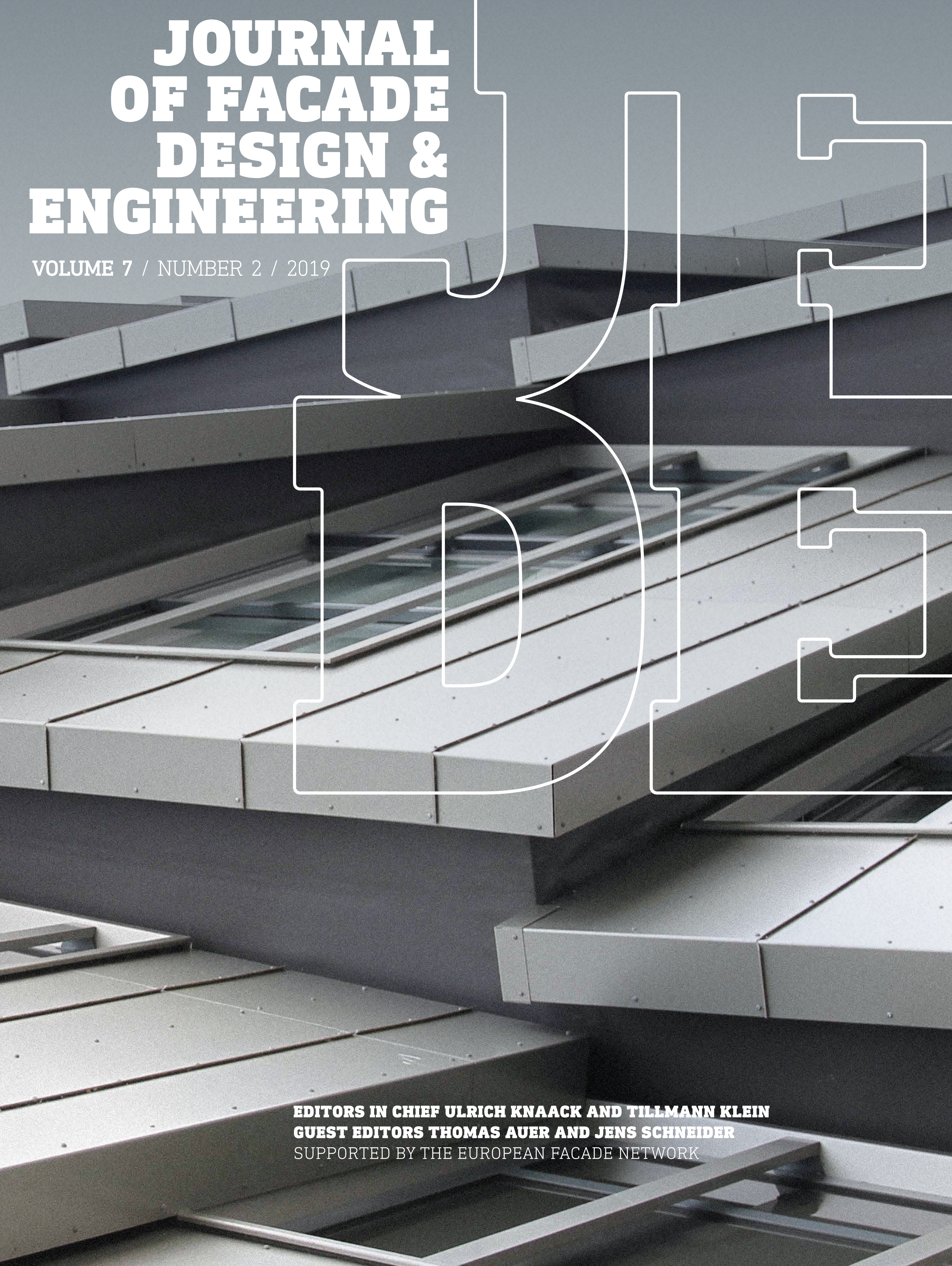
JOURNAL OF FACADE DESIGN & ENGINEERING

VOLUME 7 / NUMBER 2 / 2019



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Superposition matrix for the assessment of performance-relevant adaptive façade functions

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Abstract
The environmental boundary conditions and the demand for comfort change constantly during the use of a building. By dynamically balancing changing conditions and requirements, adaptive façades contribute to the energy efficiency of buildings. The façade fulfils a multitude of functions that are interdependent and relate to environmental conditions and requirements. By negotiating mutually supportive and competing adaptive functions, intelligent coordination offers the potential for better performance of façades in building operation. The strategy is already being applied in other application areas, such as the intelligently cooperating machines in industry 4.0. There, individual automated production plants are networked to form intelligent technical systems with regard to a common production goal. The research presented follows the assumption that this strategy can be applied to automated and adaptive functions of the façade to increase the building performance. The study identifies those functions which, due to possible automation and adaptivity, as well as effect on performance, can be considered as possible components of an intelligently cooperating system. In addition, characteristics are determined which can be used to evaluate the extent of automation and adaptivity of an individual façade function. The study shows that the detailed analysis of the automation and adaptivity within identified façade functions is possible. With a superimposition matrix, it also provides a tool that enables this assessment of the degree of automation and adaptability.

Keywords
Intelligent building envelope, superposition matrix, adaptive façade, multi-functionality, intelligent technical system

1 INTRODUCTION

1.1 BACKGROUND

The façade determines the overall performance of the building. It has an impact on the indoor comfort and the buildings´ energy efficiency. In view of current objectives related to energy saving and the increased demands on the well-being of users within buildings, there is a demand for more efficient façade systems. Researchers see a potential in adaptive façades. (Aelenei et al., 2015) The climatic conditions of the outdoor environment and the indoor requirements are constantly changing. The balancing of both presents a continuous optimisation of the construction properties with regard to the performance of the façade. This enables savings in the operation of energy-consuming building services, which can be reduced if the building envelope guarantees a desired indoor climate.

The façade fulfils a multitude of additional functions in the role of a mediator between the exterior and interior. The façade functions are derived from the influences of the environment and the requirements of building use. The façade functions are mutually interdependent. They can conflict or positively influence and complement each other. Moloney (2011) and Loonen, Trčka, Cóstola, and Hensen (2013) formulate the demand for holistic concepts instead of fragmented solutions for adaptive façades. Adaptive façades are being researched and realised, but the development is still at an early stage. (Aelenei et al., 2015) The implementation of adaptive façades often includes automation technology. Over the past decades, research and development in this field provided the technical basis for the realisation of such systems. (Schumacher, Schaeffer, & Vogt, 2009) These include the miniaturisation of electronics and computer technologies, as well as the developments in sensor and actuator technologies.

The close interaction of computer-based control and communication with physical technical systems forms the concept of Cyber-physical systems. An important aspect is the cooperation of distributed system components. (Monostori, 2014; Rajkumar, Lee, Sha, & Stankovic, 2010; Wang, Torngren, & Onori, 2015) The Internet of Things (IOT) describes the comprehensive and internet-based networking of physical objects. All devices that have an embedded control system and the ability to communicate can be part of it. (Bittencourt et al., 2018) In the current development of an Industry 4.0, the flexibility and productivity of manufacturing processes is increased by networking individual production facilities into so-called intelligent technical systems. Technological developments in various research fields, such as IT and neurobiology, are merged to provide mechatronic systems with intelligence based on embedded sensors, actuators, and cognitive abilities. The individual technical systems within an intelligent technical system work autonomously and are able to communicate and cooperate with regard to a common production goal. (Dumitrescu, Jürgenhake, & Gausemeier, 2012)

Böke, Knaack, and Hemmerling (2018) assume that such strategies can be applied to the operation of the building envelope. By networking automated adaptive façade functions within an intelligent system, the efficiency of the façade in building operation is to be increased in the sense of greater flexibility and productivity in industrial production.

For the networking, a differentiated understanding of the individual façade functions and the individual possibilities of automation and adaptivity is required. There are different lists of façade functions that do not take adaptivity into account, such as the "façade function tree" by Klein (2013).

Loonen et al. (2015), for example, provide characteristics of adaptivity for the overall system of the façade without consideration of individual functions.

1.2 PROBLEM STATEMENT

The possibility of an intelligent cooperation of automated adaptive façade functions according to the model of networked production plants in industry has not yet been clarified. The role of an individual adaptive façade function as a component of an intelligently networked façade can only be assessed by comparing it with the project-specific environmental conditions and performance requirements.

It is uncertain which façade functions can be considered as a part of an intelligently networked system due to an adaptive feasibility and an effect on the performance of the façade. Previous listings of façade functions, like the "façade function tree" by Klein (2013) or the "façade as an interface" by Hausladen, de Saldanha, Liedl, and Sager (2005) refer to the façade generally, and differ in organisation, scope, and detail. The transfer of the networking strategy from industrial production plants to the façade depends, according to the technical basis of an industry 4.0, on the comprehensive automation and adaptivity of the individual functions.

There is a lack of assigned characteristics by which the degree of automation and adaptivity of an individual façade function can be assessed. Previous studies on a possible characterisation of adaptive façades, such as the composition by (Loonen et al., 2015), refer to the façade as an overall system. They do not provide a complete result, since they refer to partial aspects such as either functionality or the degree of automation.

1.3 OBJECTIVES

The aim of the study is to develop a holistic view of adaptive façades in the interplay of requirements and external boundary conditions. The knowledge about dynamically changing factors of the boundary conditions supports a later decision as to which information must be collected via sensors for the intelligent operation of a networked façade system. For this purpose, the individual factors to which the adaptive façade must react are to be recorded. In addition, the various requirements for interior comfort are to be compiled as target values for the intelligently networked façade system.

Façade functions that can be automated and adaptive, and that affect the performance of the façade, meet the requirements for a possible cooperation with other façade functions within a networked system. One aim of this study is to identify these façade functions and assign characteristics to assess the degree of an automated adaptivity.

As a tool for the subsequent examination of the actual requirements in practice, the identified façade functions are to be superimposed with the identified characteristics of automation and adaptivity in a superposition matrix.

1.4 RESEARCH QUESTION

Main question:

How can the automated adaptivity of façade functions be assessed to systematically identify them as a possible part of an intelligently networked façade?

Sub questions:

- What are the boundary conditions of an intelligently networked façade and from which environmental conditions and comfort requirements derive its adaptive functions?
- Which façade functions are possible part of an intelligently networked façade due to a possible adaptive implementation and an impact on the building performance?
- How can the automated adaptivity of a façade function be assessed?

2 METHODOLOGY

The investigation is based on a literature review. It is organised into two main parts. In the first part, under section 3, the boundary conditions of an intelligently networked façade are recorded in response to the first sub question. These include the environmental conditions with dynamic parameters, as well as the different requirements for interior comfort. Both fields are extensively researched and documented in literature and standards. This first section, as shown in Fig. 1, provides the context for the subsequent assessment of whether a façade function can be implemented automated adaptive and whether it has an effect on building performance.

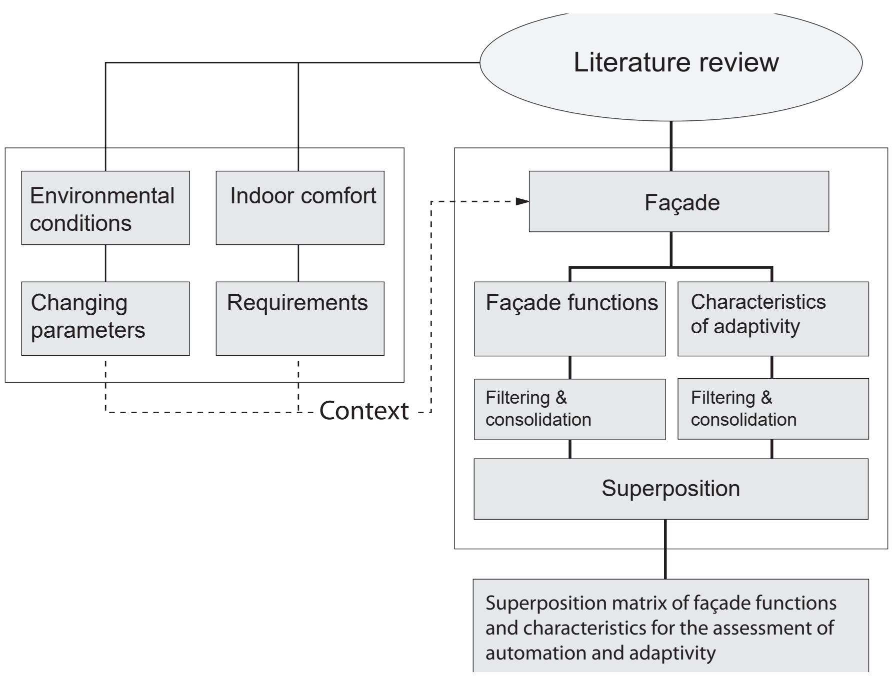

FIG. 1 Graphical abstract

A focus of the study is on the automated adaptive façade functions examined in the second part in Section 4. Previous lists such as the "façade function tree" by Klein (2013) contain an overview of all façade functions without restriction as to whether an adaptive implementation is feasible and whether it affects the performance of the building envelope. The list "façade as an interface" by Hausladen et al. (2005) corresponds to the approach of classifying façade functions in a holistic view, taking environmental conditions and comfort requirements into account. It serves as a starting point for the identification of relevant façade functions in this study. In order to ensure the completeness and accuracy of the functions identified by them, the list is overlaid with alternative layouts developed by Klein (2013) and in the research of *mppf - The multifunctional plug&play approach in facade technology* 2015). The overlaid data sets of façade functions is consolidated and filtered, as shown in Table 1 of Section 4.1, according to performance relevance as well as a basically possible adaptivity. The identification of characteristics that can be used to assess the automated adaptivity of a façade function is also based on existing literature. Different references are overlaid and consolidated based on the research by Loonen et al. (2015) with the goal of a complete list of evaluation characteristics of automation and adaptivity.

FIG. 2 Schematic representation of the superposition matrix

For the assessment of the automated adaptivity, the determined characteristics are assigned to the previously identified individual façade functions. This step is done regarding the third sub question in a systematically structured superposition matrix according to the representation in Fig. 2. The usability of the superposition matrix is tested on the basis of an exemplary application to an existing façade project. The necessary project information for the application example is derived from literature.

3 THE CONTEXT OF ENVIRONMENTAL BOUNDARY CONDITIONS AND COMFORT REQUIREMENTS

3.1 IDENTIFICATION OF ENVIRONMENTAL BOUNDARY CONDITIONS AND RELATED DYNAMIC PARAMETERS

The climate is composed by the variations of different elements. According to Dahl (2010), the detached discussion of individual aspects is difficult since they are in a constant and dynamic relationship to one another. Bitan (1988) identifies temperature, humidity, wind, precipitation, solar radiation, and special features as parameters with a high impact on the building. Hausladen, Liedl, and Saldanha (2012) designate the same climate elements as the most important for the construction planning, but without the addition of "special features". In the consideration of the "façade as an interface" Hausladen et al. (2005) designate the sound as an influencing element. van den Dobbelsteen, van Timmeren, and van Dorst (2009) also supplement this aspect. Dahl (2010) focusses on, from his point of view, the most important aspects: heat, humidity, wind, and light.

In an overarching view, the following climate elements relevant to the building industry are identified. With regard to the adaptivity of the façade, the focus is on the dynamic parameters of an environmental condition.

Solar radiation

Solar radiation is electromagnetic radiation emanating from the sun (Givoni, 1976). The energetic radiation power determines the intensity of the solar radiation. It changes with respect to the time of day or season as well as to the weather. Another important aspect is the duration of irradiation, depending on the geographical location and the weather (Ranft & Frohn, 2004). Global radiation is composed of direct sunlight and indirect, diffuse radiation. The angle of incidence of the direct sunlight is another important aspect. The greatest amount of energy is released at an incidence angle of 90 degrees to a surface. The intensity, the duration of irradiation, and the angle of incidence of the irradiation can be summarised as the important parameters of the solar radiation.

Temperature

Solar radiation indirectly affects the outside air temperature by heating the earth's surface. This provides heat energy to the air layers above. Also, the exchange with inflowing air affects the temperature. Depending on the geographic location, the season, and the time of day, the temperature is subject to great variations. Between 1.5 and 3 m depth, the average temperature of the ground remains constant throughout the year. (Givoni, 1976; Hausladen et al., 2012) The air temperature measured in degrees Celsius is determined as the decisive parameter of this climatic element.

Air quality

The air quality is determined by its oxygen content as well as its pollution. Air pollution occurs mainly in dense urban areas as a result of traffic or industrial processes. Plants can also be the cause of reduced air quality due to the formation of pollen (Hasselaar, 2013).

Sound

Developments in both transport and industry are accompanied by noise emissions. Due to the density of urban areas noise pollution can often not be avoided. Noise in the environment has an impact on human comfort and depends on the distance between the source and the building. Sound differs by type, duration, and transmission. Hausladen et al. (2005) distinguish linear and selective sound sources. The duration of a noise load can be continuous, interrupted, or recurring. Sound transmission can take place via air or via building components and materials. The sound applied to the building is measured outside in decibels (Hausladen et al., 2005).

Wind

Wind is an effect of the earth's air flow and pressure system. It is based on the distribution of air pressure, the rotation of the earth, the alternation of heat and cool over land and over water, and the topography of a respective region. Winds vary according to seasons. There are global wind systems like the trade-winds, westerlies, and polar winds. Additionally, time-bound winds exist due to high temperature differences. Local winds occur between water and land or mountains and valleys (Givoni, 1976). The microclimatic conditions such as terrain and building form have a great impact. For example, nozzle effects are possible, depending on the building arrangement (Hausladen et al., 2012). The pressure acting on a building depends on the local wind force. Force and direction of the wind are identified as crucial parameters.

Precipitation

Precipitation is a component of the water cycle. Depending on the temperature, the water changes its form from gaseous to liquid. The cooling of the air condenses the moisture stored in it and leads to precipitation. The dew point is the temperature at which this process takes effect. Along with rain, mist and dew are also forms of precipitation (Givoni, 1976). The precipitation quantity and the possible precipitation direction are identified as parameters of the climate element.

Humidity

Humidity is defined as either relative humidity or absolute humidity. Absolute humidity refers to the location-related, stored water vapour in the air. It is dependent on precipitation and the distance to the sea. Absolute humidity is constant during the day, while relative humidity is subject to temperature fluctuations. Cold days have a decreasing effect, warm days have an increasing effect (Hausladen et al., 2012).

3.2 IDENTIFICATION OF REQUIREMENTS FOR THE INDOOR COMFORT

The comfort in buildings can be in conflict with energetic performance goals. The quality of an interior climate has a significant impact on the well-being, health, and productivity of users. The demands on the interior climate of a building are guided by the needs of the comfort of the human being. They vary according to subjective perceptions and preferences (Ranft & Frohn, 2004). Comfort can be determined by a range of factors, some of which are related to each other in a way that is not scientifically understandable (Ranft & Frohn, 2004).

Essential aspects of comfort are, according to Knaack et al. (2014), perceived temperature, visual comfort, hygienic comfort, and acoustic comfort. A clear assignment of the aspects relevant to a user's comfort cannot be determined universally due to varying individual perceptions. In order to determine the climatic quality of an interior environment, specialist planners rely on the level of satisfaction of users (Hasselaar, 2013). In many cases, there are legal requirements that a building must meet. In Germany, minimum requirements for the indoor climate are defined in the following guidelines and standards: Important for the evaluation of interior comfort are ANSI/ASHRAE 55 - Thermal Environmental Conditions for Human Occupancy and DIN EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; German version EN 15251:2007. For indoor environments in general, the ISO 7730 defines requirements with regard to thermal comfort and DIN 5035 with regard to daylight. Requirements for comfort in office buildings are defined by the standards DIN1946 and DIN 33403: "Climate at the workplace". The acoustic requirements in office buildings are regulated by DIN 2569: Sound insulation in office buildings. (Ranft & Frohn, 2004) Al horr et al. (2016) identify the thermal comfort, acoustic comfort, and visual comfort as important factors for the well-being and productivity of users. Dahl (2010) complements aero-comfort and hydro-comfort in terms of the indoor air quality.

Thermal comfort

The operative temperature, also known as the sensed temperature determines the thermal comfort and is composed of the radiation and air temperature of the room (Hasselaar, 2013). It is often understood as the most important aspect in terms of interior comfort. The human body maintains an operating temperature of about 37 degrees Celsius (Dahl, 2010). Hausladen, Saldanha, and Liedl (2008) determine the operative temperature in combination with the air speed as decisive factors for the thermal comfort. Al horr et al. (2016) name air temperature, average radiation temperature, relative humidity, air speed, and individual aspects such as clothing as the six influencing factors that affect thermal comfort. An uneven distribution of the room temperature leads to discomfort. The activity of a person, clothing, age, sex, health and duration of stay in an environment influence, according to Hausladen et al. (2005), the sensitivity towards temperature. Too high temperatures can weaken the performance of a person while cold temperatures lead to illness. Hausladen et al. (2005) formulate the following temperatures as average demand values separated by winter and summer season: In winter, the comfortable operating temperature is 22C° at air speeds of approx. 0.16m/s, while in summer it is 24C° with an air speed of 0.19m/s.

Aero- and hydro-comfort

According to Dahl (2010), comfort also depends on air movement and cooling, both of which occur with convection and evaporation. As the temperature increases, larger air movements are perceived as positive. (Ranft & Frohn, 2004) The quality of the indoor air is based on the quality of the ventilated external air and possible influences by users, technical installations, materials, or indoor plants. Air pollution outdoors can have a negative effect on the air supply. High-quality air is based on a high oxygen concentration and a low dust and pollution load. The perceived contamination of indoor air is measured in Decipol (Dp). The CO2 concentration is also an aspect of air quality. In addition to the activity of the user, Hausladen et al. (2008) also name behaviours such as smoking as an influencing factor. The perceived quality of the air decreases with increasing humidity and temperature. The olf measure corresponds to the air pollution of a user doing light office activities. Hausladen et al. (2008) give 0.15vol% as the maximum CO2 concentration. Dahl (2010) describes the hydro-comfort with regard to the humidity. Relative humidity can be subject to large fluctuations between about 20% and 70%. It has an impact on health and how people feel within interior climates. Large rooms can more easily compensate for humidity due to a larger air capacity, whereas small rooms require more extensive air exchange. (Dahl, 2010; Ranft & Frohn, 2004)

Visual comfort

Hausladen et al. (2008) establish that natural light has a positive effect on the visual comfort of users. According to them, the quantity of the light provided, and its distribution, are crucial. The human eye adapts to the prevailing light conditions (Dahl, 2010). Glare can have a negative impact on the user. It occurs as a result of direct radiation originating from sun or artificial light sources, as well as reflections of light irradiation. Large contrasts in the lighting also lead to possible glare. Low contrasts and low shadows reduce it and promote spatial perception. Visual references to the outside contribute to the well-being of the users. (Hausladen et al., 2008)

Acoustic comfort

Acoustic comfort is based on the protection from noise and the guarantee of a sound environment which corresponds to the use of the building (Al horr et al., 2016). Acoustics is associated with well-being and the ability to concentrate within a room. Sources of noise pollution may be outside the building or may result from the activities within a room. Sound is measured in Decibel (Db). The volume of sound is a decisive factor. The weighted sound level considers people to be more sensitive to specific frequencies than to others. The addition (A) indicates the correspondingly filtered measured variable. Silence corresponds to the value 0Db(A) and noise above 140Db(A) is perceived to be painful (Hasselaar, 2013). The reverberation time describes the duration of a noise and has a great effect. The noise should not collide with communication or concentration in a building. Hausladen et al. (2005) formulate a noise load of 30-45db (A) as an acceptable maximum.

3.3 INTERPRETATION OF THE IDENTIFIED ENVIRONMENTAL CONDITIONS AND COMFORT REQUIREMENTS

A total of seven categories of environmental conditions have been identified as illustrated in Fig. 3. Different dynamic parameters are possible within the respective category. The influencing factors are not always subject to a natural origin but can also be the result of human intervention in the environment. Examples of such artificial influencing factors are the noise environment within urban areas or traffic-related air pollution. Depending on the project's geographical and temporal context, different patterns of influencing factors are possible. On the other hand, there are a total of four identified categories for interior comfort. Different requirements can be assigned to the individual categories. Hausladen et al. (2008) distinguish detailed requirements of the interior comfort in the "façade as an interface". The "room temperature", the "inside surface temperature", and the "supply air temperature" named by them can be assigned to the thermal comfort. Illuminance, glare protection, and visual relationships affect the visual comfort. The aero- & hydro-comfort can be detailed into air changes, air quality, and air speed, while the sound load named by Hausladen et al. (2008) can be assigned to the acoustic comfort. It is not claimed that the listed requirements are complete. They are the basic requirements that can be supplemented depending on the conditions of different building uses. Fig. 3 illustrates the context of the environmental conditions and comfort requirements from which the adaptive functions of the façade derive:

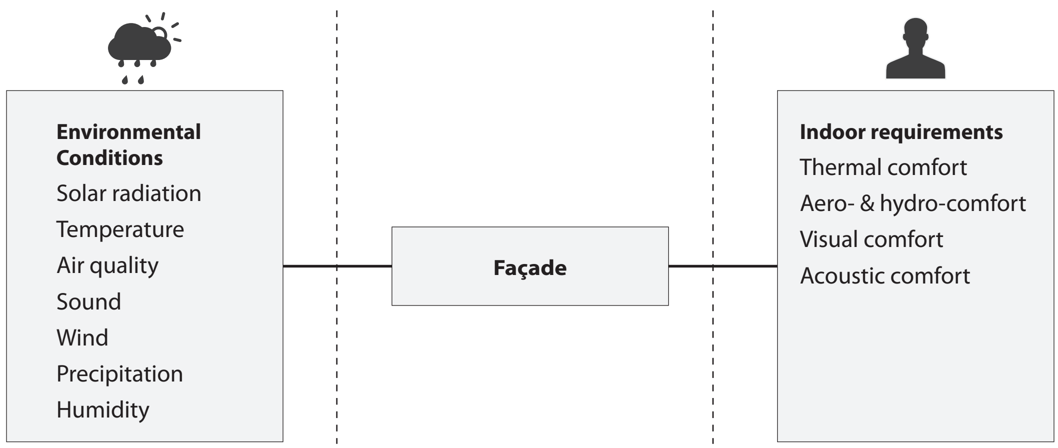

FIG. 3 Context of environmental conditions and comfort requirements

The context provides a holistic view of the façade in terms of its dependence on environmental conditions and comfort requirements. It contributes to the understanding of individual reactions of an adaptive façade function. Possible intersections between the individual reactions can be identified with regard to the differentiated environmental conditions and indoor comfort requirements.
The context is intended to serve as a decision aid in the selection of façade functions for networking and existing dependencies and interferences in cooperation.

4 IDENTIFICATION OF FAÇADE FUNCTIONS AND CHARACTERISTICS OF ADAPTIVITY

4.1 PERFORMANCE RELEVANT AND POSSIBLY ADAPTIVE FUNCTIONS OF THE FAÇADE

The façade has a great impact on the energy and comfort-related quality of a building. As shown in Fig. 4, it balances the dynamic climatic conditions of the exterior environment with regard to the requirements of the interior (Hausladen et al., 2008). It determines the appearance and contributes to the design assessment of a building (*Fassaden*, 2015; Knaack et al., 2014). Features of the façade can be distinguished according to whether they have an effect on the building's performance or solely on the aesthetic design of the façade. In this respect, Loonen et al. (2013) exclude, for example, media façades, which exclusively present visual adaptive features without contributing to the performance, from the definition of climate-adaptive building envelope.

The expectations and demands on the functional spectrum of façades continuously increased throughout the development history. (*mppf - The multifunctional plug&play approach in facade technology*, 2015) At the same time, technical possibilities available for the façade construction have multiplied. Klein (2013) notes an extensive mechanisation of the façade, which, in his view, in the latest development also fulfils additional comprehensive tasks of building services. Klein (2013) describes the functions as an elementary aspect for the investigation and development of façade constructions. According to Herzog et al. (2004) the building envelope separates and filters between the outdoor environment and interior of the building. From a historical point of view, it is the job of the façade to provide protection against the dangers and the weather of the exterior. Herzog et al. (2004) state that additional requirements for the building envelope result from the local external environment and the requirements of the interior. In this context they specify further control and regulatory functions in addition to the protection function of the façade. According to Knaack et al. (2014), the façade is a dividing element between the exterior and interior, that satisfies multiple functions with the simplest structure possible. They argue that these functions include the provision of visual openings, balancing of wind loads, and load-bearing properties. Herzog, Krippner, and Lang (2004) see the façade as an interface, which ensures a comfortable interior climate. Depending on the different requirements of different seasons, they are also confronted with a target conflict of different façade functions. Herzog et al. (2004) also identify conflicts of interest in the different requirements of different seasons. They differentiate between different requirements in summer and in winter. According to Herzog et al. (2004), it is not only crucial which functions the building envelope fulfils, but also how the functions are organised with regard to one another. The interplay of individual façade functions can allow for synergy effects. There are different, differentiated representations of the functions of a façade. They differ in scope, detailing, and organisational structure. In an overlapping composition of façade functions "The façade as an interface", Hausladen et al. (2005) contrast the functions with corresponding influencing factors and requirements. In this way, they also manifest superimpositions, for example when façade functions are derived from several external conditions or when they affect various interior requirements. They identify a total of thirteen climate-related functions. Participating researchers of the project "multifunctional plug & play facade" formulate functions of the façade in three categories. The first category refers to the basic, mainly protective and climate-related functions of the façade. Solar thermal energy and photovoltaics are listed in a separate section on energy production. In the third category, supporting functions of the façade are named. This category includes tasks such as heating, cooling, or mechanical ventilation (*mppf - The multifunctional plug&play approach in facade technology*, 2015), Klein (2013) differentiates the functions of the façade in an objective tree, based on strategies from product design. It organises the functions stepwise into primary, secondary, and support functions. The "Façade function tree" represents a comprehensive and detailed breakdown of the façade functions in five categories. These include the durability of the construction, an appropriate manufacturing process, ensuring sustainability, support for building use, and the shape of the façade. It is assumed that the functions of the categories: "Create a durable construction", "Allow reasonable building methods" and "Spatial formation of façade" can in principle not be implemented in an adaptive manner. It is also assumed that not all functions affect the performance of the building in operation. Against this background and due to the size of the composition, a pre-selection is made regarding the categories "provide comfortable interior climate" and "responsible handling in terms of sustainability".

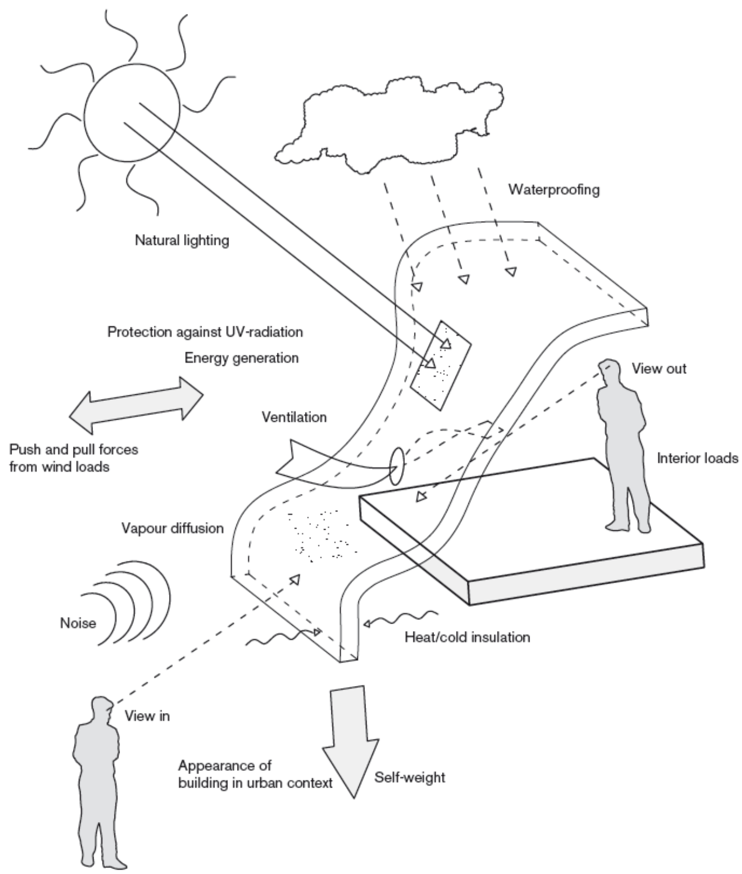

FIG. 4 Facade functions by Knaack, Klein, Bilow, and Auer (2014)

The assembly of façade functions in Table 2 is derived from the consolidation of the previously identified lists by Hausladen et al. (2005), Herzog et al. (2004), Klein (2013), and (mppf - The multifunctional plug&play approach in facade technology, 2015). The layout by Hausladen et al. (2005) is already tailored to the climate related functions of the façade. It serves as the starting point for the merging with the alternative constellations. In the superposition of the compositions it becomes clear that many of the functions, which are designated identically or slightly modified, overlap. Duplicates are removed as part of the consolidation.

	CONSOLIDATED LIST	FILTER	ACTION		CONSOLIDATED LIST FILTERED	
					General function	**Specification**
Sun						
1	Glazing fraction	Irrelevant to an adaptive implementation	Skipped	1	**Solar** shading	
2	Shading	Specified to „Solar"	Modified			
3	Solar control glass	Specification				
4	Light deflection			2	Light deflection	
5	Glare protection			3	Glare protection	
6	Control daylight radiation			4	Control daylight radiation	*Provide a comfortable daylight level*
8	Allow natural lighting of interior	Allow to control	Modified			*Allow natural lighting of interior*
Temperature						
9	Thermal insulation			5	Thermal insulation	*Heat protection*
10	Heat insulation glass	Specification (of Thermal insulation)	Modified			*maintain indoor temperature*
11	Thermal storage mass	Irrelevant to an adaptive implementation	Skipped			
12	Decentralised equipment	Is more of a property than a function	Skipped			
13	Maintain air tightness	Irrelevant to an adaptive implementation	Skipped			
Air						
14	Window ventilation	Specification (Change to Ventilation)	Modified	6	Ventilation	*Control air exchange rate*
15	Control air exchange rate	Specification				*Ventilate excessive heat*
16	Ventilate excessive heat	Specification				
User						
17	Allow visual contact	Allow to control	Modified	7	Control visual contact	*Visual contact to outside*
						Visual protection for inside
Acoustic						
18	Sound insulation	Sound insulation = reduction? Level of success		8	Sound insulation	
19	Sound reduction					
20	Insulation of connection to dividing walls	Irrelevant to an adaptive implementation	Skipped			
21	Insulation of floor connection	Irrelevant to an adaptive implementation	Skipped			
Energy						
22	Collect solar thermal energy			9	Generate energy	*Collect solar thermal energy*
23	Collect solar energy					*Collect solar energy*
				10	Store energy	
Supply (not dependent on outdoor climate but relevant to indoor comfort)						
24	heating	combination with cooling	Modified	11	heating and cooling	
25	cooling		Modified			
26	humidification	combination with dehumidification	Modified			
27	dehumidification		Modified	12	de- / humidification	
28	electricity			13	electricity	
29	artificial light			14	artificial light	
30	communication			15	communication	

TABLE 1 Development of the consolidated and filtered list of façade functions

In addition, the functions are filtered as shown in Table 1 in consideration of the environmental factors and requirements identified in Section 3 according to two decisive aspects: first, an adaptive implementation must be possible in principle. This precondition is not given for example in the case of "glazing fraction" listed by Hausladen et al. (2005). The function is definitively determined within the planning and manufacturing process and not dynamically changeable in the operating phase of the building. It is therefore not taken into account for the present assembly. On the other hand, the function must have an impact on the performance of the building. Within the scope of the consolidation, further decisions are made that have an impact on the result. In some cases, Klein (2013) provides the detailing of individual, opposite states of a front function. With regard to an adaptive implementation, these functions can be summarised. An example of such a merge are the functions "block radiation" and "let radiation pass". Correspondingly, the reduction and the insulation of sound can be combined as different degrees of fulfilment of the function. Klein formulates several of the identified façade functions with the addition "Allow". With respect to an adaptive implementation of the respective function, an opposite state is assumed to be possible and the term is converted to "Control". In the category "Responsible handling in terms of sustainability", Klein (2013) identifies functions which do not directly affect the performance of the building. The collection of solar and solar-thermal energy can contribute to the functioning of the façade depending on the climatic conditions of the exterior. The corresponding functions are also named in the list by *mppf - The multifunctional plug&play approach in facade technology* 2015) and are taken into account in the consolidated summary. In the "Supply" category, they also name functions of building technology, which have an effect on the interior climate, regardless of external boundary conditions. They are also added to the list of functions.

	GENERAL FUNCTION	SPECIFICATION
Sun		
1	Solar shading	
2	Light deflection	
3	Glare protection	
4	Control daylight radiation	*Provide a comfortable daylight level*
	Control natural lighting	*Allow natural lighting of interior*
Temperature		
5	Thermal insulation	*Heat protection*
		maintain indoor temperature
Air		
6	Ventilation	*Control air exchange rate*
		Ventilate excessive heat
User		
7	Control visual contact	*Visual contact to outside*
		Visual protection for inside

	GENERAL FUNCTION	SPECIFICATION
Acoustic		
8	Sound insulation	
Energy		
9	Generate energy	*Collect solar thermal energy*
		Collect solar energy
10	Store energy	
Supply		
11	Heating and cooling	
12	De- / humidification	
13	Electricity	
14	Artificial light	
15	Communication	

TABLE 2 Consolidated and filtered assembly of performance-related façade functions

4.2 CHARACTERISTICS OF ADAPTIVITY

Loonen et al. (2015) require uniform aspects which can be used to determine the adaptiveness of a building envelope. They identify eight characteristics of adaptivity which they also assemble in a matrix. The starting point of the investigation by Loonen et al. (2015) is the adaptivity. In the first aspect, they question the goal and purpose which should be achieved with it. Loonen et al. (2015) name a total of six objectives, which are derived from the requirements of interior comfort, user control and energy generation. For each objective, they identify appropriate, responsive functions. In contrast to the listing by Loonen et al. (2015), this study is organised according to the façade functions themselves. According to the identified façade functions in context of environmental conditions and indoor comfort requirements in Chapter 3 of this research, the objectives of a façade function are not questioned again. A relevant characteristic is whether a façade function can be adaptive at all. A distinction is made between the flexibility of the building envelope, i.e. the adaptivity which has to be initiated by the user, and the adaptiveness which requires independent, self-regulated adjustments (Ross, Rhodes, & Hastings, 2008). In addition, the technology, which can be a construction component or a material that carries out the function, is questioned as an aspect by Loonen et al. (2015). The accordingly named "spatial scale" is understood to be directly coupled to it. Under "Degree of adaptivity" they summarise the possible states of an adaptive process. These can, according to them, map the direct change between extreme states (on-off) or smooth transitions (gradients). With regard to the application to a façade function or a component, this characterisation appears to be insufficient. The question arises as to whether an open window is ON or OFF. As a supplement to this characteristic, a generalisation of the state description is proposed in "active" and "inactive". Additionally, one should define when a corresponding state is reached for each function. The response time is adopted as a criterion of adaptivity. It is assumed that it provides information on whether the adaptation processes meet the dynamic requirements of a façade function. Loonen et al. (2015) identify visibility as a characteristic of an adaptive façade. As this aspect has no effect on the performance of the façade it is not taken into account in the present study. Loonen et al. (2015) distinguish between intrinsic adaptations, the construction or material inherent adaptations in response to ambient stimuli, and extrinsic adaptations, which are based on additional automation technology. From a technical point of view, therefore, the scope of introduced automation technology can also be a criterion for the capabilities of an adaptive façade function. In this context, Moloney (2011) and Ochoa and Capeluto (2008) refer to the components of a mechatronic system, an existing input system, a processing system, and an output system. An existing sensor system, which continuously collects data on the relevant environmental conditions, can be identified as a criterion for adaptive façades. Additionally, an existing control, which processes the determined data, as well as actuators, which initiate adjustments within the façade construction, are further criteria. Table 3 is a revised list of characteristics for the adaptivity of façades.

	GENERAL CRITERIA	DESCRIPTION	POSSIBLE PARAMETERS
General			
1	Technology	The construction-related element, which ensures the fulfilment of the function.	Building component / System / Material
2	Flexible	Possible Flexibility of the construction regarding the function	Yes / No
3	Adaptive	Self-initiated adaptations (applied Automation technologies)	Yes / No
Behaviour			
4	Operation	Component or material-integrated self-adaptation or on the basis of information processing	Intrinsic / Extrinsic
5	Response time	Time intervals of adaptation processes	Seconds, Minutes, Hours, Day-night, Seasons, Years, Decades
6	Degree of adaptability	The number and type of possible states that the adaptive system can map.	Active / Inactive / Gradual
Automation			
7	Input system	Existing information gathering (sensors)	Yes / No
8	Processing system	Existing processing of the gathered information (controller)	Yes / No
9	Output system	Existing actuators, which implement adaptations of the design with regard to the function	Yes / No

TABLE 3 Revised list of characteristics of adaptivity

Using the overlapping of façade functions and characteristics of an adaptive system, a database is created in which the identified functions are organised vertically, the corresponding characteristics of adaptivity horizontally. The additionally identified specifications support the understanding of general functions and can be used for a detailing in subsequent investigations. In the present database, only the general functions are taken into account. The present breakdown of functions is made based on the assumption that they are confronted with individual dynamic factors and requirements within the façade as a holistic system.

5 SUPERPOSITION OF FAÇADE FUNCTIONS AND CHARACTERISTICS OF ADAPTIVITY

In the superposition matrix shown in Table 4, the identified façade functions are overlaid with the determined characteristics of adaptivity. The façade functions are listed vertically in the table. The respective characteristics of adaptivity contrast them in horizontal organisation.

		GENERAL			BEHAVIOUR			AUTOMATION		
		Technol-ogy	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Pro-cessing system	Output system
Sun										
1	Solar shading									
2	Light deflection									
3	Glare protection									
4	Control daylight radiation									
Temperature										
6	Thermal insulation									
Air										
7	Ventilation									
User										
8	Control visual contact									
Acoustic										
9	Sound insulation									
Energy										
10	Generate energy									
11	Store energy									
Supply										
12	Heating and cooling									
13	De- / humidification									
14	Electricity									
15	Artificial light									
16	Communication									

TABLE 4 Superposition matrix

6 EXAMPLE FOR THE APPLICATION OF THE SUPERPOSITION MATRIX

Table 5 shows the application of the superposition matrix to the façade of the KFW Westarkade in Frankfurt, Germany. The project, designed by Sauerbruch Hutton and completed in 2010, was selected because the building and the façade are extensively documented in the literature (Fortmeyer & Linn, 2014). The double façade of the building is characterised by vertical coloured blinds. It has automated ventilation flaps. A glare shield is installed in the space between the façade. Based on the literature sources, the façade functions can be assigned the characteristics of adaptivity and automation shown in Table 5. Characteristics which cannot be determined due to missing data are marked with N.A. (González, Holl, Fuhrhop, & Dale, 2010; Winterstetter & Sobek, 2013)

		GENERAL			BEHAVIOUR			AUTOMATION		
		Technol-ogy	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Pro-cessing system	Output system
Sun										
1	Solar shading	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
2	Light deflection	No	No	No	No	No	No	No	No	No
3	Glare protection	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
4	Control daylight radiation	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
Temperature										
6	Thermal insulation	Inter-mediate space	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
Air										
7	Ventilation	Ventila-tion flaps	Yes	Yes	Extrinsic	N.A	Active- In-active	Yes	Yes	Yes
User										
8	Control visual contact	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
Acoustic										
9	Sound insulation	Absorber	No	No	No	No	No	No	No	No
Energy										
10	Generate energy	No	No	No	No	No	No	No	No	No
11	Store energy	No	No	No	No	No	No	No	No	No
Supply										
12	Heating and cooling	No	No	No	No	No	No	No	No	No
13	De- / humidification	No	No	No	No	No	No	No	No	No
14	Electricity	No	No	No	No	No	No	No	No	No
15	Artificial light	No	No	No	No	No	No	No	No	No
16	Communication	No	No	No	No	No	No	No	No	No

TABLE 5 Superposition matrix applied to the façade of the KFW Westerkade

The case study shows that the characteristics determined can principally be applied to buildings. An absolute assignment of a function to a particular component of the façade is not always possible, since there are undefinable overlaps between them. In the investigated project, for example, the function of sound insulation is fulfilled by the intermediate space of the double façade. In this context, the opening of the ventilation flaps has an effect on the noise protection. Absorbent surfaces also contribute to the fulfilment of acoustic requirements, which, however, are not able to adapt. Such complex contexts can only be mapped abstractly, and interpretations are necessary in the assignment. This also applies to the determination of individual characteristics. Thus, the opening state of a ventilation flap can be evaluated as an active or inactive state; however, in the case of a plurality of ventilation flaps that are capable of opening, it is also possible to estimate that a gradual adaptation is present. It is necessary to clarify whether the respective evaluation refers to a single element or to the overall system.

7 CONCLUSION

The study compiles the external boundary conditions and interior comfort requirements of adaptive façades. Based on existing literature, the following seven external influencing factors were identified: "solar radiation, temperature, air quality, sound, wind, precipitation, and humidity". As stated above in Section 2.3, apart from natural factors, human intervention in the environment also has an impact on the functions of the façade. In terms of interior comfort, the four requirement categories "thermal comfort, aero- & hydro-comfort, visual comfort, and acoustic comfort" were identified. The listing provides an initial basis and is not understood to be complete. Depending on the field of application and in further research, more aspects may be added. Taking the identified framework conditions into account, the study provides a detailed breakdown of performance-relevant and possibly automated adaptive façade functions as potential parts of an intelligently networked, adaptive façade system. While some of the identified functions have a direct impact on the façade performance by balancing of environmental conditions and comfort requirements, others are cited because of an existing reference to environmental conditions and an indirect impact on the system, for example, through the provision of energy. The "Supply" functions category lists such functions that are not necessarily linked to external influences but do affect the interior comfort. As an extension of previously existing research results, the found characteristics of an adaptive façade as an overall system are summarised, supplemented with automation aspects, and applied to the individual functions. This detailing enables a differentiated consideration of dependencies and shared requirements between individual performance-relevant and automated adaptive façade functions within an intelligently networked façade system. The superposition matrix developed in this study can contribute to the design of intelligent-networked and multifunctional-adaptive building envelopes. As a theoretical assembly based on existing literature, it does not provide information about the actual realised automated adaptive functions in building practice. The superposition matrix can be used as organisational tool for the systematic assessment of automated and adaptive façade functions in realised building envelopes to examine the technical basis for intelligent networking. A corresponding practical investigation is identified as a future research task for the clarification of a possible intelligent cooperation of automated adaptive façade functions according to networked production plants in industry.

Acknowledgements
The study is part of a PhD research project and is not subject to any specific funding.

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Rethinking Adaptive Building Skins from a Life Cycle Assessment perspective

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Abstract

Adaptive building technologies have opened up a growing field of research aimed at ensuring indoor comfort while reducing energy consumption in buildings. By focusing on flexibility over short timeframes, these new technologies are, however, rarely designed for sustainability over their entire lifecycle. This paper aims to address an information gap between the research field of architectural Life Cycle Assessment (LCA) and the state of the art of adaptive façades, by presenting an analysis of the main aspects in traditional and adaptive façades that are relevant to understanding whether parallels can be drawn between available LCA databases.

The literature is reviewed following an inductive method based on a qualitative data collection aimed at answering a list of research questions, and a deductive method starting from the descriptions of adaptive building envelopes. The findings highlight four main points: i) where and how adaptivity is integrated, ii) the design targets that are able to reduce the environmental impact, iii) the importance of a qualitative as well as a quantitative LCA of the technology, and iv) lists a number of knowledge gaps currently limiting the diffusion of LCA as a design and verification tool in Adaptive Building Skins.

Keywords

Life Cycle Assessment, building skin, adaptive, systematic mapping, design parameters

1 INTRODUCTION

The building sector is the largest consumer of energy, accounting for over one-third of final energy consumption and carbon dioxide (CO2) emissions globally. According to the European Commission, the energy use during the active life of the buildings in Europe is responsible for approximately 40% of energy consumption and 36% of CO2 emissions. In order to address these issues, research in the building sector has mainly focused on maximising the supply of energy from renewable sources and reducing the operational energy consumption in buildings' life cycle by massively integrating low-energy building technologies and systems (IEA, 2013).

The concept of 'energy' in buildings has often been used in referring to 'operational energy' (OE), while largely disregarding embodied energy (EE) or embodied carbon (EC). This encompasses initial, recurring, and demolition embodied energies (Azari & Abbasabadi, 2018). Although it is true that in many conventional buildings OE represents a relatively larger proportion of the life cycle energy (OE 80-90% compared to EE 10-20%) the rates vary depending on the building type (in an adobe/clay residential building the rate is closer to OE 66% - EE 33%) (Dixit, Culp, & Fernández-Solís, 2013; Ramesh, Prakash, & Shukla, 2010). The need to consider the complete life cycle of the building is therefore significant, especially since the amount of embodied energy is expected to grow with the rising number of low energy buildings that reduce their OE at the expense of an increase in their EE by integrating active and passive technologies and building systems (thicker envelopes, shading devices, etc.) (Azari & Abbasabadi 2018; Dixit, Culp, & Fernández-Solís 2013).

It is mainly in answer to the demands for optimisation of operational energy in buildings that the field of architectural façades has developed a great variety of technological solutions that advocate for higher comfort conditions while reducing energy use. Much of the technological research on adaptive building envelopes or skins (ABS) is centred on developing flexibility of the building surfaces within the timeframes of the human activity cycle, ranging from interactive systems reacting within seconds to seasonal adaptations changing the building skin over a range of months. As most building technologies, ABSs rarely take into consideration other aspects than the energy efficiency or the user comfort, reflecting only a very partial view of the system's real sustainability. Therefore, if the aim of adaptive building technologies truly is to improve on the sustainability of the built environment, ABSs need to be designed and contextualised within the broader framework of a complete Life Cycle Assessment (LCA), evaluating the technologies throughout all building LCA stages, as defined by the European Standard EN 15804:2012 (Table 1).

This paper takes a further step towards the integration of LCA principles in the design of ABSs by reviewing the differences between adaptive and traditional façades, highlighting information gaps and focusing on aspects regarding architectural Life Cycle Assessment which are mostly not considered in the ABS research field. The study is based on an analysis of the state of the art of adaptive façades and integrates definitions and classifications with insights on the possible environmental impacts involved, setting the bases for a Life Cycle Inventory. The aim is to give a more comprehensive understanding of the function and the assembly of materials and technological parts of the building skin, but also of the effects each design choice has throughout the phases in the life cycle, and by extension, its impact on the environment. The outcomes integrate the previously mapped framework by Crespi, Persiani, and Battisti (2017), preparing for a complete LCA system for ABSs.

Production stage (A1-A3)	
(A1)	Raw material supply, including processing of secondary material input
(A2)	Transport of raw material and secondary material to the manufacturer
(A3)	Manufacture of the product, and all upstream processes from cradle to gate
Construction stage (A4-A5)	
(A4)	Transport of the products to the building site
(A5)	Installation/construction (of the product)
Use stage (related to the product) (B1-B5)	
(B1)	Use of the product
(B2)	Maintenance of the product
(B3)	Repair of the product
(B4)	Replacement of the product
(B5)	Refurbishment of the product
Use stage (related to operation) (B6-B7)	
(B6)	Operational energy use
(B7)	Operational water use (not relevant for ABS)
End of life (C1-C4)	
(C1)	Demolition (/disassembly) of the product
(C2)	Transport of the waste to waste processing facility
(C3)	Waste processing operations for reuse, recovery, recycling
(C4)	Final disposal of end-of-life product
Benefits and loads beyond the product's boundary	
(D)	Reuse/ recovery/ recycling potential evaluated as net impacts and benefits

TABLE 1 Building LCA stages according to (EN 15804:2012)

2 LITERATURE REVIEW

Existing classifications of adaptive building envelopes are broadly recognised to be partial and few (Loonen,Trčka, Cóstola, & Hensen, 2013; Loonen et al., 2015; Luible et al., 2015; Sachin, 2016). In order to provide an inclusive review and directly address the aspects relating to LCA, the research is structured according to the method of data analysis of the 5 Ws (Creswell, 1998), aimed to identify basic questions that are relevant to the topic for information gathering and problem solving (Who, What, Where, When, Why, How). With the overview of the ABS classification systems taken as a base, the study proceeds to redefine ABSs from an LCA perspective by answering the research questions in Table 2. Questions Who and Why are answered by the body of the paper and are therefore not further developed.

ABS	ABS IN TERMS OF LCA	LCA STAGES INVOLVED[1]
What?		
1. What is commonly defined as an ABS? 2. What are ABSs in terms of LCA?	- Which parts compose an ABS and how are these assembled? (Fig. 2)	A1-A3 Production stage B6 Operational energy use C3 Waste processing C4 Final disposal, end of life D Reuse/ recovery/ recycling potential
	-.How are distinctions adaptive/static, active/passive relevant in LCA?	
Where?		
3. At which component level, and where in the façade are adaptive proprieties integrated?	- Which are the most common ABS technologies and materials? (Fig. 3)	A3 Manufacturing A4-A5 Construction stage B2-B4 Use stage C1 De-construction demolition D Reuse/ recovery/ recycling potential
	- At which scale of the building skin is adaptivity integrated? - Are users involved in the operation of the technology?	A3 Manufacturing A4-A5 Construction stage B2-B4 Use stage B6 Operational energy use C1 De-construction demolition
How?		
4. How does the adaptation work? (Fig. 4, Fig.5)		A1-A3 Production stage B2-B4 Use stage B6 Operational energy use
When?		
5. Within which timeframe do adaptive processes occur?	- What impact does the timing of adaptation have on LCA? (Fig. 6)	B2-B5 Use stage B6 Operational energy use C1-C4 End of life
	- How can adaptive processes be assessed for an LCA?	B6 Operational energy use

1 *Life cycle stages according to the European Standards EN 15804 (2012) (Refer to Table 1).*

TABLE 2 'Ws' research questions

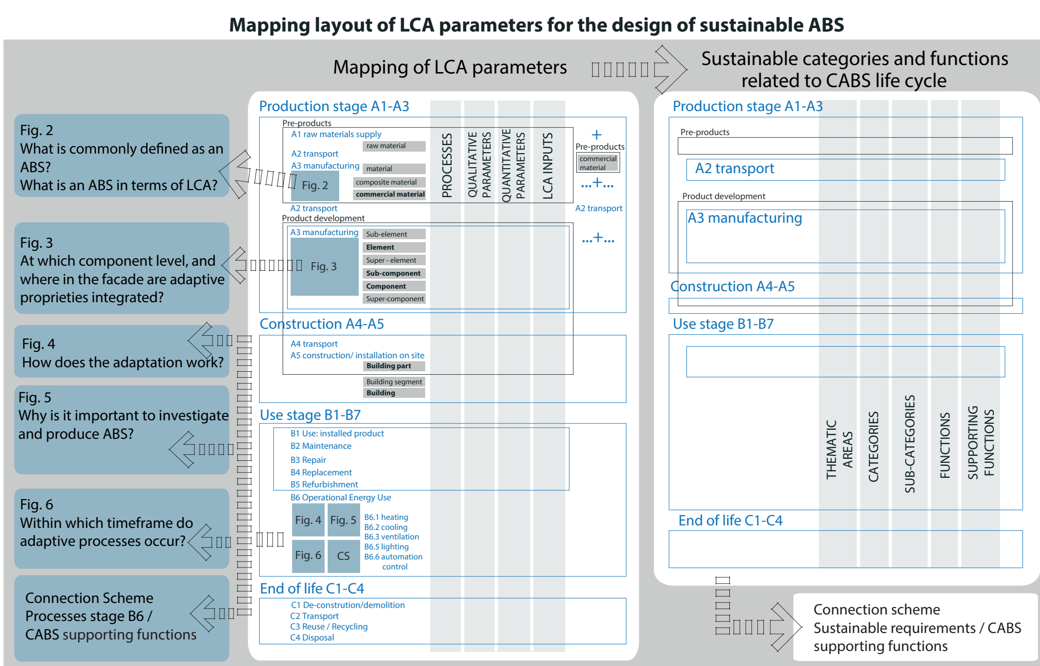


FIG. 1 General mapping of the LCA process and parameters for ABSs (from Crespi et al., 2017), with the layout of how Figs. 2-6 in this paper can be included in the mapping.

The main aspects characterising ABSs in an LCA perspective are summed up in five infographic representations (Figs. 2 - 6), that can be further included in the mapping framework (Fig. 1).

2.1 DATA COLLECTION

Data collection was conducted by reviewing databases such as ScienceDirect, Scopus, and ResearchGate. Among the keywords searched were: adaptive, innovative, dynamic, responsive, climate, building envelope, façade components, building shells, building skins, LCA, materials, and photovoltaic. The academic literature was reviewed following two main paths:

- an inductive method based on a qualitative data collection aimed at answering the research questions;
- a deductive method starting from the aforementioned descriptions of adaptive building envelopes.

In a first step, a broad range of academic publications were selected based on the innovative technologies introduced in the building envelope. Although not directly mentioning 'Adaptive Building Skins', these allowed for the incorporation of a great number of technological solutions that are effectively employed in ABSs, such as photovoltaic systems, which are among the most widespread technologies in active façades. The importance of identifying a method of classification used for existing envelopes' products lies in the possibility of highlighting shortcuts to available information on substances' emission data to be further employed in future Life Cycle Inventories for ABSs (such as the Ecoinvent database, 2007), without needing to reconstruct the emissions path due to the individual production processes of the materials making up the product.

In a second step, the research focused on the more recent findings on adaptive façades, examining only literature published after 2012. The literature was classified by topic, terminology, and methodological approach used (Technological, Life Cycle, Systematic, Biomimetic). The outcomes are summarised in the annexes. This approach helped to identify the many nuances the concept of ABS spans, not necessarily related to specific technological solutions.

2.2 STATE OF THE ART REVIEW

The study of the existing literature on adaptive façades reveals a very broad understanding of these technologies, although, in many cases, 'adaptiveness' is not directly mentioned. Definitions and classifications reveal the recurring features and characters typical of ABSs that are important to take into consideration within the LCA. Existing and emerging building skin technologies have been classified, of which two main aspects were identified:

- A classification of the physical features (Tucci, 2012), with innovative materials to building parts categorised according to behaviour (active/passive) and appearance (opaque, semi-transparent, translucent, transparent).
- A classification of the functional behaviour (Loonen et al., 2015 & 2013) listing eight basic criteria for façade adaptivity: goal, responsive function, operation, technologies (materials & systems), response time, spatial scale, visibility, and degree of adaptability.

The annexes give a further overview of how the collected literature has addressed the evolution of building envelopes through a technological, biomimetic, or systematic approach. The multiplicity of approaches is indicative of the interdisciplinary nature of the topic and the broad category of technologies employed in ABS.

Emerging technologies identified by the literature review (detailed list in annexes) require further integration in ABS inventories to enable a further mapping in terms of LCA. These can be subdivided into three macro-families:

1. Façades that integrate renewables, from solar façades (Quesada, Rousse, Dutil, Badache, & Hallé, 2012a &b), solar cooling (Prieto, Knaack, Auer, & Klein, 2017), Building Integrated Solar Thermal (BIST) technologies (Zhang et al., 2015), and dynamic Building Integrated PhotoVoltaic systems (BIPV) (Jayathissa, Jansen, Heeren, Nagy, & Schlueter, 2016; Curpek & Hraska, 2017).
2. Active building envelopes, integrating smart glasses and motor-based shading devices (Sachin, 2016), robotic materials that combine sensing and controlling features (McEvoy & Correll, 2015), IOT sensor network systems and the several devices associated with them (e.g. sensors, actuators, controllers) (Konis & Selkowitz, 2017).
3. Passive stimuli responsive materials and components. Although being mostly at an experimental stage, these elements are considered to be of strategic importance for the coming generation of ABS. Examples are hygromorphic materials, Phase Change Material (PCM)-based mortars (Curpek & Hraska, 2017; Koláček, Charvátová, & Sehnálek, 2017), self-shading building tiles with shape memory polymers, etc. (among others Aresta, 2017; Bridgens, Holstov, & Farmer, 2017; Clifford et al., 2017; Mao et al., 2016; Persiani, Molter, Aresta, & Klein, 2016b; Ribeiro Silveira, Louter, Eigenraam, & Klein, 2017).

With such a broad variety of technologies and functions characterising adaptive building envelopes, it is understandable that many sibling concepts are used to describe adaptive systems. Adaptive Building Skins are described from a systematic point of view as sets of interacting parts with specific multiple functions, behaviours, and goals. The most diffused way to distinguish between types and categories of adaptive envelopes, however, is to identify their purpose and the dynamic behaviour of the components. Climate Adaptive Building Shells (CABS), for instance, address more specifically the energy efficiency and performance of the building envelope (Loonen et al., 2013).

The review also highlighted further directions for developing ABSs in terms of sustainability.

- A number of studies were reviewed where the generation of design concepts is tackled through a biomimetic problem-solving methodology (Wang, Beltrán, & Kim, 2012; Persiani, Battisti, & Wolf, 2016; Badarnah, 2012, 2016, 2017). From an LCA point of view, investigating the relation Environmental agents – means of adaptation – Building functions – Operation of the technology – LCA can create a systematic design-oriented framework open to innovative and creative concepts. These concepts have been introduced in the early design phases in previous research through a preliminary (simplified) systematic LCA mapping (Crespi, Persiani, & Battisti, 2017). The framework, built on a method for the design and construction of integral façades, aims to enable decision-making in the early design phases of adaptive envelopes and introduces LCA optimisation through an evolutionary design method with a multi-objective solution finding.
- A new methodology which is widely recognised as a reliable means of data acquisition, information feedback, and a solid base for decision making in the context of sustainable design and LCA is Building Information Modelling (BIM). The model enables cross referencing of graphic and numerical information of the building and its parts, allowing not only the system to be controlled during its design and construction phase, but also allows it to be managed throughout its complete lifecycle (Soust-Verdaguer, Llatas, & García-Martínez, 2017; Volk, Stengel, & Schultmann, 2014).

- Research reveals that no single mitigation strategy alone can tackle the problem of transiting to a low-carbon built environment. A pluralistic approach is absolutely necessary, combining better design, the use of low-Embedded Carbon (EC), and reuse of high-EC materials together with stronger policy drivers (Pomponi & Moncaster, 2016).

The State-of-the-Art review underlines four topics of importance for ABS in terms of LCA:

- Different classifications of ABSs and ABS technologies, highlighting possible shortcuts to available information on substances' emission data to be further employed in future Life Cycle Inventories for ABS;
- A list of emerging technologies to be further integrated in ABS inventories and mapping of ABS in terms of LCA;
- Commonly shared definitions of ABS;
- Directions for further development: the biomimetic approach, integration of information through BIM, and a pluralistic approach.

What appears to be missing in the State of the Art is the implementation, comparison, and alignment of the terminology of building products with those in BIM libraries and standards. This would allow a shared base of understanding through the different design and simulation software, from design to facility management, and greatly facilitates the LCA process.

3 ADAPTIVE BUILDING SKINS FROM AN LCA PERSPECTIVE

In order to describe which aspects are relevant for ABS in terms of LCA in a straightforward way, the study is structured through thirteen research questions listed in Table 2.

3.1 WHAT IS COMMONLY DEFINED AS AN ADAPTIVE BUILDING SKIN?

Adaptive façades, or adaptive building envelopes, is a general term used to refer to a new generation of multifunctional façade systems that are able to change their function, features, or behaviour over time in response to transient performance requirements and boundary conditions with the aim of improving the overall building performance (COST Action TU1403, 2018; Persiani et al., 2016a). This emerging research area can be found at the crossroads between environmental architecture, building technologies, and artificial intelligence. As in all emerging fields, the first stages are characterised by an non-uniform variety of terms and definitions with analogous meanings. Adaptive Building Skins (ABS), Climate Adaptive Building Shells (CABS), Adaptive Façades, Autoreactive Façades, and Acclimated Kinetic building Envelope (AKE) are just a few of the many sibling concepts that can be found in the current State of Art. These terms describe variations of entities within the same family of technologies with a common 'blueprint concept', highlighting and focusing on some aspects more than others.

There are four definitions of ABS indicated in the reviewed studies (Wang et al. 2012; Badarnah, 2012; Loonen et al., 2013; Persiani et al., 2016a). While the wording has evolved over time, the core of the concept is mostly shared. The definition focuses on goals and performances to be achieved in a responsive way by the building envelope, which is described of as a system of parts. Physical characteristics or technological solutions are not mentioned, although built examples are given in some cases. The aesthetics of the movement are not considered central to the definition, its potential to involve the users and raise awareness with a positive impact on behaviour is however widely recognised. This approach is shared for the purpose of this research, as it gives the opportunity for façade designers to have unlimited creative boundaries inside a systematic framework driven by specific performance goals and dynamic behaviours.

3.2 WHAT ARE ABSs IN TERMS OF LCA?

As mentioned previously, ABSs enable dynamic responses to changing environmental conditions, boosting indoor comfort and energy performances in the Operation stage (B6) but should also contain environmental impacts in the other life cycle phases, such as Production, Use of the product (B1), Maintenance (B2-B4), Refurbishment (B5), and End of Life (C1-C4), in order to fully justify their use. On the one hand, LCA is a means to measure the real impact of ABSs on the environment, and on the other hand it is a tool to optimise its design, initiating a cycle of experimentation and verification (Table 3). Among many objectives, an LCA identifies opportunities to improve the environmental performance of products at various points in their life cycle (ISO 14040 & 14044 2006). Adaptive Building Skins can therefore be redefined in the broader perspective of the entire life cycle where 'adaptivity' assumes a broader meaning, involving the conservation of natural resources and the reduction of pollution.

DESIGN TARGET	REDUCES IMPACT ON LCA PHASE														
Use low-EC materials	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Use of local materials		X		X					X	X					
Use renewable materials	X								X	X					
Use of materials with low processing energy	X		X												
Include waste, by-products, and used materials	X	X	X												X
Design for disassembly	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Enable re-use and recovery of materials (especially of EE/EC materials)								X	X	X		X		X	X
Enable refurbishment of existing structures extend-ing the product's life							X	X	X	X		X	X	X	X
Develop more efficient construction processes / techniques	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Increased use of prefab-ricated elements/off-site manufacturing					X	X	X	X	X	X		X		X	
Prefabricate bigger parts of the façade					X				X	X					
Design for autoreactivity	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**C4**
Enable operation at zero energy						X					X				
Dynamics are embedded in the material, reducing the number of parts	X	X	X	X	X	X	X	X	X	X					

TABLE 3 Design targets to reduce the impact on different phases of the LCA

Adaptive building envelopes are multifunctional façade systems able to change their features or behaviour over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall performance of the building, while contributing to the reduction of the environmental impacts in all the phases of the building's life.

As previously pointed out, ABSs are strongly focused on energy efficiency in the operational energy use phase (B6). For a full LCA approach, it is necessary to identify and evaluate which among the commonly adopted technologies, components, and materials can have a significant impact on the other phases in the life cycle. High-tech components for instance typically have a shorter lifecycle than that of the building and become obsolete increasingly quickly as newer products are developed, with the common side effect of a higher impact on the production (A1-A3) and maintenance phases (B2-B4) of the system.

When designing new ABS technologies, the main variations on LCA impacts can be expected in the following phases (see also Table 3):

- Production phase (A1-A3), due to use of resources to produce specific components, elements and materials, rising complexity and use of high-tech materials to achieve kinetic façade components, etc.
- Construction phase (A4-A5), depending on the effectiveness of the assembly (and disassembly) of the product, construction times, and resources can be reduced.
- Maintenance, Repair, and Replacement phases (B2, B3, B4) and the End of Life phase (C1-C4) can be strongly impacted through designing for disassembly (especially of interest for the replacement of kinetic parts in ABSs).
- Benefits and loads in the phase of Reuse/ recovery/ recycling (D) are mainly considered beyond the product's boundaries, as it enters another system's life cycle when integrated under any of the three forms.

3.2.1 Which parts compose an ABS and how are these assembled?

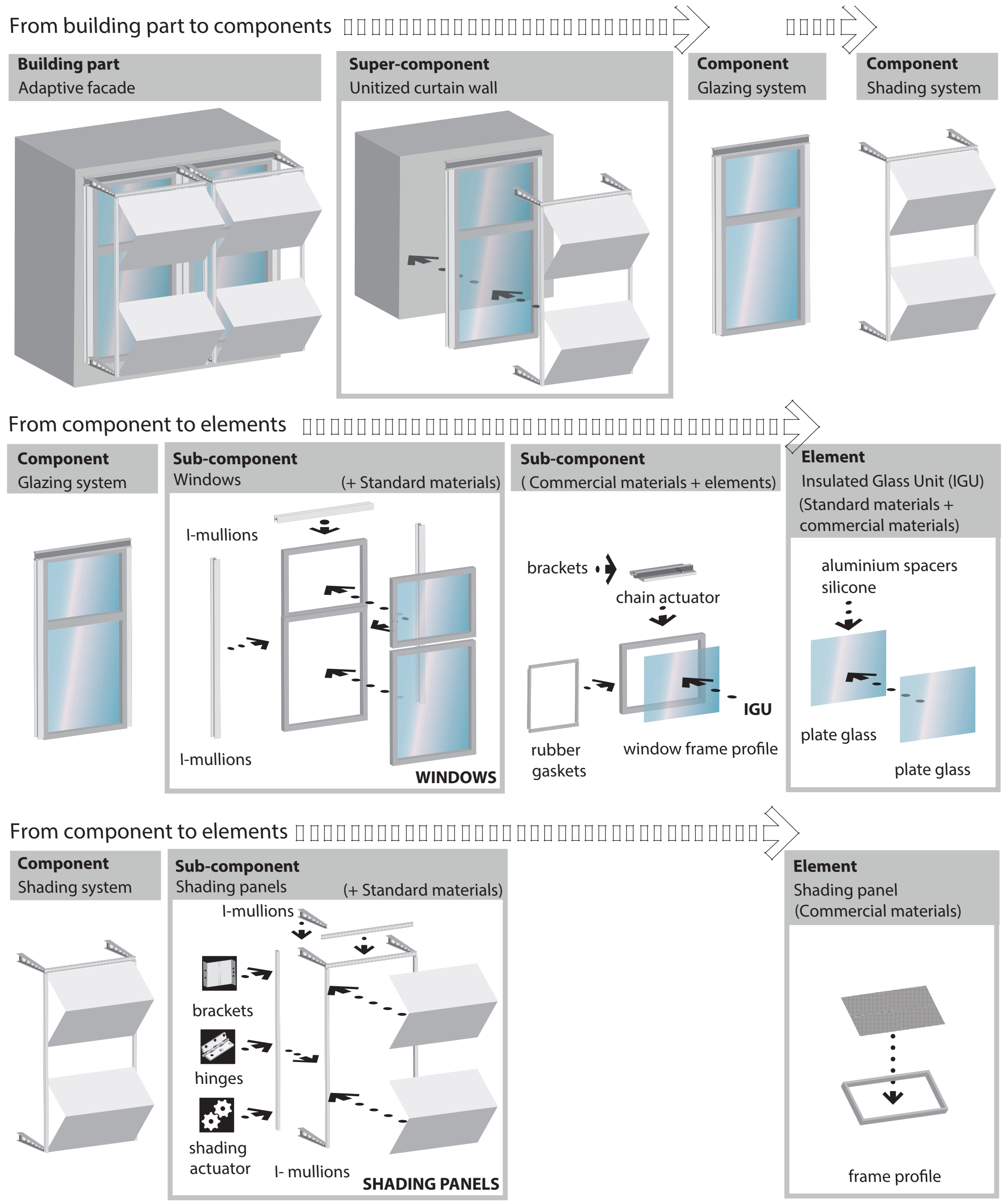


FIG. 2 Study of a hierarchical disassembly of a basic façade unit composed of glazing and dynamic shading (based on *Klein, 2013*). LCA stages involved: (A3-5), (B2-4), (C1), (D).

3.2.2 How are distinctions adaptive/static, active/passive relevant in LCA?

There are fundamental differences between active and kinetic, adaptive and static systems. 'Active' and 'passive' refer to the energy requirements of the technology: while an active system is powered though an input of energy (mainly electrical), a passive system uses the latent energy from its surroundings (as for thermal Phase Change Materials) (Persiani et al., 2016a). 'Adaptive' and 'static' refer to the physical capacity of the material or the technology to change in determinate conditions. Because of the tendency to design increasingly complex façade systems, the boundaries between active and passive systems slowly disappear: adaptive properties are no longer characteristic of active systems, as latent energy reaction can now also be enabled in passive systems (Persiani et al., 2016b). In an LCA, these characters need to be considered, including stratigraphic façade solutions (like shaded double-glazing systems) and spatial structures with climate-regulating purposes (like greenhouses), which may reduce the impacts in the production phase (A1-A3).

3.3 AT WHICH COMPONENT LEVEL, AND WHERE IN THE FAÇADE ARE ADAPTIVE PROPERTIES INTEGRATED?

A great variety of aspects in an LCA depend on the hierarchy of the parts in the ABS, on the assembly methods and above all, the wear of elements or components. A designer aware of these processes can effectively have an impact on:

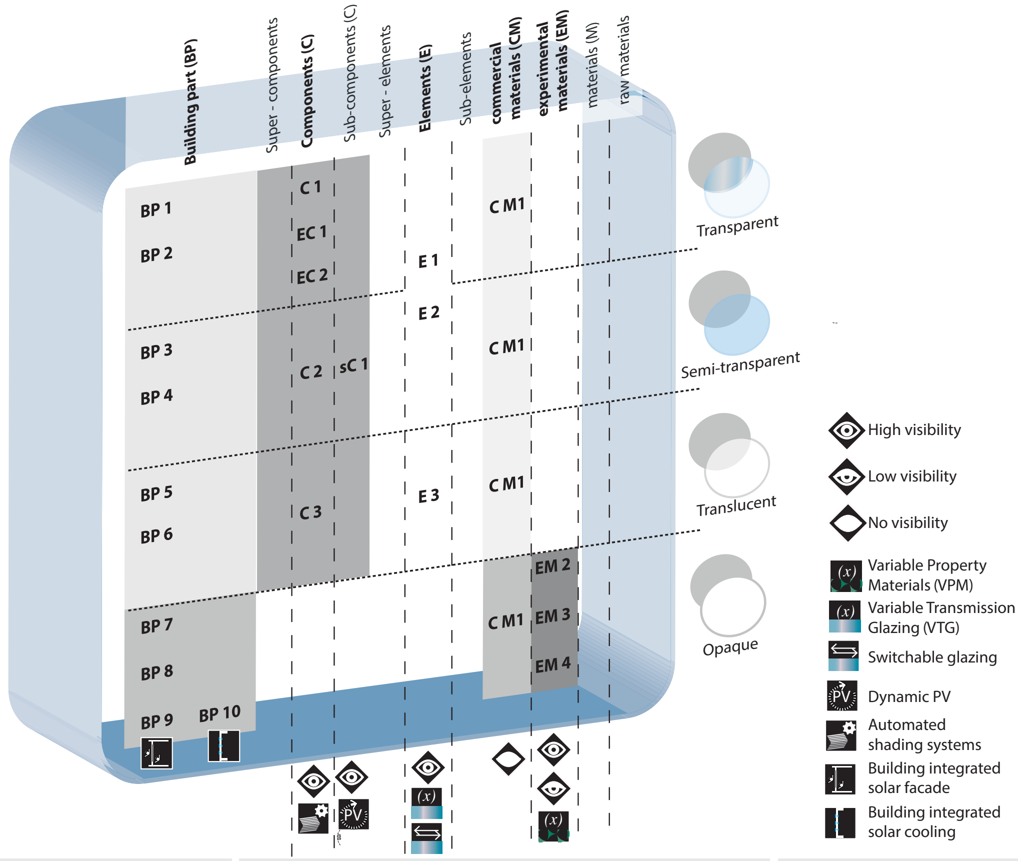
- Controlling at which stage in the production chain the manufacture and assembly takes place (in factory / on site), with the related impacts;
- Design disassembly to reduce impacts in the Use stage (B2-B4), simplify maintenance and repair, avoiding the replacement of a whole when only part is damaged;
- Design disassembly for deconstruction (C1), maximising the possibility of reuse, recycling, and separate materials that need special disposal.

Static envelopes are also included in this framework (traditional passive spatial solutions in Fig. 3), being the technical base for many technologies. These can be implemented with adaptive elements, components, or materials, and can be used as reference for future solutions. The main purpose with identifying these solutions is to highlight the presence of elements with a substantial impact on the production and maintenance phase.

3.3.1 Which are the most common ABS technologies and materials?

Technologies. The most commonly used technologies are different types of glazed components with shading systems (C1 - C3) that may also include elements with controlled solar light and heat transmittance (such as chromogenic E1 - E3).

Mechanical ventilation systems can be found in some static and dynamic building façade technologies (Building Part - BP2) as well as energy generating components (BP3, BP4, BP7, BP8, BP9). A new trend is represented by Building Integrated solar cooling technologies (BP10), where the cooling system, integrated in the façade, also generates energy through solar electrical or solar thermal processes. The cooling generation principles are several (thermoelectric cooling, absorption cycle, indirect evaporation, vapour compression) and the transfer medium can be either solid-based, water-based, or air-based. The delivery systems, depending on the medium, are radiative walls, mounted pipes, induction units, diffusers, or may be absent. In this case, ABSs include HVAC systems and the Life Cycle impact might be consistent.



Building Parts (BP) related to static envelopes

BP 1. - Naturally ventilated transparent facade (NVTF)
BP 2. - Mechanically ventilated transparent facade (MVTF)
BP 3. - Semi-transparent building-integrated PV system (STBIPV)
BP 4. - Semi-transparent building-integr. PV thermal system (STBIPV/T)
BP 5. - Thermal storage wall
BP 6. - Solar chimney
BP 7. - Building-integrated photovoltaic system (BIPV)
BP 8. - Building-integrated solar thermal system (BIST)
BP 9. - BiPV thermal system (BIPV/T)
BP 10. - Thermo-electric facades

Components (C), Elements (E), experimental/commercial materials (EM/CM) related to dynamic systems

sC 1. - dynamic PV
C 1. ventilated double skin facade (DSF) with shading system
C 2. - Prismatic louver
C 3. - translucent ventilated with chromogenic glass & shading system
EC 1*. - autoreactive components
EC 2*. - Ventilation units with PCM for vdsf

E 1. - Chromogenic: Photochromic, Electrochromic, Thermochromic, Gasochromic Chromogenic / angular selective glass
E 2. - SPD smart windows
E 3*. - VTG under development: Micro - ElectroMechanical Systems

CM 1. - Phase Change Materials

EM 1*. - VPM under development:
Shape Change Materials (SCP)
Thermal Expansion Materials (TEM)
Thermobicomposite Materials (TBM)
Shape Memory Foam (SMF)
Shape Memory Ceramics (SMC)
Shape Memory Biosystems (SM-BS)
Bicomposite materials (BM)
Absorbent Polymers (Aps)
Superabsorbent Polymers (SAPs)
Wood based hygromorphic materials
PCM - based mortars
Thin glass
EM 2. - Shape Memory Polymers + Shape Memory Alloys
EM 3. - Shape Memory Polymers + Hydrogel
EM 4. - Thermobimetal

Other most used materials (M)°

M 1. - 3. Wood
Derived timber products
M 2. - 4. Metals
Steel products, Aluminium, Zinc , Lead
M3. - 6. Plastics
Profiles, Elastic plastic profiles, Foils and fleeces, Sealing materials
M4. - 7. Components for windows and curtain walls

* materials, elements and components under development

° Classification from the Ökobau database, built on Gabi database

FIG. 3 Systematic illustration of the typologies of ABSs, with classified the most widespread technologies and materials (classification from the Ökobaudat database). LCA stages involved (A1-3), (B6), (C3-4), (D).

Material innovation in construction depends, to a large degree, on technological improvements in other manufacturing sectors (such as medical or communications). A number of reviewed publications list new materials used in the context of adaptive façades (refer to the literature review in the annexes). During the production phase of the envelope, the most used materials are glass, aluminium, and inorganic polymers for films and textiles, of which the energy embodied in the manufacturing process is hardly ever taken into consideration. However, in 2017, an Environmental Product Declaration (EPD) on an ETFE-based cladding system was published, showing growing concern and interest of stakeholders for environmental issues (Maywald, 2017).

At the current rate of technological development grow rapidly obsolete, the long-term sustainability of specific high-tech solutions becomes challenging with respect to both the Production phase (A1-A3) and to the End of life scenarios (C1-C4). Adaptive materials (EM1 - EM4) for instance, are able to change their physical features in reaction to the action of external agents (humidity, heat, radiance, etc.). These are mostly under development for the field of building technologies, with few exceptions (as PCM, that are already available on the market). The category is expected to grow increasingly wider, adding on new technologies making use of them. In order to fully evaluate the sustainability of these materials and technologies more specific LCA studies are needed.

3.3.2 At which scale of the building skin is adaptivity integrated?

Adaptivity can be manifested either at material or at component scale. Designing for disassembly allows the adaptive parts to be easily removed and replaced, benefitting the life cycle of the whole façade as:

- adaptive parts tend to become worn out more quickly when compared to static solutions, because of their changing characters (as for kinetic adaptivity). Moreover, the duration and resistance of these new materials has not been tested over many years of use;
- technologies grow obsolete increasingly quickly, and disassembly allows adaptive materials or parts to be replaced with more advanced solutions without changing the whole façade system.

So far, major innovations on adaptivity have been developing at material scale, followed by a few categories of elements and components such as chromogenic glasses and shading devices that have existed for many years on the market.

3.3.3 Are users involved in the operation of the technology?

The possibility of users directly interacting with the functioning and the dynamics of ABSs introduces the question of whether the LCA should address the Operational energy use (B6) from a qualitative or a quantitative point of view. As comfort is a very subjective matter, it is difficult to achieve optimal conditions that satisfy all users. From a qualitative point of view, users are therefore often enabled to intervene and bypass the system (e.g. opening the windows for ventilation).
On the other hand, when users are allowed to override the set conditions, the quantification of energy consumption (lighting and HVAC) becomes difficult to control and is likely to rise. Building automated domotic monitoring systems have been suggested as high-tech solutions, that are however difficult to evaluate from an LCA point of view, as the system is tailored to the users and the potential variations are infinite.

Distinctions between transparent and opaque elements can give additional information on the performance, as a common low-tech way to introduce adaptivity is through visual and thermal permeability. The increased daylighting and thermal performance have a varying range of energy efficiency, which very much depends on use.

3.4 HOW DOES THE ADAPTATION WORK?

ABSs are programmed to adapt to surrounding environmental conditions and transfer energy in different forms (radiant, kinetic, potential) to achieve human comfort requirements. The great majority of ABSs are actuated through systems of sensors that analyse the surrounding conditions, communicating with a control unit that takes simple decisions and orders counter-actions. To these systems belong HVAC technologies and active building systems.

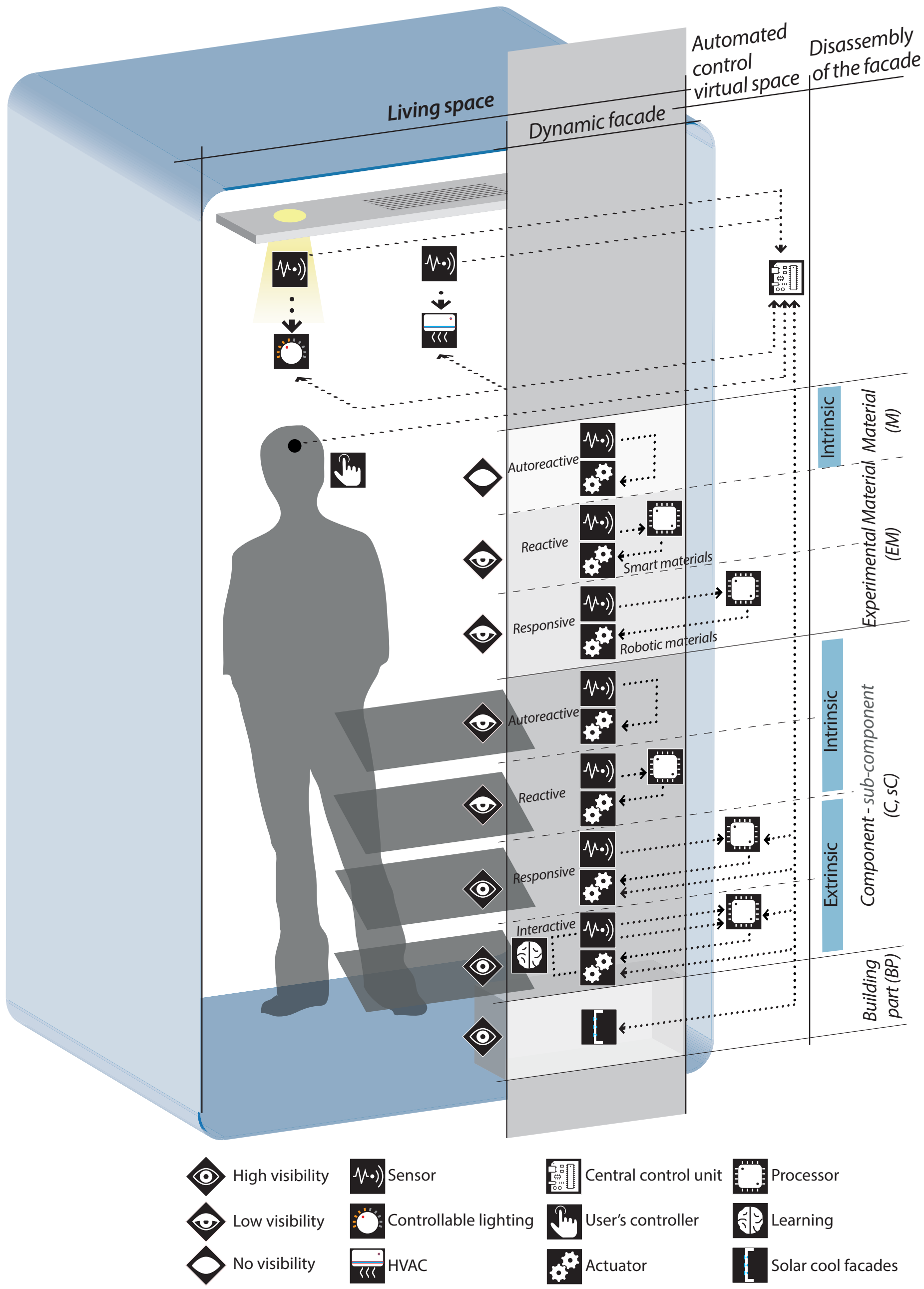


FIG. 4 Systematic illustration of the typologies of ABS through the possible variations in adaptivity (adapted from *Konis & Selkowitz, 2017; Loonen et al., 2013; Loonen et al., 2015; Persiani et al., 2016a*). LCA stages involved (A1-3), (B2-4), (B6)..

Research goals are generally aimed at improving ABS effectiveness by reducing uncontrolled user behaviour and energy (HVAC, lighting, and plug loads) through the integration of smart materials and systems. In continuous dynamic skins, users' interaction is often enabled through an Energy Management and Control System (EMCS), which on one hand aims to optimise but on the other adds up to the energy consumption during the usage phase being an active system.

Developing trends are energy-generating kinetic devices (as dynamic PV sub-components) and unpowered kinetic features that are however still in a prototyping phase (Persiani et al., 2016b). These latter technologies, referred to as "autoreactive", lack the control unit and wiring as reactions to specific stimuli are predetermined and embedded in the material itself. These systems react to latent energy conditions and can therefore be considered as high-tech passive systems requiring zero-energy in the Operational energy use phase (B6). Moreover, the reduction of wiring and Information Technology devices noticeably reduces the impact on the Production stage (A1-A3) and the Use stage (B2-B4).

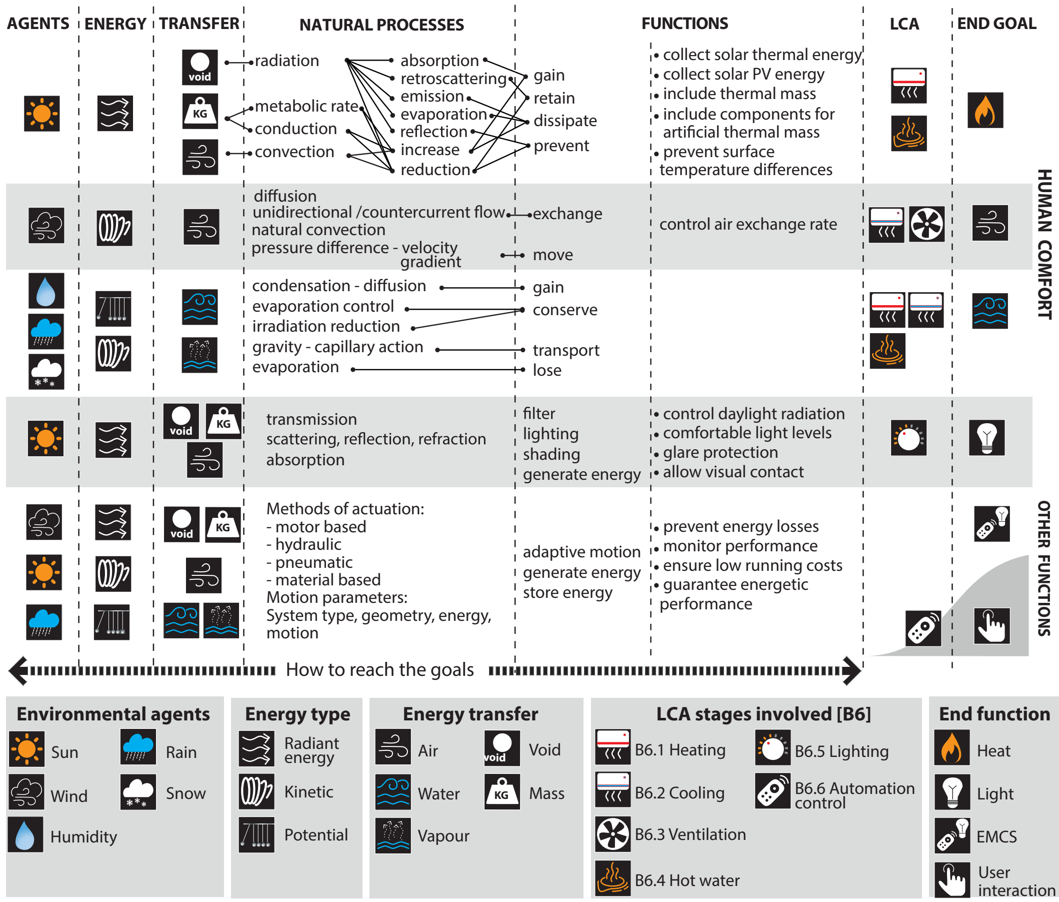


FIG. 5 Summary of the connections between environmental agents and ABSs final goals highlighting the means of energy transfer and the LCA processes involved (B6) (summarised from *Badarnah 2012, 2016, 2017; Persiani et al., 2016a*).

3.5 WITHIN WHICH FRAMEWORK DO ADAPTIVE PROCESSES OCCUR?

As adaptive building technologies adapt to both indoor and outdoor changing contexts, the translation of situational information in real time is among its main advantages and purposes. In this framework, LCA should be carried out considering more aspects than those pertaining only to static building skins.

LCAs are mostly based on the collection of a great amount of hard data describing the system through analysis (EN 15804 2012, Ecoinvent database 2007) and includes information on single materials (embodied energy, recyclability potential), material quantities, usage patterns, and stage processes (as extraction, production, maintenance and recycling processes). This quantitative (calculated) data is largely based on assumptions and estimations, wherever more precise information is not available.

Every LCA, however, is affected by a varying degree of uncertainty derived from the cumulative effect of imprecisions either due to lack of knowledge in the available data or to variability in the data. This is why qualitative considerations (transient or subject to interpretation) can play an important role in determining the overall environmental impact of a given object. Soft data refers to human intelligence and behaviour, and is bound to interpretation, contradictions, and uncertainty but is also very useful to understand environmental occurrences and situational nuances. This is why sensitivity analyses, estimating the effects of the choices made regarding methods and data on the outcome are recommended as part of an LCA (ISO 14040 2006, Budavari et al., 2011). Moreover, as the current technologies quickly evolve towards increased connectivity and Internet of Things (IoT), the relationships between hard and soft data become ever more intertwined.

The integration of variated typologies of information – such as user behaviour – into the analysis is therefore all the more interesting in ABS than in more traditional façade technologies.

3.5.1 What impact does the timing of adaptation have on LCA?

To achieve environmental comfort, the technology will ideally perform better if it can be adjusted more continuously, calling for a very reactive technology that will adapt within short timeframes. From an LCA point of view, however, constant reactivity in active ABSs also means constant use of energy resources, as well as rising maintenance issues due to the frequency of usage.

Energy use in ABSs is hypothesised in Fig. 6, referring exclusively to active systems, as passive systems are intended to operate at zero energy. Timeframe parameters (from Loonen et al., 2015) as seconds, minutes, hours, day-night, and seasons refer to climate adaptivity, while years and decades refer to the capacity of extending the life of building parts through maintenance, repair, replacement, or refurbishment.

ABSs are expected to have a higher energy cost the faster and the more frequent the adaptations, as reacting within seconds requires the system to be constantly ready for change. Moreover, fast movements typically require active and more complex energy-intensive brain elements (Persiani, 2018).

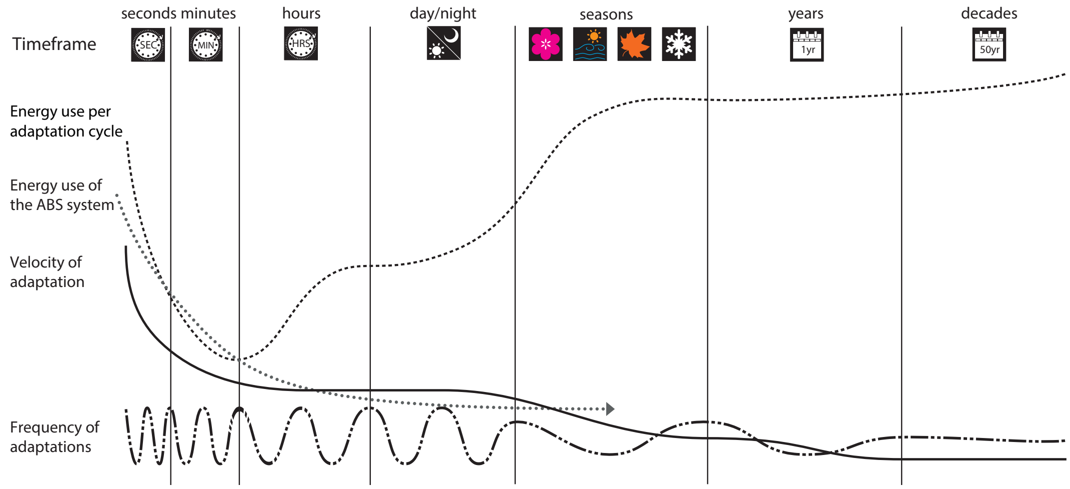


FIG. 6 Temporary and metabolic framework of adaptations in ABSs (timeframe, number of adaptations and hypothesised energy intensity). LCA stages involved (B2-6), (C1-4).

In view of optimising the relationship energetic expenditure/adaptive output, the metabolic cost (energy use per adaptation cycle) of the reactions is hypothesised in relation to the adaptation timeframe. By observing the energy expenditure in animal gaits, where each mechanism reaches its optimal relationship between energy expenditure and kinetic output at specific speeds (Persiani, 2018), the energetic cost per adaptation in ABSs is suggested as higher at slow and very fast speeds. What is of interest is to highlight these aspects in the context of an LCA, where the balance between product's lifespan and operational energy phase must be reached.

3.5.2 How can adaptive processes be assessed for an LCA?

The definition of ABSs being characterised by their specific functioning – and not as many other systems, a set of parts – is in this context of great relevance. It is not only the embodied energy of the system that is of interest, but also its potential to reduce the environmental impacts on the usage phase. For this, other methods of calculation are needed. Adaptive processes can be considered as peculiar characteristics in the façade system and can be assessed separately in the Operational energy use phase (B6). The methods of assessment and calculation of the adaptive features play a decisive role in the evaluation of an LCA, when compared with traditional façades, and hence also in the design of the technology. Assessment of the energy-intensity of ABSs in the Operational energy use stage (B6) is achieved through dynamic simulations during the design phase and is confirmed through monitoring during usage. Post occupancy reports also help to evaluate the optimal response time in relation to the user's ability to intervene in the regulation of ABSs, and whether it interferes negatively with the targeted energy efficiency. For all other life cycle phases (A1-A5, B1-B5, C1-C4) the methods of calculations are essentially the same for ABS as for traditional façades, which, however, does not mean that the results are the same, as the inputs can vary substantially.

4 CONCLUSIONS

The research has suggested an understanding of current and emerging ABSs and their functioning, focusing on aspects regarding LCA which have been mostly unconsidered up to now. The following points have been highlighted:

- ABSs are described as systems characterised by sets of interacting parts with specific multiple functions, behaviours, and goals. An integration to the definition is suggested to include "containing the environmental impacts in all the phases of the building's life" in the scope of the technology. Illustrations of the typologies of ABSs and a summary of the connections between environmental agents, energy transfer, LCA processes, and ABSs' final goals are provided.
- Adaptivity is either integrated by designing completely new technologies and uses or optimising traditional passive building systems with adaptive features. However, as increasingly sophisticated adaptive technologies are developed, the boundaries between active-dynamic and passive-static systems blur.
- The integration of variated typologies of information, as situational and real time information is among the main advantages and purpose of ABSs. Both quantitative and qualitative assessment, such as dynamic simulations and information on user behaviour, play a decisive role in LCA the evaluation of the technology.
- Energy use in ABSs is hypothesised in terms of metabolic costs (energy use per adaptation cycle) through the relationship energetic expenditure/adaptive output.
- LCA is suggested as a tool to optimise the design of ABSs by identifying opportunities to improve the environmental performance of products at various points in their life cycle. To effectively enable LCA as a design and verification tool in ABSs, a number of knowledge gaps need to be filled:
- The terminology and ontology of a building's products need to be implemented for an effective comparison with BIM libraries and standards in order to allow for a shared base of understanding from design to facility management, through the different design and simulation software.
- Future developments of smart materials need to be further investigated in terms of LCA to provide good databases of knowledge to support the integration of new adaptive features in façade technology.
- Designers need to be more aware of the hierarchy of parts, the processes of production, assembly, and the end of use of these technologies in order to be enabled to effectively design better and support industry to develop sustainable solutions. Specifically, designers can contribute by carrying forward specific design targets able to reduce the impact on different phases of the LCA. A study of a hierarchical disassembly of a basic façade unit is provided.

This system mapping is not intended to be exhaustive, but as a base for further implementation on the basis of stakeholders' needs. It is a first step to facilitate the process of Life Cycle Inventory during LCA and Life Cycle design. Adaptive building skins' energy-saving behaviour need to balance out its environmental impacts during the production, the usage, and the end of life phases to be considered fully sustainable. As adaptive envelopes can be expected to extensively grow in use and address an increasingly wider range of building technologies and construction scales, from building parts to components, the need for LCA to support ABS research and development greatly increases. Indeed, with the purpose of broadening the approach to ABSs and consider the full range of their environmental impact, this study will be the basis on which to carry out a comparative analysis between traditional and adaptive façades.

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Annexes

INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Quesada et al.	2012a	Review of solar façades	Technological	What	Building-integrated solar thermal system (BIST); Building-integrated photovoltaic system (BIPV); Building-integrated photovoltaic thermal system (BIPV/T); Thermal storage wall; Solar chimney
Quesada et al.	2012b	Review of solar façades	Technological	What	Mechanically ventilated transparent façade (MVF); Semi-transparent building-integrated photovoltaic system (STBIPV); Semi-transparent building-integrated photovoltaic thermal system (STBIPV/T); Naturally ventilated transparent façade (NVTF)
Tucci	2012	Innovative materials and components	Technological Systematic	What Where	Innovative technologies; Variable Property Materials VPM: TIM, PCM, Dynamic gel; Variable Conduttance insulation VCI, Aereogel, Dielectric glass; Variable Transmittance Glass VTG, Variable Convection Diodes VCD, Chromogenic glass, Prismatic panes and films; Dynamic Trombe Walls; Shading systems.
Klein	2013	Integral Façade Construction	Technological Systematic	What Where Why	Integral Façade; Systematic design; Product levels; Supporting functions
Zhang et al.	2015	BIST and applications	Technological	What Where How	Building Integrated Solar Thermal (BIST): air based, water based, refrigerant based, PCM based
ADAPTIVE FAÇADES					
Badarnah	2012	Biomimetics for building enve-lope adaptation	Biomimetic	Why How	Multi-functional interface: key functions, morphological means, multi-regulation; Environmental challenges; Processes
Wang et al.	2012	Review of Acclimated Kinetic building Enve-lopes (AKE)	Biomimetic Technological	What How	Acclimated Kinetic building Envelope (AKE); Static vs Kinetic; (climate) responsive, active, intelligent, (climatic) adaptive, smart, interactive, (high) performa-tive, kinetic, dynamic; Architectural aesthetics; Solar responsive, air-flow responsive;
Loonen et al.	2013	State of the art Climate Adaptive Building Shells (CABS)	Systematic	What Where How When	Relevant physics; Time scale; Scale of adaptation; Control type; Typology
Loonen et al.	2015	Classification approaches for adaptive façades	Systematic	What Where Why How When	Unified and systematic characterization; Façade classification; Responsive function; Operation: intrinsic, extrinsic; Response time; Spatial scale; Visibility; Adaptability; Dynamic exterior shading and louver façades; PCM glazing; BIPV double-skin
Luible et al.	2015	Common CABS research topics	Mixed	What	PV; Advanced materials; Façade glazing; Façade shad-ing; Control systems; Façade functions
McEvoy & Correll	2015	Materials that couple sensing, actuation, computation, and communication	Technological	What How	Sensing; Actuation; Multifunctional materials; Robotic materials; Shape-changing materials

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INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Vlachokostas & Madamopoulos	2015	Daylighting technology in high-rise commercial buildings	Technological	What Where How	Liquid filled prismatic louver (LFPL);
Badarnah	2016	Light management: lessons from nature	Systematic Biomimetic	Why How	Biomimetic design process; morphological means
Jayathissa et al.	2016	LCA of dynamic BIPV	Technological Life Cycle	What How When	Building-integrated photovoltaic system (BIPV); Adaptive solar façade (ASF); Actuator
Mao et al.	2016	3D Printed Reversible Shape Changing Components	Technological	What Where How	Stimuli responsive materials; Reversibly actuating components; Shape changing components; Shape memory polymers; Hydrogels; 3D printed components;
Persiani et al.	2016a	Autoreactive architectural façades	Systematic Biomimetic	How	Unpowered kinetic building skins; Adaptive systems: responsive, reactive, interactive, autoreactive; Motion parameters: System type, geometry, energy
Persiani et al.	2016b	Adaptive materials and autoreactive building skins (ABS)	Biomimetic Technological	What Where How	Type of energy in the environment: radiant, potential, kinetic; adaptivity in materials: SMP, SCP, TEM, TB, TBM, SCP, SMP, SMA, SMF, SMC, SM-BS, BM, Aps, SAPs
Sachin	2016	Dynamic Adaptive Building Envelopes (DABE): state of the art technology	Technological	What How	Methods of actuation: motor based, hydraulic actuators, pneumatic actuators, material based; Robotic materials; Smart glass
Aresta	2017	Auto-reactive strategies. Materials for innovative façade components	Technological	What Where How	Innovative; Adaptive; Passive; auto-reactive systems; input-Energy and output-Stategy
Badarnah	2017	Environmental adaptation in buidling envelope design	Systematic Biomimetic	Why How	Environmental adaptation; Adaptation means;
Bridgens et al.	2017	Wood based responsive building skins	Technological Life Cycle	What Where When	Wood based responsive; Hygromorphic materials; responsiveness; Reactivity; Actuation capacity; Durability; Sustainability, Aesthetics; Weathering
Clifford et al.	2017	Application of shape-memory polymers to climate adaptive building façades	Technological	What Where How	Shape-memory polymers; Climate adaptive building façades; Dynamic materials; Smart materials; smart tiles
Curpek & Hraska	2017	Ventilation units with PCM for double-skin BiPV façades	Technological	What Where How	PCM; double-skin BiPV façades

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INNOVATIVE TECHNOLOGIES FOR THE BUILDING ENVELOPE					
Author	**Year**	**Topic**	**Approach**	**Answers to Ws**	**Terminology**
Koláček et al.	2017	Thermal Properties of a PCM Window Panel	Technological	What Where How	PCM
Konis & Selkowitz	2017	Advancing façade performance	Technological	What Where How	IOT-based sensor network: dynamic façade, sensor, controllable lighting, user input
Maywald	2017	Texlon ETFE green building factsheets – product data, LEED, BREEAM and DGNB	Technological Life Cycle	What Where When	ETFE foils; ETFE cladding system; EPD; Building certification systems
Molter et. al.	2017	Autoreactive components in double skin façades	Technological	What Where How	Autoreactive components; double skin façades; Adaptive building envelope; closed cavity
Olivieri et al.	2017	Development of PCM-enhanced mortars for thermally activated building components	Technological	What Where How	PCM; Thermal energy storage (TES); Thermally activated building systems (TABS); Radiant wall
Prieto et al.	2017	Solar cool façades, review of solar cooling integrated façade concepts	Technological	What Where How	Solar cooling technologies; integration; high-performance, intelligent, adaptive façades
Ribeiro Silveira et al.	2017	adaptive thin glass façade panels	Technological	What Where	Chemically strengthened Thin glass; Adaptive panels; Lightweight façade; Kinetic façade

TABLE 4 Overview of the Academic Literature

Effects of a Vertical Green Façade on the Thermal Performance and Cooling Demand

A Case Study of a Tube House in Vietnam

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Abstract
Traditional architecture has often applied greenery in the design to improve the thermal performance of indoor spaces. Such a bioclimatic approach is not often seen in the contemporary tube houses of Vietnam. Vietnamese architects recently started to focus more on greenery solutions for housing projects. However, the quantitative effects of plants on the building performance has not yet been investigated in Vietnam. This paper reports on an experiment to quantify the benefits of a vertical greening system for thermal performance and energy saving. A typical tube house in Hanoi was selected and two similar rooms were monitored during July and August, 2018. One of the rooms' façades was covered by the climbing plant Bougainvillea. Outdoor and indoor temperature and energy for air-conditioning were measured for the two rooms to quantify the effect of the greenery on the existing aluminium shading device and a bare window. Results for the green façade showed that the difference between outdoor and indoor temperature can be as high as 8°C. In addition, the climbing plants helped to reduce the indoor temperature by around 1°C and thus cooling energy was saved by up to 35%.

Keywords
Green façade, thermal performance, cooling demand

1 INTRODUCTION

Traditional Vietnamese architecture has often been designed with bioclimatic principles to maintain a good thermal environment without the help of a mechanical heating or cooling system. A Vietnamese proverb that describes green bioclimatic principles as follows: "to plant palm trees at the front (south) and banana trees at the rear (north)". The high palm trees at the front provide shading and at the same time enable the cool summer air to ventilate the house. On the other hand, the lower banana trees at the rear help to block the cold north-easterly wind in winter.

Despite its popularity in the past, plants and trees are limited around contemporary tube houses. A 'tube house' is a contemporary attached row house in Vietnam with a narrow width and long depth. The contemporary tube houses were built after economic reform in 1986. While one can easily find green aspects in a traditional rural house in Vietnam, high-density population and fast-growing urban development leave less room for trees to grow in the cities. Maintenance is also the reason for not having a lot of plants in and around the houses. The lack of greenery might not only negatively affect the energy and indoor climate performance of a single house but may also contribute to the urban heat island (UHI) effect (Szkordilisz, 2014).

FIG. 1 A housing refurbishment case in Vietnam. Left: old house. Right: refurbished house *(Vo Trong Nghia Architects, n.d.)*

Recently, with a clear aim to improve the aesthetic and thermal performance, more and more houses are built with integrated greenery. Such trends were applied by famous Vietnamese architects such as Vo Trong Nghia, Hoang Thuc Hao, and Nguyen Hoang Manh. Fig. 1 shows a housing refurbishment case by Vo Trong Nghia, where he redesigned the façade with a whole new layer of greenery. In Vietnam, such projects are collated under the term 'green buildings' or are sometimes also referred to as 'sustainable buildings'. However, there is little scientific evidence that shows the actual benefit of green solutions.

The research presented in this paper conducts an experiment of the greenery system on an existing tube house of Vietnam. The experiment investigates the effect of vertical greenery on the thermal behaviour and energy consumption and compares it with an aluminium shading device and a normal bare façade.

2 LITERATURE REVIEW

Green walls (GW) are categorised based on their construction and characteristics (Manso & Castro-Gomes, 2015).They can be classified into two main groups: green façades (GF) and living walls systems (LWS) (Dunnett & Kingsbury, 2004; Köhler, 2008) In green façades, walls and windows are often covered by climbing plants, whereas LWS often have integrated supporting materials and technology so greenery can grow uniformly on an extended vertical surface. There are direct green façades (plants grow directly on the wall surface) and indirect green façades (plants grow on a supporting system) (Manso & Castro-Gomes, 2015). Different types of green walls are shown in Fig. 2.

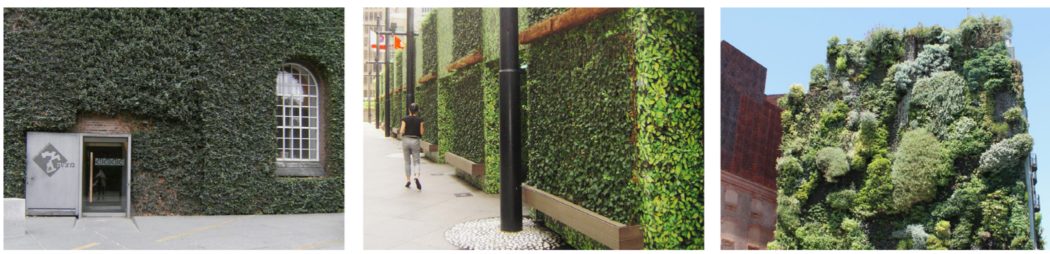

FIG. 2 From left to right: direct green façades, indirect green façades, living wall system *(Manso & Castro-Gomes, 2015)*

Previous studies have investigated the effects of green façades and living wall systems on the building environment and the energy performance. Vertical greenery systems work as a natural sun shading since, compared to a bare façade, they reduce the air surface temperatures behind the green layer (Perini et al., 2011; Kontoleon & Eumorfopoulou, 2010). Evapotranspiration effects of the plants were confirmed by a slightly lower air temperature and higher air humidity of the space between a normal façade and a green façade (Pérez et al., 2011). The maximum cooling effect of a greenery system is reported during the summer period, and better efficiency is found in locations with higher solar radiation. A greenery system also mitigates the urban heat island effect by lowering the air temperature in a large urban area (Wong et al., 2010; Alexandri & Jones, 2008). In terms of energy saving, a green façade has much potential to reduce the cooling load in both temperate and hot climatic regions (Coma et al., 2017; Haggag et al., 2014; Pérez et al., 2017). Effects of green façades on the thermal and energy performance in winter conditions are still debatable (Raji et al., 2015).

TABLE 1 Summary of previous experiments on green façades & living wall systems

#	LOCATION TIME	FACADE – PLANT TYPE	METHOD	KEY FINDINGS/ REFERENCE
1	Spain 2011 - 2013	Green façade Ivy, Honey suckle, Boston Ivy & Clematis	Experiment on 2 house-like cubicles (2.4x2.4x2.4 meter)	(Coma et al., 2014) Reduction of up to 14°C on outside wall surface temperature. No significant energy saving was found
2	Spain 2014	Green façade Boston Ivy	Experiment on 2 house-like cubicles (2.4x2.4x2.4 meter)	(Pérez et al., 2017) DSGF can provide comparable shadow factor values to other factors, such as façade setbacks, cantilevers, etc. Reduction of outside surface temperature Energy savings are dependent on orientation
3	Spain 2014 - 2015	Green façade Ivy Ever green	Experiment on 3 house-like cubicles (2.4x2.4x2.4 meter)	(Coma et al., 2017) Energy saving in summer: up to 58% (GW) and 34% (GF) Energy saving in winter: up to 4.2%
4	China	Living wall system	Experiment on 2 thermal labs	(Chen et al., 2013) Outside surface, inside surface and indoor temperature reduce by a maximum of 20.8, 7.7 and 1.1 Celsius degree respectively The LWS closer to the wall perform better in cooling effect.
5	Singapore 2010	Living wall system	Experiment on 8 living wall systems on a wall only	(Wong et al., 2010) Reduction in surface temperature
6	Hong Kong 2011–2012	Living wall system	Experiment on external wall of a n apartment	(Dahanayake & Chow, 2017) Reduction in surface temperature and outdoor mean radiant temperature during intense exposure period
7	UAE July	Planter boxes of vegetation	Experiment on an existing school building, 2 east-facing classrooms were selected.	(Haggag et al., 2014) Peak time indoor temperature is reduced by at least 5 Celsius degree Air-conditioning energy is reduced by 20%
8	Netherlands 2017	Direct GF & LWS based on planter boxes and mineral wools	Experiment on a climate chamber (1.1x1.4x1.4 meter)	(Ottelé & Perini, 2017) Due to the insulation layer, no difference in indoor temperature was found Green facades help bring surface temperature differences of up to 5.8°C in the summer and 2.1°C in the winter

Among the research on vertical greenery systems, many studies refer to physical experiments and measurements. Table 1 summarises the experiments on green façades and living wall systems. These experiments were located in Spain, the Netherlands, China, Singapore, Hong Kong, and the United Arab Emirates (UAE) in the period from 2010 to 2018. The three studies in Spain were carried out by the same authors. The plant species chosen for the Spanish studies was Boston Ivy, which grew in a double skin green façade. The studies in Asia had a more diverse selection of plants, with different plant types in a living wall system or in planter boxes. Most of the studies were conducted in a laboratory environment (Chen et al., 2013; Ottelé & Perini, 2017), or in a real outdoor context but with small-scale prototypes (Coma et al., 2017, 2014; Pérez et al., 2017; Wong et al., 2010). The main reason for this was the lack of greenery in the field and the diversity of the experimental outdoor conditions between the cases, such as orientation and environmental parameters (Ottelé & Perini, 2017). Furthermore, in a laboratory, boundary conditions are easily controlled and different types of greenery can be compared under the same environmental conditions. The most commonly measured value was the surface temperature of the external wall and the improvement in this regard was generally quite substantial. The experiment in China showed a significant reduction in outside surface temperature of 20.8°C. However, the living walls system in this case only helped to reduce the indoor temperature by 1.1°C.

Conclusions from these experiments show that, in general, green walls can help to reduce the surface temperature efficiently in both a temperate and warm tropical climate. However, the improvement of the indoor temperature is rather limited. The green wall only has a significant effect in the extremely hot climate of the UAE, where the peak indoor temperature was lowered by 5°C (Haggag et al., 2014). Nevertheless, the experiments showed considerable savings in air-conditioning consumption, 20% in the case of the UAE school and 34% and 58% in the case of the Spanish cubic units. The former case was less effective in energy saving despite its greater thermal performance. This could partly be because the former case was a real building experiment while the latter was a lab-based experiment.

No such experiment on green walls was found in Vietnam. Among the studies, Singapore is most similar to Vietnam in terms of climate conditions. However, that experiment was designed only for testing the surface temperature without any internal spaces.

3 EXPERIMENT DESIGN

3.1 CLIMATIC CONDITIONS

The experiment house is located in Hanoi, the capital city in the northern part of Vietnam, under the humid subtropical climatic conditions defined according to Koppen-Geiger climate classification (Kottek et al., 2006) as Cwa (warm temperate; winter dry; hot summer). Generally, Hanoi is affected by seasonal monsoon winds. It has a short cold and dry winter; the air temperature can reach as low as 5°C. Protection from the cold wind from the northeast is required. The summer is hot and the air temperature can reach up to 40°C. Annual precipitation is considerably high. The average rainfall in summer is approximately 300 mm per month (Nguyen et al., 2011)

3.2 EXPERIMENT SPACES

The selected rooms are a bedroom on the second floor and a living room on the first floor, both facing southwest, in a typical Vietnamese tube house. The dimensions of the rooms are 3.3 x 4.6 x 3.9 metres (w x l x h). The front façade consists of single lightweight masonry wall with a big window of 7.2 m^2 (56% of the external wall area) for each floor. The external walls are composed of 110mm brick work with 15mm of cement plaster on both sides. The U value is 2.57 W/m^2-K. The windows are composed of 6mm grey single glazing within an aluminium frame and a U value of 5.78 W/m^2-K. At the front, the first floor is covered with the climbing plants. The second-floor façade has an aluminium shading device, with a solar transmittance of 0 and a solar reflectance value of 0.5. The back side of the room is a glass wall with an aluminium frame that connects to the staircase. On both right and left sides of the rooms are single masonry walls adjacent to neighbouring walls. The two rooms are equipped with 12,000 Btu (British thermal unit) or 3.52 kWh air-conditioners which provide both cooling and (electric) heating. The existing building is presented in Fig. 3.

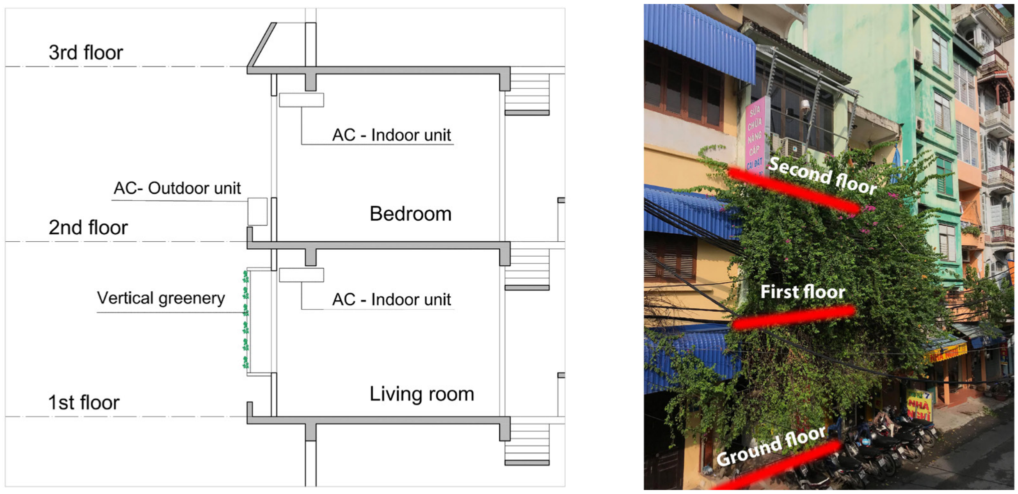

FIG. 3 Existing Vietnamese building for experiment. Left: cross section & floor plan, Right: outside view

3.3 THE PLANTS

In this study, the plant has already grown and covered most of the 1st floor façade. The other façade has an aluminium shading device. The plant type is Bougainvillea, a climbing tree that is regularly found in Vietnam thanks to its fast growth and low maintenance.

3.4 MONITORING EQUIPMENT

The performance of the two similar spaces is simultaneously measured. One of the spaces has a greenery system on the façade. There were eight measurement configurations in total, as listed in Table 2.

TABLE 2 Equipment names and measuring parameters

#	EQUIPMENT	SYMBOL	MEASURING
1	Sense 1	S1	Second floor outdoor temperature and relative humidity
2	Sense 2	S2	Second floor indoor temperature and relative humidity
3	Sense 3	S3	First floor outdoor temperature and relative humidity
4	Sense 4	S4	First floor indoor temperature and relative humidity
5	Sense 5	S5	Third floor outdoor temperature and relative humidity
6	Voltcraft	V	Solar radiation on the front southwest facade
7	Circle 1	C1	Electricity consumption of second floor air-conditioner
8	Circle 2	C2	Electricity consumption of first floor air-conditioner

Two sense data loggers (Plugwise) were put inside the rooms to measure the indoor temperature and relative humidity. Three other sense data loggers were installed just outside the windows to measure the outdoor temperature and relative humidity of the first, second and third floor. The temperature sensor has a range of 0 to 60˚C; the relative humidity sensor has a range of 5 to 95%. The accuracy of the data loggers is: temperature: 0.3°C at 25°C and 0.8°C at 60°C; relative humidity: 2.2% between

10%- 90%, 3.2% in other conditions. Two circle units (Plugwise, Type F) were connected to the two air-conditioners in the two rooms to measure electricity consumption. The accuracy is 5% ±0.5W for current usage and 1% ± 0.2W for cumulative usage. All of the Plugwise sensors were wirelessly connected to a computer and data was retrieved from the same software named Source. A solar data logger (Voltcraft) was used to measure the solar radiation on the façade. The sensor was oriented 45° from the horizontal plane and faced directly southwest. The reason for this was that the shading device and the leaves on the green façade have the same 45° inclined position, facing the sun directly in the afternoon. The sensor has a range from 0 to 1999 W/m^2 with an accuracy of 5% or 10W/m^2. All data is recorded at 15-minute intervals and presented in hourly intervals. The location of the equipment is presented in Fig. 4.

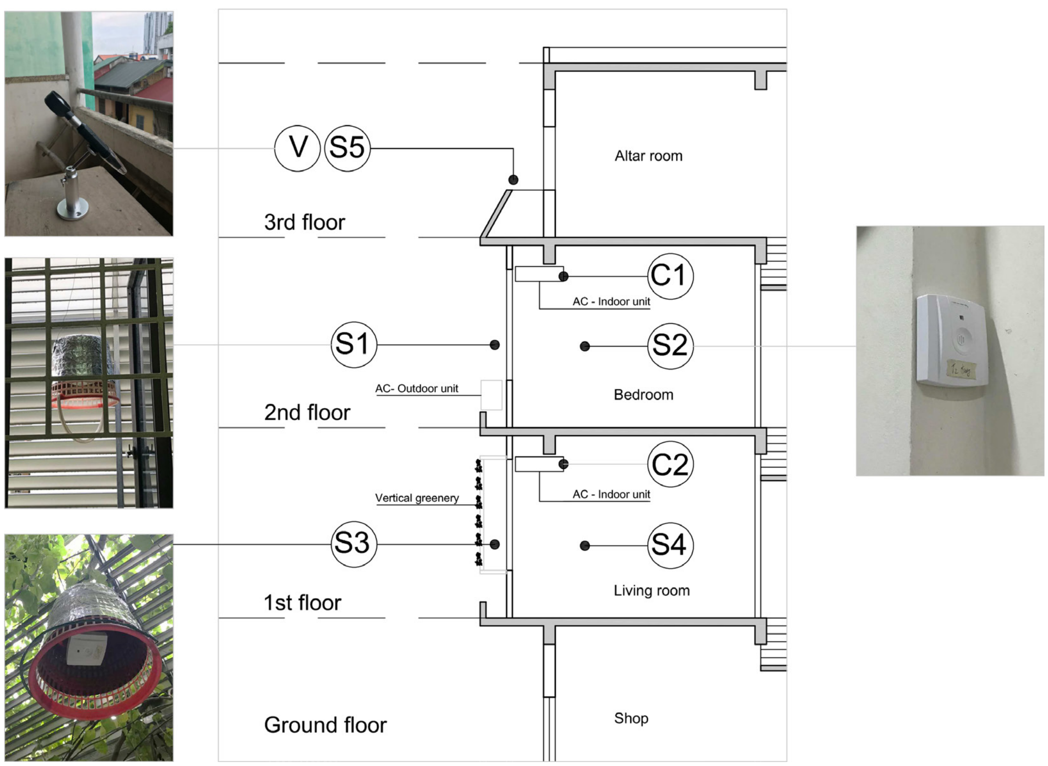

FIG. 4 Locations of the measurement equipment

3.5 MEASUREMENT PLAN

The experiments were conducted during the summer months of July and August, 2018. During this period, the two rooms were vacant to make sure that there would be no variation in heat gain from occupants and equipment. Details of the measuring schedule are shown in Fig. 5.

The first scenario aims to validate if the two rooms have similar thermal performance. From 9th - 15th August, both façades were bare and from 26th August - 3rd September, both façades were shaded.

FIG. 5 Three scenarios of the experiment

The second scenario in Fig. 5 compares the thermal performance and the energy consumption of the room with a green façade (first floor) with the room with a bare façade (second floor), from 27th July - 8th of August. From 10th of July - 24th July, the performance of the green façade room (first floor) and the shaded façade room (second floor) were compared under the third scenario.

The order of the scenario did not align with the time sequence because the experiments were conducted on a real building in which a green façade is a climbing plant. Once the plant was removed, it could not grow back in a short period of time.

Scenario 2 and Scenario 3 both lasted about 2 weeks. During the first week of each scenario, the rooms were naturally ventilated and only the temperature and humidity levels were monitored. During the other weeks, air-conditioners were used for 5 hours in the afternoon, and the energy for cooling was recorded. The air-conditioners were both set at the same cooling set-point of 27°C, based on a study of adaptive thermal comfort by Nguyen (Nguyen, Singh, & Reiter, 2012)effective temperature, standard effective temperature. Outside the air-conditioned periods, the rooms were naturally ventilated.

3.6 BOUNDARY CONDITIONS

This research specifically investigates the performance of an existing urban tube house in Vietnam. The energy consumption comparison is more valid in a real building case. The ideal setting was to compare two identical adjacent houses. However, it was not possible to have access to two such houses, so two similar rooms in one house were selected. The selected rooms were in two different levels of the house so the existing spaces may not have performed exactly the same. This limitation has been taken into account in the analysis and the presented result section.

The limitation of this experiment is that there were only two spaces available so we could only compare two different façade types at a time. Therefore, this study did not focus on comparing different greenery systems but mainly investigated the differences in performance between a room with a green façade and one without a green façade.

The experiment recorded both the temperature and humidity levels of the spaces. A green façade may impact the humidity level of the indoor spaces and hence influences the perception of the temperature. However, within the scope of this paper, the investigation of humidity is temporarily neglected.

Thermal inertia may have some effects on the performance of the rooms. However, as the rooms are of a lightweight construction, thermal inertia effects were not considered within the scope of this paper.

4 RESULTS

4.1 SOLAR RADIATION

Solar radiation was measured because it provides radiative energy and stimulates the evaporation process in the greenery system, see Fig. 6. Although July and August were hot months, solar radiation was not very high due to overcast skies and heavy rainfall during this period. The maximum and minimum daily solar radiation values were 1869 Wh/m^2 and 129 Wh/m^2, respectively. The average daily solar radiation was 921 Wh/m^2. During the period from 24th - 27th July and from 14th - 20th August, the measurement equipment was not working correctly and data is missing. Solar radiation often peaked at 15:00 because the main orientation of the house is South-West.

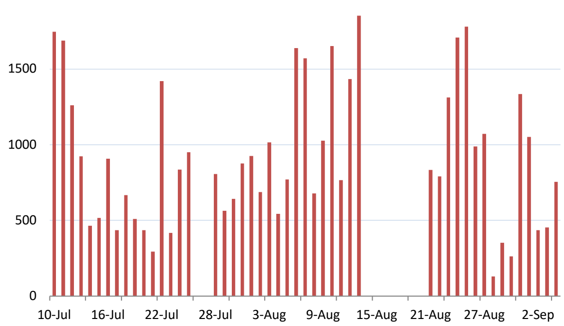

FIG. 6 Daily solar radiation during the experiment period (Wh/m^2)

4.2 THERMAL PERFORMANCE

4.2.1 Thermal performance of the two rooms

This part presents an overview of the thermal performance by showing the highest and lowest daily temperature of the two rooms during the whole period (Fig. 7) and on one of the hot days during this period, July 31st, in the cross section (see Fig. 8).

In general, the minimum outdoor temperature was not lower than 25°C. The maximum daily outdoor temperature varied during the period. Outdoor air could reach up to 42°C on the hottest day while the peak temperature on the coolest day was only 27°C. Although this was summertime, the rainfall could be really heavy and constant on some days, which caused a fluctuation in the temperature measured. The indoor temperature generally had a smaller fluctuation range and did not exceed 35°C. In all cases, the peak temperature of the second-floor room was generally higher than on the first floor room.

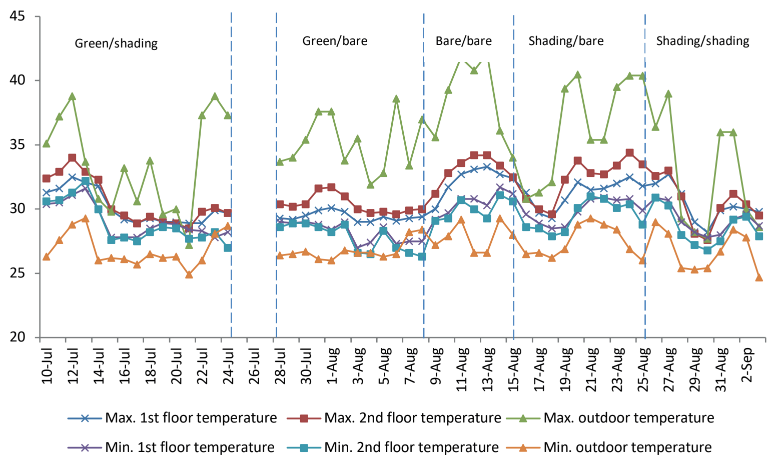

FIG. 7 Maximum and minimum daily outdoor and indoor temperature (°C)

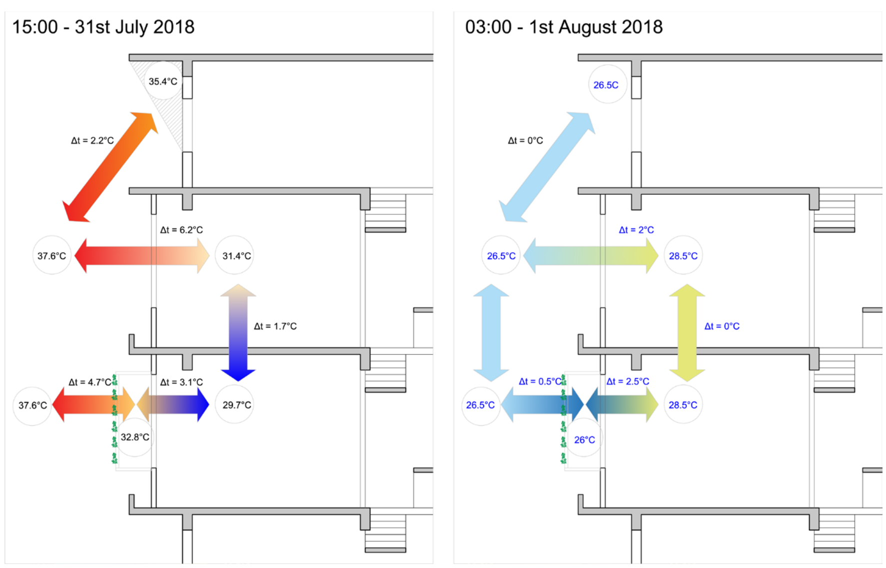

FIG. 8 Peak day time temperature at 15:00 on the 31/7/2018 and lowest night temperature at 03:00 on the 01/8/2018

Regarding the performance on 31st July, the outdoor temperature reached as high as 37.6°C at 15:00 and cooled down to 26.5°C at 03:00. A thermometer placed outside the 3rd floor showed that in the shaded area on the terrace the outdoor temperature was reduced to 35.4°C, which was 2.2°C lower than the temperature in the unshaded area. The climbing plants on the first floor provided significant cooling as the air temperature decreased 4.7°C to 32.8°C. The first-floor room was the coolest indoor space, where the temperature went down to 29.7°C, a 3.1°C further reduction behind the external wall with window glazing. Surprisingly, the indoor temperature of the second-floor room was also as low as 31.4°C, which led to a 6.2°C difference with the outdoor temperature, a relatively great difference compared to the expected outcome of a bare façade without shading or greenery. This also meant that the indoor temperature difference between the two floors was only 1.7°C. It is also worth noting that on 31st July, the maximum solar radiation was only 209 W/m^2, hence the effect of direct solar gain was not so significant. Such a minor difference was also believed to be due to the heat transfer between the floors. As the rooms accumulated heat during the day and peaked at 15:00, there was also a heat transfer through the slab between the floors which dragged the air temperature of the spaces closer to each other. The performance difference between the two façade types might be larger.

On the following night, the outdoor temperature lowered to 26.5°C. As can be seen from the figure, the indoor temperature was the same at 28.5°C, 2°C higher than outdoors, regardless of the façade type. The green façade in this case did not have much influence on the indoor temperature.

4.2.2 Temperature of a room over the course of a day

The relation between the indoor and outdoor temperature was examined by plotting the values against each other in different periods (see Fig 9). The measurement period was from 18th - 24th of August. Each of the colours represents temperature values over the course of one day, measures at 15-minute intervals. The two values do not have a simple linear relationship. The daily temperature pattern has a looped shape that comprises of two curves. The temperature often rises following the lower curve, peaks around early afternoon, and then slowly cools down following the upper part of the curve. For some days, although the outdoor temperatures were similar, the indoor values were different because the starting temperature of each day was different. In other words, the indoor temperature also depends on the average temperature of a longer period rather than just on one-day weather conditions. Internal heat gains accumulated after a few days could result in higher indoor temperatures compared to the first day. Therefore, analysing the thermal performance of the rooms should cover a longer period with constant microclimate conditions. A stable external environment in an extended period leads to more accurate performance of the internal space, enhancing the validity of the comparison.

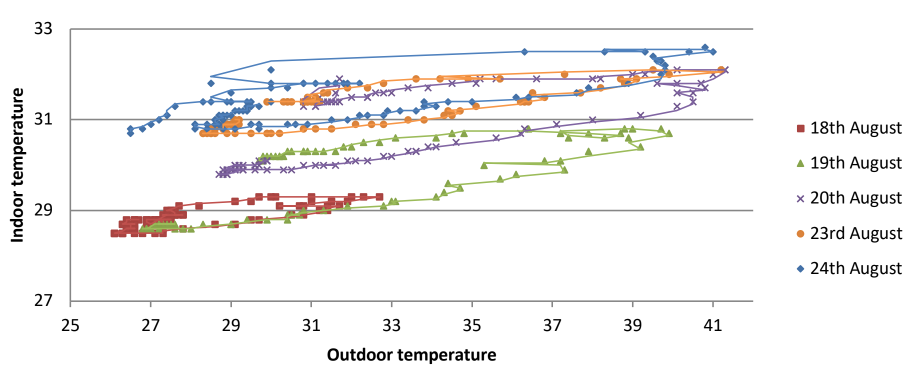

FIG. 9 Indoor and outdoor temperature of the first floor room with shading device (18th - 24th August)

4.2.3 Comparison of thermal performance for different scenarios

Scenario 1: Similar façade (9th – 15th August & 26th August – 3rd September)

Due to the fact that the experiment was based on a real case study, the experiment started with a comparison between two façade types (green façade & bare façade) and ended with a scenario in which the two floors had the same façade type. The latter period aimed at examining the similarity in performance of the two spaces by comparing thermal data. There were two periods in which the two floors had the same configuration. The first period was from 9th - 15th August, during which both façades were unshaded. During the last period, from August 26th to September 3rd, both windows were shaded by similar aluminium shading devices.

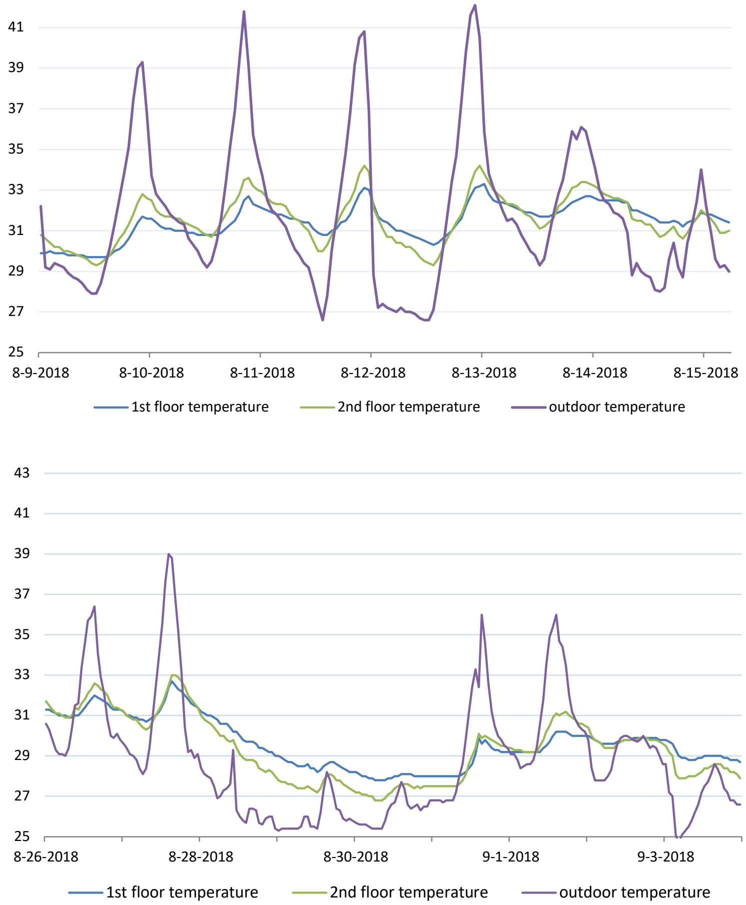

FIG. 10 Outdoor and indoor temperature of the two floors (°C) [above] 9th - 15th August (unshaded façade)[below] 26th August - 3rd September (aluminium shading devices)

Regarding the indoor temperature, although the shape of the graphs was similar, there were still differences of up to 1°C throughout the days (Fig. 10). During the days, the second-floor room was often slightly warmer during daytime and cooler at night, compared to first floor room. The correlation between the indoor temperatures of the two floors is shown in the scatter graph in Fig. 11 with R^2 values of 0.81 for the first period and 0.93 for the latter. However, the values deviate from the average fit lines. Such behaviour can be explained by the slightly larger exposure of the second floor; a part of the second-floor ceiling was the 3rd front balcony floor. Another reason could be the thermal mass effect of the floor layers. The second floor is closer to the roof and acts as an insulation layer for the first floor. Therefore, the upper room heated up at noon and cooled down at night more quickly than the lower one.

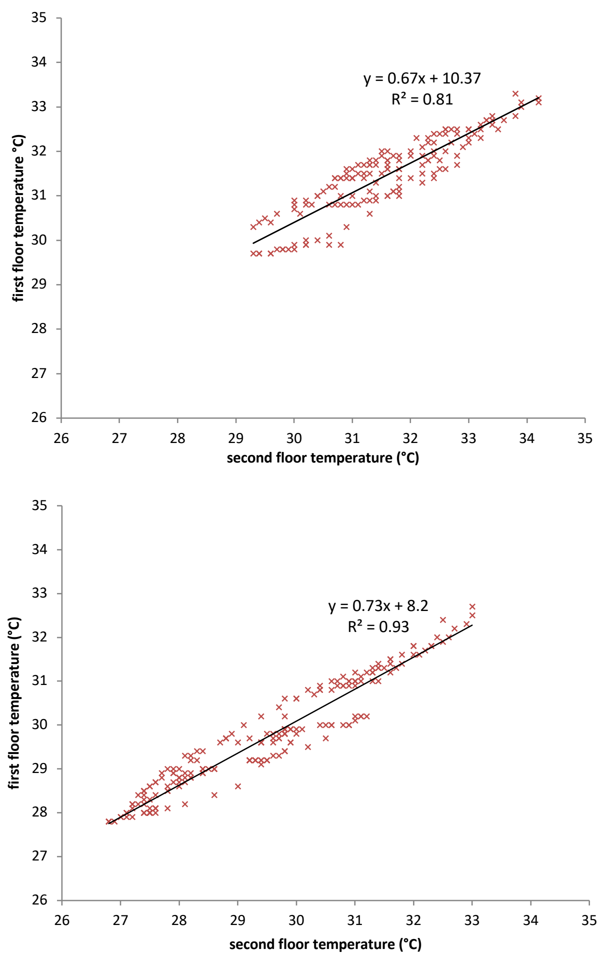

FIG. 11 Scatter plot of indoor temperature of the two floors (°C) [above] 9th - 15th August (unshaded façade)[below] 26th August - 3rd September (aluminium shading devices)

The thermal mass effect was also found while comparing the indoor temperature of the first floor, second floor, and third floor (top floor), as shown in Fig. 12. The lowest floor temperature, indicated by the blue line, did not vary and the top floor temperature (green line) fluctuated the most.

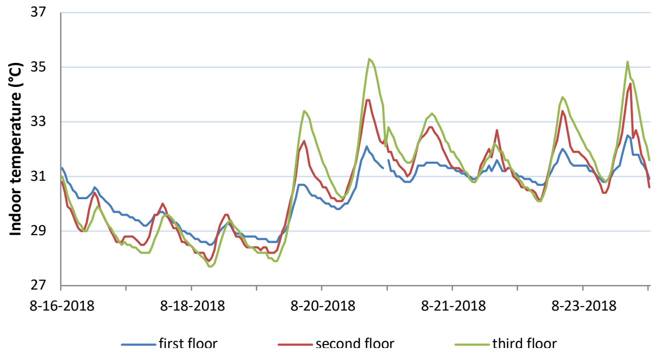

FIG. 12 Indoor temperature of the 1st, 2nd & 3rd floor during the period from the 16th - 24th August (°C)

Although the two rooms were configured similarly, it is important to note that indoor temperatures were not exactly equivalent. Nonetheless, the strong correlation in performance of the two spaces with same façade settings is significant enough to continue comparing the performance of the rooms in other scenarios.

Scenario 2: Green façade & unshaded façade

Throughout a two-week period, from 27th July - 9th August, the green façade on the lower floor was kept and compared to the unshaded façade on the upper floor. The rooms were naturally ventilated during the first week and air-conditioned during the afternoon of the second week. The thermal performances of the rooms were measured during the first week and are shown in Fig. 13.

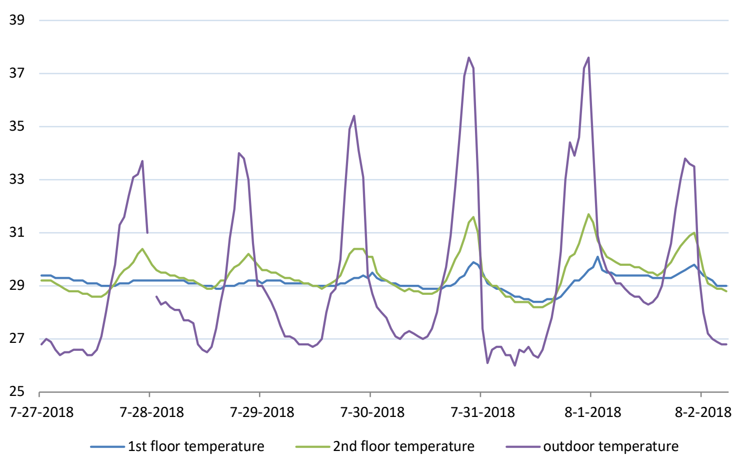

FIG. 13 Indoor and outdoor temperature measured on the 1st & 2nd floor from July 27th – Aug 2nd (°C)

At night, there was no temperature difference between the two spaces. The indoor temperature of the second floor rose more quickly during the daytime and peaked at around 2°C higher than the lower floor temperature.

Two ways are suggested to compare the performance of the two façade types. The first method is to directly compare the indoor temperature of the two rooms over the same period (27th July - 2nd August), when one room was unshaded (second floor) and the other room was covered with a green façade (first floor). With this method, the thermal mass effect or difference in the levels of the rooms need to be considered (see Scenario 1). With the second method, the thermal mass effect can be eliminated by comparing the performance of the same first floor room over two different periods, in which the room was unshaded (9th - 15th August) or equipped with a green façade (27th July - 2nd August). This method does not take into account the difference in other climate factors, such as solar radiation, wind speed, relative humidity or precipitation.

Comparing two rooms in the same period (27th July – 2nd August)

This part compares the thermal performance of the first floor (green façade) and the second floor (bare façade). Fig. 14 shows the indoor temperature difference between the two floors and the outdoor temperature over the same week. The climate condition of the week was stable as 4 out of 6 days the outdoor temperature ranged from 26 to 35°C. During those days, the temperature difference was around 1 - 1.2°C. The other two days had a higher peak temperature of 37.6°C resulting in a higher indoor temperature difference. The green façade room was up to 2.1°C cooler than the other.

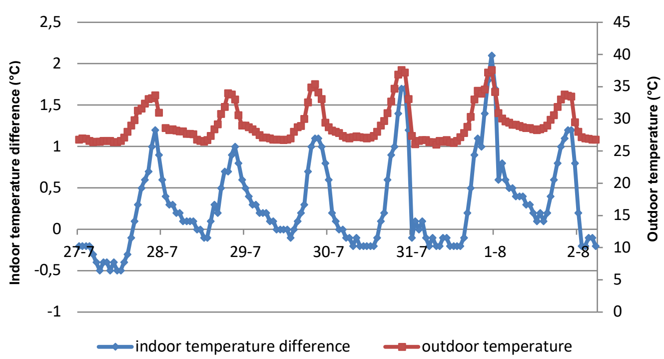

FIG. 14 The indoor temperature difference between first floor (green façade) and second floor (bare) and outdoor temperature (July 27th - August 2nd)

Taking into account the differences in the levels of the rooms (as discussed in Scenario 1), the temperature difference of the two rooms in the period 9th - 15th of August, when both rooms where unshaded, was plotted in Fig. 15. During the first four days, the maximum outdoor air temperature was high, ranging from 39.3°C to 42.1°C. However, the temperature difference was only around 1°C. On the 15th of August, when the maximum outdoor temperature was only 34°C, the indoor temperature of the two rooms were very similar, with the highest temperature difference only 0.1°C. Combining the results of the two periods, the green façade is shown to lower the indoor temperature by at least 1°C compared to the bare façade (temperature difference of 2.1°C compared to 1°C on warmer days, and 1°C to 0°C on cooler days). This result is similar to Chen's findings (Chen et al., 2013), where the living wall system helps to reduce the indoor temperature by 1.1°C.

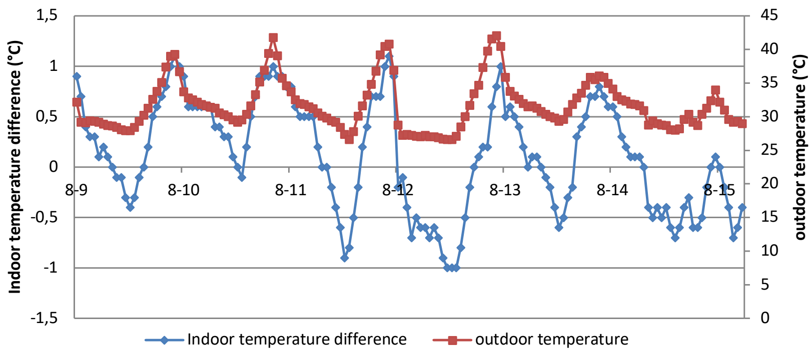

FIG. 15 The indoor temperature difference of the two floors (both bare façade) and outdoor temperature (09th until 15th of August)

Comparing the same room in two different periods

Fig. 16 shows the indoor and outdoor temperature of the first-floor room against each other during the two periods mentioned in the second comparison method. The differences in indoor temperature during the same outdoor temperature are visibly quite large (2°C on average). However, section 4.2.2 showed that indoor temperature also depends on the average temperature of the building over a longer period. The average indoor temperature in the two periods are not the same because the outdoor temperatures are not the same. Therefore, the benefit of the green façade over the bare façade cannot be proven if based solely on this comparison.

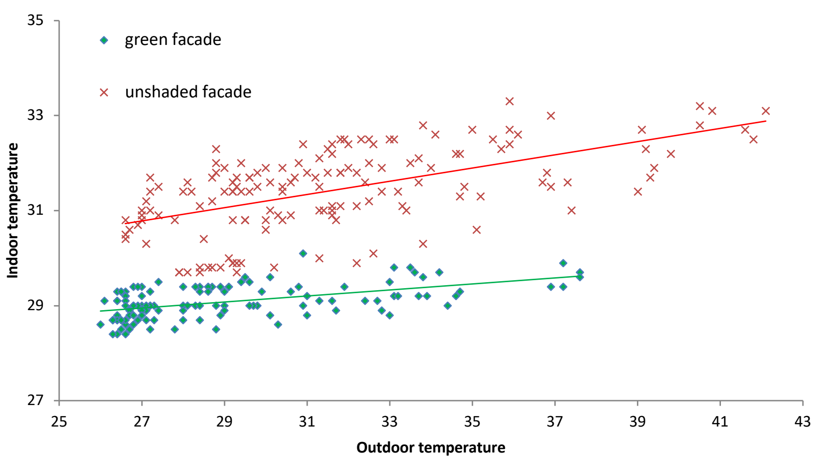

FIG. 16 Indoor and outdoor temperature of the 1st floor with a green façade (July 27th - August 3rd) and an unshaded façade (August 9th – 15th)

Scenario 3: Shading device & bare façade (16th – 24th August)

This part discusses the benefit of a shading device on the performance of the rooms. During the period from 16th - 24th August, the first floor was shaded by the aluminium shading device while the upper floor was unshaded. Measured data of indoor and outdoor temperatures were shown in Fig. 17. There are differences in indoor temperatures between the two rooms. The second floor (bare façade) was warmer during the day and cooler at nights and highest difference was 1°C at noon. However, since the performance of the two rooms is different even when the façades are the same, such a comparison might not accurately reflect the difference in performance of the two façade types. Therefore, indoor and outdoor temperatures of the 1st floor during the two different periods were plotted in Fig. 18. The first period is 9th - 15th August where the room was unshaded, the second period is 16th - 24th August where the room is shaded by the aluminium shading device. In both periods, the second-floor room was unshaded. Generally, the shading device helped to reduce the indoor temperature of the room. The differences peaked at around 1°C when the outdoor temperature is not high (27 - 29°C). At higher outdoor temperature (higher than 35°C), the average temperature difference is not more than 0.5°C. The larger effect at a lower outdoor air temperature range can be explained by the difference in outdoor conditions of the two periods. During the shaded period (16th - 24th August), the maximum air temperature was lower than 32°C, see Fig. 18. & Fig. 17.

As discussed above, both shading devices and greenery improve the performance of the tube house façade by lowering the indoor temperature in warm weather conditions. Considering the above results, the green façade is believed to have a slightly better cooling effect when compared to the shading device.

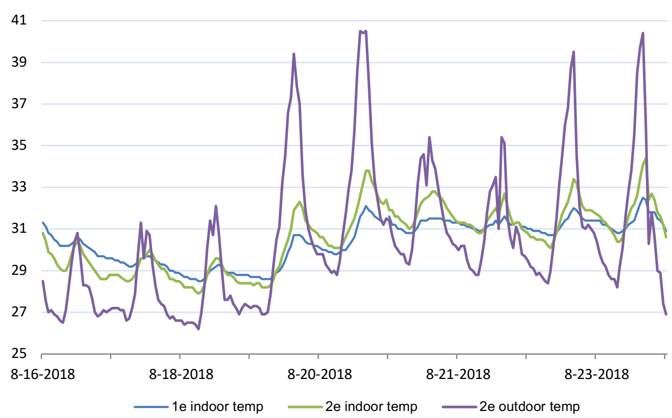

FIG. 17 Indoor and outdoor temperature of 1st & 2nd floor during the period from 16th - 24th August (°C)

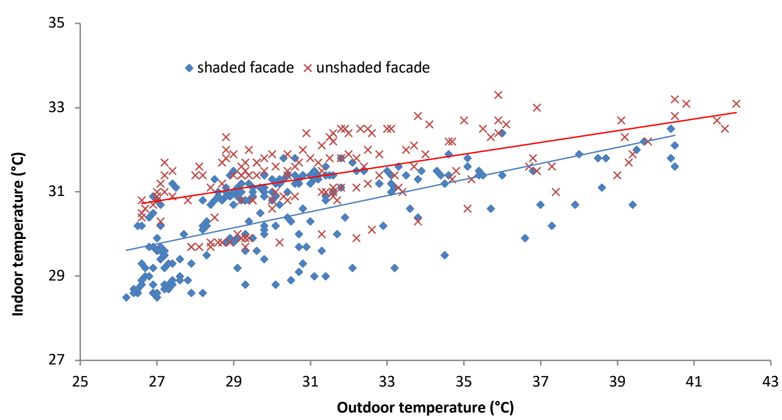

FIG. 18 Indoor and outdoor temperature of the 1st floor when unshaded (9th – 15th August) & shaded (16th – 24th August)

4.3 ENERGY PERFORMANCE

There were 2 periods in which air-conditioners were being used and monitored for assessing the energy performance of the different façade types. The first period was 15th - 24th July, with the green façade on the first floor and a shading device on the second floor. Air-conditioners were used on 15th, 16th, 17th, 23rd and 24th July. The air-conditioner was used for a total of 25 hours. The cooling set-point was 27°C, based on a study of adaptive thermal comfort by Nguyen (Nguyen et al., 2012)effective temperature, standard effective temperature . There was not much difference in the consumption during the first three days when the outdoor temperature was not high (Fig 19). Moreover, in the first three days, 5 hours of air-conditioning were divided in two sub-periods of 2 hours and 3 hours, from 12:00 until 14:00 and from 16:00 until 19:00. Because it takes some time to cool the space to the desired temperature level, a short air-conditioned period can lead to a minimum difference in performance of the two rooms. On 23rd and 24th of July, the outdoor temperature was higher and the air-conditioned period was 5 consecutive hours and a different consumption was recorded. In total, the first-floor unit consumed 12.39 kWh while the upper room's consumption was 14.75 kWh.
The difference was 12.5% in total cooling energy.

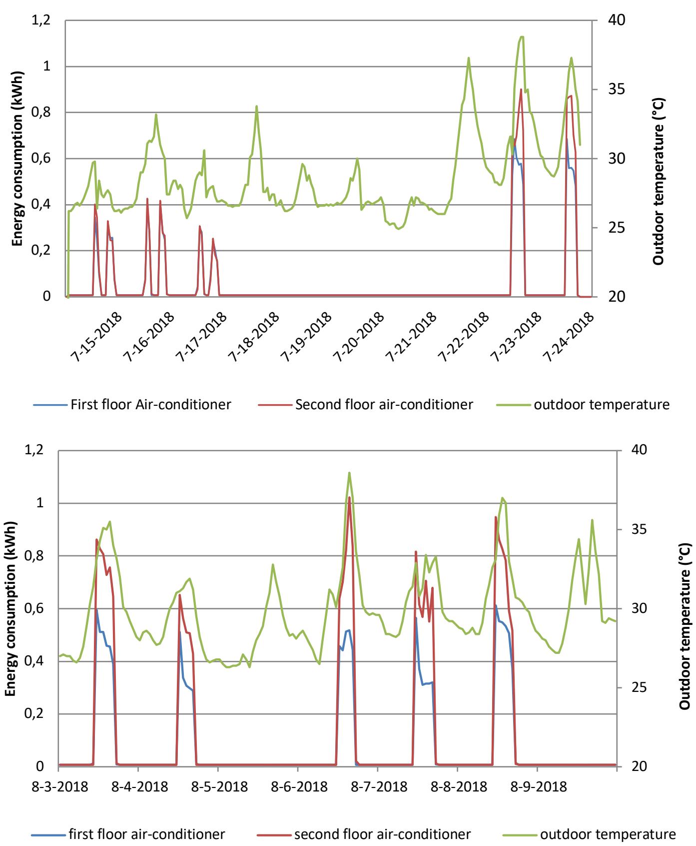

FIG. 19 Air-conditioner electricity consumption of the two rooms (kWh) and outdoor temperature (°C)[a] 15th July – 24th July [b] 3rd August – 9th August

The second air-conditioned period was from 3rd - 8th of August, with an exception made on 5th August. There was a green façade on the first floor and an unshaded façade on the second floor. The cooling set-point was 27°C and the heating hours were 5 consecutive hours during the day, from 12.00 until 17.00. The difference in the consumption was clearly seen in Fig. 19. The first floor required much less energy to be cooled down compared to the second floor. Energy consumption was 13.44 kWh and 20.87 kWh for the first floor and second floor respectively, which resulted in an energy saving of 35%.

5 DISCUSSION & CONCLUSION

The two rooms were configured exactly the same way in two floors and they were tested for difference in performance. The higher room is warmer when the outdoor temperature is higher. The maximum difference was in the afternoon when the outdoor temperature was at its peak. When outdoor conditions were cooler (at night or cooler days), the higher room had a lower temperature. This difference in thermal performance alerts the follow-up tests to take this effect into account as a boundary condition.

During the 2 months of experimental period, the outdoor environment was not stable. There were some hot days where the temperature exceeded 40°C and there were cooler days with lots of rain. This had some effects on the results of the paper. Similar research in the future is recommended to consider this boundary condition before conducting an experiment to enhance the quality of the results. The indoor temperature of the green façade room and the bare façade room were compared. The first test compared two different rooms (first floor and second floor) in the same period and the other test compared the same first floor room in two different periods. Both showed that there is a potential reduction of up to 1°C in indoor temperature by applying a green façade.

A room with an aluminium shading device was also tested. The shading device was equally effective as the green façade, for example, 1°C lower in indoor temperature compared to the bare façade, when the outdoor temperature is not too high (lower than 30°C). However, when the outdoor temperature rises beyond 30°C, the aluminium shading device became less effective and the peak difference was only 0.5°C.

Despite little improvement compared to the shading device, the green façade is still recommended in this specific case because of the following reasons. Firstly, measurements of temperatures just behind the green façade show that the green façade can help to reduce the outdoor temperature and improve the thermal performance of outdoor spaces. A lot of houses with green façades can contribute to a greater improvement in the urban scale. Secondly, plants and trees in general have many other benefits such as purifying the air, noise cancellation, creating a relaxing atmosphere for the occupant, etc. Finally, in terms of thermal performance, the leaves of this climbing plant will naturally fall off during winter season which allows direct solar gain and hence reduces heating costs.

In terms of energy consumption, the green façade in this case could save up to 35% of the cooling demand during the days, if the air-conditioners were used for 5 consecutive hours. Such a difference might be due to the 1°C temperature difference provided by the green façade, as discussed in section 4.2.3. During the cooler days, the energy consumption for cooling is less, hence the energy saving of the green façade is also lower, or the air-conditioning is even not necessary. A significant energy saving was seen when the peak outdoor temperature was higher than 33°C.

Energy savings on winter days for heating need further investigation to gain a better assessment of the benefits of a green façade.

The current construction of the building is lightweight masonry, single glazed windows, no thermal insulation, and high infiltration rate. Such practice is very popular in Vietnam as it is believed to enhance passive cooling, removing heat from the building. However, as the outdoor conditions are becoming hotter, especially in the urban area, using an air-conditioner is often inevitable. In that case, it is recommended that residential buildings need a higher performance envelope. It can prevent heat gain from the external hot air temperature and save further cooling energy. It is also suggested that, for the same total duration of air-conditioning period, air-conditioners should be used in an uninterrupted period, rather than in multiple, separated shorter periods, for better energy saving.

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A Methodological Approach to Assess the Climatic Potential of Natural Ventilation Through Façades

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Abstract

Due to the rapid development of super insulated and airtight buildings, the energy requirement for mechanical ventilation is becoming more and more dominant in today's highly efficient buildings. In this scenario, natural ventilation has the potential to reduce energy use for buildings while maintaining ventilation rates that are consistent with acceptable indoor air quality. The increase in air temperature and frequency of extreme weather events (e.g. heavy rains, heat and cold waves) due to climate change will alter future outdoor boundary conditions and consequently the potential for natural ventilation in buildings. Therefore, to respond to the fluctuations in outdoor boundary conditions, the building envelope should become more and more dynamically responsive. In that sense, the façade plays an important role by regulating indoor comfort based on outdoor environmental conditions. This paper presents a methodological approach to investigate the potential of natural ventilation through the façade in office buildings in present and future climate conditions. It reviews technologies and strategies that maximise the use of natural ventilation in office buildings located in six selected different European climates. Numerical analyses were conducted, considering outdoor air temperature and humidity. Integrated façades with hybrid systems and strategies is one of the key solutions for increasing the potential of natural ventilation. The results showed that a hybrid solution with low-pressure drop heat recovery had the greatest potential to maximise the possibilities of low energy façade integrated ventilation.

Keywords

Natural ventilation, building façade, climate change

1 INTRODUCTION

Buildings currently contribute to 40% of global primary energy consumption and 30% of CO_2 emissions (World Energy Council (WEC) (2013)). The European Commission has set a low carbon economy road map that states that greenhouse gas emissions shall be cut to 80% below 1990 levels by 2050, and 20% by 2020. One of the strategies to achieve this goal is to develop high-performance building skins that are responsive and dynamically regulate the heat flows, light distribution, air and vapour transport (Perino, 2008). As the thermal insulation of a building is improved, energy demand is reduced and heat loss due to ventilation becomes an increasingly important entry in the energy balance of the building. In fact, thermodynamic treatment of ventilation air still requires a significant amount of energy which makes exploiting natural ventilation, here with the meaning of ventilation air without thermodynamic treatment, an important strategy to consider. Over the years, natural ventilation has developed from being merely considered as a mostly uncontrolled phenomenon based on air infiltration through cracks and airing through windows, to a demand-controlled fresh air supply system that also provides a cooling function. Therefore, a hybrid ventilation system that couples both natural- and mechanical ventilation can represent a robust and sustainable solution (Heiselberg, 2002). Office buildings are an interesting case for the implementation of natural and hybrid ventilation solutions because of the strict regulation for indoor climate conditions and regular occupancy schedules. The larger size of office buildings is also often an asset as it creates conditions with substantial thermal and pressure differences on each side of the façade and which can be utilized (Walker, 2006).

Building facades play an important role in architecture both from an aesthetics' perspective and as the interface between the indoor- and the outdoor environment which makes them a key element in natural ventilation and indoor climate strategies. Facades should, to a certain degree, respond to changing external environmental conditions to ensure a stellar performance in terms of energy and indoor comfort. This means that incorporating climate change predictions is more and more an emerging area of interest in the façade's development (Barclaya, 2012). Since climate change is expected to affect the global trends of the variables which influence natural ventilation potential in buildings (such as outdoor air temperature, wind, irradiation), this study aims at investigating the extent to which strategies for natural ventilation in buildings can effectively account for changing weather patterns and their resulting ability to reduce energy use for ventilation in present and future climatic conditions.

This paper also presents a numerical investigation of the impact of the present and future climatic conditions on the façade's ability to integrate natural ventilation by calculating the Climatic Potential of Natural Ventilation (CPNV) index and looking at the sensitivity of the CPNV at different European latitudes. The climate analysis conducted in this work is used to estimate the variability of the CPNV due to temperature and relative humidity changes (i.e. preheating/precooling, humidifying/dehumidifying) of the ventilation air coupled with active and passive treatments through solar availability and heat recovery systems. The CPNV index is therefore modified, and the Extended Climatic Potential of Natural ventilation (ΔCPNV) is assessed to understand how a small change in the thermodynamic conditions of the air, implemented through an action carried out at the façade level, can increase the potential use of natural airflow for building climatization.

Because the main output of this paper is to develop a methodology to carry out the above-mentioned analysis, the results are limited to selected locations and south-facing facades.

The objectives of this paper are therefore:

- To present a novel methodological approach to investigate the potential of natural ventilation through the façade in office buildings;
- To apply such a methodology that considers present and future climate conditions in a few selected locations;
- To assess the extent to which the potential of natural ventilation through the façade is affected by modified patterns in climate change scenarios;
- To identify what are the most promising functionalities that an integrated building envelope system should incorporate to maximise the exploitation of natural ventilation through minimal air treatment at façade level.

2 METHODOLOGY

The paper presents a methodological approach to assess the CPNV through façades in past, present and future climate conditions. It is based on earlier work by Causone (Causone, 2016) (see section 2.1) and it consists of processing past climatic data (historical scenario) (i.e. historical periods depending on the data collection for each location), present (Scenario 2020) and future (Scenario 2050). *Energyplus* (U.S. Department of Energy's Building Technologies Office, National Renewable Energy Laboratory, 2019) weather data files (*.epw*) were used as climatic data input for the past scenario and as the basis for creating the weather data files for the present and future climate scenarios using the Climate Change World Weather (CCWW) file generator version 1.8 (v1.8) (Sustainable Energy Research Group - University of Southampton, 2019). The CCWW v1.8 uses the HadCM3 scenario data of experiment ensemble available from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre related to the Third Assessment Report of IPCC (Belcher, 2005), (IPCC Data Distribution Centre, n.d.). Hourly *.epw* weather data for the present-day climate is adjusted with the monthly climate change prediction values of the HadCM3 scenario datasets. The generated weather data files were used in the analysis conducted in *Energyplus*, while data was processed and visualized using Python programming language and Excel.

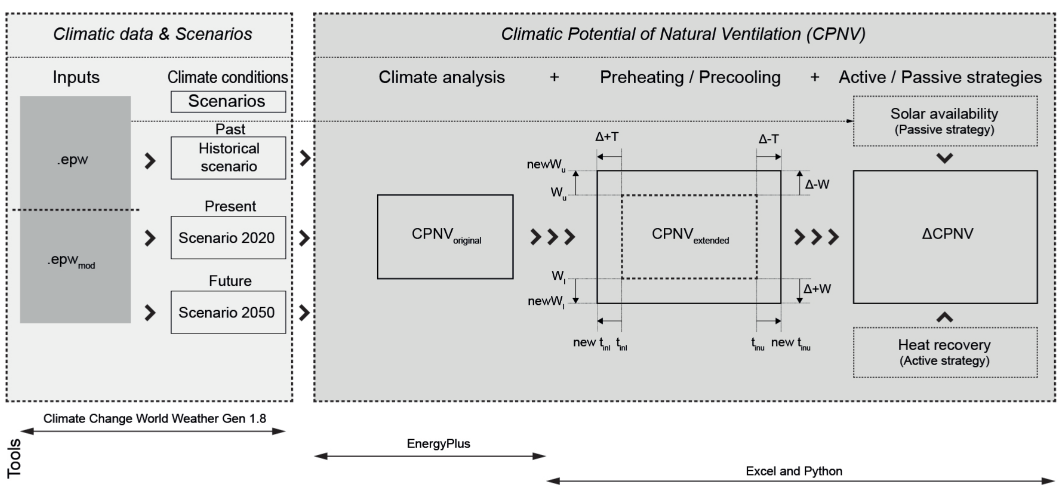

FIG. 1 Workflow of the process for the calculation of climatic potential of natural ventilation in each case study city

Fig. 1 summarizes the workflow elaborated for the calculation of CPNV in each location. The analysis of the solar availability, i.e. global solar irradiance on vertical and horizontal planes, (W/m^2), and heat recovery systems were performed to determine the active and passive strategies to adopt when the use of natural ventilation was not possible.

2.1 CLIMATE ZONES AND CITIES SELECTION

The climate analysis was conducted for six selected European cities incrementally separated by of 5-degrees of latitude and located in different climate zones according to the Köppen-Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006) (Fig. 2).

The selected cities were spread out over the following zones:

- *Nordic zone*: Oslo (59.9° N, 10.7° E) classified as warm-summer humid continental climate [Dfb] and Copenhagen (55.6 ° N, 12.5° E) with temperate oceanic climate (Cfb).
- *Continental zone*: Brussels (50.8° N, 4.3° E) where the climate is warm and temperate (Cfb) and Milan (45.4° N, 9.1° E) with humid subtropical climate (Cfa).
- *Mediterranean zone*: Madrid (40.4° N, 3.7° W) and Valletta (35.4° N, 14.3° E) classified as Mediterranean hot-summer humid continental climate (Csa).

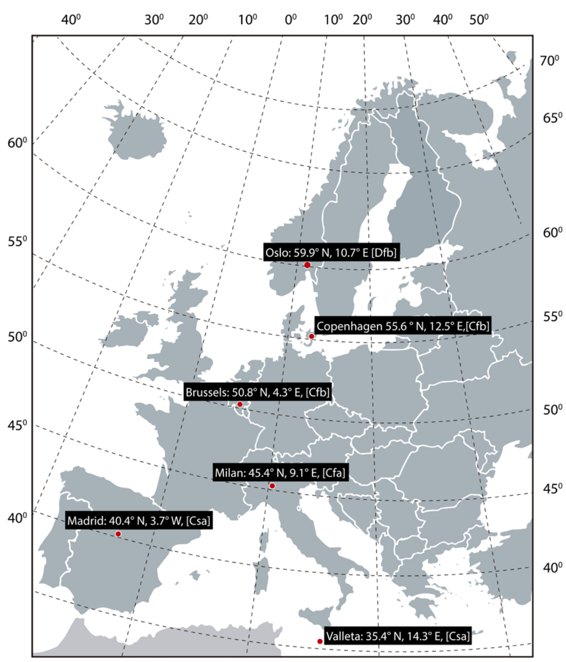

FIG. 2 Map of Europe with the six selected European cities evenly distributed (5-degrees of latitude) according to the Köppen-Geiger climate classification.

After selecting the cities based on general climatic characteristics, the yearly outdoor temperature variation is plotted against the upper and lower temperature boundary conditions for thermal comfort (Fig 3 a) determined by the adaptive (ASHRAE, 2013). According to (Givoni, 1969) (Berglund, 1998) (Fountain, 1999) (Wyon, 2006) (ASHRAE, 2009), 30–70% relative humidity (RH) was assumed as a range to guarantee comfortable conditions for both thermal and indoor air quality (IAQ). Additional selection criteria were also considered such as: (i) the diversity of the meteorological conditions during the year (e.g. different percentage of sky coverage, level of precipitation) for the cities in the same climate zone according to Köppen-Geiger climate classification (e.g. Copenhagen and Brussels or Madrid and Valletta), which might result in a variability in the climatic potential of using natural ventilation; and (ii) the mean monthly global solar irradiance available on the different orientations (Fig. 3). Although there are other factors than the latitude which influence the local climate, the cities were chosen to provide a basic overview of the climatic variations in terms of potentials of solar energy exploitation, and which influences the dynamic interaction between buildings and the outdoor environment.

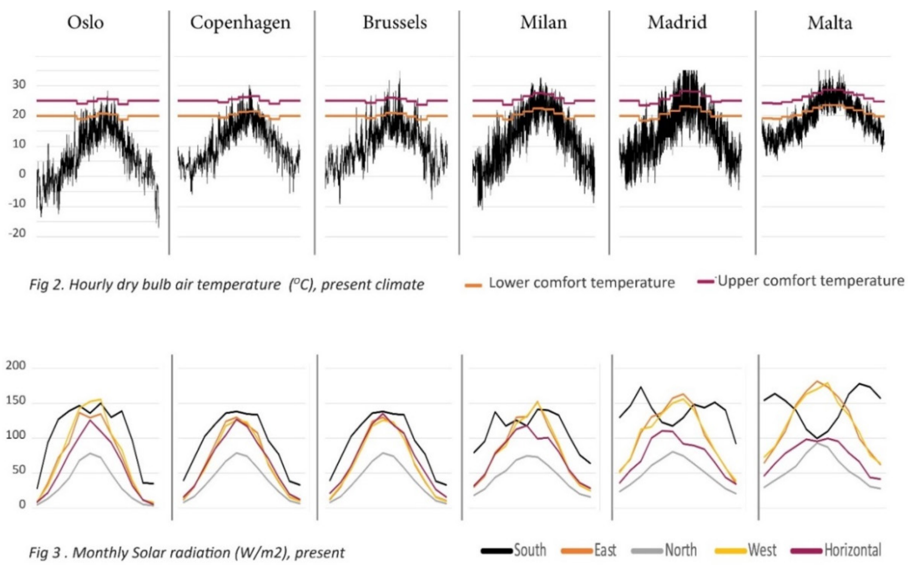

FIG. 3 (above) Hourly dry bulb air temperature and (below) average monthly solar irradiance on vertical (South, East, North and West) and horizontal planes at the historical climatic data. Data has been processed from the original .epw file

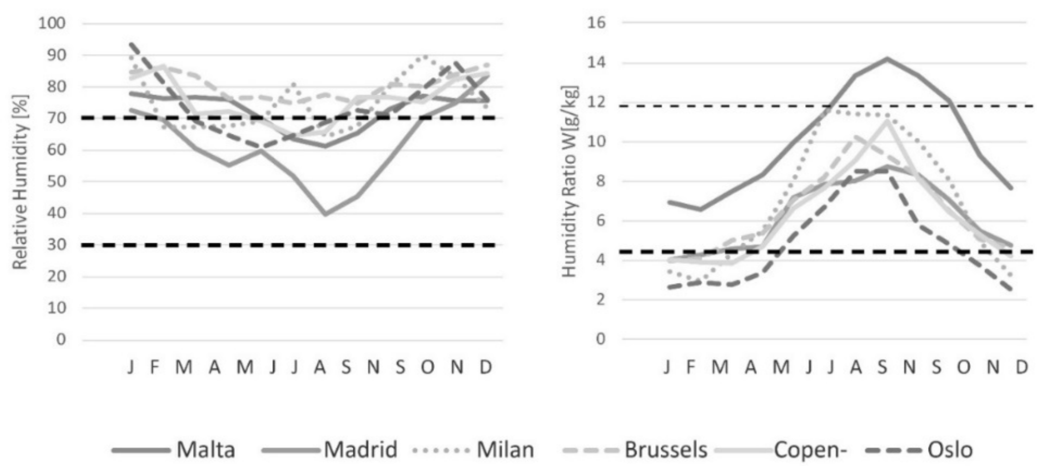

FIG. 4 (left) Monthly relative humidity and (right) average humidity ratio W (g/kg) for the selected cities in present climate conditions

Fig. 4 (left) shows that considering only RH, most climates provide conditions that are outside the comfort zone. In fact, humidity level of the outdoor air in cold climates is too high to be used as a direct fresh air supply. Therefore, Causone (Causone, 2016) proposes absolute humidity ratio (W) (g/kg) as adaptive humidity constraints linked to the adaptive comfort temperature limits in relation to the assessment of the potential of natural ventilation, since the RH of the outdoor air is of little significance when the possibility to ventilate the building directly with outdoor air is evaluated. The W ratio illustrates the opposite situation to RH boundaries (Fig. 4 right).

2.2 CLIMATE ANALYSIS

The methodology that was used to assess the extent to which a climate provides favourable (thermodynamic) conditions for natural ventilation is based on the method developed by Causone (Causone, 2016). This methodology evaluates the suitability of using natural ventilation in a given climatic context by calculating the Climatic Potential of Natural Ventilation (CPNV). The CPNV is defined as the number of hours in a year when natural ventilation can be used

$(\sum_{i=1}^{n} h_{NV,i})$

without incurring any heating or cooling load for the indoor space, divided by the total number of hours in a year (h_{yr}). This method is based on a climate analysis and is intended for conceptual designs where quick calculations are necessary, and a first approximation of the natural ventilation potential is required. It relies only on climate weather data and includes adaptive comfort models reported in the literature as well as the adaptive humidity constraints linked to the adaptive comfort temperature limits (Causone, 2016). It is therefore important to underline that the method only considers the suitability in terms of the temperature and relative humidity levels of the incoming air and does not analyse nor account for the natural mechanisms that assure the airflow. The word "natural ventilation" needs thus to be read as "without change in the thermodynamic conditions of the air" and in not related to natural-induced airflow movement. In this study, the CPNV is calculated during working hours ($CPNV_{work}$) in an office building occupied from Monday to Friday between 8:00 a.m. to 6:00 p.m. (). The $CPNV_{work}$ is defined as the following equation:

$$CPNV_{work} = \frac{\sum_{i=1}^{n} h_{NV,i}}{h_{yr-work}}$$

Ranges defining the upper (u) and lower (l) thresholds for temperature and humidity ratio were set to determine the use of natural ventilation in the selected locations in different periods of the year, since, according to the previous literature (Givoni, 1969) (Berglund, 1998) (Fountain, 1999) (Wyon, 2006) (ASHRAE, 2009), the air temperature range which is considered comfortable in an indoor space may change during the year according to seasons. This happens when the outdoor temperature (T_{out}) and outdoor humidity ratio (W_{out}) are within the comfort range established for their fluctuations (Fig. 5), as follows:

$T_{in,l} \leq T_{out} \leq T_{in,u}$ and $W_{in,l} \leq W_{out} \leq W_{in,u}$

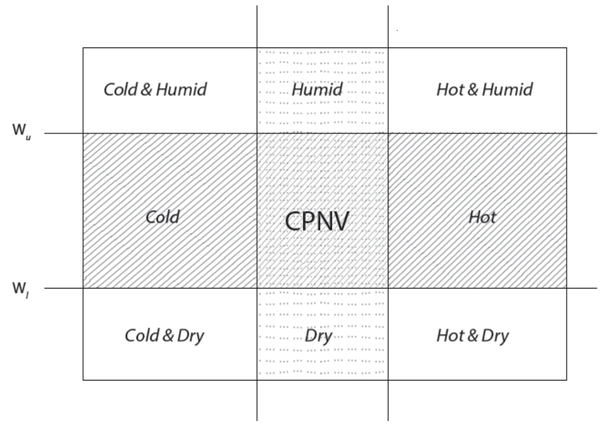

FIG. 5 Illustration of boundary conditions for CPNV, based on (Causone, 2016)

2.2.1 Extended Climatic Potential of Natural ventilation (ΔCPNV)

The CPNV is an index developed without any specific reference to the façade. However, in this work, the index was modified to understand how small of a change in the thermodynamic conditions of the air, implemented through an action carried out at the façade level, was necessary to increase the potential use of natural airflow for building climatization. The next step was then to estimate the difference (ΔCPNV) between the initial CPNV ($CPNV_{original}$) and the extended CPNV ($CPNV_{extended}$) achieved by expanding the boundaries ($T_{in,l}$, $T_{in,u}$, $W_{in,l}$, $W_{in,u}$) as a result of treating the temperature and humidity of the ventilation air (i.e. preheating/precooling, humidifying/dehumidifying) at the façade level (Fig. 6 left). The calculation of the ΔCPNV highlighted, for example, that the outdoor air should be preheated if it fell below the lower comfort temperature threshold or preheated and humidified if it fell below both the temperature and the specific humidity comfort conditions. This did not mean that the comfort range was increased because of a lower or a higher inlet temperature or humidity ratio, but rather that the periods of time in which natural ventilation is used could be extended with small treatments on the ventilation air.

$$\Delta CPNV = CPNV_{extended} - CPNV_{original}$$

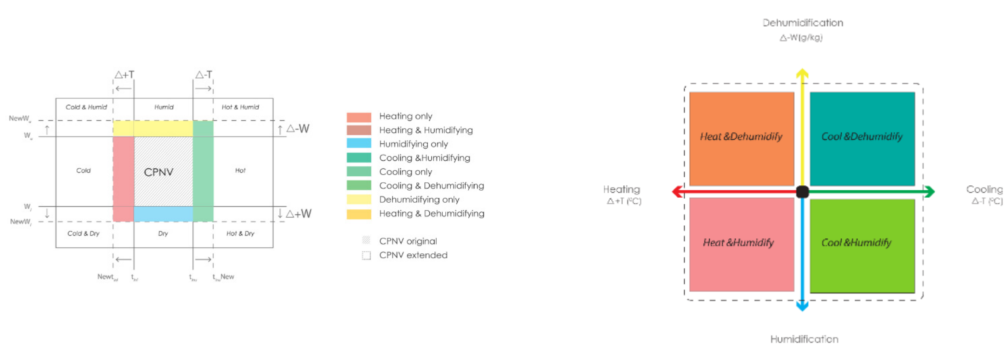

FIG. 6 (left) Visualization of different measures to maximize the CPNV (right) Concept of matrix graph for the results' visualization

This calculation was performed with a purposely developed script programmed in Python. The choice of the programming language was a functional one and allowed creating a tool (e.g. a digital dashboard with a user-friendly interface to calculate and optimize the climatic potential of natural ventilation according to a given climate. See section 5) which could later be shared through open access to a wider community. However, the automated procedures proposed in this methodology could have been implemented in any programming language.

Fig. 6 (left) shows that an increase of the CPNV can achieved by expanding the CPNV area and shifting at least one of the four boundaries of the CPNV domain. When deciding to move one or more of the boundary edges making up the original CPNV area, a corresponding action on the inlet air can be identified (Fig. 6 left). In Fig. 6 (right) the original area of the CPNV ($CPNV_{original}$) is represented as a point and the treatments of temperature and humidity of inlet air are shown on the x-axis and y-axis. The changes in humidity following the positive or negative y-axis mean that dehumidification or humidification of the incoming air is carried out, respectively.

A change in the temperature indicates the addition (preheating) or reduction (precooling) of heat to the inlet air along the positive and the negative x-axis, respectively. In the quarters the combination of both a change in the temperature and the humidity are visualized (Fig. 6 right). The figure was simplified from a 3D matrix graph to a two-dimensional graph with the negative values on the x-axis (-ΔT) representing preheating and positive values representing precooling (+ΔT), while the y-axis shows the change in ΔCPNV. The effect of humidity is shown parametrically on the same graph (see section 3. Results and discussion).

2.2.2 Solar availability and heat recovery

When calculating ΔCPNV, no information is given on how the air is thermodynamically treated.

This means that it can be done either naturally or mechanically. In this part of the study, some passive strategies enabled through active façade technologies, such as solar thermal energy availability and heat recovery, are assessed in connection to the ΔCPNV. The time during which sunlight is available was compared against the time when preheating or precooling is required and evaluated to assess whether the direct solar heat gain would be enough to preheat or precool the inlet air to the required temperature. The heat recovery was selected as a hybrid/natural ventilation strategy to assess to what extent it could expand the natural ventilation potential, by assuming the possibility to pre-heat/pre-cool the incoming airflow by recovering heat from the exhaust flow.

Different efficiency factors of the heat recovery unit were tested for both heating and cooling, within the range 60-90%, which is a realistic range for different types of heat recovery systems currently available. The supply temperature after the heat recovery with an efficiency (η) and the outdoor temperature (T_{out}) was calculated as follows:

$$\eta = \frac{T_{supply} - T_{out}}{T_{exhaust} - T_{out}}$$

3 RESULTS AND DISCUSSION

3.1 CPNV IN THE PAST, PRESENT AND FUTURE CLIMATE CONDITIONS

The annual percentage of time when outdoor conditions were within the comfort zone varied from one climate zone to another. This affected the domain of the $CPNV_{original}$.

The conducted climate analysis demonstrated that, at high latitudes (i.e. above 55° N) characterized by a cold climate, the $CPNV_{original}$ had the lowest potential in the historical scenario with a value of 5% in Oslo and Copenhagen, but that it increased by about 2% in both cities in the future weather scenario. Oppositely, in the Continental and Mediterranean zones which included the cities of Milan, Madrid and Valletta, the $CPNV_{original}$ in 2020 reached 16%, 15% and 17% respectively but in 2050, these numbers were reduced to 13% in Milan and Madrid and 14% in Valletta. Brussels represented the exception within its climatic zone, being the only city where the $CPNV_{original}$ was equal to 4% in the present climate and increased 7% in 2050, a behaviour otherwise only seen in the Nordic zone (Table 1).

TABLE 1 $CPNV_{original}$ in selected cities in the past, present, and future climate conditions

CLIMATE ZONES	CITY	CLIMATE CONDITIONS / SCENARIO		
		Past / Historical scenario	**Present / Scenario 2020**	**Future / Scenario 2050**
Nordic zone	Oslo	5%	7%	7%
	Copenhagen	5%	5%	7%
Continental zone	Brussels	4%	5%	7%
	Milan	16%	15%	13%
Mediterranean zone	Madrid	15%	14%	13%
	Valletta	17%	15%	14%

3.2 ΔCPNV BY PREHEATING AND PRECOOLING OF THE SUPPLY AIR

One of the possible actions that can be carried out at façade level to support its use as a ventilation inlet for the building is to pre-heat or pre-cool the airflow so that its thermodynamic conditions are within the CPNV area. Contrary to conventional ventilation systems, which can pre-heat or pre-cool air within a relatively large range, façade-integrated ventilation technologies face many technical challenges. For this reason, the analysis of the pre-heating and pre-cooling potential is limited to a range of ±10 C°. This arbitrary limit has been set considering that larger increases/decreases in the temperature would probably become uninteresting in a façade integration perspective. This analysis shows how façade-integrated solutions, which can be either small active devices or passive solutions for pre-heating/cooling, can extend the CNPV both in present and future climate conditions.

3.2.1 Nordic zone

The analysis conducted with the historical climate scenario in Oslo showed that by only preheating the inlet air by up to an additional 10 ˚C, the ΔCPNV increased by 30%. This means that it was possible to use natural ventilation 30% more of the time during the year (Fig. 7). By combining preheating and either humidifying or dehumidifying, the ΔCPNV increased even more in all scenarios. For the 2020 and 2050 scenarios, the ΔCPNV could be increased by 28% and 27% respectively. A combination of humidification and preheating allowed the most substantial increase in potential, and humidifying with 4g/kg could provide a ΔCPNV up to 35%, 33%, 32% for historical, 2020 and 2050 scenarios, respectively.

Precooling did not contribute substantially to the ΔCPNV in the historical climate and present scenario conditions in the Nordic zone. In fact, precooling gave less than a 1% change in the ΔCPNV because Oslo is predominantly a cold climate. However, in the future climate scenario, the precooling treatment could increase the ΔCPNV by around 2% ΔCPNV considering a precooling that lowers the inlet temperature by 4°C and humidifying rate of 3g/kg.

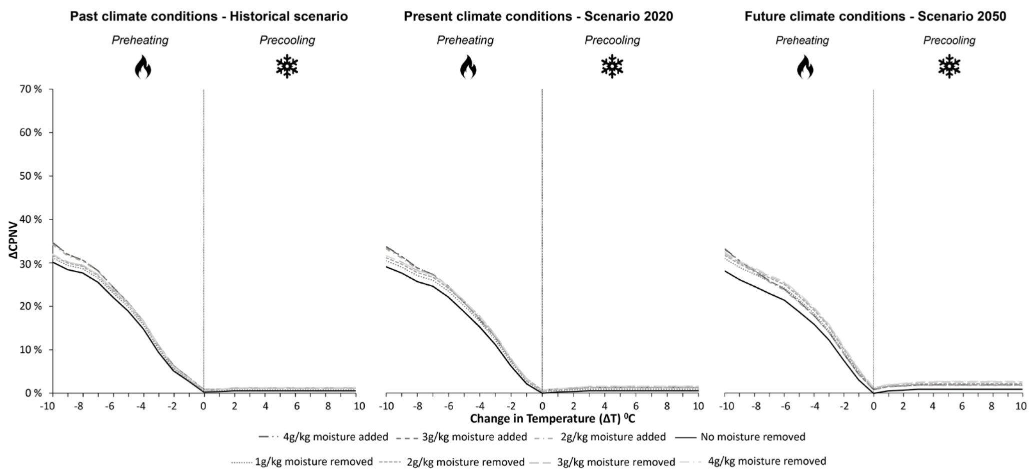

FIG. 7 Graph of ΔCPNV, for preheating and precooling in Oslo in the historical, 2020 and 2050 scenarios

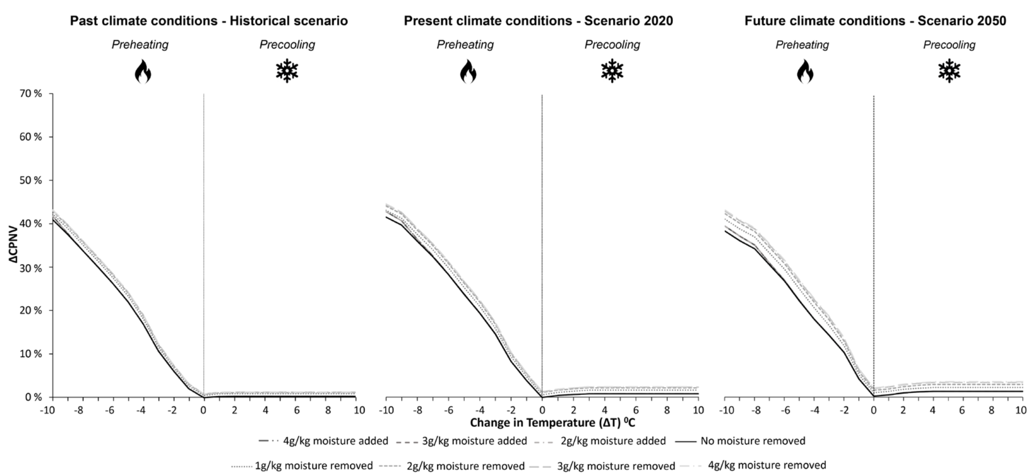

FIG. 8 Graph of ΔCPNV, for preheating and precooling in Copenhagen in the historical, 2020 and 2050 scenarios

The outcomes in Copenhagen showed that preheating with ΔT of 10 ˚C increased the ΔCPNV to 40% in the historical scenario and 41% in the 2020 scenario, while in the 2050 scenario, the ΔCPNV was just below 38%. A change in the humidity content of the inlet air did not contribute to improving the ΔCPNV in the past or present climate scenario but did provide benefits in the future climate conditions scenario for 2050, in which both preheating and precooling had a positive impact. Precooling of the inlet air was not relevant for the historical scenario but was increasingly beneficial in the scenarios for 2020 and 2050. Coupling precooling with 4 g/kg of dehumidification allowed a maximum 3% of ΔCPNV to be achieved in 2050 (Fig. 8).

3.2.2 Continental zone

Brussels and Milan have high levels of relative humidity throughout the year, which makes dehumidification a key aspect in improving the ΔCPNV for both preheating and precooling treatments.

In Brussels, preheating the inlet air alone could increase the ΔCPNV to 43% in the historical scenario, 44% in the 2020 scenario, and 45% for the 2050 scenario. However, the combination of preheating and dehumidification could lead to a ΔCPNV above 50% in 2050. The effect of dehumidification was such as that, even without increasing or reducing the inlet air temperature, the ΔCPNV could be increased to 3% regardless of the climate scenario. The combination of precooling with dehumidification was also shown to be progressively interesting and ranged from 7% in the historical scenario to 10% in the scenario 2050, while precooling alone only yielded a ΔCPNV of 2% (Fig. 9).

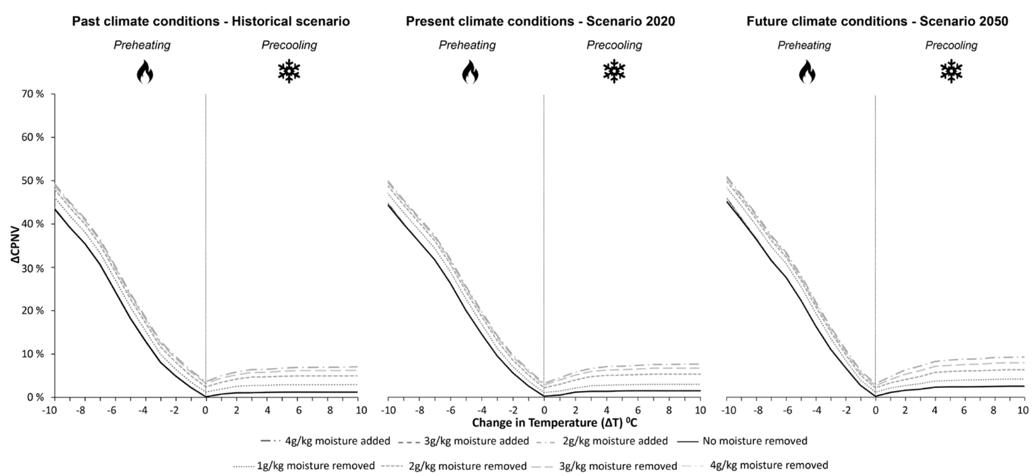

FIG. 9 Graph of ΔCPNV, for preheating and precooling in Brussels in the historical, 2020 and 2050 scenarios

In the historical scenario of Milan (Fig. 10), the ΔCPNV reached 27% by only preheating the inlet air, while it rose to 39% when coupled with dehumidification.

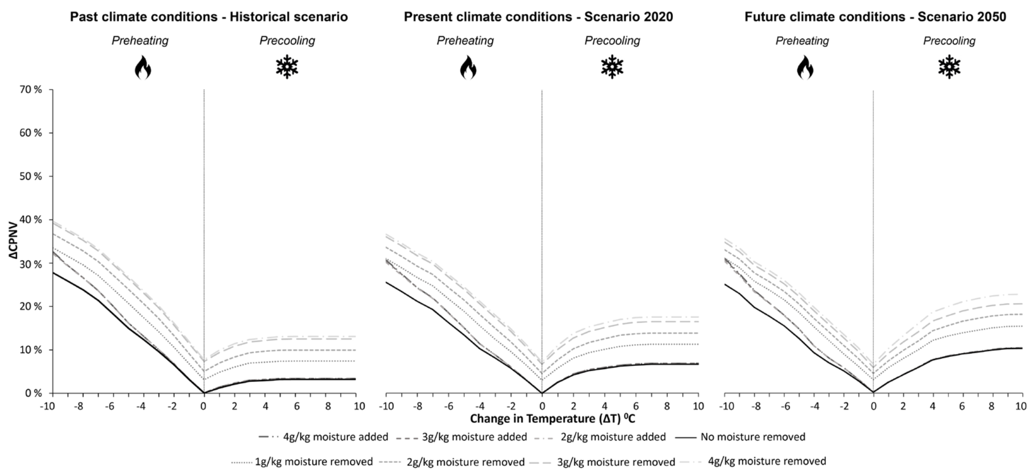

FIG. 10 Graph of ΔCPNV, for preheating and precooling in Milan in the historical, 2020 and 2050 scenarios

The ΔCPNV for preheating alone was slightly lower in 2020 and 2050, with an estimated value of 25%. Preheating combined with humidifying/dehumidifying was consistently more beneficial despite the ΔCPNV progressively reducing from 2020 to 2050. The combined treatment of preheating and humidifying became meaningful only when heating up the inlet air by 10˚C and by adding moisture content of 2 g/kg. Precooling alone raised the ΔCPNV to 3% in the historical scenario to 10% in the scenario 2050. Combining precooling and humidification or dehumidification was also increasingly interesting with a ΔCPNV of 12% for the past scenario and a ΔCPNV of 15% in 2020. The highest value of ΔCPNV was 21%, reached in the 2050 scenario by coupling precooling with a rate of dehumidification of 4 g/kg.

3.2.3 Mediterranean zone

In Madrid, for the past climatic scenario conditions, the ΔCPNV was 38% with the preheating treatment alone, but only reached 36% and 34% in the 2020 and 2050 scenarios, respectively. Generally, the humidification treatment improved the potential of natural ventilation in Madrid due to a relatively dry climate. In fact, the humidification of the inlet air by 2g/kg coupled with preheating of 10 ˚C contributed to an additional to 8% compared to the preheating treatment alone. The precooling treatment displayed higher potential when coupled with humidification by contributing to an additional 3% compared to precooling alone in the 2050 scenario. Finally, regardless of the scenario, the dehumidification did not seem to provide a substantial contribution in Madrid (Fig. 11).

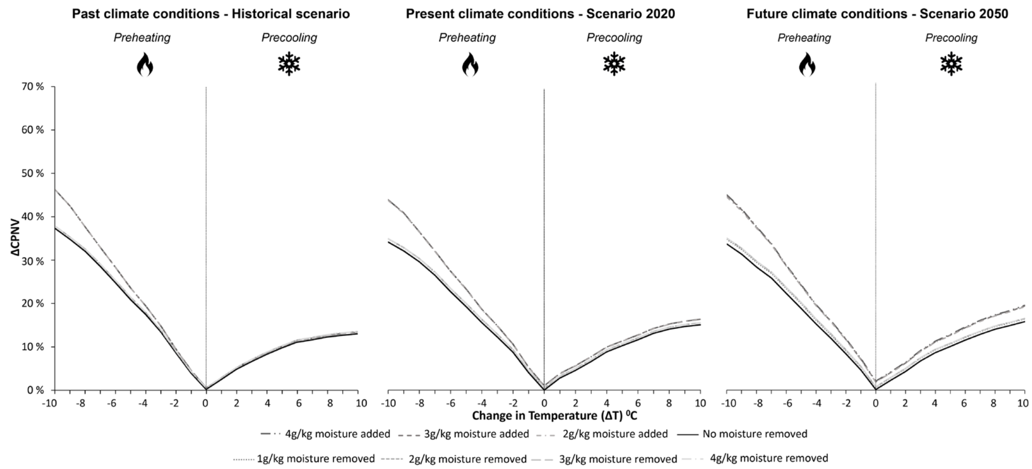

FIG. 11 Graph of ΔCPNV, for preheating and precooling in Madrid in the historical, 2020 and 2050 scenarios

The climate in Valletta was the mildest amongst all the analysed climates. Therefore, it exhibited the highest potential for natural ventilation for both preheating and precooling seasons. By preheating the inlet air by an additional 10 ˚C, the ΔCPNV was almost as high as 50% in the historical scenario, while in scenario 2020 and in scenario 2050 the value dropped to 47% and 41% respectively. If the inlet air was preheated and dehumidified by removing 4 g/kg moisture, the ΔCPNV could be increased to reach 69% in the historical climate scenario and despite some reductions seen in the 2020 and 2050 scenarios, the value was still always above 60%.

In the historical scenario, the ΔCPNV using precooling alone was only about 3%, and remained relatively constant for the 2020 and 2050 scenarios. Dehumidifying without preheating or precooling could increase the ΔCPNV up to 15% in all scenarios, and when combined to precooling, in the 2050 scenario, the ΔCPNV could be as high as 30%. The dehumidification process was then also important in Valetta as well, despite the lower relative humidity (Fig. 12).

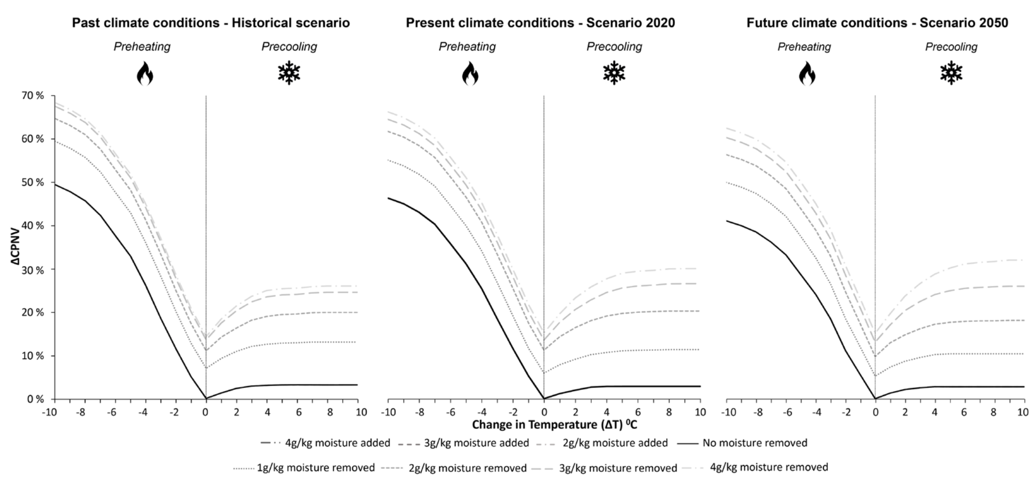

FIG. 12 Graph of ΔCPNV, for preheating and precooling in Valletta in the historical, 2020 and 2050 scenarios

3.2.4 Discussion on the ΔCPNV by preheating and precooling inlet air

The results indicated that the potential for natural ventilation in Europe increased significantly (30-50%) when the inlet air was preheated (Fig. 13).

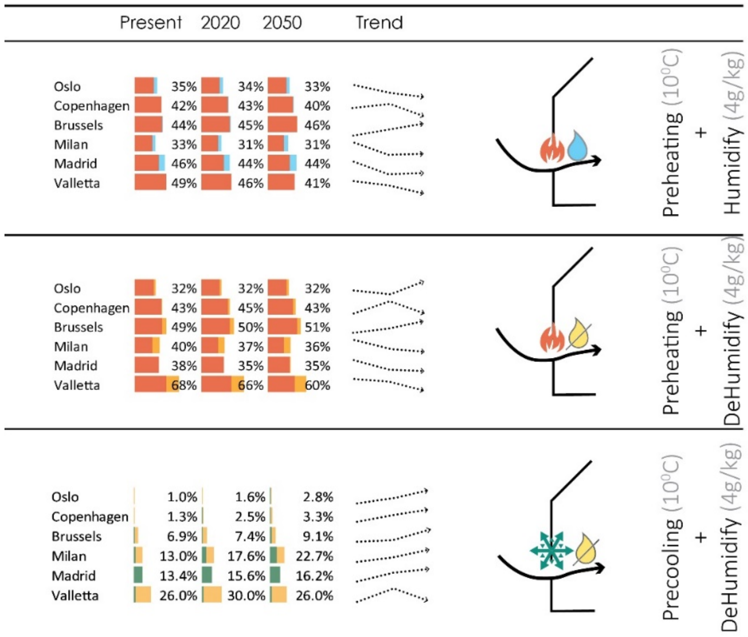

FIG. 13 Summary of ΔCPNV and treatments on the inlet air for all scenarios in the analysed cities

However, in future climatic conditions this potential was estimated to slightly decrease by 2-3% in all the analysed climates, except in Brussels. Precooling the air became more important in the future climate conditions of Europe and particularly at lower latitudes. Humidity was not as important as temperature when preheating at higher latitudes. However, dehumidification still played an important role when using precooling in all climates and especially at lower latitudes. Finally, the combined effect of changing the temperature and the humidity of the ventilation air supply provided relevant effects in terms of potential use of natural ventilation in all of the analysed cities.

3.3 SOLAR AVAILABILITY

Solar availability plays a crucial role in passive preheating of the ventilation supply air through the façade. The meaningfulness of solar availability resides in the possibility to convert solar power via integrated systems or use it as a passive thermal energy source. However, to maximise the direct use of solar energy at façade level without adding too many components such as batteries, it is important that the availability of solar energy matches as much as possible the energy requirements of the building. The analyses conducted in this study was useful to understand how solar energy could be used to provide energy for small air treatment systems directly integrated in the façade, as well as to understand if the timing between solar energy availability and energy demand for pre-heating and pre-cooling could be improved in a way that solar energy is best utilised and used in its most efficient form (as thermal energy or converted to electricity). In this part of the study a sub-layer is added to the investigation of the ΔCPNV and considers how solar availability in terms of available sunlight hours and solar radiation intensity can be coupled to partially solar powered preheating systems of the inlet air. The investigation assumes that the different preheating systems can require a minimum value of solar irradiance of 0 to 400 W/m^2 to function on solar power, which makes them dependant on the two components that define solar availability, namely the time of the day when solar energy is available (in consideration to when it is required i.e. timing) and the amount of solar energy available.

3.3.1 Nordic zone

In Oslo and in Copenhagen preheating the incoming air using solar energy allowed the ΔCPNV to reach 10% in the historical climate scenario when the system required a solar irradiance greater than 400 W/m^2 on the south oriented facade. In Oslo, the ΔCPNV decreased to 7% in the 2020 scenario and 6% in the 2050 scenario. While in Copenhagen, it maintained the values of the historical scenario all the way through to the 2050 scenario.

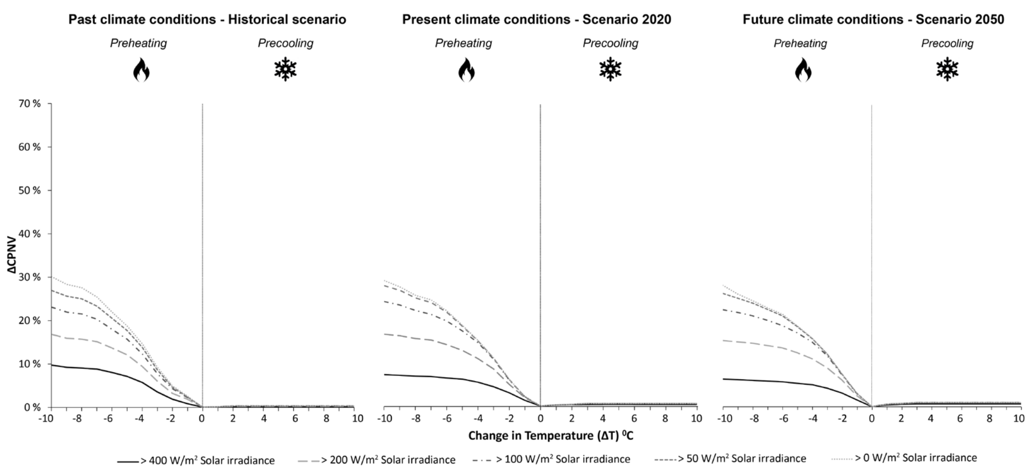

FIG. 14 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Oslo for historical, 2020 and 2050 scenarios

In Oslo, during the preheating season in the historical climatic scenario, a system requiring a solar irradiance of 50 W/m^2 or more could provide a ΔCPNV 25% when the air was preheated by an additional 10°C. This figure slightly increased by a small amount (around 2-3%) in the scenarios 2020 and 2050 (Fig. 14). During the warm season, the precooling needs almost always occurred when there was a solar irradiance of more than 400 W/m^2 on the south façade, in both cities of Nordic zone.

During the preheating season in Copenhagen, for preheating systems which needed a solar irradiance value of 100 W/m^2 or more could provide a ΔCPNV above 35% in the past climate scenario and up to 30% in 2050 (Fig. 15).

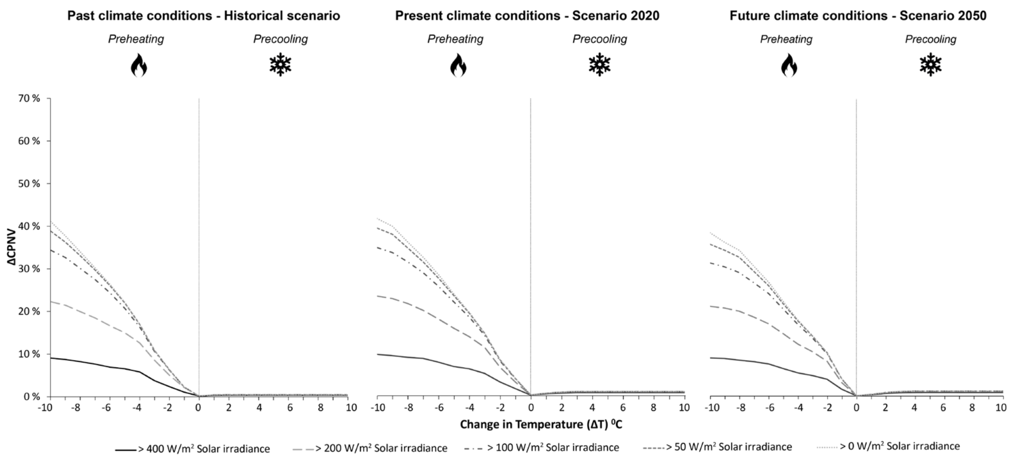

FIG. 15 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Copenhagen for historical, 2020 and 2050 scenarios

3.3.2 Continental zone

In Brussels, a ΔCPNV of around 10% was achievable by preheating with a value of solar irradiance of 400 W/m^2 or more but decreased to only 6% in the 2050 future scenario. Similarly all of the ΔCPNVs decreased for all the cases in which preheating was dependent on given amounts of available solar energy present and in future climate condition scenarios in Brussels (Fig. 16).

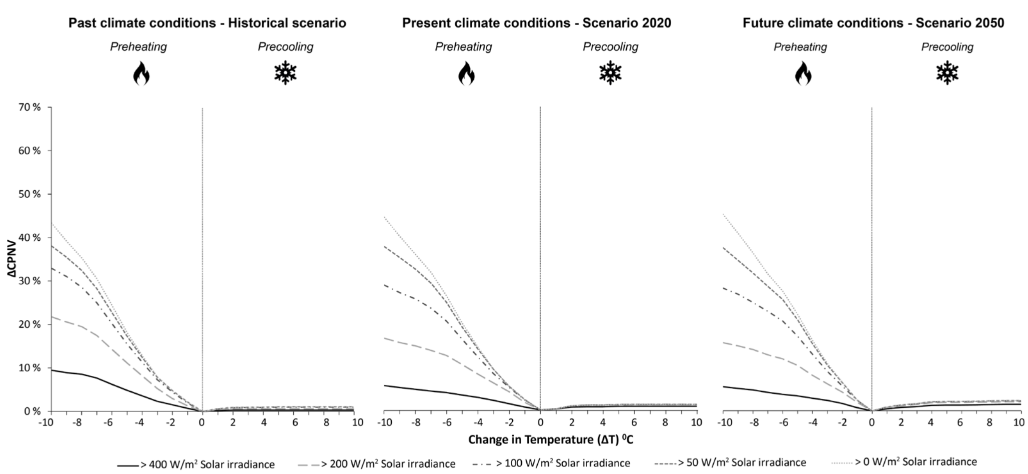

FIG. 16 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Brussels for historical, 2020 and 2050 scenarios

In Milan, a ΔCPNVs of 6% could be achieved through preheating inlet air with systems requiring a solar irradiance value of 400 W/m^2 or more on the south oriented façade but this figure decreased to 4% in 2050. For cases requiring 50 W/m^2 or more irradiance available, the ΔCPNV reached 20% during preheating in the historical scenario but showed a decrease to about 3% in the 2050 future scenario. During the precooling season, when an irradiance od 400 W/m^2 or more was available on the facade, a ΔCPNV of 8% was achieved. Furthermore, there was a substantial change in terms of solar availability for precooling from 1.8% in historical climate scenario to 6.9% in the 2050 scenario in Milan. In 2050, the ΔCPNV was higher during precooling than preheating when an irradiance of 400 W/m^2 or more was available (Fig. 17).

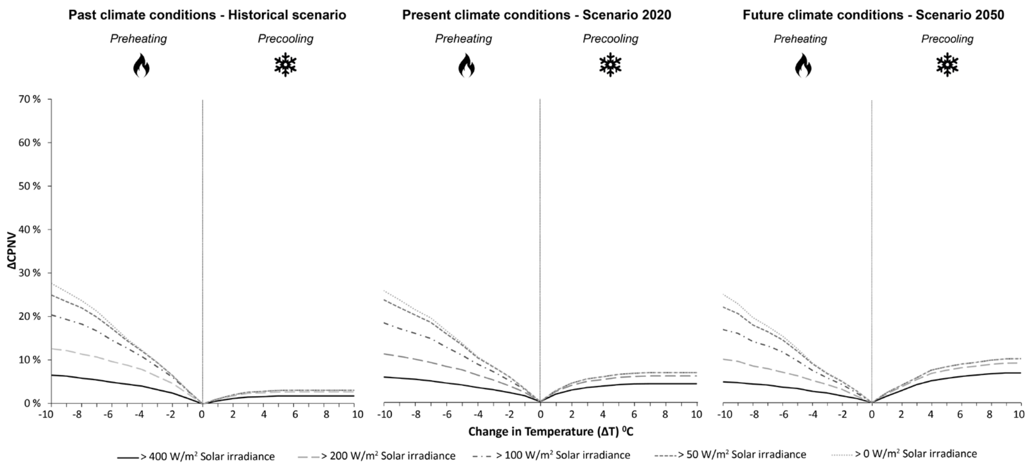

FIG. 17 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Milan for historical, 2020 and 2050 scenarios

3.3.3 Mediterranean zone

In Madrid the ΔCPNVs was in the 10% range when 400 W/m^2 or more were available during the preheating season in all three climatic condition scenarios. During the precooling season, the future climate scenarios showed a slight increase of the ΔCPNV when solar irradiance available was equal or greater than 400 W/m^2 (Fig. 18).

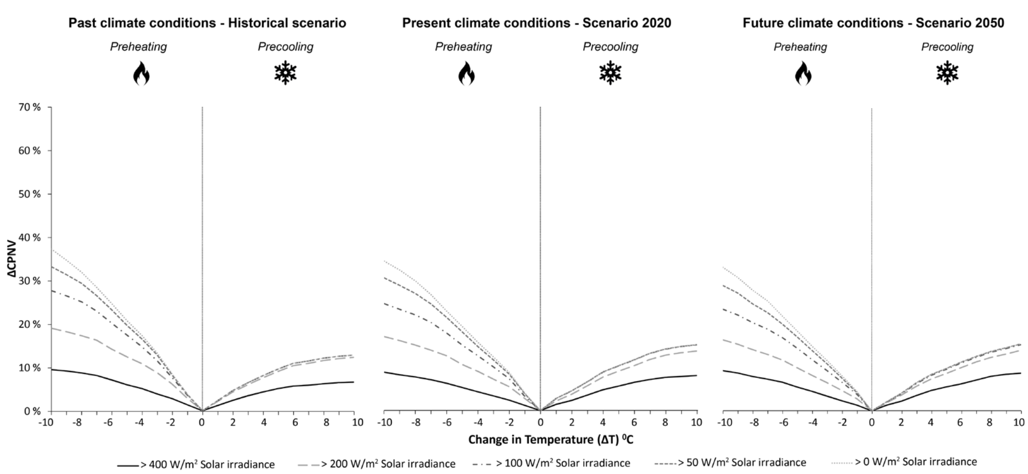

FIG. 18 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Madrid for historical, 2020 and 2050 scenarios

In Valletta, a ΔCPNV of 20% could be achieved through preheating the incoming air using an irradiance of 400 W/m^2 or more, but this possibility slightly decreased (by 4 %) in 2050. In Valletta, there was a quite small need for precooling. The solar availability maintained the same trend in the scenario for 2050 where a preheating system requiring a solar irradiance availability of 200 W/m^2 was sufficient to reach a ΔCPNV of 30% or more but a system requiring 400 W/m^2 only covered about 20% (Fig. 19).

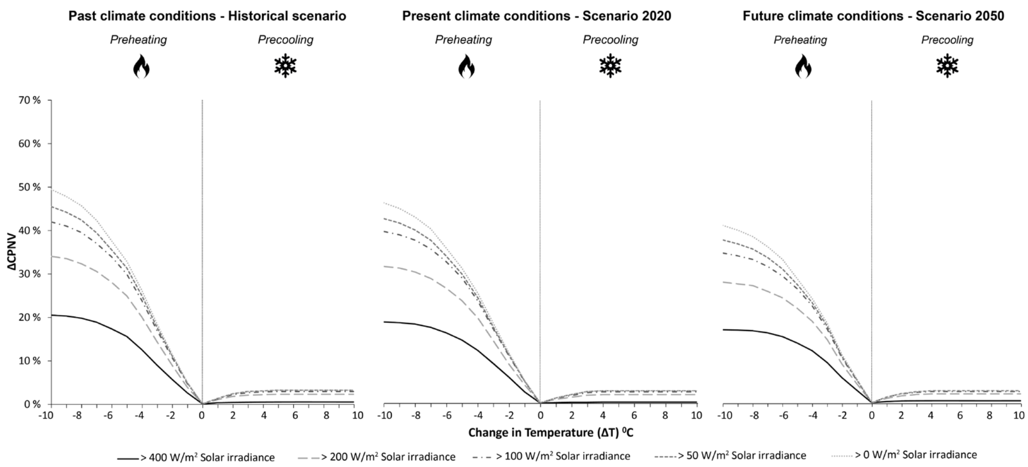

FIG. 19 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Valletta for historical, 2020 and 2050 scenarios

3.3.4 Discussion on the ΔCPNV by preheating and precooling inlet air through solar radiation

Regardless of the differences in latitude, in all locations except Valletta, similar behaviours were exhibit with regard to solar availability and their impact on the ΔCPNVs. In historical climatic condition scenarios, ΔCPNVs of less than 10% were achievable during the preheating season when the required availability of solar energy resulted in an irradiance of 400 W/m^2 or more for the system. This percentage decreased in the scenarios for 2020 and 2050 in all climate zones. This might suggest that other active strategies requiring lower values of solar irradiance should be investigated since passive heating (e.g. solar heat gain) did not have the capacity to preheat the inlet air and this ability will deteriorate further in the coming years. At low latitudes, except in Valletta, in the 2050 scenario there was a substantial increase of solar availability for precooling. In Madrid and in Milan the results showed that the preheating and precooling treatments became of equal importance by 2050. This implied the potential use of active strategies to convert the solar power into cooling energy (Fig. 20).

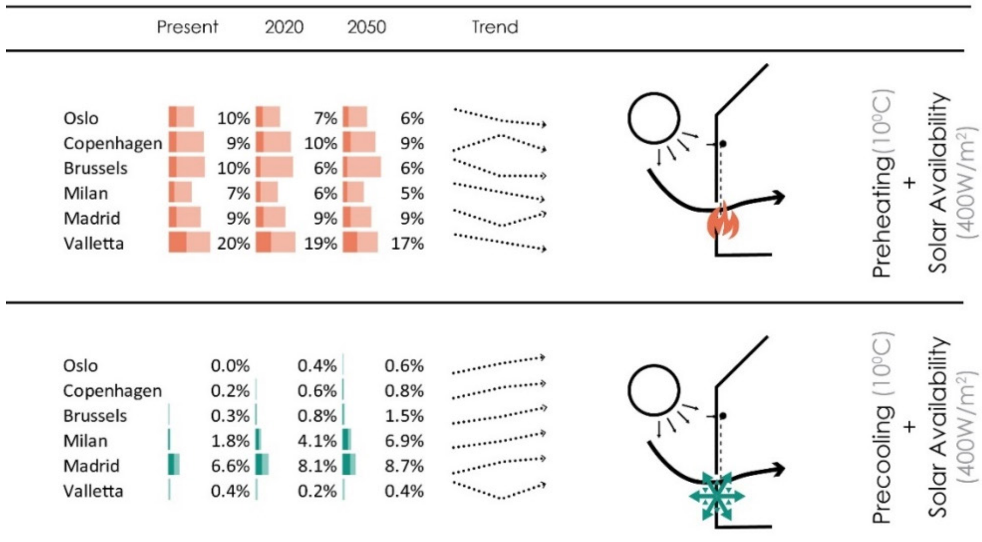

FIG. 20 Summary of ΔCPNV in historical, 2020 and 2050 scenarios and solar availability in the analysed cities

3.4 HEAT RECOVERY

The recovery of the heat contained in the exhaust airflow could be reused to maximize the potential for natural ventilation through the façade. Heat recovery is a standard feature in today's ventilation systems for highly efficient buildings, and the implementation of such a strategy at facade level has shown to significantly increase the potential to ventilate buildings through integrated systems in their facades. Coupling passive ventilation and heat recovery can lead to significant reductions in terms energy use for ventilation, heating and cooling by using the energy from the exhaust air to condition the incoming air and satisfy the thermal comfort levels desired by the occupants.

3.4.1 Nordic zone

In Oslo, using heat recovery with preheating provided a potential for natural ventilation over 40%, which was 10% more than could be achieved through preheating only (Fig. 21). In the 2050 scenario, this difference grows bigger because the ΔCPNV obtained by using heat recovery in combination with preheating increases while the ΔCPNV calculated for the preheating treatment only decreases.

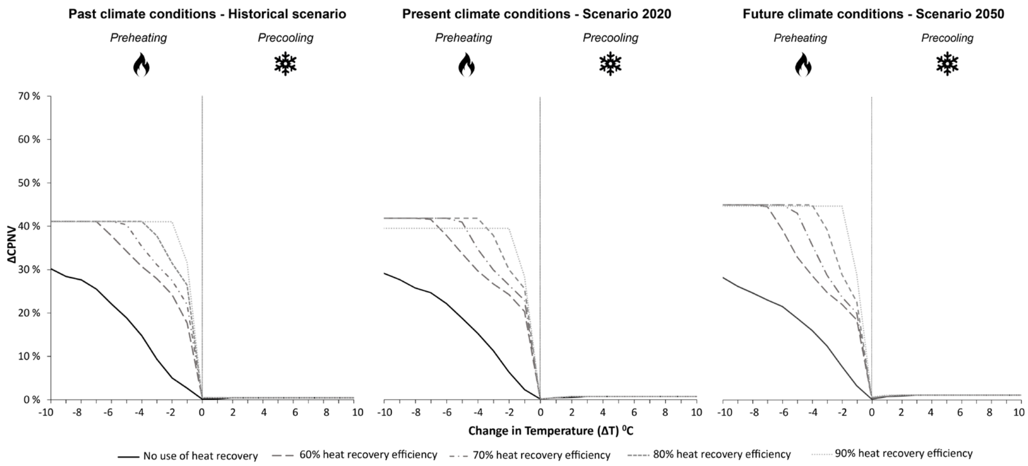

FIG. 21 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Oslo for historical, 2020 and 2050 scenarios

The climatic conditions were favourable for heat recovery in Copenhagen too. In fact, the heat recovery system was able to provide a ΔCPNV of 56% in the historical scenario and this percentage increased to 60% in 2050 (Fig. 22).

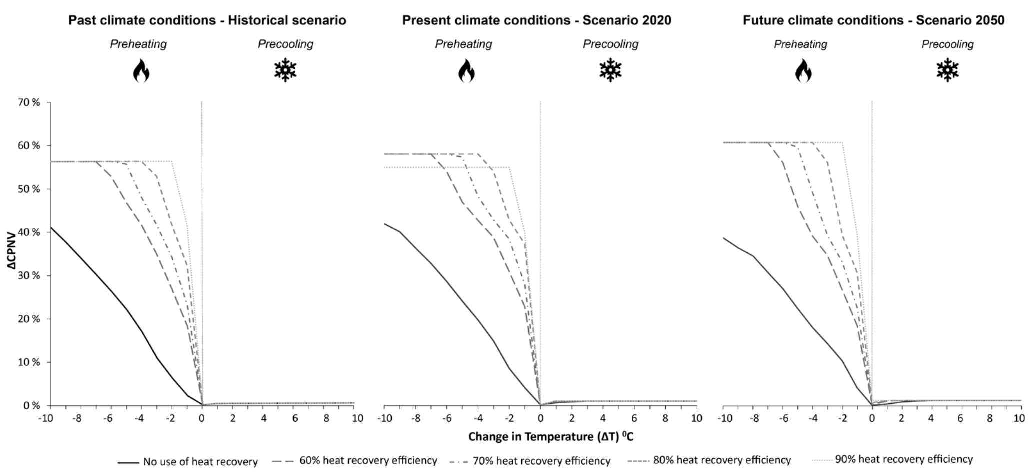

FIG. 22 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Copenhagen for historical, 2020 and 2050 scenarios

All the different efficiencies of the heat recovery units in combination with preheating were able to obtain the maximum ΔCPNV. However, the difference was in the amount of required for the preheating before using the heat recovery. In that regard, a heat recovery with 90% efficiency could attain the max ΔCPNV with only 2˚C of preheating, while a heat recovery efficiency of 70% yielded the max ΔCPNV with 4 ˚C, and a 60 % efficiency with 6 ˚C preheating of the outdoor air (Fig. 21 and Fig. 22). In the Nordic zone, it could be seen that heat recovery did not have substantial contribution in the precooling season (Fig. 21 and Fig. 22).

3.4.2 Continental zone

In Brussels, heat recovery increased the potential of ventilation to up to 67%. This increased about 1% in the 2050 scenario similarly to in the Nordic zone (Fig. 23).

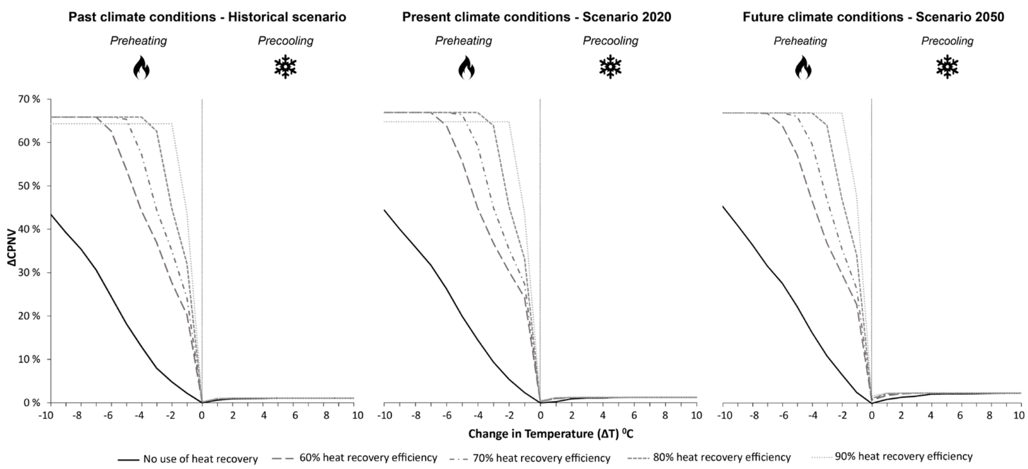

FIG. 23 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Brussels for historical, 2020 and 2050 scenarios

For precooling season, the heat recovery did not have significant contribution in the historical climate, while it had a modest increase of up to 2% in the 2050 scenario (Fig. 23).

The climate in Milan revealed that heat recovery could be used for both preheating and precooling (Fig. 24).

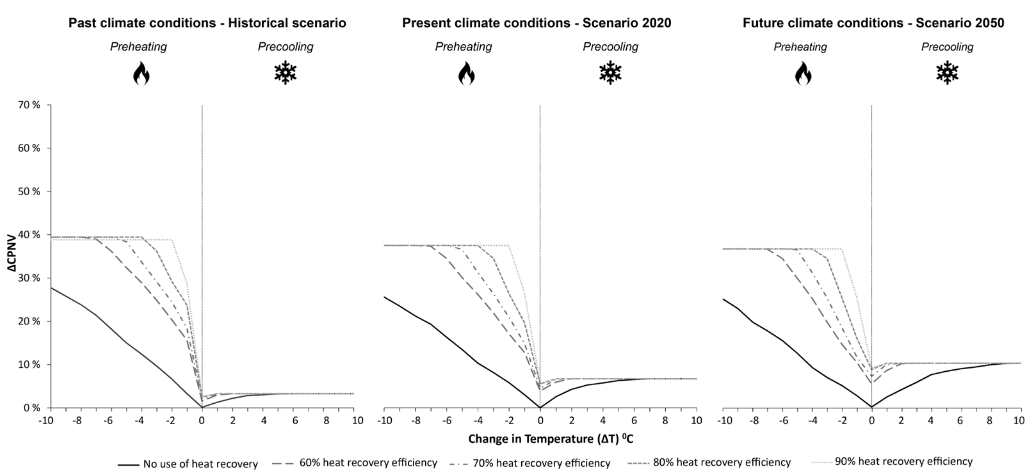

FIG. 24 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Milan for historical, 2020 and 2050 scenarios

ΔCPNV reached up to 40% in historical scenario, while it declined by around 2%, in the scenario for 2050. Heat recovery for precooling showed a notable contribution to the ΔCPNV in the scenario for 2050 by rising from 2.5% in the past climate conditions to 10% in the future. In addition, heat recovery efficiency for cooling was not relevant because it quickly reached the peak with 2˚C of precooling. In 2050, the need for heat recovery will increase by 7% if both preheating and precooling are considered.

3.4.3 Mediterranean zone

In Madrid in the historical scenario, a ΔCPNV of 50% could be obtained by using a heat recovery system for preheating (Fig. 25).

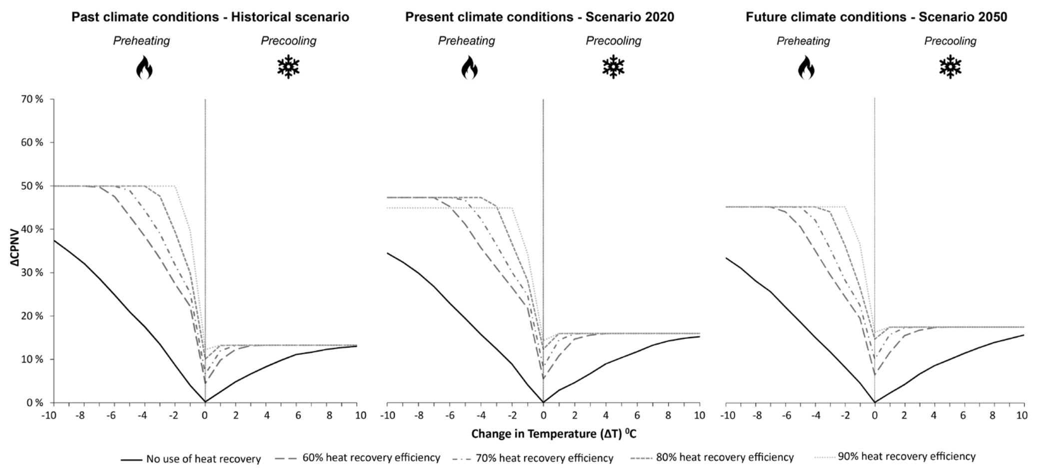

FIG. 25 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Madrid for historical, 2020 and 2050 scenarios

This showed notably decreased by 5% in 2020 and in 2050. For cooling purposes, heat recovery played an important role with a ΔCPNV of 12% in the past climate conditions and up to 19% in future conditions of 2050. This means that in the future, the decrease preheating would be balanced out by the increase in cooling potential by using extract air to precool fresh air.

In Valletta, a ΔCPNV of 51 % could be obtained by using heat recovery for preheating and which was very close to the percentage previously determined to be achieved through preheating alone (50%). A sharp decline to 41% was registered in the use of heat recovery for preheating in the 2020 and 2050 scenarios. Surprisingly, the climate of Valletta showed no change in precooling with heat recovery both in present and future climate scenarios. This might be due to the mildness of the climate, given that there were previously no significant changes in the air treatment with only precooling as well (Fig. 26).

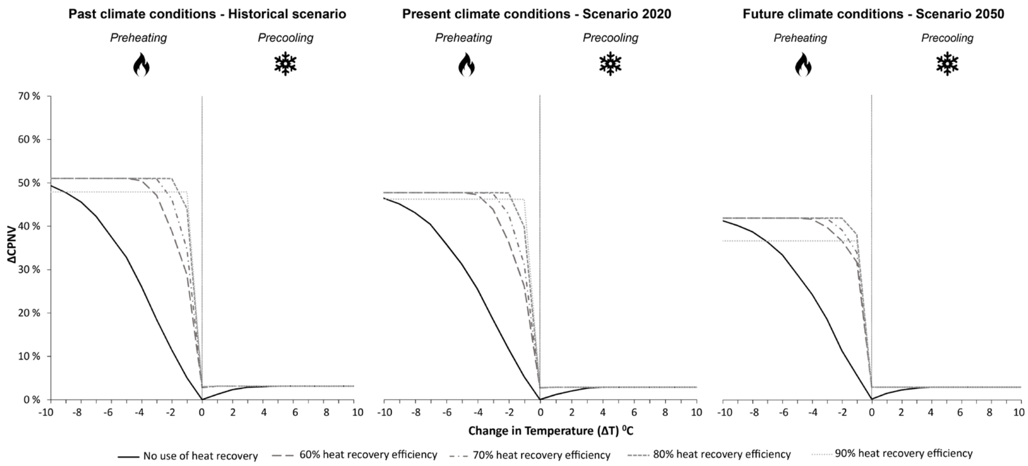

FIG. 26 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Valletta for historical, 2020 and 2050 scenarios

3.4.4 Discussion

The amount of change in the potential for natural ventilation differs from climate to climate but a range of 40-70% ΔCPNV is attainable in all climate during the preheating season. Relatively colder climates, such as in the Continental zone, gained the most from heat recovery treatment, while cold climate in the Nordic zone could suffer from too dry indoor air when using heat recovery and consequently, would see a reduction in their potential for natural ventilation. However, some dryer air might not necessarily be unacceptable because it could to some extent be compensated by the naturally-occurring generation of water vapour from occupants. A heat recovery system with a 90% efficiency clearly showed the most gain of potential of natural ventilation requiring less than 2 ˚C of preheating to reach the maximum potential in all the cities and in all climate zones. It might even be enough to provide the air without preheating the air up to 2 ˚C in order to compensate for internal gains in a building.

In future climate scenarios, buildings located at higher latitudes showed that they would only see a minor increase in their ΔCPNV for both preheating and precooling with the aid of heat recovery (Fig. 27).

At lower latitudes and in relatively warmer climate, such as in Milan, Madrid and Valletta, there was a notable decrease in the preheating potential for heat recovery and at the same time as there was a significant increase in the cooling potential using heat recovery. Therefore, the needs balanced each other out, and the use of heat recovery remained the same or improved slightly.

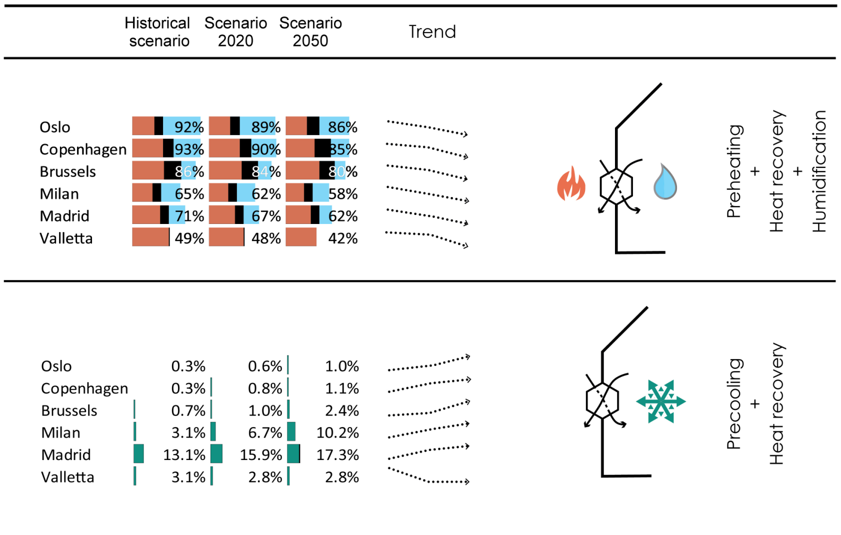

FIG. 27 Summary of the ΔCPNV attained through preheating (orange) and precooling (green) with humidification (blue) and using heat recovery (black) in historical, 2020 and 2050 scenarios in all the analysed cities

3.4.5 Implications of façade design and operation

Nowadays there exist a large range of possibilities for façade-integrated systems for exploiting renewable energy sources (RES). Such systems are primarily based on the integration of photovoltaic layers, solar thermal panels, and heat pumps which can be integrated into the building envelope and building energy concepts partly for pre-heating and pre-cooling of the air of the building. These technologies can also be integrated inside the cavity of double skin façades, which could work as an air-based solar thermal collector, allowing the preheating of the inlet air in winter and precooling (though a heat pump) in summer. These capabilities could make the double skin façade system a worthwhile field for further investigation, with a vast field of possible improvements regarding functionality and performance.

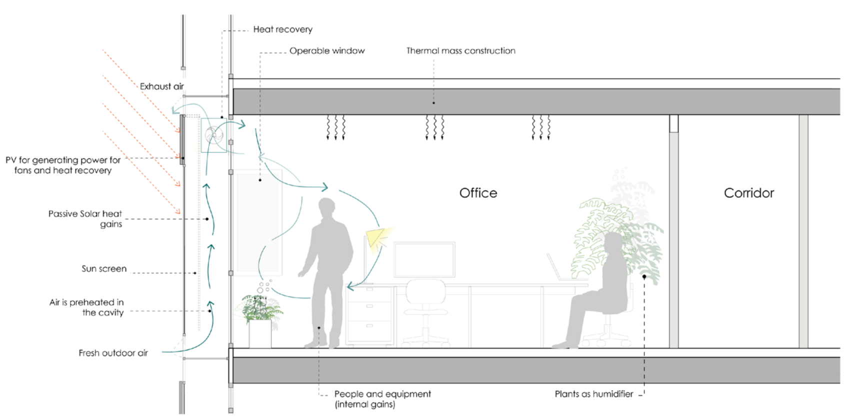

FIG. 28 Conceptual scheme of the section of hybrid ventilation system in integrated double skin facade system

Fig. 28 shows a conceptual scheme of a hybrid integrated double skin façade system where there could be a minor treatment of the air at the façade level with the use of fans and low-pressure drop heat recovery. The use of photovoltaic integrated shading devices (PVSD) (Taveres-Cachat, Lobaccaro, Goia, & Chaudhary, 2019) (Taveres-Cachat, Bøe, Lobaccaro, Goia, & Grynning, 2017), which can be either fixed or movable, installed in the facade cavity, may also be employed to power the heat recovery process.

4 LIMITATIONS OF THE STUDY

The analysis conducted in this study considers only the thermodynamic properties of the outdoor air, temperature and humidity to calculate the potential of natural ventilation of specific climates. However, it does not consider other factors that are also essential when considering naturally-driven airflows in a building. In that regard, the study does not consider the mechanism of airflows through the facade. It assumes that the incoming air would be treated at the façade level and enters the building without any impact on the air treatments in the cavity of the facade. In addition, even though wind data is also included in weather data climate files, it was not considered as it also relates more to the airflow mechanism.

5 CONCLUSION AND FURTHER DEVELOPMENT

This paper presents a methodology to investigate the potential of natural ventilation through the facade in office buildings in present and future climate scenarios (2020 and 2050). It reviews advantages, possible technologies, and strategies to maximize its use in a building. It analyses selected climates in Europe via numerical analysis, with the consideration of temperature and humidity. The main findings of the study can be summarized follows:

- The analysis on the future climate scenarios indicated that climate change scenarios will negatively influence the potential for natural ventilation in the future of Europe by increasing cooling needs and reducing heating needs.
- There is not enough solar availability in all analysed cities and climate zones during the preheating season and there is sufficient available solar radiation in the cooling season, which implies that there is a need for active technologies at the façade level to compensate for the periods without the potential for natural ventilation.
- Heat recovery systems can be successfully used to treat the air at the façade level and maximise the potential for low energy ventilation solutions for heating and cooling requirements in both present and future climates. This will bring about a 40-90% increase in the potential of natural ventilation through the façade in all climates during the heating season, and up to 15% in warmer climates during the cooling season.

A further development of the study implies a creation of a digital dashboard as graphical user-friendly interface (GUI) (Fig. 29).

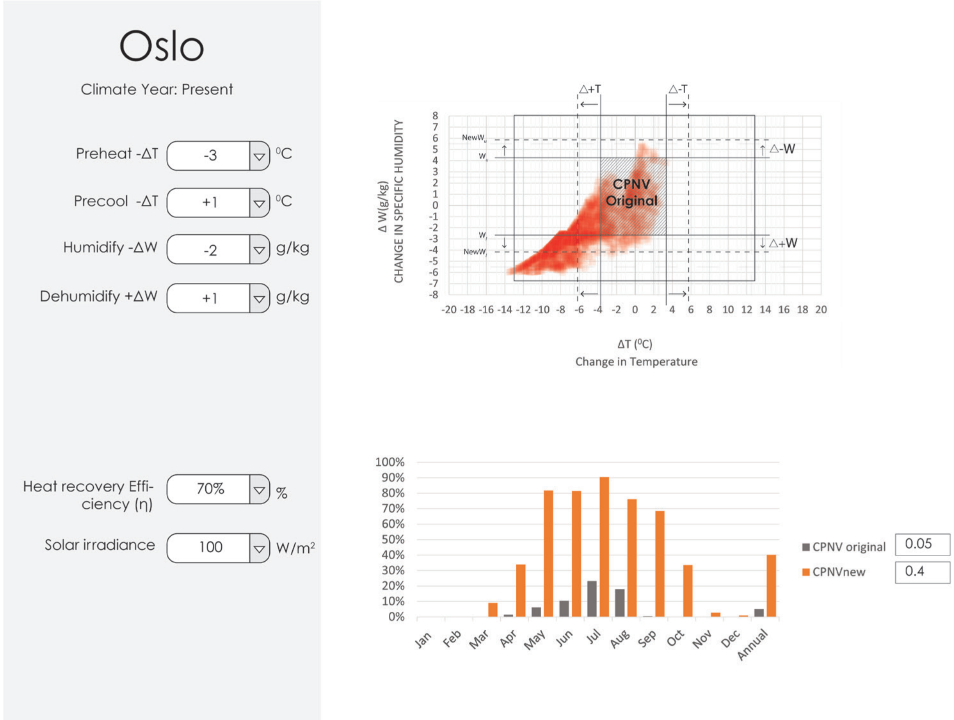

FIG. 29 Possible Digital dashboard as a user-friendly interface to calculate and optimize the climatic potential of natural ventilation of a given climate

This GUI will allow the users to easily comprehend at once glance the effects of changing the geographical parameters (e.g. location with latitude and longitude, comfort zone, year) and the air treatments parameters (i.e. preheating, precooling, humidifying, dehumidifying, heat recovery and solar availability). A user would be able to input the different changes in temperature and humidity (-ΔT, +ΔT, +ΔW, -ΔW) and get the CPNV extended and compared with the original potential (comfort zone hours) in real time. It would also be interesting to develop a functionality to maximize the climatic potential for natural/hybrid ventilation based on the optimum use of the combination of the different air treatments in any specific location.

Acknowledgement
This paper is part of the research activities developed in the "SkinTech" project and in the "ReInVent Windows" project funded by the Research Council of Norway and the industrial partners in the project under grant No. 255252 and No. 262198.

The authors would like to thank Ellika Taveres-Cachat for helping to improve the quality of the English language in this publication

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Shape-changing Architectural Skins

A Review on Materials, Design and Fabrication Strategies and Performance Analysis

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Abstract
In recent years, there has been an increasing interest in shape-changing smart materials in design fields. The ability to design responsive architectures that adapt to different climatic conditions is, without doubt, an appealing idea. One area in which shape-changing materials are applied is in the design of building skins or envelopes. This paper presents a systematic review of the literature on the use of shape-changing materials in the development of active skin systems, identifying patterns in design and manufacturing strategies. We also note the stage of development of the proposed designs and whether performance analysis was conducted to predict their behaviour. The results show that the most commonly used materials are SMA (Shape Memory Alloys) and wood-based bio-composites. Other shape-changing materials used for developing skin systems are, in order of popularity, thermo bimetals, electroactive polymers, composite bimetals, shape memory polymers, and hydrogels. The patterns identified among the studies are (1) design strategies: smart material as the skin, smart material as the actuator, combination with other non-responsive materials, responsive structures, geometric amplification; and (2) manufacturing strategies: bilayer systems and additive manufacturing. Finally, while the argument for the development of responsive skin systems is often based on the idea of efficiency and improved performance, we found that few studies can predict the performance of such skin systems.

Keywords
Smart materials, shape-changing materials, responsive architecture, building skins

1 INTRODUCTION

Living systems are complex and have feedback mechanisms that enable a response to environments for harvesting energy, managing resources, or survival. In the advanced functional materials, we can see some aspects of the responsivity of materials, particularly with the so-called smart or functional materials. Smart materials are characterised by having intrinsic sensors and actuators that allow them to sense a stimulus, respond to the stimulus in a controlled manner and return to their original state after the stimulus is removed (Ahmad, 1988). While these materials have long been in the research agendas of material scientists and engineers, only recently have they started to permeate the design field.

Over the past decade, smart materials have become increasingly popular among designers. Smart materials can add functionality to the design of buildings, opening up a conceptual and practical framework for architects to design "truly environmentally responsive" architectural systems (Kretzer, 2016). For instance, buildings could be designed with enhanced functionality to dynamically adjust to changing weather conditions, saving energy, and improving interior comfort. Furthermore, smart materials can potentially help to make buildings lighter and more efficient, replacing existing larger and more complex architectural systems (Addington, 2010).

FIG. 1 Diagram characterising the behaviour of smart materials. Based on the Heckman Diagram

Shape-changing smart materials are particularly interesting for researchers in the design fields due to their potential to create responsive structures that adjust their configuration in response to a defined stimulus, constructing responsive architectural systems (Correa et al., 2015; Fiorito et al., 2016; Wood, Vailati, Menges, & Rüggeberg, 2018). Furthermore, shape-changing materials could potentially be incorporated into building envelopes to achieve improved performance through their actuation capabilities in response to shifting environmental conditions. For this reason, there is a growing number of design-oriented studies that use shape-changing materials for developing, mostly, architectural skin systems. Coupled with advancements in computational design, digital fabrication, and simulation technologies, shape-changing materials that harvest energy from the environment are at the core of a new, material-oriented design approach for the design and manufacturing of responsive skin systems that do not require any additional energy source or mechanical control.

While this review focuses only on shape-changing materials, this represents only one group among different types of smart materials. To characterise the behaviour of smart materials, one can use the diagram shown in Fig. 1, which is based on the Heckman diagram and describes the relationship between material properties. In shape-changing smart materials, a stimulus causes a physical change such as strain, thereby causing the material to deform. As shown in Fig. 1, the stimulus can be water, a change in temperature, or an electric field, among others. Different shape-changing materials can be perceived in the diagram: electrostrictive and piezoelectric materials enable the quadratic and linear relationship between mechanical (strain) and applied electrical properties, while hydrophilic smart materials enable the relationship between chemical properties and mechanical properties, and so on.

The envelope is the system that controls energy exchange between the inside and outside of buildings, and it is known to have a great impact on the building's energy efficiency (Echenagucia et al., 2015). Not surprisingly then, façades and windows have been the most common targets for the implementation of smart material systems on buildings. Addington & Schodek (2012) identified several building requirements related to the building envelope kinetics that could be addressed with smart materials: control of solar radiation, control of conductive heat and interior heat, and conversion of ambient energy, among others. There is a growing body of literature of design-oriented studies that propose how shape-changing materials can construct responsive building skins, focusing on such requirements. The terms building skin or architectural skin refer to a biologically inspired strategy for conceptualising the behaviour of a building envelope (Velikov & Thun, 2013), drawing upon concepts of transformation and adaptation, which are very common in living systems (Fig. 2).

FIG. 2 Transformation of a sunflower. Photograph by Elena Burns

In the area of responsive building skins, Fiorito et al. (2016) discussed the use of three shape-changing smart materials (Shape Memory Alloys, Shape Memory Polymers, and Shape Memory Hybrids) in issues related to comfort, and included the human factor in responsive shading devices. Another review by Juaristi et al. (2018) presented a qualitative analysis of promising materials for responsive façade systems. While several shape-changing materials were discussed (under 'kinetic behaviour'), the review was not focused on shape-changing material. Furthermore, the review included technologies developed in other fields not yet applied to the design of building envelopes. This paper presents a systematic review of the literature on the use of shape-changing materials for developing active skin systems. The goal is to identify the most commonly used shape-changing materials in studies that include a design component, that is, studies that propose responsive architectural skin designs. In addition to identifying patterns in design and manufacturing strategies, we assessed the level of development of the proposed designs and indicated whether any performance analysis was conducted to predict the system's behaviour.

2 SCOPE AND METHODOLOGY

In this review, we present a systematic mapping of the literature, following the method described by Pickering and Byrne (2014). The material presented includes both quantitative and qualitative analyses. We use a quantitative analysis when surveying the shape-changing materials most used in skin systems and identifying the level of scientific development of such studies. We are applying a qualitative analysis in identifying design and manufacturing patterns in the literature, and when describing the kind of performance evaluation used to determine the efficiency of the proposed designs.

The first step in this review was the definition of keywords and databases. Keywords were defined after using iterative search in Google Scholar to refine words and synonyms. The conditional AND was used to restrict the search area to studies involving building systems. The resulting keywords are shown in Table 1. The second part of this review aimed to identify studies that assessed the performance of responsive building skin systems, as shown in Table 1. These keywords were used to search in several databases – Google Scholar, Web of Science, Science Direct, ProQuest, Sage Journals, Cumincad – to ensure the identification of a large number of studies.

TABLE 1 Keywords and databases

	KEYWORDS	DATABASE
Part 1	„shape changing materials" AND "buildings" „shape changing materials" AND "facades" „shape changing materials" AND "building envelope" „smart materials" AND "building envelope" „responsive materials" AND "skin system" „responsive materials" AND "building envelope" „active materials" AND "building envelope" „climate responsive" AND "building envelope"	Google Scholar, Web of science, Science direct, ProQuest, Sage Journals, Cumincad
Part 2	„responsive materials" AND "facade" AND „performance" „smart materials" AND "buildings" AND „performance" „shape changing materials" AND "buildings" AND „performance".	

2.1 RESEARCH QUESTIONS

The main goal was to establish state-of-the-art opportunities in the use of shape-changing materials for architectural skin systems. For this review, a skin system refers to the barrier that delimits the interior of the building, protecting it from adverse exterior conditions. As mentioned above, the use of the term denotes a biologically inspired approach to building envelopes. However, we use the term "skin system" instead of building envelope or façade because most studies are still in a prototype stage and therefore lack the level of development necessary for a building system. Furthermore, we use the term to include studies that do not present a solution for the entire envelope system, but for only some of its elements. We are also interested in studies where there is an intention to speculate on the form and structure of shape-changing skins, to identify if there are common design and materialisation strategies across the studies. This is addressed as the language of shape-changing architecture is an emerging one, and studies have yet to define a design language. Finally, we are also interested in the level of scientific development of the studies, and whether the performance of the proposed skin designs was assessed. The main reason for this interest is that the performance argument is often present in the discourse on the use of smart materials in the design and architecture fields. Consequently, the research debate for this review centred around the following questions:

- Which shape-changing materials have been used in research to develop architectural skin systems?
- Are there any common design and manufacturing strategies?
- Was the environmental performance of skin systems studied and, if so, how?

2.2 INCLUSION CRITERIA

The studies reported in this review are both from peer-reviewed publications and academic dissertations. We decided to include dissertation documents due to the small number of studies published to date on the subject. On the other hand, we only focus on studies that involve the development of architectural skin systems, ranging from building façades such as exterior shading devices to prototypes of entire façade systems. We excluded other architectural elements such as interior furniture and self-assembled objects, among others. The functionality of an architectural skin system had to be, at least, suggested to be included in this review.

It is also important to mention at this point that we only included studies that have a design component. In the studies, there is a design decision on the skin configuration, which derives from understanding the material properties. We also included studies that present only early-stage prototypes. That is to say that not all of the studies presented in this paper present fully developed designs of skin systems, but rather present different levels of development and are, to a certain extent, speculative as well as visionary.

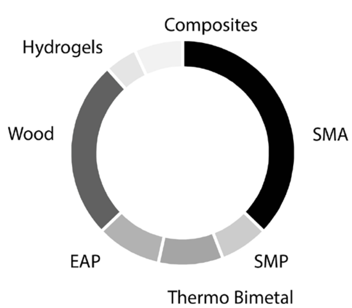
3 RESULTS

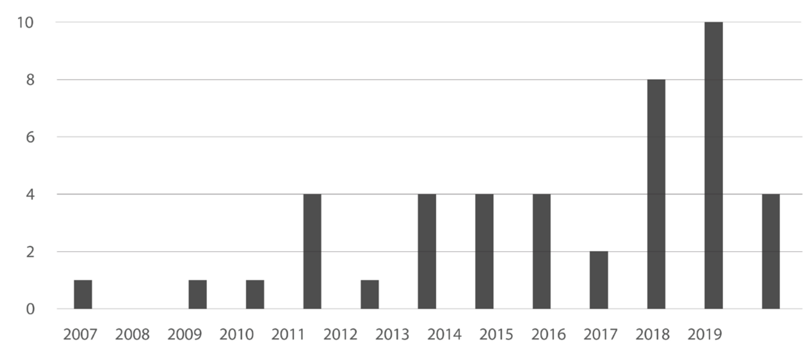
3.1 SHAPE-CHANGING MATERIALS

We identified 44 different publications that report on research aimed at developing responsive architectural skins using shape-changing materials between 2007 and 2019. Some studies published in 2019 may not be included in this review because we conducted the review in that year. Table 2 lists existing studies on shape-changing skin systems grouped by types of materials. This classification was preferred over a stricter one because many researchers report testing different materials of the same type in a single study. For instance, Abdelmohsen et al. (2018) combined softwoods (fir) and hardwoods (beech) to construct hygroscopic actuators.

TABLE 2 Shape-changing materials and their use in design research

MATERIALS	REFERENCES
Shape Memory Alloy	(Diniz, Branco, & Sales Dias, 2017); (Lignarolo, Lelieveld, & Teuffel, 2011); (Decker & Zarzycki, 2014); (Juaristi, Monge-barrio, Sánchez-ostiz, & Gómez-acebo, 2018); (Hannequart, Peigney, Caron, Baverel, & Viglino, 2018); (Abdelmohsen, Massoud, & Elshafei, 2016); (Jun et al., 2017); (Khoo et al., 2012); (Khoo & Salim, 2013); (Formentini & Lenci, 2017); (Verma & Devadass, 2013); (Coelho & Maes, 2009); (Doumpioti, Greenberg, & Karatzas, 2010); (Mokhtar, Leung, & Chronis, 2017); (Pesenti, Masera, & Fiorito, 2018)
Shape Memory Polymer	(Doumpioti, 2011); (Clifford et al., 2017); (Yoon, 2019)
Thermo Bimetal	(Juaristi, Gómez-Acebo, et al., 2018); (D. Sung, 2016a); (Adriaenssens et al., 2014); (Pasold & Worre Foged, 2010)
Composite Bilayers	(Worre Foged & Pasold, 2015); (Worre Foged, Pasold, & Pelosini, 2019); (El-Dabaa & Abdelmohsen, 2019); (Mazzucchelli, Alston, Brzezicki, & Doniacovo, 2018)
Electroactive Polymer	(Kretzer & Rossi, 2012); (Shimul, 2017); (Kolodziej & Rak, 2013)
Wood	(Holstov, Farmer, & Bridgens, 2017); (El-Dabaa & Abdelmohsen, 2018); (Vailati, Bachtiar, Hass, Burgert, & Rüggeberg, 2018); (Augustin, 2018); (Reichert et al., 2015); (Holstov, Bridgens, & Farmer, 2015)(Correa & Menges, 2017); (Correa et al., 2015); (Vazquez, Gursoy, & Duarte, 2019); (Anis, 2019)
Hydrogel	(Markopoulou, 2015) (Khoo & Shin, 2018)





As can be seen in Table 2, the largest group is of studies that use Shape Memory Alloys (SMA) for the development of skin systems. A SMA is an alloy that "remembers" its original shape; that is, after being deformed, it returns to its pre-deformed shape when heated. The commercial availability of

SMAs in the form of springs, as noted by Fiorito et al. (2016), might be one of the reasons for them being the most used shape-changing material. The simplicity of spring actuation, i.e., elastic springs designed to store mechanical energy and release it with compression or tension, might also be a reason for the use of these materials over others. Most studies use SMAs in the form of springs since the additive manufacturing of this material is in the early stages of development (Elahinia et al., 2016). These studies also use electricity to heat the springs, seen in the work by Khoo, Salim, and Burry (2012), since the activation temperature of SMAs can be over 200° Celsius.

The next most researched material is wood. While not traditionally considered a "smart" material, it displays shape-changing behaviour in response to humidity. In the presence of water, wood shows anisotropic swelling, which is highly dependent on the direction of the wood fibres. Hygroscopic structures that represent pinecones can be assembled, and which open when dry and close under humid conditions. Mechanistically this relies on the bi-layered structure of the individual scales that change conformation when there is a variation in the environmental humidity (Reyssat & Mahadevan, 2009). By controlling the orientation of wood fibrils, it is possible to design shape-changing architectures (Wood et al., 2018). Some of the selected studies use commercially available wood sheets, as seen in the work by Reichert et al. (2015). The availability of wood as an inexpensive material might be the reason for the material's popularity. Furthermore, wood is the most widely used biological material for structural purposes, which makes it attractive for designers to take advantage of its natural response to humidity. Finally, wood and related cellulose materials (paper) is a material family well-known to designers and architects, which also favours its adoption.

Other shape-changing materials that have been used for developing skin systems are thermo bimetals, electroactive polymers, composite bimetals, shape memory polymers, and hydrogels, in decreasing order of popularity or age. Thermo bimetals refer to a bilayer configuration where two metal layers that have different coefficients of thermal expansion are attached, causing it to bend in response to increased temperatures. Sung (2016b) has demonstrated the potential of thermo bimetals for developing responsive and aesthetically appealing architectural skins. The next category is the composite bilayers, where two or more different materials are used in a bilayer configuration, for example, Corten steel and polypropylene forming thermally active composites (Worre Foged & Pasold, 2015), and aluminium and beech bilayers (El-Dabaa & Abdelmohsen, 2019). Electroactive polymers are materials that demonstrate considerable strain when subjected to an applied electric field (see Heckman Diagram in Fig. 1). Like SMAs, shape memory polymers can remember their original configuration and return to it when heated. Finally, hydrogels are hydrophilic polymers that can hold large amounts of water in their three-dimensional structures, like the active adsorbing materials in diapers.

These five material categories are much less explored as building envelope materials than shape-memory alloys and wood-based biocomposites. There are probably several reasons for this. In the case of shape-memory polymers, there are various studies in the area of additive manufacturing and self-assembled structures, as described in the review by Shin et al. (2017). The same can be said of hydrogels, which have also been studied as materials for self-assembled structures in 4D printing, for instance, in Gladman et al. (2016). Issues of scalability might be preventing the incorporation of these two materials in large scale building applications. Nevertheless, with the overall increase of studies on smart materials in design fields, as shown in Table 1, one may expect more and more applications of these materials to emerge in the near future if cost benefits and scalable production can be achieved.

3.2 PATTERNS IN DESIGN AND MANUFACTURING

Several shape-changing materials have been used in the development of architectural skin systems. What follows now is the identification of common design and manufacturing strategies across different studies. This section of the paper presents a qualitative analysis of the studies in this regard. Design strategies identify how the material is used within the system and how the transformation mechanics are established. After identifying design strategies, we move on to describe common manufacturing strategies. The main idea is not to describe design or manufacturing processes in detail, but rather to discuss the common points between these processes in shape-changing skin studies.

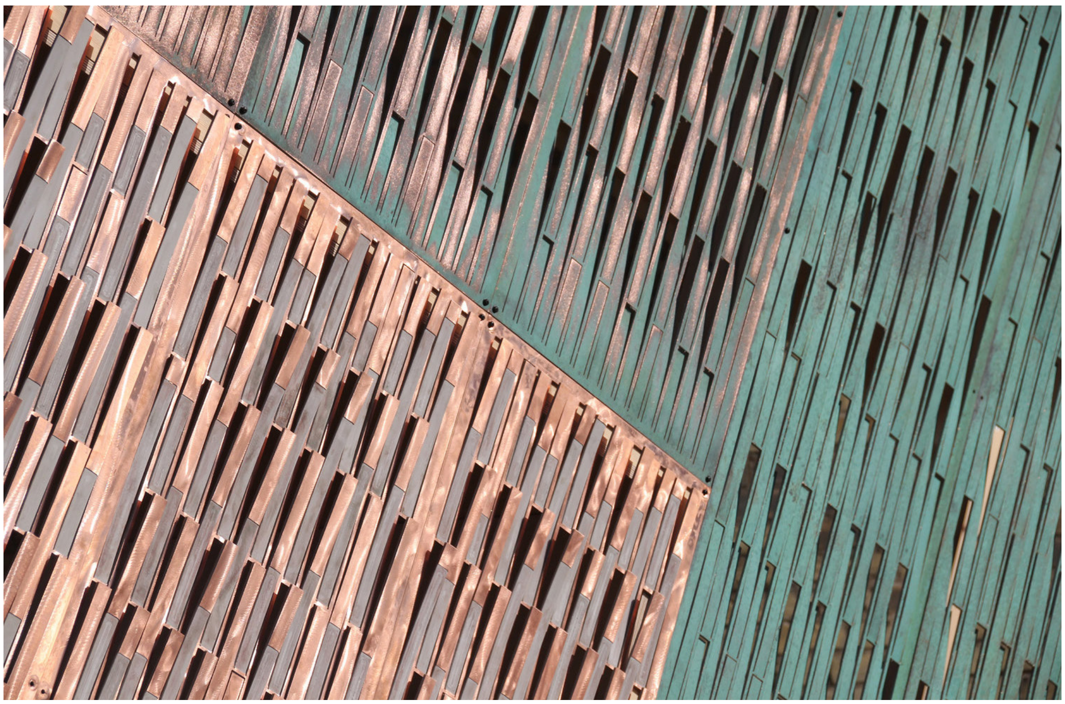
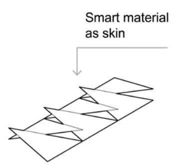
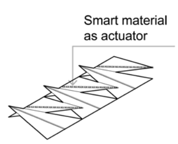
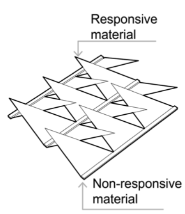
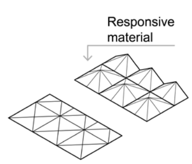
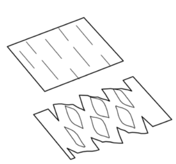


FIG. 3 Sense Envelope III. Copper and polypropylene are forming a thermally active composite. Design/fabrication by Isak Worre Foged and Anke Pasold. Photograph by: Isak Worre Foged.

Table 3 identifies five different design strategies used in developing shape-changing architectures. The first strategy refers to how the responsive material is used within the system. One common strategy is to use smart materials as the skin itself. In this approach, the entire skin is mostly made from the smart material, and the material is used as a planar actuator, as seen in the hygroscopic wood cladding system by Holstov et al. (2015). Furthermore, the material conditions the aesthetic nature of the built element, so parameters like texture, colour, and porosity become increasingly important, as seen in the work by Worre Foged and Anke Pasold shown in Fig. 3. The studies that present this approach rely on different materials: shape-memory polymers, thermo bimetals, electroactive polymers, and wood-based materials. These studies have in common that the material can come in the form of sheets. Thermo bimetals and wood projects are composed mostly of thin sheets of materials. In the case of shape-memory polymers, the final form is obtained by either casting (Clifford et al., 2017) or additive manufacturing (Yoon, 2019). Finally, in the case of electroactive polymers, these are mostly used as planar actuators due to their significant planar deformations (Kretzer, 2016).

TABLE 3 Design strategies

DESIGN STRATEGY	FIGURE	MATERIAL	REFERENCE
Smart material as skin		SMP	(Clifford et al., 2017); (Yoon, 2019)
		Thermo Bimetal	(Sung, 2016a); (Adriaenssens et al., 2014); (Pasold & Worre Foged, 2010)
		Composite bilayers	(Worre Foged & Pasold, 2015); (Worre Foged et al., 2019); (El-Dabaa & Abdelmohsen, 2019); (Mazzucchelli et al., 2018)
		EAP	(Kretzer & Rossi, 2012); (Shimul, 2017); (Kolodziej & Rak, 2013)
		Wood	(Holstov et al., 2017) (El-Dabaa & Abdelmohsen, 2018) (Vailati et al., 2018) (Augustin, 2018) (Reichert et al., 2015) (Holstov et al., 2015) (Correa & Menges, 2017) (Correa et al., 2015); (Vazquez et al., 2019); (Anis, 2019)
Smart material as the actuator		SMA	(Lignarolo et al., 2011); (Decker & Zarzycki, 2014); (Abdel-mohsen et al., 2016); (Jun et al., 2017); (Khoo et al., 2012); (Khoo & Salim, 2013); (Formentini & Lenci, 2017); (Verma & Devadass, 2013); (Coelho & Maes, 2009); (Doumpioti et al., 2010); (Mokhtar et al., 2017); (Pesenti et al., 2018)
		Hidrogel	(Markopoulou, 2015)
Combination responsive + non-responsive material		SMP, Thermo bimetal, EAP, Wood, SMA	(All)
Responsive structure			(Kyu, Yin, & Tang, 2018)
Geometric amplification		SMA	(Pesenti, Masera, & Fiorito, 2015); (Pesenti et al., 2018)
		SMP	(Kyu et al., 2018); (Yoon, 2019)

A second design strategy uses the smart material merely as an actuator for another material acting as the skin. This strategy is used in all the examples found in the literature that use Shape Memory Alloys. In these studies, SMA springs are used to move other materials -such as metal panels (Formentini & Lenci, 2017) or aluminium louvres (Grinham, Blabolil, & Haak, 2014), which give form to the responsive structure. This strategy can also potentially be used with other shape-changing materials. An electroactive actuator can be used to move a wooden panel, for instance. The way SMAs are commercially available also conditions this design strategy. In this approach, the systems' aesthetics is not conditioned by the SMA, but by the skins' material qualities. Other materials that have been used in the same fashion are hydrogels, specifically, in the project by students detailed in Markopoulou (2015). The study presents a series of case studies using different smart materials, one being the development of a hygroscopic skin system using hydrogel joints that actuate a silicone panel.

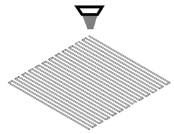
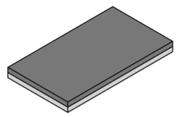
A third design strategy identified is related to a combination of shape-changing materials with other non-responsive or passive ones. Typically, in the design of an architectural skin system, there are dynamic and static parts. This is the case with most of the case studies, where there is an underlying frame that gives structure to the system. For instance, in the wood prototypes developed by Reichert et al. (2014), there is a wooden frame with square-shaped openings covered by planar sheets of plywood. Similarly, in the Bloom pavilion, detailed in Sung (2016) there is a metal structure covered by a large amount of thermo bimetal pieces.

An alternative approach, the fourth design strategy in Table 3, relies on complex geometric transformations of entire structures, triggered by the actuation of the smart material. This is a less common strategy in the reviewed studies, probably due to the need to place these responsive systems within the broader context of a building envelope that has ribs, structure, and so on. Nevertheless, Kyu et al. (2018) present a responsive Kirigami structure as a shading device, where the entire geometry of the system changes when temperature changes activate the material.

The fifth design strategy relies on the use of kirigami and origami-inspired geometries for amplifying the shape-change of smart materials. One challenge for incorporating shape-changing materials in building-scale applications is the limited actuation response that they present concerning the scale of application. Therefore, the use of kirigami and origami geometries with shape-changing materials offers a solution to this problem, combining different localized responses that result in an overall more significant shape-changing mechanism. Pesenti et al. (2018), for instance, explored the use of origami geometries to amplify the movement of SMA actuators in a responsive shading system. Similarly, Kiu et al. (2018) use kirigami geometries with thermo-active materials for shading devices.

The ability to scale and to integrate hierarchical dynamic and static components into the desired envelope requires one to identify the most appropriate manufacturing strategies. Table 4 details two material manufacturing strategies identified across the selected studies. The first strategy relies on the use of additive manufacturing to construct responsive systems. In this category, toolpath design and printing settings condition how the material responds to the activation energy. This strategy has been widely used in research on 3d printing or additive manufacturing of soft materials (Gladman et al., 2016; Truby & Lewis, 2016). Recently, these principles of additive manufacturing have been applied at an architectural scale for a dynamic shading device (Correa et al., 2015). The main principle is that responsiveness and hierarchical structure can be programmed into the objects through printing path designs that cause anisotropic behaviours, which leads to shape-change when activated.

TABLE 4 Manufacturing strategies

FABRICATION STRATEGY	FIGURE	MATERIAL	REFERENCE
Additive manufacturing		SMP	(Clifford et al., 2017); (Yoon, 2019)
		Wood	(Correa & Menges, 2017); (Correa et al., 2015); (Vazquez et al., 2019)
Bilayer		Wood	(Holstov et al., 2017) (El-Dabaa & Abdelmohsen, 2018) (Vailati et al., 2018)(Holstov et al., 2015); (Anis, 2019)
		Composite bilayers	(Worre Foged & Pasold, 2015); (Worre Foged et al., 2019); (El-Dabaa & Abdelmohsen, 2019); (Mazzucchelli et al., 2018)
		Thermo bimetal	(D. Sung, 2016a); (Adriaenssens et al., 2014); (Pasold & Worre Foged, 2010);

The studies in this category used additive manufacturing with shape-memory polymer materials (SMP) and wood-based biocomposites. Recently, Yoon (2019) proposed a design and manufacturing workflow of a responsive building using commercially available SMP filaments. Through iterative tests, adequate printing settings were found to achieve a suitable shape-transformation of the polymers. In a series of studies, researchers used both commercially available wood filaments and fabricated their own for creating responsive architectural prototypes (Correa & Menges, 2017; Correa et al., 2015). One of the advantages of this approach is that additive manufacturing allows for creating functionally graded composites. This advantage is demonstrated in Correa & Menges (2017), where a multi-material strategy was adopted to create a 3d printed prototype that combines responsive and non-responsive materials. The second advantage of 3D printing responsive structures is the ability to materialise complex geometries and patterns. Fig. 4 shows how, by designing the toolpath orientation and using active layers (AL) and constraint layers (CL), one can embed responsiveness into materials with 3d printing. Nonetheless, one possible limitation of this approach stems from difficulties in scaling-up the prototypes to an architectural scale.

The second manufacturing strategy is the use of the bilayer principle for programming responsiveness into structures. In a bilayer configuration, two layers of materials with differential thermal expansion or swelling response are tightly bound together, and thus tend to curve when activated by heat or humidity, respectively. The activation energy depends on the material: in the case of wood bilayers, two layers of wood present different swelling responses to water or humidity; in thermo bimetals, two layers of metal strips with different thermal expansion coefficients tend to curve when heated. This strategy has been used in wood (Dylan Wood, Correa, Krieg, & Menges, 2016), bimetallic strips (Sung, 2008), and composites bilayers (Worre Foged & Pasold, 2015). Fig. 4 shows some possible configuration of bilayer structures. Case A represents two wood veneer sheets put together while arranging the fibre orientation of each layer - an example of this approach can be seen in the work by Vailati et al. (2018). Case B illustrates the use of wood veneer and metal sheets, as seen in the bilayer shape-changing prototypes by El-Dabaa & Abdelmohsen, (2019). Case C presents the use of metal layers with different thermal expansion coefficients, present in work by the DOSU architectural studio (https://www.dosu-arch.com/). Finally, case D is the use of a bilayer configuration combined with other smart materials or systems, seen in the study by Mazzucchelli et al. (2018), where the researchers combine a hygroscopic bilayer system with thin-film solar cells.

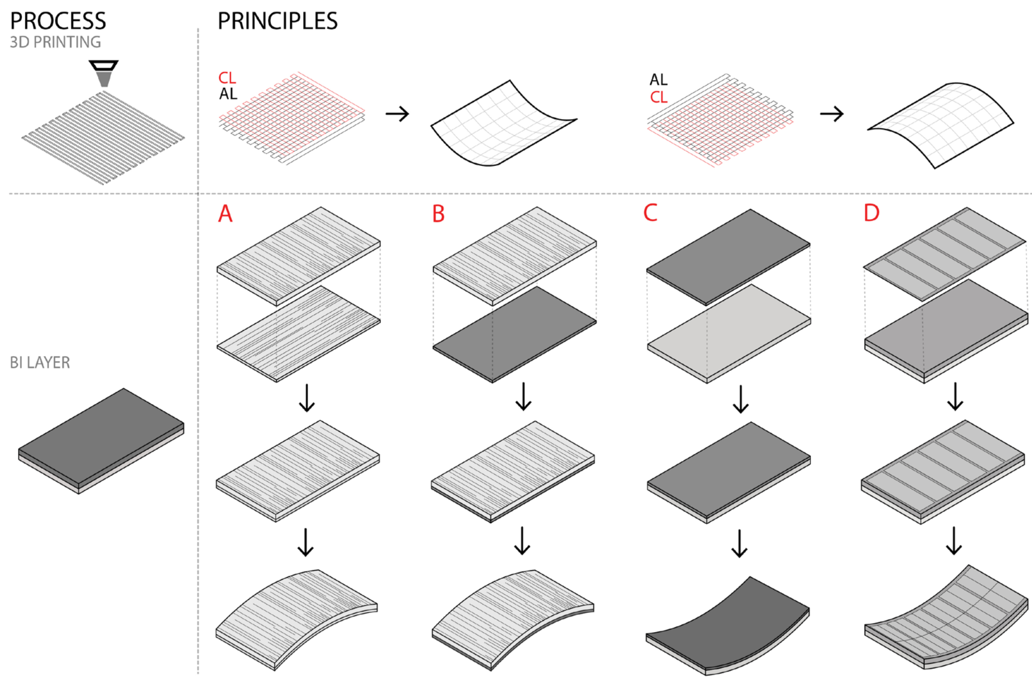


FIG. 4 Manufacturing principles

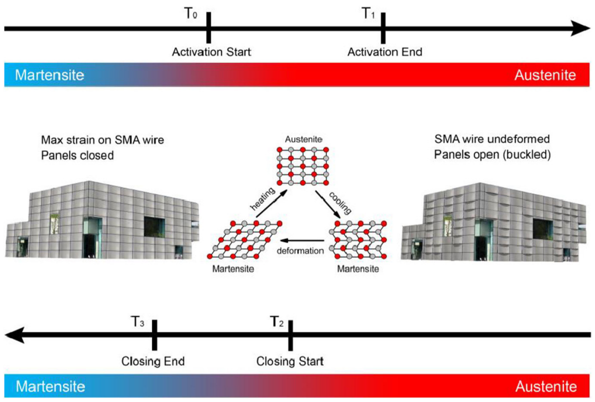
Research on developing responsive skin systems using wood has relied on both additive manufacturing and bilayer strategies. Nevertheless, with this review, we identified that most of the studies found in the literature use wood sheets and bilayer strategies. The commercial availability of wood sheets most likely makes it the preferred choice. However, wood-based filaments have become increasingly available from multiple vendors, varying he percentage of wood fibres in a polymer matrix. For instance, Laywood filament has 40% wt. of wood fibres. Furthermore, filament extruder DIY kits have also become available, which could represent an opportunity for more research into the use of 3D printed wood to create responsive structures.

It is also important to note that the strategies just described are not mutually exclusive. 3D printing can also be used to construct responsive structures in a bilayer configuration, as shown in Fig. 4. By designing tool-paths with varying printing directions, or different materials being deposited on subsequent layers, a 3D-printed bilayer structure will also tend to curve when activated. The use of bilayer principles with additive manufacturing can be seen in the work of Correa & Menges (2017).

The identified manufacturing strategies are mainly used to create planar actuators. Bilayer constructs have been used for creating actuators for some time now, with thermo-bimetals being among the most widely known and utilised smart materials (Kretzer, 2016). On the other hand, additive manufacturing has allowed for the fast development of soft materials for several applications such as actuators and soft robotics, among others. This strategy has just recently permeated design practice to create shape-changing architectures. Other smart materials are already commercially available as actuators. Shape memory alloys, for instance, are available as spring actuators and therefore do not require a specific manufacturing strategy, such as those described above.

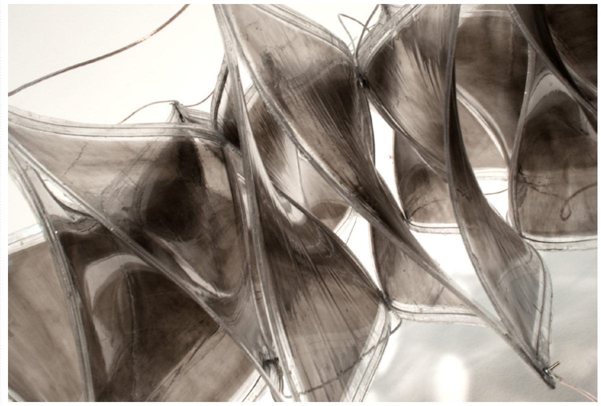
TABLE 5 Levels of development (I)

(A) LEVEL 1: CONCEPT DESIGN



Formentini and Lenci (2017)

(B) LEVEL 2: PROTOTYPE

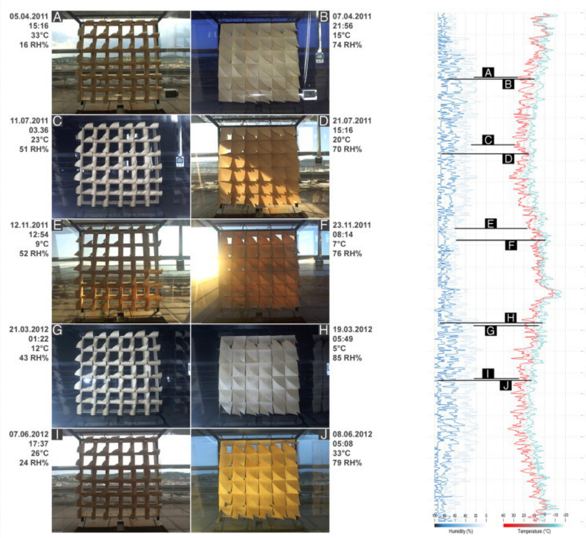


Kretzer and Rossi (2012)

(C) LEVEL 3: LARGE-SCALE TEST

Sung (2016)

(D) LEVEL 4: ENVIRONMENTAL PERFORMANCE ANALYSIS



Reichert et. al (2014)

(A) Conceptual design of a responsive façade using SMA. Reprinted from Automation in Construction, Formentini, M., & Lenci, S. An innovative building envelope (kinetic façade) with Shape Memory Alloys used as actuators and sensors , p. 220-231, Copyright (2017), with permission from Elsevier.

(B) Shapeshift. Credits: INSTITUTE: Chair for CAAD, ETH Zürich. TEAM: Edyta Augustynowicz, Sofia Georgakopoulou, Dino Rossi, Stefanie Sixt. SUPERVISION Manuel Kretzer SUPPORT Christa Jordi, Gabor Kovaks

(C) Bloom pavilion.Image credits: Brandon Shigeta

(D) Long term performance test of a hygromorphic skin system. Reprinted from CAD Computer Aided Design, 60, Reichert, S., Menges, A., & Correa, D. Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness, p. 50–69, Copyright (2014), with permission from Elsevier.

3.3 LEVELS OF DEVELOPMENT

This section describes the levels of development of shape-changing architectural skin systems. Four different levels were identified, as illustrated in Table 5. Level 1, the conceptual level, corresponds to studies in which there is a design concept developed for a responsive skin system. Level 2 is the prototype level, in which physical prototypes are constructed and used to develop and refine concepts and design of the skins. Level 3 corresponds to a larger scale test, in which mock-ups are built after initial prototypes in an attempt to scale up the system to an architectural scale. Finally, on Level 4, researchers consider the environmental performance of the proposed skins to verify how much they improve the functionality of buildings. Environmental performance can be verified from different viewpoints, from wind studies to daylight analysis. This section identifies studies that addressed environmental performance in some way, followed by a discussion on the subject.

TABLE 6 Levels of development (II)

MATERIAL	CONCEPT	PROTOTYPE	LARGE-SCALE TEST	ENVIRONMENTAL PERFORMANCE ANALYSIS
SMA	(Diniz et al., 2017); (Lignarolo et al., 2011); (Decker & Zarzycki, 2014); (Juaristi et al., 2018); (Hannequart et al., 2018); (Abdelmohsen et al., 2016); (Jun et al., 2017); (Khoo et al., 2012); (Khoo & Salim, 2013); (Formentini & Lenci, 2017); (Verma & Devadass, 2013); (Coelho & Maes, 2009); (Doumpioti et al., 2010); (Mokhtar et al., 2017); (Pesenti et al., 2018)	(Diniz et al., 2017); (Decker & Zarzycki, 2014); (Hannequart et al., 2018); (Abdelmohsen et al., 2016); (Jun et al., 2017); (Grinham et al., 2014); (Khoo & Salim, 2013); (Formentini & Lenci, 2017); (Verma & Devadass, 2013); (Coelho & Maes, 2009)	(Grinham et al., 2014); (Khoo & Salim, 2013); (Formentini & Lenci, 2017);	(Lignarolo et al., 2011); (Verma & Devadass, 2013); (Pesenti et al., 2018)
SMP	(Doumpioti, 2011); (Clifford et al., 2017); (Yoon, 2019)	(Doumpioti, 2011); (Clifford et al., 2017); (Yoon, 2019)		(Yoon, 2019)
Thermo Bimetal	(Juaristi, Gómez-Acebo, et al., 2018); (Sung, 2016a); (Adriaenssens et al., 2014); (Pasold & Worre Foged, 2010)	(Sung, 2016a); (Adriaenssens et al., 2014);	(Sung, 2016a);	(Sung, 2016a);
Composite Bilayers	(Worre Foged et al., 2019); (Mazzucchelli et al., 2018); (Worre Foged & Pasold, 2015)	(Worre Foged et al., 2019); (El-Dabaa & Abdelmohsen, 2019)	(Worre Foged et al., 2019); (Worre Foged & Pasold, 2015)	
EAP	(Kretzer & Rossi, 2012); (Shimul, 2017); (Kolodziej & Rak, 2013)	(Kretzer & Rossi, 2012); (Shimul, 2017)		(Kolodziej & Rak, 2013)
Wood	(Holstov et al., 2017) (El-Dabaa & Abdelmohsen, 2018); (Vailati et al., 2018); (Augustin, 2018); (Reichert et al., 2015); (Holstov et al., 2015); (Correa & Menges, 2017); (Correa et al., 2015); (Anis, 2019)	(Holstov et al., 2017) (El-Dabaa & Abdelmohsen, 2018); (Vailati et al., 2018); (Augustin, 2018); (Reichert et al., 2015); (Holstov et al., 2015); (Correa & Menges, 2017); (Correa et al., 2015); (Vazquez et al., 2019); (Anis, 2019)	(Holstov et al., 2017); (Reichert et al., 2015); (Holstov et al., 2015); (Anis, 2019)	(Augustin, 2018); (Reichert et al., 2015)
Hydrogel	(Markopoulou, 2015) (Khoo & Shin, 2018)	(Markopoulou, 2015) (Khoo & Shin, 2018)		

Table 6 identifies the development level of the various studies, which are grouped by material. Not surprisingly, most of the studies are at the conceptual and prototype levels. Large-scale tests were conducted only in a few studies. One key publication describes what is probably the first full-scale application of a Shape Memory Alloy (Nitinol) on a shading screen device, in the context of the 2013 Solar Decathlon competition (Grinham et al., 2014). The study reports on several full-scale prototypes and on the construction and testing of a selected design during the competition. Other large-scale tests include the use of an SMA system for responsive skin for visual communications purposes (Khoo & Salim, 2013). Finally, a building envelope system was developed with SMA actuators, for a ventilated façade that opens up during summer months and closes down during winter months (Formentini & Lenci, 2017).

FIG. 5 Bloom, by DOSU Studio Architecture. Photograph by Brandon Shigeta.

Other materials that were used in large-scale tests are thermo bimetals and wood. Among the studies using thermo bimetals, the work of Sung (2016) is probably the most developed example of a responsive architectural skin system utilising this material. The Bloom pavilion, shown in Fig. 5, was designed for shading, ventilation, and lighting, using 9000 pieces of thermo bimetals, and demonstrates the potential of a responsive system that utilises this material. Worre Foged & Pasold (2015) also reported on the construction of full-scale prototypes of 600 x 1200 mm that were designed to be mounted on glazed facades, (Fig. 3). Large-scale tests were also conducted using wood. In a seminal study, Reichert et al. (2014) provide a summary of five years of research into developing responsive architectural systems using wood veneer, showing a series of prototypes constructed at various scales and two full-scale constructions. Another example of large scale testing can be seen in the work of Holstov et al. (2015), which presents large-scale prototypes for hygroscopic panels and a responsive umbrella. In a second study, Holstov et al. (2017) study the applicability for wood-based responsive systems for external architectural applications by constructing full-scale prototypes and conducting one-year outdoor durability tests, which showed that the panels had a consistent hygroscopic behaviour.

Regarding environmental performance analysis, Table 6 shows that very few studies conducted environmental performance analysis of any type. For instance, within studies using SMAs, only four studies out of sixteen included detailed simulation studies for predicting the performance of the designed responsive systems. In this category, we identified studies that performed either a simulation study or a test with a full-scale prototype where the environmental performance was predicted or assessed. This includes simulation studies for how the sunlight will affect the architectural skin, and simulation studies of how wind, daylight, and temperature will affect the interior spaces protected by such skins. Considering that these materials change shape in response to the environment, we believe that it is essential to use simulation tools to see how the transformation mechanisms of the proposed skins will impact the building's performance.

3.4 ASSESSING PERFORMANCE: SIMULATION AND TESTING

The previous section of this paper described the scientific maturity of the research for the development of responsive architectural skin systems using shape-changing smart materials. Overall, most of the studies are at the conceptual and prototype stage. This section will discuss the different types of environmental performance analysis conducted in this area of research to date. The aim is to identify how the performance of the proposed skin systems was evaluated. A summary of the studies performed is shown in Table 7, including the considered variables and the main findings.

TABLE 7 Performance evaluation of building skins

TYPE OF STUDY	VARIABLES	RESULTS SUMMARY
Natural Ventilation	Augustin (2018): wind speed 4 m/s, Design settings include the proposed screen design, enclosed area.	Visualisation of internal flows.
Wind pressure and velocity fields	Lignarolo et al. (2011): tested Roughness of façade in different design iterations, obtained wind velocity fields.	Proved that roughness of the façade affects the wind flow field. Types of façade iterations tested in CFD studies are after that conceptualised with SMA adaptive system.
Daylight	Verma & Devadass (2013): 2 different locations, types of actuators, skin design, date, and time of the simulation.	Daylight factors with the proposed roof decrease to around 20-22%, on a specific hour/day.
	Pesenti et al., (2018): Standard reference room for testing, 210 origami-inspired designs tested, percentage of contractions.	The authors found optimised solutions with multi-criteria optimisation. They concluded that optimal designs for the day, month, and year are not the same.
Radiation and Thermal Analysis	Yoon (2019): 5 distinct design configurations made with SMP.	Selected promising designs from differentials of radiation simulations between open and closed positions but failed to verify impacts on shading devices between open and closed positions on thermal analysis.
	Mokhtar et al. (2017): 9 different investigated geometries. 4 SMAs used per design.	Performed radiation studies to inform the design of a SMA morphing envelope.

Natural ventilation studies: Augustin (2018) used CFD simulation studies to visualise the internal wind flows and study how the system would interact with the environment. A single design solution was tested, having as variables wind velocity and pressure.

Pressure and velocity fields: Lignarolo et al. (2011) explore the use of a dynamic system to enhance air-flow in high-rise buildings. In this study, computational fluid dynamic (CFD) simulations inform the design of an adaptive façade system using SMA, testing wind pressure and velocity fields. The researchers argue that since façade roughness affects the aerodynamics of the building, and the wind load is always changing, an SMA adaptive system could be used to improve the building's performance to wind loads.

Daylight studies: The study by Verma & Devadass (2013) investigates the use of SMA in developing responsive building skins. The authors first use optimisation algorithms to find the actuator design that has the most extensive actuation range. The second set of studies analyses how a proposed adaptive skin design used both as roof and screen change daylight and solar radiation metrics on two defined case studies in two different locations. In another study, Pasold & Worre Foged (2010) perform daylight analysis to optimise the geometric configuration of their prototypes. Pesenti et al. (2018) perform daylight simulation studies as part of a performance-based form-finding framework for the design of shading devices. The authors assess daylight glare probability, useful daylight illuminance, daylight autonomy, and total energy consumption as targets in optimisation studies to find the best configurations. The study was conducted with a simple rectangular test room with a large opening on the front, and daily, monthly, and yearly values were obtained to find the optimal origami configuration for the responsive system.

Thermal analysis and radiation: A recent study by Yoon (2019) perform thermal analysis and radiation studies as a means to evaluate the performance of prototypes and compare the system's performance in *open* and *closed* positions. The main idea is to use this analysis to select the prototypes for further development in the next stages of the study. In this case, as in others mentioned above, simulation studies are an integral part of the design process of responsive skin systems. In the work of Sung (2016), solar radiation studies are performed to inform the design of geometries in the Bloom Pavilion. Finally, in the work of Mokhtar et al. 2017, solar radiation studies predict the behaviour of SMA responsive structures.

Other studies assessing the environmental performance of responsive architectural skins include CFD simulations for predicting interior temperature (Kolodziej & Rak, 2013) and long term durability studies (Reichert et al., 2015) As mentioned in the previous section, not many studies tested the environmental performance of developed skin systems. Even fewer studies utilise performance criteria as a form-finding strategy to optimise design solutions. Since this area is an emerging field in architecture and design, there is still room for the development of simulation strategies and performance-based frameworks to aid the design of responsive skins.

3.5 DISCUSSION

This section summarises the main findings of the review and discusses the implications of such findings:

Shape-changing materials for responsive architectures

The review on shape-changing materials for architectural skin systems indicated that the most commonly used materials are SMA and wood-based bio-composites. This is most likely because of the commercial availability of such materials, which makes them accessible to the architectural design research community at large. The lack of commercial availability limits the scope of application of such materials: designers and researchers have to rely on materials that were either developed for other purposes or that have limited properties (Kretzer, 2014). The technological transfer of smart materials from different fields such as material science and engineering to architecture and design is, therefore, one of the challenges in the development of skin systems. Consequently, a multidisciplinary approach for developing architectural skin systems is needed in order to explore the use of other innovative materials that were not mentioned in this review, such as electroactive materials. The need for such an interdisciplinary approach has already been identified in the literature on smart materials: Kretzer (2018) argues for a framework that enhances interdisciplinary exchange and collaboration when educating designers on the use of smart materials.

Design strategies

This review has identified several design patterns, including the use of the smart material as the skin itself – as a planar actuator – and the use of the smart material as the actuator to move another material that acts as the skin. The strategy of using shape-changing materials as the skin itself has the advantage of creating more room for design innovation, by orchestrating the parameters of the skin geometry, the actuation mechanism, and the possibilities that the material presents. For instance, wood veneers could be used to construct responsive skins that display a unique folding angle according to daylight requirements by changing only the orientation of the wood fibres. The strategy of using the shape-changing materials as actuators has the advantage of being able to automate existing building mechanisms. For instance, existing designs of shading devices could be automated with SMA actuators. Future research could use these two approaches to develop responsive architectural skin systems.

Manufacturing strategies

This paper has identified two recurrent manufacturing strategies: the use of bilayer composites and additive manufacturing. The studies using bilayer composites are, in general, more developed than those that use 3d printing as the main strategy. Research into bilayer skins could, therefore, move on to the evaluation level by assessing the performance and durability of the prototypes. Scaling-up dynamic systems is not typically an issue in bilayer structures, as opposed to 3d printed structures, which tend to have scale limitations. The issue of scale can be addressed in future research on 3d printed responsive skin systems. On the other hand, additive manufacturing has the potential to build more complex designs by varying textures, porosity, and geometries. This potential could be further explored in future research through the systematic exploration of design alternatives that could be fabricated using additive manufacturing.

Level of development of responsive skins

Most of the studies reviewed in this paper are on the first prescriptive level of development. In other words, design concepts and prototypes have been developed and proposed as alternative models to static architecture solutions. Considering that research on shape-changing materials for architectural skin systems is in its early stages, it is only natural that most studies are at this stage.

Shape-changing materials and building performance

The review identified that few studies have conducted environmental performance analysis of the proposed shape-changing skin systems. We argue that assessing the performance of architectural skin systems should be an integral part of the research agenda on responsive skin systems using shape-changing materials. One of the main arguments for the use of smart materials is that they could potentially be used to construct responsive systems that improve the environmental performance of buildings. For instance, Kretzer (2014) argues that architecture needs to become more responsive to “face unprecedented societal and environmental challenges” (p. 463) and that smart materials can help achieve this goal. The efficiency argument is present in most studies that develop skin systems, for example, Holstov et al. (2015) argues for the development of “sustainable design strategies” (p. 571) using materials with hygroscopic properties. Similarly, it is argued that the implementation of adaptive systems that present a real-time automated response to changing environmental conditions can improve buildings’ energy efficiency (Holstov et al., 2017). In short, this paper postulates that, considering the argument for the use of shape-changing materials to develop building skins is based on achieving improved efficiency, it is essential to assess how and to what extent building performance is improved.

4 CONCLUSION

This paper presents a systematic review of the literature on the use of shape-changing materials for the development of responsive skin systems. It is important to note that the review did not discuss the limitations of using shape-changing materials for responsive skin systems. This is because most of the studies are very experimental and in the early stages, therefore there are several limitations inherent to each material, for example: mechanical degradation of wood, scalability issues, cost, life cycle analysis, legal frameworks for implementing them in the building industry, etc. Such limitations can be addressed in future studies as the field becomes further developed, and there are more executed examples of shape-changing architectural skins.

The first part of the paper identified the shape-changing materials used in the design of such systems, showing that there has been an increasing number of studies in the area. Shape-changing materials in building skins is a relatively new area of inquiry and, therefore, the most commonly used materials are those that are commercially available, such as wood veneer and SMA actuators. Other less used shape-changing materials include thermo bimetals, composite bimetals, electroactive polymers, shape memory polymers, and hydrogels. We argue that a multidisciplinary research approach can achieve the technological transfer of these and other innovative materials into architectural research.

The next part of the paper identified underlying patterns in the literature on responsive skins: (1) design strategies: smart material as the skin, smart material as the actuator, combination with other non-responsive materials, responsive structures, geometric amplification; and (2) manufacturing strategies: bilayer systems and additive manufacturing. The characterisation of these patterns allowed us to identify gaps in the literature. For instance, few studies propose complex geometrical transformations of entire structures that are completely responsive. Future research could combine the use of kirigami and origami geometries and shape-changing materials in developing complex material transformations for skin systems. Another aim in identifying design and manufacturing strategies was to start the task of describing the language of designing architectural skins with smart materials. This characterisation of the shape-change architectural design language will help formalise and guide future studies in the area.

Finally, we also identified the level of scientific maturity of the proposed designs and identified whether any performance analysis was conducted. While the argument for the development of responsive skin systems is based on the idea of efficiency and improved performance, we found that few studies predict the performance of such skin systems. We identified that most of the studies are in a prescriptive stage, where systems are proposed rather than tested. The testing and validation of such systems with, for instance, simulation methods, would be a fruitful area for future work.

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