Exploring the Potential of Smart and Multifunctional Materials in Adaptive Opaque Façade Systems

Miren Juaristi[1], Aurora Monge-Barrio[1], Ana Sánchez-Ostiz[1], Tomás Gómez-Acebo[2]

1 Universidad de Navarra, School of Architecture
2 Universidad de Navarrra, TECNUN, School of Engineers

Abstract
Climate adaptive façades are considered promising breakthroughs for the reduction of energy consumption, as energy exchange is enabled when the weather conditions offer benefits instead of threats. So far, conventional building envelopes enhance thermal performance through opaque façade components and static insulations. Therefore, natural resources from the building environment remain untapped. Little research has been done in adaptive opaque façades, even if their dynamic behaviour shows a strong potential to exploit environmental resources. For the successful development of these innovative façade systems, a balance between sophistication and benefit is necessary. To manage this objective, the implementation of smart and multifunctional materials in the envelopes seems promising, as they are able to repeatedly and reversibly change some of its functions, features, or behaviour over time in response to environmental condition. Consequently, to trigger the response of the envelope, no external actuator or complex software management would be necessary. Nevertheless, these materials do not fulfil all of the façade requirements by themselves. Thus, they need to be combined with other adaptive technologies and building elements. This paper shows an initial definition of different façade configurations that include reactive materials, which enable the adaptiveness of opaque façade systems. The desired results are new façade roles suitable for a temperate climate, according to the potential of these multi-performance materials in the external layer of the envelope: the dynamic temperature change of the external cladding through the solar reflectance change and the enhancement or prevention of thermal losses through shape-changing ventilated façades. To achieve these new high performances, an ideal approach to the thermal behaviour of each façade layer was taken, and the required physical properties of each element was highlighted. As a result, we propose a mapping of a potentially suitable combination of reactive materials with other building elements that might enable holistic adaptive thermal performance.

Keywords
Climate response, environmental resources, temperate climate, thermal performance, adaptive technologies, innovative systems

DOI 10.7480/jfde.2018.2.2216

1 INTRODUCTION

Traditionally, the main objective when designing building envelopes was to balance the optimal performance for average climatic situations with their reasonable behaviour under adverse conditions. Most of the time, this meant that the envelope was not optimised from the point of view of construction design and performance. However, nowadays, adaptive or smart technologies can provide suitable and more efficient outputs under diverse climatic conditions. Smart and multifunctional materials belong to these kinds of technologies, as they are engineered materials that respond automatically and reversibly to environmental stimuli. Some Smart Materials (SMs) can change one or more of their properties as direct responses, whilst other SMs transform one energy form into another (Addington & Schodek, 2005). Multifunctional materials (MM), also known as information materials, are less sophisticated raw materials whose "multi-properties" were designed by manipulating their structure by computational techniques (Kretzer, 2017). These advanced materials are applied in different fields, such as robotics or biomedicine, and some researchers have already pointed out their potential to develop successfully climate adaptive building envelopes (Loonen, Trčka, Cóstola, & Hensen, 2013). Even if there are some conceptual proposals for their application in the façade industry (Badarnah & Knaack, 2005; Lelieveld, 2013), they are still at an early research stage. This could be due to their technical limitations, as will be discussed in section 3.2, but may also be due to the fact that their application and potential performances haven't yet been proposed in a defined, holistic way. To address the above-mentioned challenges, we propose two new roles of opaque adaptive façades and we follow a holistic first-stage design strategy, based on a literature review about reactive materials and responsive building elements. The objective of the proposed adaptive opaque façade systems is to enhance their thermal performance due to the dynamic response of smart and multifunctional materials, even when they are combined with other façade components. These roles are specially proposed for temperate climates with small day-night oscillations, characterised by their diverse climatic conditions changing in short time periods, as well as by their rich environmental resources that could contribute in the reduction of energy demand.

2 NEW ROLES OF THE OPAQUE FAÇADES: OUTLINING THE IDEAL THERMAL PERFORMANCE

2.1 THE POTENTIAL OF EXTERIOR CLADDINGS WHICH ADAPT THEIR SOLAR REFLECTANCE

Vernacular architecture makes use of different colour coatings in façades depending on the thermal behaviour that is required for each location. However, when we need to define the finishing for a temperate climate, a conflict exists and we must make a choice that won't always be ideal, especially if the temperate climate doesn't have any dominant climatic condition. In these climates, when ambient temperatures are below the comfort temperature range, the transmission of solar heat gains through façades are effective in the reduction of energy demand. High absorptance and emittance materials, which are usually dark in colour, are the perfect choice to enhance these gains (Table 1). Meanwhile, if the exterior temperatures are above the comfort temperatures, the use of cladding materials with low absorptance and emittance (clear or light coloured materials) is advisable to prevent overheating (Ibañez-Puy, Vidaurre-Arbizu, Sacristán-Fernández, & Martín-Gómez, 2017; Sánchez-Ostiz Gutiérrez, 2011). Therefore, the ideal material is an adaptive one that could change its reflection coefficient. Smart materials called thermochromics have the ability to reversibly change these properties upon reaching a specific temperature. In fact, the experiments undertaken by Ma and Zhu (2009) and Karlessi, Santamouris, Apostolakis, Synnefa, and Livada (2008) reveal that the reflectance of these materials increases towards long wavelengths, which provokes a reduction in the temperature of the coating. Furthermore, exterior cladding material also influences the intensity of thermal flux depending on their thermal diffusivity and conductivity. In this sense, we couldn´t find any multifunctional materials that could dynamically adapt their diffusivity and conductivity, so the heat transferring to the inner façade layer will depend on the "static" material that we choose, as shown in Table 1.

Thermal performance	Physical properties	a) Enhance solar gain	b) Thermal dissipation	Technology	
Heat gain	Absorptance	High	Low	Thermochromic finish	
	Reflectance	Low	High		
Heat transfer to the inner façade layers	Emittance	High	Low	Thermochromic finish	
	Thermal diffusivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding
	Thermal conductivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding

TABLE 1 Relevant physical properties of exterior cladding materials to obtain adaptive thermal control.

Thermal performance	Physical properties	a) Enhance solar gain	b) Thermal dissipation	Technology	
Thermal conservation	Thermal conductivity	High	Low	Adaptive Air Cavities Dynamic Insulations Adaptive Insulations	
	Thermal diffusivity	High	Low		
Thermal storage	Time-lag	Low	High	a) Lightweight	a) Heavyweight
	Thermal diffusivity	High	Low	a) Air, metal	b) Ceramic, stony material
	Sensible heat content	High	Low	a) Stone, concrete, ceramic, clay, water	b) Air, light wood, thermal insulation material
	Latent heat content	High	Low	PCM	
Heat transfer to the interior space	Thermal diffusivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding
	Thermal conductivity	High	Low	a) Metallic cladding	b) Light woods, Synthetic cladding

TABLE 2 Relevant physical properties of interior façade materials to obtain adaptive thermal behaviour.

Possible adaptive control of solar thermal radiation through the cladding needs to be properly understood in terms of the overall thermal flux of the system. For instance, it would be useless to foster solar heat gains under certain climatic conditions if the internal layers of the façade component were blocking that thermal flux. Therefore, to meet all the environmental boundary conditions, they must also include a dynamic behaviour to afford suitable heat transfer, thermal conservation and storage. Table 2 summarises the determining physical properties in each stage of the thermal flux, and promising technologies and building materials that could provide the target performance, are detected.

2.2 SHAPE-CHANGING CLADDINGS TO SEEK HIGH PERFORMING VENTILATED FAÇADES

Opaque ventilated façades enhance thermal performance under mild and warm climatic conditions. These façade systems consist of two opaque layers with an air cavity between. The convective movements in the cavity cause heat dissipation and decrease the surface temperature of the second opaque layer (Ibañez-Puy et al., 2017; Sánchez-Ostiz Gutiérrez, 2011). Nonetheless, in cold periods this behaviour is detrimental as it increases thermal losses, especially if the convective movements reach high velocities. Ibañez-Puy et al. point out that the appropriated outer skin, as well as joints configuration, change depending whether conditions are hot or cold and windy (Ibañez-Puy et al., 2017). Transferring that to a temperate climate, where sequences of threatening climatic scenarios coexist with mild scenarios (even in the same season), it is impossible to choose an optimal, static solution. Adaptive configuration of the outer skin seems like a promising solution to meeting all climatic scenarios, and smart and multifunctional materials may play a role. There are two material families that look favourable: Shape memory alloys (SM) and thermobimetals (MM). The former, such as Ni-Ti alloys, are capable of returning to their original shape from a deformed state, when a certain temperature is reached. Thermobimetals, like Ni-Fe alloys, are two different sheets of differing metal alloys that, laminated together, expand at different rates within a few seconds, causing the bending of the piece (Fig. 1). When the heat source is gone, they can return to their original shape (López, Rubio, Martín, Croxford, & Jackson, 2015).

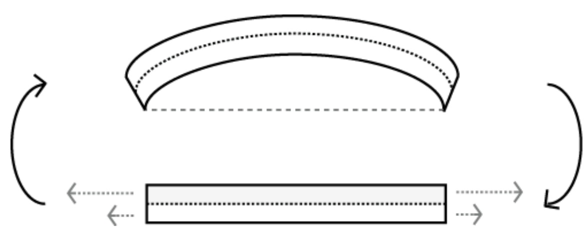

FIG. 1 Thermobimetals bend when they are exposed to the operational temperature, as they are composed of two different metal alloys that expand at different rates.

However, shape changes in the exterior cladding, which aim to control convective heat transfer, would only be effective if physical events are analysed in a holistic way. Firstly, we need to understand that convective movements inside the cavity can happen because of two phenomena: a temperature gradient due to solar gains or wind pressure. Both phenomena can enhance thermal dissipation if physical parameters are considered in the design. If the exterior cladding controls thermal dissipation triggered by solar radiation, then cladding material is a critical factor. For instance, materials with high absorptance and emittance would be suitable to boost convective insulation. Otherwise, when playing with wind action to promote thermal dissipation, material choice has little relevance (Table 3).

Thermal performance	Physical properties	Thermal dissipation		Convective insulation	Promising Responsive material
		Solar gain	Wind action		
Heat gain	Absorptance	Low	Little relevance	High	Thermochromic finish
	Reflectance	High	Little relevance	Low	
Heat transfer	Emittance	Low	Little relevance	High	Thermochromic finish
	Thermal diffusivity	*	Little relevance	Low	*
	Thermal conductivity	*	Little relevance	Low	*

**Further numerical and experimental assessments are needed to discover required physical property*

TABLE 3 Physical property requirements of exterior cladding materials to shift from thermal dissipation to convective insulation

In addition, the morphology and dimensions of the air cavity are important for thermal performance (Table 4). Ventilated façades with significant height and low roughness, will more easily prevent overheating. When this dissipation is due to solar heat gains, it is more appropriate to have a ventilated cavity and a cladding element with closed joints, as the stack effect is boosted, whereas to prevent overheating by making use of the wind, it is better that joints are open (Ibañez-Puy et al., 2017). On the other hand, if we want to avoid the thermal losses that wind would create, the air cavity should be 1-5cm thick, unventilated, and with the lowest height possible (Sánchez-Ostiz Gutiérrez, 2011).

Thermal performance	Ideal morphology	Thermal dissipation		Convective insulation	Promising Responsive material
		Solar gain	Wind action		
Heat transfer	Opening degree (Ibañez-Puy et al., 2017)	Ventilated, closed-joint	Ventilated, open-joint	No ventilated	SMA thermobimetals
	Thickness	7-35cm(Balocco, 2002)	*	1-5cm(Sánchez-Ostiz Gutiérrez, 2011)	
	Roughness	Low	Low	High	
	Height	Higher, better	Higher, better	Higher, better	

** Further numerical and experimental assessments are needed to discover required physical property*

TABLE 4 Morphological requirements of the air cavity to shift from thermal dissipation to convective insulation

Thermal dissipation by both wind and solar action broadens the scenarios in which the façade would perform in an optimal way. It must be considered that dissipation by solar heat gains becomes less effective as wind velocity increases, and is negligible over 2.5m/s. Besides, convective thermal dissipation overnight can occur in windy conditions, or in situations in which there is not enough solar radiation (Ibañez-Puy et al., 2017).

3 POSSIBLE IMPLEMENTATIONS OF SM & MM IN ADAPTIVE OPAQUE FAÇADES: A PROPOSITION OF PROMISING FAÇADE CONFIGURATIONS AND THEIR CHALLENGES

3.1 SUITABLE COMBINATION OF SM OR MM WITH OTHER FAÇADE TECHNOLOGIES

Adaptive solar control façades result from the adequate combination of thermochromic-coated claddings with other façade components. It can be concluded from the information shown in Table 1 that when the façade aims to gain thermal energy from solar radiation, heat transfer needs to be as fast and effective as possible in the cladding, in such a way that it can be stored in the internal layer or transferred to the interior environment (Fig. 2). Heat gained in the outer skin is transferred to the internal layers, where it should be stored by thermal mass, sensible heat, or latent heat. Finally, it is transferred to the interior environment through convection and radiation. When solar gains are detrimental to thermal comfort, the radiant heat that can't be reflected by the exterior cladding is dissipated by convective movements (if there is an air cavity placed just behind the outer skin). This, coupled with thermal conservation layers, minimises thermal gains by conduction in the indoor environment.

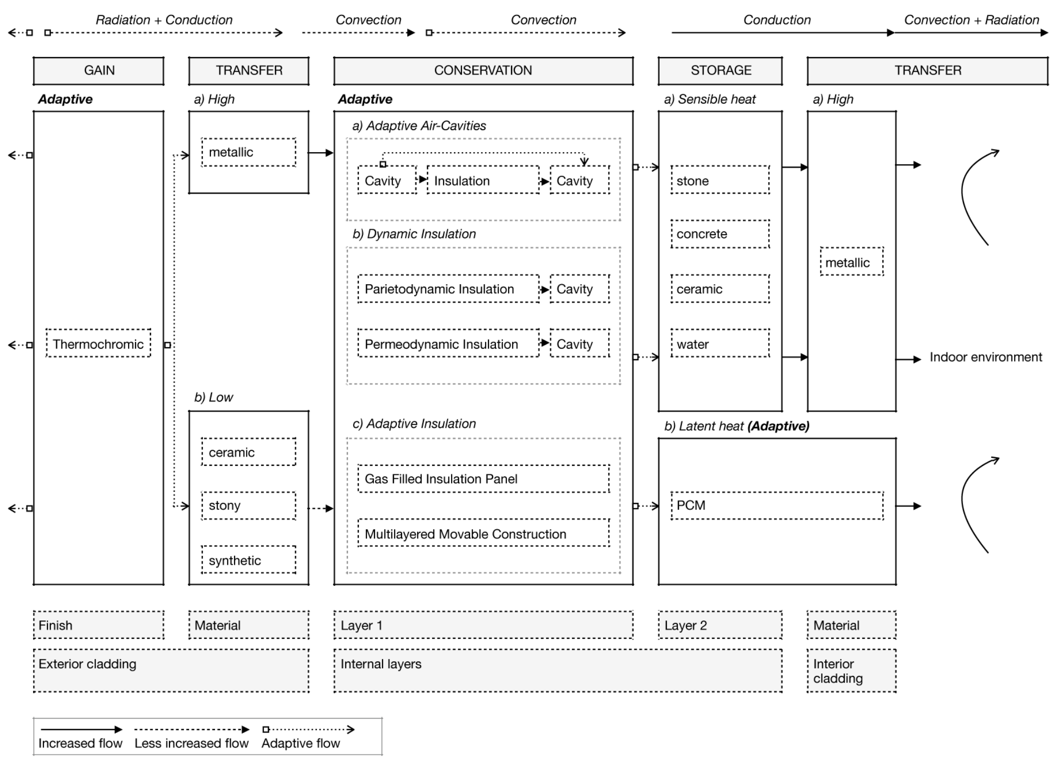

FIG. 2 Possible combination of thermochromics with other technologies.

The thermal behaviour shown in Fig. 2 might be achieved through a different configuration of thermochromics with other building elements. This can be illustrated briefly by the cladding material, which modifies the intensity of the thermal flux depending on the material type that is chosen. When applying a thermochromic finish in a metallic cladding, thermal flux is more intense than if ceramic, stony, or synthetic materials were chosen. Regarding thermal conservation, as energy exchange is profitable at certain climatic conditions, it would be inadequate to use regular insulation materials. Indeed, an adaptive conservation layer should be placed in the internal layers. A possible solution is to place an adaptive air cavity behind the external cladding, which could include an autoreactive damper (made by SM/MM or an electro-mechanical actuator). To open this damper, heat would be transferred to the intermediate layer by introducing pre-heated air, and a second air cavity would, by necessity, be in contact with the storage façade element (Fig. 3).

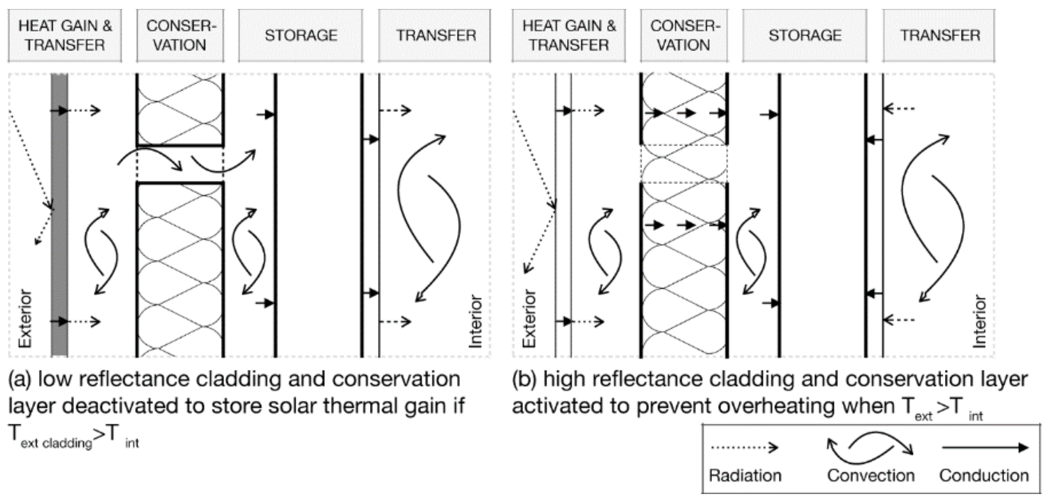

FIG. 3 Possible configuration combining thermochromic finish applied in exterior cladding and adaptive air cavities to achieve adaptive thermal performance in an opaque façade system.

Another option is to replace the traditional insulation material with a dynamic insulation element, which changes its behaviour to enhance or block thermal conduction (Fig. 4), or adaptive insulations (Favoino, Jin, & Overend, 2017), which adapt their features to change their thermal performance (Fig. 5). Finally, thermal storage could be achieved by combining the aforementioned elements with an internal layer of high sensible heat content, such as concrete, ceramic, or water, or high latent heat, such as phase change materials (Fig. 2).

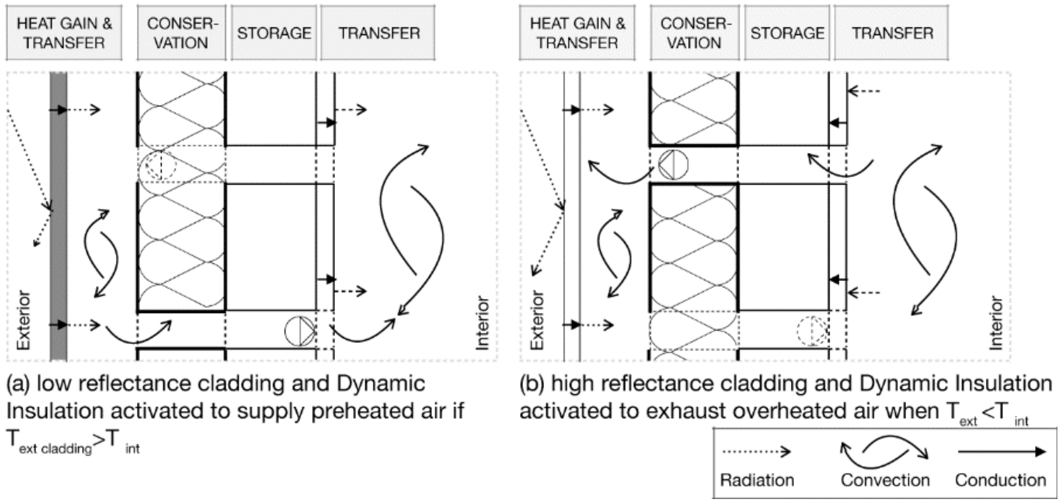

FIG. 4 Possible configuration combining a thermochromic finish applied in exterior cladding and a dynamic insulation element to achieve adaptive thermal performance in an opaque façade system.

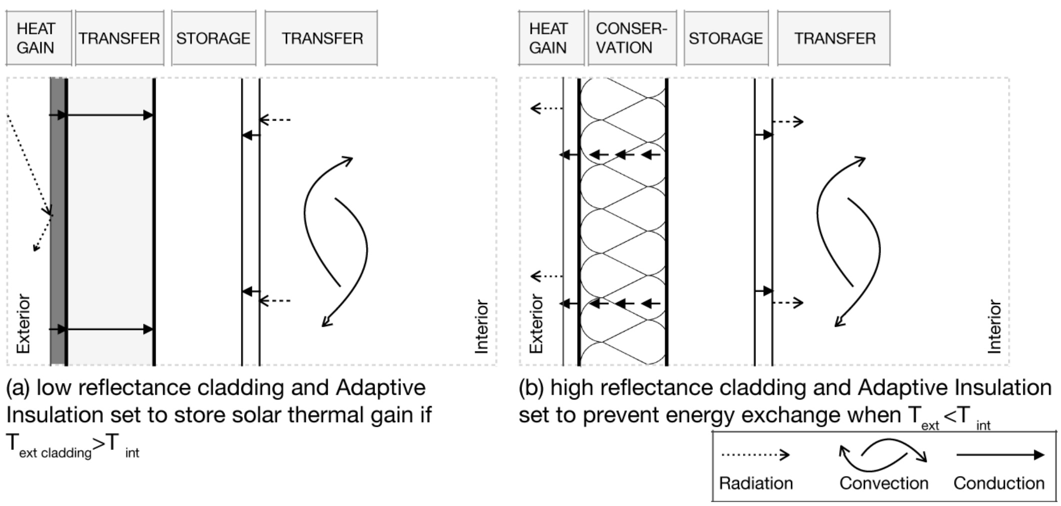

FIG. 5 Possible configuration combining thermochromic finish applied in exterior cladding and adaptive insulation element to achieve adaptive thermal performance in an opaque façade system.

With respect to shape-changing ventilated façades, morphology variations of the outer cladding must be set properly within the system to enhance or reversibly block thermal flux. In order to meet all the possible requirements in each climatic condition, three possible morphological configurations are proposed for a ventilated façade system. The first shape configuration provides a ventilated façade with a closed air cavity, as the external cladding geometry has a closed-joint arrangement and furthermore, the upper and lower dampers of the cavities are closed. The second configuration enables heat dissipation by solar radiation, as the outer skin has a closed-joint geometry but the dampers of the cavities are opened, which enhances the stack effect due to the temperature gradient. The third and final configuration makes thermal dissipation possible by wind action, as both cavity and cladding joints are opened.

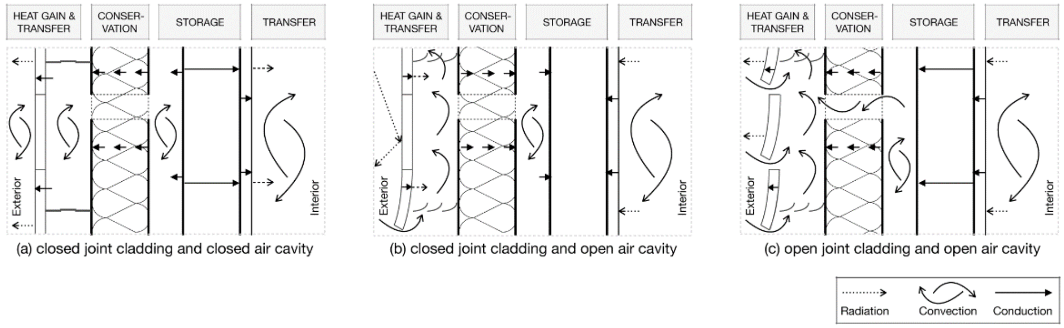

FIG. 6 Possible configurations of a shape-changing ventilated façade using SM or MM as actuators embedded in the cladding and in the dampers. Different morphologies would allow the control of thermal losses due to convective movements. Configuration (a) would allow a convective insulation, (b) would enable thermal dissipation triggered by solar thermal radiation, and (c) would prevent overheating in the interior space, enhancing thermal losses by wind action.

SM and MM would be the actuators of the kinetic behaviour and they would react automatically and reversibly to a set operational temperature. This would prevent or allow ventilation of the air cavity. Besides, the opening degree of the outer skin would be controlled by opening or closing the joints of the cladding and/or by partitioning the air cavity at specific temperatures.

When thermal dissipation is intended, the direction of energy exchange would be from indoor to outdoor (Fig. 7). In order to reduce the temperature of the interior environment, different strategies could be provided by a single façade system. On one side, internal heat loads could be minimised by the storage layers, to redistribute that energy by conduction when it is needed. Furthermore, disabling conservation layers could improve thermal comfort when the exterior conditions are more suitable than the interior ones, as heat could be transferred from the interior to the cavity by conductive and convective fluxes. Finally, as previously discussed, convective movements in the air cavity could cause significant thermal losses. On the contrary, to use the exterior cavity as a convective insulation element, it should be fully closed, and the conservation layer should be activated, impeding convective flows and blocking thermal flux by conduction. In this case, material combinations fit with the ones that were exposed in Fig. 2. Once more, adaptive flow from the internal layers to the exterior cavity would only be possible if the conservation layers performed in a dynamic way according to different boundary conditions.

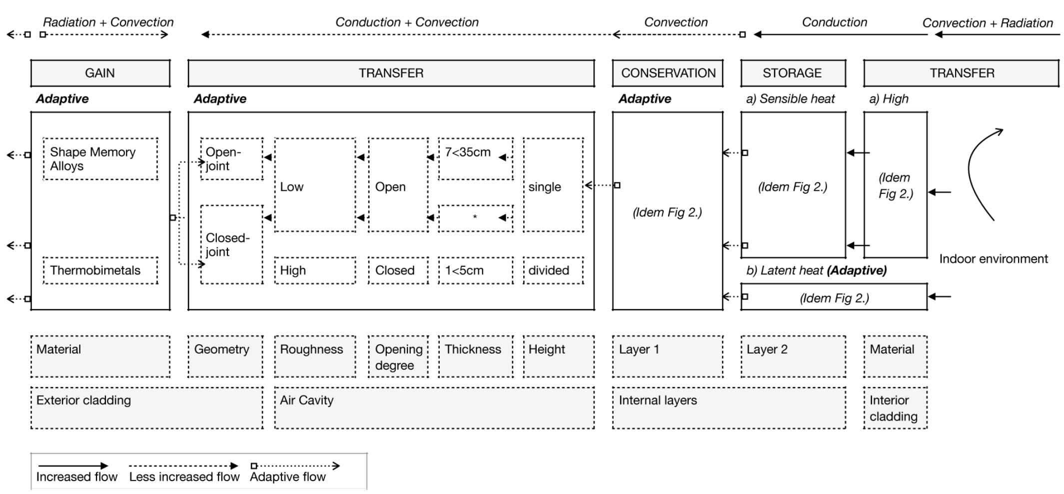

FIG. 7 Possible combination of shape-changing materials with other technologies

3.2 TECHNICAL LIMITATIONS

Technical limitations delay the success of some smart and multifunctional materials in the building industry. Their drawbacks need to be properly understood to overcome this challenge, in such a way that they could be addressed by finding suitable combinations with other building technologies. For instance, according to the literature reviewed, thermochromic materials have a serious problem with degradation, especially when they are exposed to ultraviolet radiation (Addington & Schodek, 2005) and their mechanical properties decay (Ma & Zhu, 2009). This is the reason why the number of reversible adaptation cycles are considered too short for façade application. However, we can find commercialised products containing thermochromics in the glass industry, which ensure optimal fatigue life. In fact, they are usually applied as thin films between glass panels; the glass prevents UV radiation. When applying SMAs or thermobimetals, we must combine these materials in a multi-layered façade system to face thermal, hygrothermal, and acoustic requirements. In addition, these alloys are oxidised when they are in contact with aggressive environments (marine or industrial). But while the oxide layer of some SMAs, such as Ni-Ti alloys, is compact, thin, and passive, and it acts as a protection layer, the oxide layer of thermobimetals (Ni-Fe alloys) is porous and, therefore, destructive. As these materials act kinetically, a hypothetical protection layer would be useless, as it could be broken by the repetitive deformation of the piece. Consequently, thermobimetals shouldn't be used in marine or industrial atmospheres.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper has shown different possible façade configurations in which to apply smart and multifunctional materials in adaptive opaque façades. To reach this stage, it was necessary to consider the physical events in a conceptual way, so that the ideal thermal behaviours in the overall systems were designed. This analysis allowed for the anticipation of the most appropriate physical properties for each layer of the systems, according to the pursued dynamic roles. Based on the literature review, we highlighted promising materials and technologies that could meet these requirements and we explained briefly how they could work in a holistic way.

To more accurately scope the potential of these new systems and to find out which configurations are the most suitable ones, further research is still needed, starting with numerical assessments. They would allow for the optimisation of the adaptability range, the velocity of adaptation, and the operational scenario (operational temperature setting) of these materials. Moreover, they would allow for the determination of whether the proposed combinations with other building materials would enable a holistic responsive performance. Lastly, these new façades must be validated through experimental assessments to prove that current technologies can offer suitable adaptive responses over an adequate lifespan.

Acknowledgements

The authors would like to thank the support to the Asociación de Amigos of the Universidad de Navarra. In addition, we would like to gratefully acknowledge COST Action TU1403 "Adaptive Façade Network" for providing excellent research networking.

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