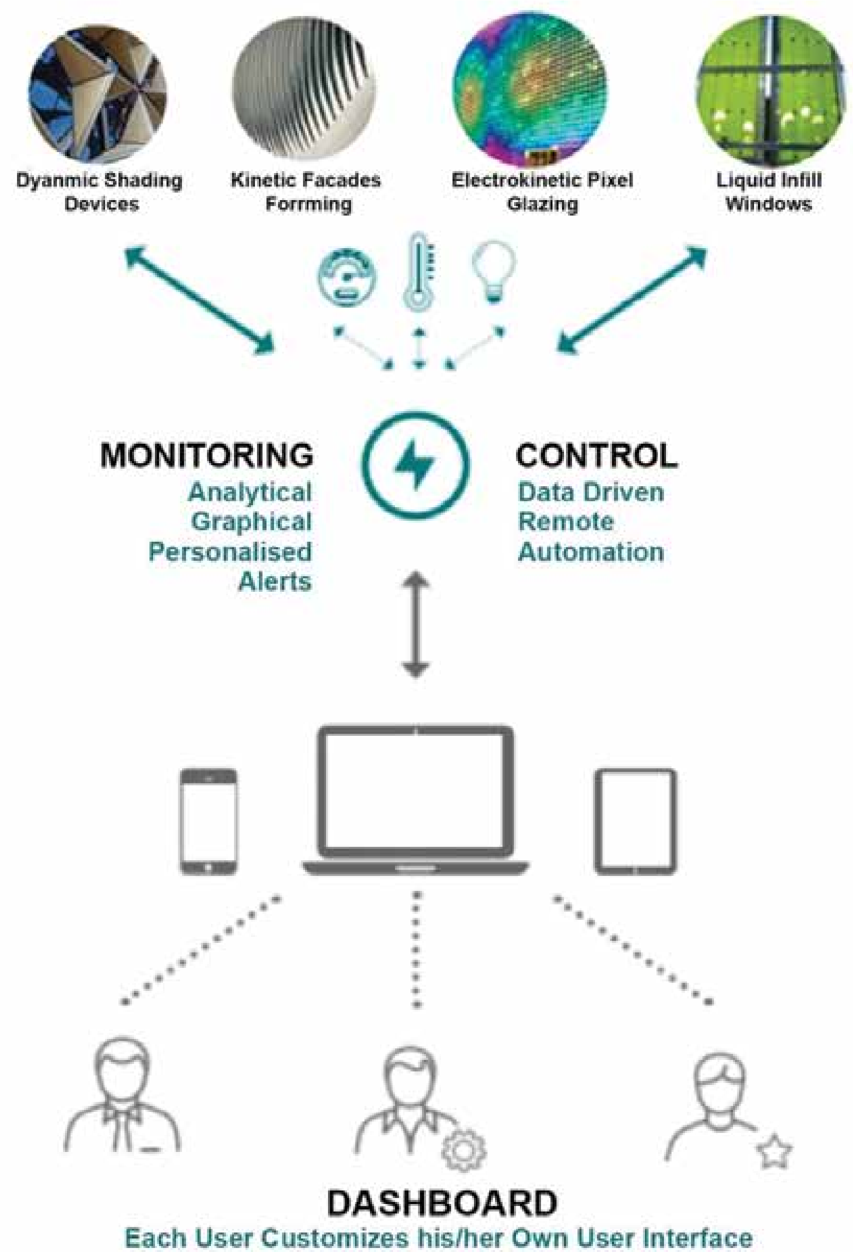

Fig. 6 Adaptive façade framework for smart sensing and control

Finally, our study did not test the proposed framework through a case study but this can be the next step for future research. More importantly, we defined the basic components of smart sensing and control and articulated a frame to guide the interaction of different stakeholder.

8 Conclusion

This paper provided a brief introduction to smart sensing and control technologies for adaptive facades monitoring. We identified a number of the opportunities, as well as some of the associated challenges. Personal control strategies for AF, occupant comfort, energy management and occupant experience/satisfaction are currently overly burdensome and often neglected. Smart sensing and building automation technologies became a necessity that provides building owners, managers and users a control of AF. Voiceover technologies, where users can interact with the façade automation system directly and the integration of artificial intelligence in the form of predictive control models into those façade automation systems are considered as the promising technology to smart sensing and control technologies for adaptive facades.

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Study of a BIPV Adaptive System: Combining Timber and Photovoltaic Technologies

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The paper presents the first results of research that was partly conducted within the framework of European COST Action TU1403 – Adaptive Façades Network, on the development of an adaptive BIPV (Building Integrated Photovoltaic) solution able to change its curvature in relation to the external environmental conditions, orientating itself in order to optimise the energy production without the aid of any mechanical and electrical systems. After analysing the characteristics of the main adaptive materials that are currently used for such applications, the contribution outlines the main features of the proposed system, which consists of thin film solar cells coupled with a thin layer of hygromorphic material, manufactured from two wooden slats joined together and produced from different types of wood and trunk cuts. The hygromorphic layer thus obtained can change its shape as a function of temperature and relative humidity of outdoor conditions, thanks to the different expansion coefficients of the two wooden slats. To evaluate the performance of the component, three shape configurations for the adaptive strips have been assumed. For each hypothesis, the lamellae have been modelled using the Rhinoceros 5 Software, according to the curvatures taken during the different months of the year. The Rhino models have been imported into Autodesk Ecotect Analysis to calculate the incident solar radiation and to study the self-shadowing effect in the various configurations (in relation to the climatic conditions of the city of Milan). The paper outlines the system and PV energy production optimisation process, as well as possible applications in the field of façade design.

Keywords: adaptive façades, adaptive component, hygromorpic materials, BIPV technology, wood, timber

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