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).

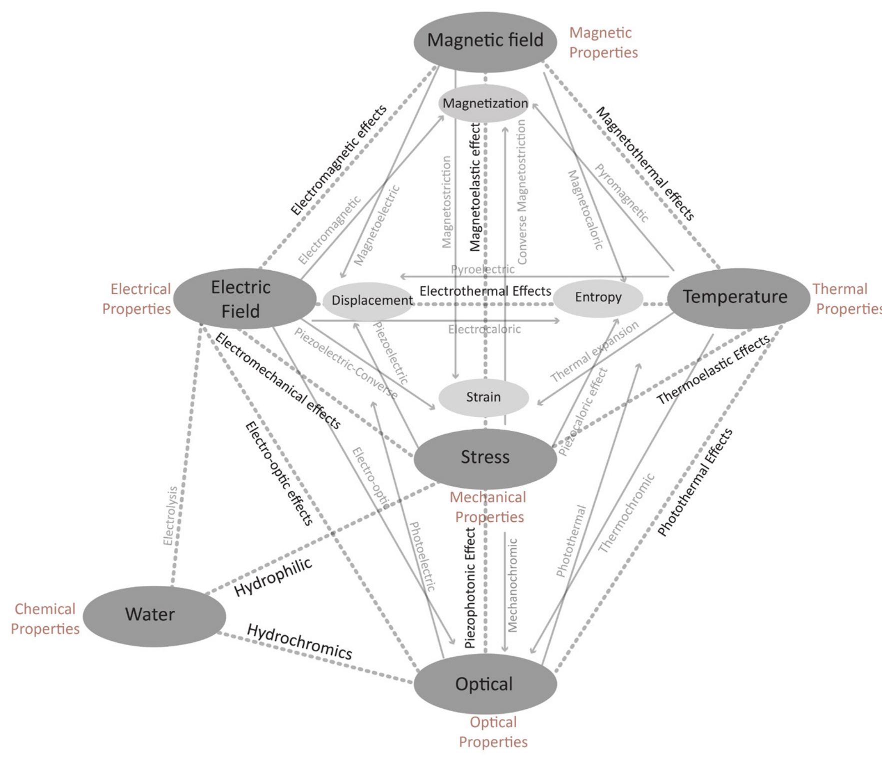


FIG. 1 Diagram characterising the behaviour of smart materials. Based on the Heckman Diagram

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.

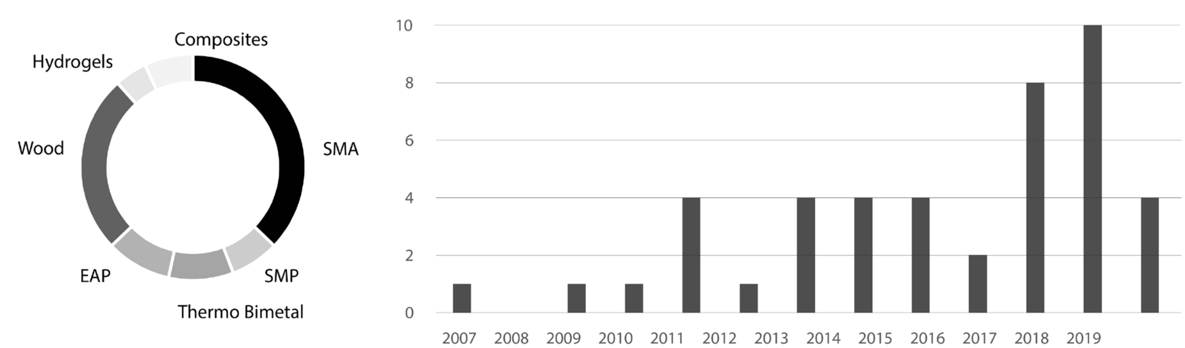
3 RESULTS

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.

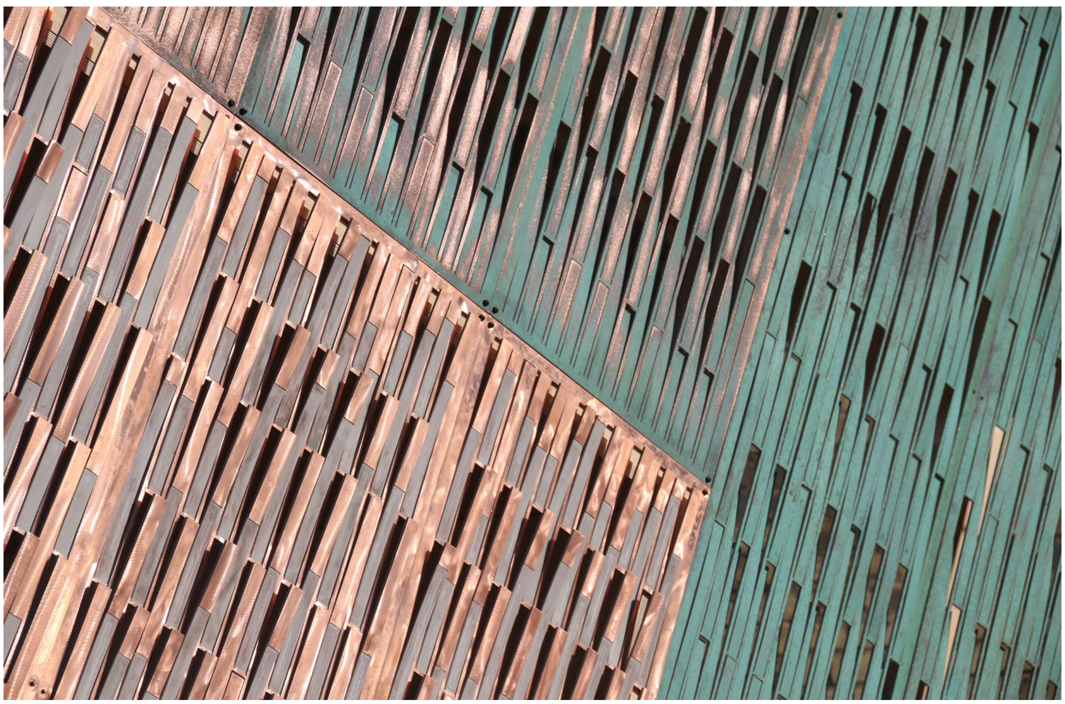
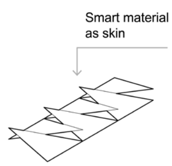
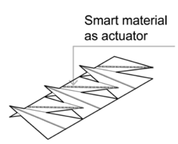
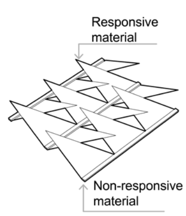
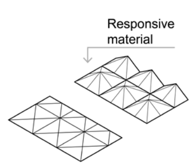
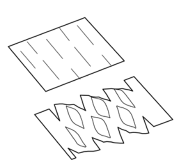


FIG. 3 Sense Envelope III. Copper and polypropylene are forming a thermally active composite. Design/fabrication by Isak Worre Foged and Anke Pasold. Photograph by: Isak Worre Foged.

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.

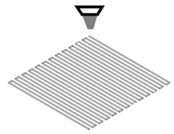
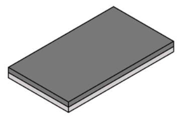
A third design strategy identified is related to a combination of shape-changing materials with other non-responsive or passive ones. Typically, in the design of an architectural skin system, there are dynamic and static parts. This is the case with most of the case studies, where there is an underlying 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.

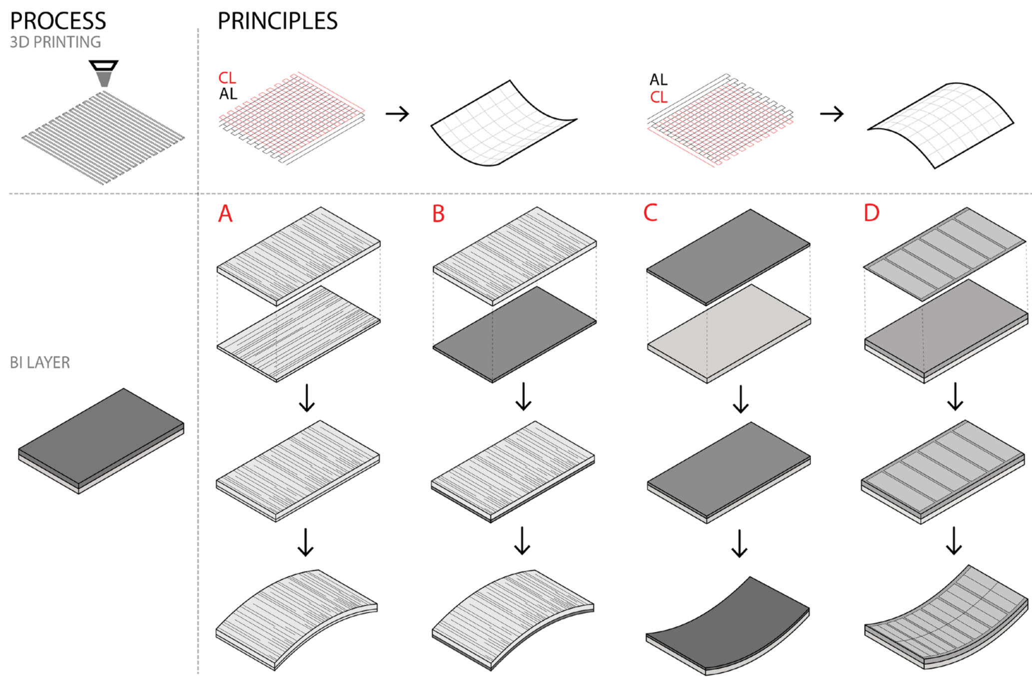


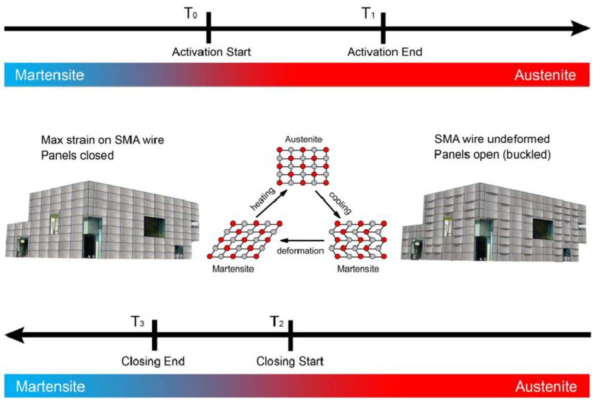
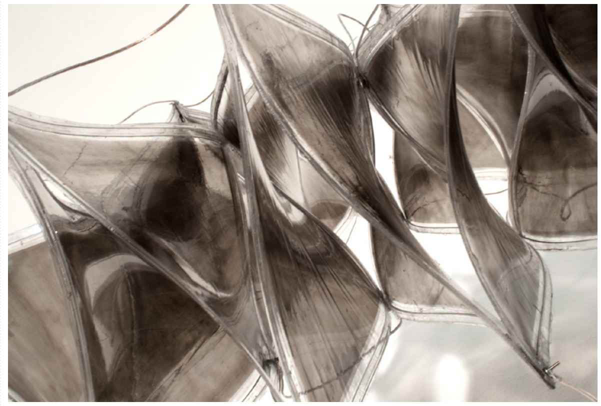
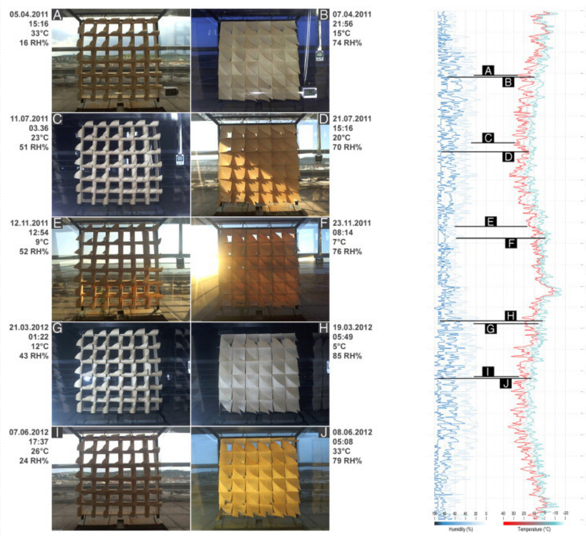
FIG. 4 Manufacturing principles

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	(B) LEVEL 2: PROTOTYPE
	
Formentini and Lenci (2017)	Kretzer and Rossi (2012)
(C) LEVEL 3: LARGE-SCALE TEST	(D) LEVEL 4: ENVIRONMENTAL PERFORMANCE ANALYSIS
	
Sung (2016)	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.

References

Abdelmohsen, S., Adriaenssens, S., El-Dabaa, R., Gabriele, S., Olivieri, L., & Teresi, L. (2018). A multi-physics approach for modeling hygroscopic behavior in wood low-tech architectural adaptive systems. *CAD Computer Aided Design*, *106*, 43–53. https://doi.org/10.1016/j.cad.2018.07.005

Abdelmohsen, S., Massoud, P., & Elshafei, A. (2016). Using Tensegrity and Folding to Generate Soft Responsive Architectural Skins. In A. Herneoja, T. Österlund, & P. Markkanen (Eds.), *Complexity & Simplicity - Proceedings of the 34th eCAADe Conference* (Vol. 1, pp. 529–536). Oulu.

Addington, M. (2010). *Smart Materials and Sustainability*. Austin: Center for Sustainable Development - The University of Texas at Austin.

Addington, M., & Schodek, D. (2012). *Smart Materials and Technologies in Architecture: For the Architecture and Design Professions*. Oxford: Routledge.

Adriaenssens, S., Rhode-Barbarigos, L., Kilian, A., Baverel, O., Charpentier, V., Horner, M., & Buzatu, D. (2014). Dialectic form finding of passive and adaptive shading enclosures. *Energies*, *7*(8), 5201–5220. https://doi.org/10.3390/en7085201

Ahmad, I. (1988). Smart structures and materials. *Proceeding of US Army Research Office Workshop of Smart Materials, Structures and Mathematical Issues, Virginia Polytechnic Institute and State University, Technomic Publishing*, 13–16.

Anis, M. (2019). Designing an adaptive building envelope for warm-humid climate with bamboo veneer as a hygroscopically active material. *ARCC Conference Repository*. Retrieved from https://www.arcc-journal.org/index.php/repository/article/view/652%0A

Augustin, N. (2018). *Motion with moisture: Creating Passive Dynamic Envelope Systems Using the Hygroscopic Properties of Wood Veneer*. University of Waterloo.

Clifford, D., Zupan, R., Brigham, J., Beblo, R., Whittock, M., & Davis, N. (2017). Application of the dynamic characteristics of shape-memory polymers to climate adaptive building facades. *13th Conference on Advanced Building Skins 2017*, 171–178. Bern.

Coelho, M., & Maes, P. (2009). Shutters: A permeable surface for environmental control and communication. *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, 13–18. https://doi.org/10.1145/1517664.1517671

Correa, D., & Menges, A. (2017). FUSED FILAMENT FABRICATION FOR MULTI-KINEMATIC-STATE CLIMATE- RESPONSIVE APERTURE. In A. Menges, B. Sheil, R. Glynn, & M. Skavara (Eds.), *Fabricate 2017* (pp. 44–47). London: UCL Press.

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A., & Tibbits, S. (2015). 3D-Printed Wood: Programming Hygroscopic Material Transformations. *3D Printing and Additive Manufacturing*, *2*(3), 106–116. https://doi.org/10.1089/3dp.2015.0022

Decker, M., & Zarzycki, A. (2014). Designing Resilient Buildings with Emergent Materials. *Fusion - 32nd ECAADe Conference. Conference Proceedings 2014, Northumbria University, Newcastle upon Tyne, England, 10-12 September 2014*, *2*, 179–184. https://doi.org/10.13140/2.1.1060.8967

Diniz, N., Branco, C., & Sales Dias, M. (2017). MORPHOSIS: A responsive membrane. In A. Dong, A. Vande Moere, & J. Gero (Eds.), *Computer-aided Architectural Design Futures 2007: Proceedings of the 12th International CAADFutures Conference 2007* (pp. 489–498). Dordrecht: Springer.

Doumpioti, C. (2011). Responsive and Autonomous Material Interfaces. In J. Taron, V. Parlac, B. Kolarevic, & J. Johnson (Eds.), *Integration through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)* (pp. 318–325). Calgary/Banff: The University of Calgary.

Doumpioti, C., Greenberg, E. L., & Karatzas, K. (2010). Embedded Intelligence: Material Responsiveness in Façade Systems. In A. Sprecher, S. Yeshayahu, & P. Lorenzo-Eiroa (Eds.), *In LIFE in:formation, On Responsive Information and Variations in Architecture: Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)* (pp. 258–262). New York: Cooper Union, Pratt Institute.

El-Dabaa, R., & Abdelmohsen, S. (2018). A Methodology for Evaluating the Hygroscopic Behavior of Wood in Adaptive Building Skins using Motion Grammar. *IOP Conference Series: Materials Science and Engineering*, *362*(1). https://doi.org/10.1088/1757-899X/362/1/012011

El-Dabaa, R., & Abdelmohsen, S. (2019). H M T M: Hygromorphic-Thermobimetal Composites as a Novel Approach to Enhance Passive Actuation of Adaptive Façades. *Ji-Hyun Lee (Eds.) "Hello, Culture!" [18th International Conference, CAAD Futures 2019, Proceedings / ISBN 978-89-89453-05-5]*, 290–300. Daejeon.

Elahinia, M., Shayesteh Moghaddam, N., Taheri Andani, M., Amerinatanzi, A., Bimber, B. A., & Hamilton, R. F. (2016). Fabrication of NiTi through additive manufacturing: A review. *Progress in Materials Science*, *83*, 630–663. https://doi.org/10.1016/j.pmatsci.2016.08.001

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, *55*, 863–884. https://doi.org/10.1016/j.rser.2015.10.086

Formentini, M., & Lenci, S. (2017). An innovative building envelope (kinetic façade) with Shape Memory Alloys used as actuators and sensors. *Automation in Construction*, *85*, 220–231.

Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., & Lewis, J. A. (2016). *Biomimetic 4D printing*. *15*(April). https://doi.org/10.1038/NMAT4544

Grinham, J., Blabolil, R., & Haak, J. (2014). Harvest Shade Screens Programming Material for Optimal Energy Building Skins. *ACADIA 14: Design Agency [Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 281–290. Los Angeles.

Hannequart, P., Peigney, M., Caron, J., Baverel, O., & Viglino, E. (2018). The Potential of Shape Memory Alloys in Deployable Systems — A Design and Experimental Approach. *Humanizing Digital Reality*, Vol. 2, pp. 237–246. Singapore: Springer.

Holstov, A., Bridgens, B., & Farmer, G. (2015). Hygromorphic materials for sustainable responsive architecture. *Construction and Building Materials*, *98*, 570–582. https://doi.org/10.1016/j.conbuildmat.2015.08.136

Holstov, A., Farmer, G., & Bridgens, B. (2017). Sustainable materialisation of responsive architecture. *Sustainability (Switzerland)*, *9*(3). https://doi.org/10.3390/su9030435

Juaristi, M., Gómez-Acebo, T., & Monge-Barrio, A. (2018). Qualitative analysis of promising materials and technologies for the design and evaluation of Climate Adaptive Opaque Façades. *Building and Environment*, *144*(August), 482–501. https://doi.org/10.1016/j.buildenv.2018.08.028

Juaristi, M., Monge-barrio, A., Sánchez-ostiz, A., & Gómez-acebo, T. (2018). Exploring the Potential of Smart and Multifunctional Materials in Adaptive Opaque Façade Systems. *Journal of Facade Design and Engineering*, *6*(2), 107–117. https://doi.org/10.7480/jfde.2018.2.2216

Jun, J. W., Silverio, M., Llubia, J. A., Markopoulou, A., Chronis, A., & Dubor, A. (2017). Remembrane: A Shape Changing Adaptive Structure. In G. Çagdas, M. Özkar, L. F. Gül, & E. Gürer (Eds.), *Future Trajectories of Computation in Design [17th International Conference, CAAD Futures 2017, Proceedings* (pp. 180–198). Istambul.

Khoo, C. K., Salim, F., & Burry, J. (2012). Designing Architectural Morphing Skins with Elastic Modular Systems. *International Journal of Architectural Computing*, *09*(04), 397–419. https://doi.org/10.1260/1478-0771.9.4.397

Khoo, C. K., & Salim, F. D. (2013). Lumina : A Soft Kinetic Material for Morphing Architectural Skins and Organic User Interfaces. *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 53–62. https://doi.org/10.1145/2493432.2494263

Khoo, C. K., & Shin, J. (2018). Designing with Biomaterials for Responsive Architecture: A soft responsive " bio-structural " hydrogel skin. In A. Kepczynska-Walczak & S. Bialkowski (Eds.), *Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference* (Vol. 2, pp. 285–292). Lodz.

Kolodziej, P., & Rak, J. (2013). Responsive building envelope as a material system of autonomous agents. In B. T. R. Stouffs, P. Janssen, S. Roudavski (Ed.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)* (pp. 945–954). Hong Kong.

Kretzer, M. (2014). Architecture in the Era of Accelerating Change. *ACADIA 2014 Design Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, 463–472. Los Angeles: Riverside Architectural Press.

Kretzer, M. (2016). *Information materials: smart materials for adaptive architecture*. https://doi.org/10.1007/978-3-319-35150-6

Kretzer, M. (2018). Educating smart materials. *Cuadernos Del Centro de Estudios En Diseño y Comunicación. Ensayos*, (70), 1–3.

Kretzer, M., & Rossi, D. (2012). ShapeShift. *Leonardo*, *45*(5), 480–481. Retrieved from https://www.muse.jhu.edu/article/484764.

Kyu, Y., Yin, J., & Tang, Y. (2018). Developing an advanced daylight model for building energy tool to simulate dynamic shading device. *Solar Energy*, *163*(July 2017), 140–149. https://doi.org/10.1016/j.solener.2018.01.082

Lignarolo, L., Lelieveld, C., & Teuffel, P. (2011). Shape morphing wind-responsive facade systems realized with smart materials. *In Adaptive Architecture: An International Conference, London, UK, March 3-5, 2011*, 1–12. London.

Markopoulou, A. (2015). Design Behaviors ; Programming Matter for Adaptive Architecture. *Next Generation Building 2*, *1*, 57–78. https://doi.org/10.7564/15-NGBJ17

Mazzucchelli, E. S., Alston, M., Brzezicki, M., & Doniacovo, L. (2018). Study of a BIPV adaptive system: Combining timber and photovoltaic technologies. *Journal of Facade Design and Engineering*, *6*(3), 149–162. https://doi.org/10.7480/jfde.2018.3.2602

Méndez Echenagucia, T., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy*, *154*, 577–591. https://doi.org/10.1016/j.apenergy.2015.04.090

Mokhtar, S., Leung, C., & Chronis, A. (2017). Geometry-Material Coordination for Passive Adaptive Solar Morphing Envelopes. In M. Turrin, B. Peters, W. O'Brien, R. Stouffs, & T. Dogan (Eds.), *Proceedings of the Symposium on Simulation for Architecture and Urban Design* (pp. 211–218). Toronto: The society for modeling and simulation international.

Pasold, A., & Worre Foged, I. (2010). Performative Responsive Architecture Powered by Climate. In A. Sprecher, S. Yeshayahu, & P. Lorenzo-Eiroa (Eds.), *In LIFE in:formation, On Responsive Information and Variations in Architecture: Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)* (pp. 243–249). New York: Cooper Union, Pratt Institute.

Pesenti, M., Masera, G., & Fiorito, F. (2015). Shaping an origami shading device through visual and thermal simulations. *Energy Procedia*, *78*, 346–351. https://doi.org/10.1016/j.egypro.2015.11.663

Pesenti, M., Masera, G., & Fiorito, F. (2018). *Exploration of Adaptive Origami Shading Concepts through Integrated Dynamic Simulations*. *24*(4), 1–14. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000323.

Pickering, C., & Byrne, J. (2014). *The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers*. *4360*. https://doi.org/10.1080/07294360.2013.841651

Reichert, S., Menges, A., & Correa, D. (2015). Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. *CAD Computer Aided Design*, *60*, 50–69. https://doi.org/10.1016/j.cad.2014.02.010

Reyssat, E., & Mahadevan, L. (2009). Hygromorphs: from pine cones to biomimetic bilayers. *Journal of the Royal Society Interface*, *6*(39), 951–957.

Shimul, S. (2017). *Alive by Material: A Study of Dielectric Polymer as a Material with Intrinsic Kinetic Properties for Architectural Application*. Texas Tech University.

Shin, D. G., Kim, T. H., & Kim, D. E. (2017). Review of 4D printing materials and their properties. *International Journal of Precision Engineering and Manufacturing - Green Technology*, *4*(3), 349–357. https://doi.org/10.1007/s40684-017-0040-z

Sung, D. (2016a). Smart Geometries for Smart Materials : Taming Thermobimetals to Behave Smart Geometries for Smart Materials. *Journal of Architectural Education*, *4883*. https://doi.org/10.1080/10464883.2016.1122479

Sung, D. (2016b). *Smart Geometries for Smart Materials : Taming Thermobimetals to Behave Smart Geometries for Smart Materials*. *4883*. https://doi.org/10.1080/10464883.2016.1122479

Sung, D. K. (2008). Skin Deep : Breathing Life into the Layer between Man and Nature. In *AIA Report on University Research* (Vol. 3).

Truby, R. L., & Lewis, J. A. (2016). Printing soft matter in three dimensions. *Nature*, *540*(7633), 371–378. https://doi.org/10.1038/nature21003

Vailati, C., Bachtiar, E., Hass, P., Burgert, I., & Rüggeberg, M. (2018). An autonomous shading system based on coupled wood bilayer elements. *Energy and Buildings*, *158*, 1013–1022. https://doi.org/10.1016/j.enbuild.2017.10.042

Vazquez, E., Gursoy, B., & Duarte, J. P. (2019). DESIGNING FOR SHAPE CHANGE: A Case study on 3D Printing Composite Materials for Responsive Architectures. In M. Haeusler, M. A. Schnabel, & T. Fukuda (Eds.), *Intelligent & Informed - Proceedings of the 24th CAADRIA Conference - Volume 2, Victoria University of Wellington, Wellington, New Zealand, 15-18 April 2019* (pp. 243–252). Wellington: Victoria University of Wellington.

Velikov, K., & Thun, G. (2013). Responsive Building Envelopes: Characteristics and Evolving Paradigms. *Design and Construction of High-Performance Homes: Building Envelopes, Renewable Energies and Integrated Practice*, 75–92.

Verma, S., & Devadass, P. (2013). adaptive [skins]: Responsive building skin systems based on tensegrity principles. *FUTURE TRADITIONS 1st ECAADe Regional International Workshop Proceedings*, 155–170. Porto: University of Porto, Faculty of Architecture.

Wood, D., Vailati, C., Menges, A., & Rüggeberg, M. (2018). Hygroscopically actuated wood elements for weather responsive and self-forming building parts – Facilitating upscaling and complex shape changes. *Construction and Building Materials*, *165*, 782–791. https://doi.org/10.1016/j.conbuildmat.2017.12.134

Wood, Dylan, Correa, D., Krieg, O. D., & Menges, A. (2016). Material computation-4D timber construction: Towards building-scale hygroscopic actuated, self-constructing timber surfaces. *International Journal of Architectural Computing*, *14*(1), 49–62. https://doi.org/10.1177/1478077115625522

Worre Foged, I., & Pasold, A. (2015). Thermal Activated Envelope : Development of a Method and Model for Programming Material Behaviour in a Responsive Envelope. In B. Martens, G. Wurzer, G. T, W. Lorenz, & R. Schaffranek (Eds.), *Proceedings of the 33rd eCAADe Conference - Volume 2, Vienna University of Technology, Vienna, Austria, 16-18 September 2015* (pp. 449–458). Vienna, Austria: Vienna University of Technology.

Worre Foged, I., Pasold, A., & Pelosini, T. (2019). Material Studies for Thermal Responsive Composite. *Sousa, JP, Xavier, JP and Castro Henriques, G (Eds.), Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th ECAADe and 23rd SIGraDi Conference*, *1*, 207–214. Porto, Portugal.

Yoon, J. (2019). SMP Prototype Design and Fabrication for Thermo- responsive Façade Elements. *Journal of Facade Design and Engineering*, *7*(1), 41–62. https://doi.org/10.7480/jfde.2019.1.2662