

Computational tools for designing shape-changing architectures

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ABSTRACT: Smart materials or systems are characterized by having built-in sensors and actuators, adjusting their properties in response to external stimulus. The rapid development of these technologies presents an immense opportunity for designers and architects to provide innovative and creative solutions for adaptive buildings. However, there are several challenges for the incorporation of smart materials in the toolbox of architects in design practice: The lack of an overlap in knowledge between material science fields and design practices; the addition of time as a condition that renders these materials inherently dynamic; and the general disconnect between material issues in typical design settings. This paper discusses the challenges for designing shape-changing architecture and examines the way in which computational tools or digital technologies can help overcome those limitations in design practice. Finally, we discuss an approach for designing shape changing architectures with the aid of digital technologies, highlighting the different considerations that must be taken into account.

KEYWORDS: Smart materials, shape-changing materials, responsive architecture, material-based design.

INTRODUCTION

In recent years, there has been an increasing interest in smart materials within design fields. The ability to design responsive and dynamic architectures that adapt to different climatic conditions is, with no doubt, an appealing idea. Furthermore, smart materials have already been declared as “the answer to 21st century technological needs”(Addington and Schodek 2012, 1). While these materials have long been part of the research agenda of material scientists and engineers with workshops on Smart Materials dating as far as 1988 (Smart Materials, Structures, and Mathematical Issues- US Research Army Workshop), smart materials have just recently started to permeate design research and practice.

There are multiple definitions of smart materials. Most authors agree that what characterizes smart materials is the ability to adjust their properties in response to a defined stimulus, as defined by (Kretzer 2016, 54) “Materials that can change their property in response to environmental conditions”, or similarly, in (Kretzer and Hovestadt 2014, 44) “can adjust their properties dynamically”. A comprehensive definition is provided by Ahmad (1988), who states that smart materials or systems are characterized by having intrinsic sensors, actuators and a control mechanism that allow them to sense a stimulus – a change in environmental conditions, for instance – and respond in a determined manner in a short time, as well as return back to their original state once the stimulus is removed. This definition highlights the intrinsic nature of both sensors and actuators in smart materials, while remarking that the response has to be controlled and occur in a short period of time.

Among the different types of smart materials, shape-changing materials have received particular attention from design-oriented studies due to their potential for constructing climate-responsive adaptive architectures (Fiorito et al. 2016; D. Wood et al. 2018; Correa et al. 2015). In shape-changing smart materials, a stimulus (i.e. heat, water) causes a strain in the material, thus changing its shape. Shape-changing materials are slowly being incorporated into design studies, not without challenges in the process such as, the lack of an overlap in knowledge between material science fields and design practices (Addington and Schodek 2012); the addition of time as a condition that renders these materials inherently dynamic (Kretzer and

Hovestadt 2014); and the general disconnect between material issues in typical design settings.

To overcome the challenges mentioned above, researchers have used computational tools that link material properties, design considerations, and enabling manufacturing technologies. This paper discusses the challenges to designing shape-changing architecture and examines the way in which computational tools or digital technologies can help overcome such limitations in design practice. The following section summarizes the difficulties of incorporating shape-changing materials into architectural practice by providing a review of the literature on smart materials in design fields. The second section identifies several computational tools that can aid the design of shape changing materials, considering existing design-oriented studies on shape-changing materials. Finally, we discuss an approach for designing shape changing architectures with the aid of digital technologies, highlighting the different considerations that must be taken into account.

1.0 CHALLENGES IN DESIGNING FOR SHAPE CHANGE

Smart materials and more specifically, shape changing materials, present several advantages over traditional materials, particularly, in developing innovative and responsive architectures. Kretzer (2014) argues that there is a current need for architectural systems to become more responsive and adaptable to deal with unprecedented societal and environmental challenges. A main advantage of incorporating smart materials into architecture systems is that they can be used as both actuators and sensors, which places them, according to Addington (2010), on the middle ground between low tech and high-tech approaches. This is because even though smart materials are clearly sophisticated, they do not have any mechanical systems. In this sense, smart materials can be used to replace much more complex systems. Another advantage of using smart material relies on their ability to present more than one state, having an inherent dynamic nature. Identifying this characteristic, Mann (2009) makes a case for the use of smart materials due to their problem-solving abilities, particularly, for design problems with contradicting requirements.

The incorporation of shape changing materials into architecture practice presents several challenges. Shape changing smart materials cannot simply replace existing architectural technologies, due to their inherent dynamic nature that contrasts with the rigidity of traditional construction materials. In fact, one recurring theme found in the literature on smart materials is how the dynamic nature of shape-changing materials presents a challenge for architectural practice. This is because designers have traditionally aimed for concepts such as stability and solidity instead of dynamism when designing buildings and spaces. Kretzer (2014b) argues that architects should rethink environments as dynamic and soft, beyond the paradigms of longevity, stability and performance. In this sense, the dynamic nature of smart materials certainly challenges what architecture should evoke and transmit.

Furthermore, Addington and Schodek (2005) claim that conventional means of representation in architectural design privileges static materials, which becomes a problem for designing with dynamic smart materials. Conventional forms of representation – plans, sections and so on – can hardly incorporate the fourth dimension related to time, showing how these materials can transform when activated by a stimulus. Alternative modes of representation that convey the dynamism and transformation of shape changing materials are needed in the design process. For instance, Sung (2016), when describing her research on thermo bimetal argue: “The still images require extensive explanation (...). A 30-second video, on the other hand, explains it all” (Sung 2016, 106). Consequently, it is not only conventional ideas about what architecture should look like that need to change, but also the process of designing, to successfully incorporate shape-changing materials in architectural practice.

Another challenge for the incorporation of smart materials in design fields has to do with the lack of synthesized information on smart materials for non-experts in the field, such as designers and architects (Kretzer 2016). There is a need for constructing a common language

between design fields and other areas of inquiry that are more closely related to smart materials such as material science and chemistry (Kretzer 2018). This common language could be gradually constructed with an experimental yet systematic approach to designing shape-changing architectures. The architect's ability to synthesize information, as pointed out by (Kennedy 2012) can be seen as an advantage from this viewpoint, orchestrating technical considerations of innovative materials with spatial, structural and environmental aspects in the design of dynamic architectures.

The general detachment of material issues in design practice also constitutes a problem for designing with shape-changing materials. Addington (2010a) argues that conventional materials in architecture are usually treated as artifacts, or as things that have fixed and static attributes. In other words, materials are usually subordinated actors in design practice. This approach probably has its roots in the conceptual separation between the processes of design and fabrication that has dominated architecture since Renaissance. The problem with treating smart materials in the same way is that the dynamic nature of smart material is intrinsically connected to their properties, which requires designers to adopt a material-centered perspective to understand such properties and design with them. Furthermore, shape-changing materials can transform their configuration constructing dynamic architectures, and as such, they must be part of the conceptual definition of the design idea. These dynamic materials cannot be assigned to geometries as an after-thought but must be an integral part of the design process, predicting their transformation within the larger context of the architectural space.

To this point, we have argued that smart materials are dynamic by nature, and that this property presents challenges when we want to incorporate them in architectural design and practice. The conflict between the traditional static view and the required dynamic approach to design appears in multiple facets of architectural practice, mainly, in design representation. Then, we have stated that in order to design with shape changing materials, designers must be able to synthesize knowledge from different areas other than architecture. Finally, we have argued that shape-changing materials cannot be considered as subordinate or passive actors in designing dynamic structures, thus identifying the need for a material centered approach.

2.0 DIGITAL TECHNOLOGIES FOR DESIGNING WITH SHAPE-CHANGING MATERIALS

With the increasing integration of digital design and fabrication, architects and designers are becoming more involved in materialization technologies (Kolarevic 2003). Consequently, designers are regaining control over material processes in design with the emergence of a material-based design approaches that favors an experimental model of practice (R. Oxman 2012). This experimental model of practice is what Kennedy (2012) defines as a vertical integrated model, which emphasizes the rapid synthesis of new technologies. Digital technologies, by integrating design and fabrication, favor the emergence of such experimental models of practice that help introduce shape changing materials into architecture practice.

On the other hand, computation in architecture is increasingly becoming a medium for material exploration challenging the separation of the processes of design and making (Menges 2015). The development of digital technologies is also extending the mental process of design into the material realm (Gursoy 2016). As a result, designers are regaining their position as the orchestrators of materialization processes. This digitally-enabled material-based approach has the potential to encourage the design philosophy described by DeLanda (2001) in which materials are not passive property assigned to forms but active participants in the design process. Computation, we argue, can become the medium for exploring shape changing materials, in a framework where material properties, structure and form become strictly interdependent. This approach could help prevent smart materials to be "patched atop an existing structural or architectural system" (N. Oxman 2010, 83) and rather be innovatively designed to develop their full potential.

In short, we argue that digital technologies can help design for shape change, by providing a tool that integrates digital design and fabrication, promoting the emergence of a vertical model of practice. Furthermore, computational design technologies help designing with innovative materials because they can help enable the mediation between material properties, form and structure. Nevertheless, in shape-changing materials, material properties and design are not the only principles to consider. As mentioned before, shape-changing materials are inherently dynamic, which means that the concept of time and how materials transform in time must also be considered. In addition, the activation energy or what triggers the transformation is also a principle to consider. What follows now is a discussion of which computational design tools can be used in orchestrating this and other principles for designing shape changing architectures.

A recent essay by Papadopoulou et al. (2017) argues that to program materials, designers need to consider three principles: material composition, activation energy, and transformation mechanics. These principles for programming materials provide a framework for designing shape-changing architectures. By placing design at the center of these three principles, we identify how computational tools can help dealing with the interdependencies between the described principles of material, energy and transformation. Figure 1 illustrates these three principles and identifies how computational tools can be used for this purpose. What follows is a discussion of the computational design strategies adopted for developing shape-morphing architecture in previous studies, from a design research perspective.

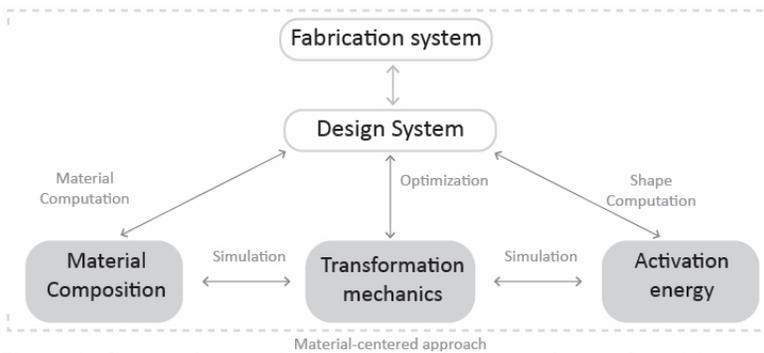


Figure 1: Computational tools for designing for shape change. Based in the principles proposed by Papadopoulou et al. (2017)

Material computation appears in the conceptual framework as a strategy that links material composition to design. In material-based design approaches, computation has allowed designers to integrate material properties with design at different scales, from the toolpath design of 3d printed objects for embedding shape-change into elements (Correa and Menges 2017) to the assembly logic of large scale objects conditioned by fiber orientation (D. Wood et al. 2018). This approach is often referred to as material computation, where design is conditioned, and emerges from, material properties and composition (Menges 2012). Physical computing allows researchers to quantify and measure shape change and understand how this behavior is strictly connected to design and material properties. This approach can also be seen in the work of Markopoulou (2015): The author presents a series of material explorations using physical computing to design responsive structures, using several shape-changing materials such as shape memory alloys and hydrogels.

Shape computation could be used as a strategy to predict and design the transformation mechanics of shape-changing architectures. The dynamic nature of shape-changing architectures requires the emergence of computational strategies to predict this behavior. The incorporation of dynamic concepts into digital theory is not without precedents: Liu and Lim (2006) introduce dynamic factors such as motion in digital tectonics. Shape computation entails defining shape operations, with a before and an after geometry. With this approach, the

'after' geometries could be the resulting geometry of the shape-transformation presented by the smart material. An approach for computing with shape transformation can be seen in the work of El-Dabaa and Abdelmohsen (2018), where the author proposes the use of motion grammars for characterizing and predicting the hygroscopic behavior of wood elements.

As mentioned before, one of the main advantages of using shape-changing smart materials is their ability to adapt to different environmental conditions. Design solutions could therefore be optimized for improving efficiency in buildings by including specific transformation mechanics that respond to defined activation energy. For instance, architecture skins or façade systems that change configuration in response to different environmental conditions, could be optimized to allow for sufficient daylight to enter buildings throughout the day. This responsive or dynamic optimization approach greatly differs from other types of optimization. In a static optimization approach, designs are optimized before construction, adjusting form and structure for improved performance. Through static optimization, designs can be adjusted only before materialization, therefore there is no dynamic adaptation of the building to the changing requirements of the environment. In a dynamic optimization approach, mechanical systems can adjust the building geometry to adapt to the environment, seen, for instance, in the design of a responsive skylight system, that adapts its form to maximize sunlight (Henriques, Duarte, and Leal 2012). The complexity of these systems that separate structure and the driving actuators becomes a major disadvantage of this approach (Kretzer 2016), as well as elevated fabrication and maintenance costs (Ball 1997). In other words, optimization strategies could be used to improve efficiency in buildings with shape-changing materials, designing for targeted transformation mechanics triggered by an activation energy.

Optimization strategies could also be used to find optimal material configurations for creating shape-changing actuators. For instance, Worre Foged & Pasold (2015) used an evolutionary search mechanism to find the adequate combination of materials and their bonding temperature for two materials in a bilayer configuration. The authors successfully applied the evolutionary search optimization technique in creating a composite material that reacts to temperature changes.

Simulation studies have been conducted in different stages of research involving shape-changing architectures. The literature includes simulation studies to predict shape morphing of kinetic solar skin designs using shape memory alloys – a shape-changing smart material – in the work of (Pesenti et al. 2015) and visual and thermal simulations to predict the performance of a dynamic shading device in its multiple configurations (Pesenti, Masera, and Fiorito 2015). However, computer simulation could also be used in predicting how different material compositions react to the material's activation energy, as depicted in Figure 1. For instance, Abdelmohsen et al. (2018) studied the hygroscopic behavior of wood elements, developing a parametric model for predicting its shape-changing behavior considering different material properties such as fiber orientation and material thickness. A similar approach can be seen in the work of (D. M. Wood et al. 2016), where the authors use simulation tools for designing responsive timber structures, defining grain orientation and thickness as per targeted geometries in a multi-part system.

Overall, the computational tools identified above help orchestrate the interdependences between design, material composition, activation energy and transformation mechanics. There are several other computational tools that can be used in developing designs for shape-changing materials. However, the goal of this paper is not to provide a complete list of such strategies and approaches, but rather, to argue that digital technologies enable the development of material-centered design and fabrication systems that incorporate the described principles for programming shape-changing architectures.

3.0 DESIGNING SHAPE-CHANGING ARCHITECTURES

So far, this paper has focused on describing the challenges for designing shape-changing architectures, arguing that digital technologies can help designing with dynamic smart materials. The previous section outlined ways in which specific computational tools and

strategies such as material computation and simulation can help deal with the basic principles for programming shape change in materials. Nevertheless, it is important to remember that designing architectures – shape-changing or not – entails shaping the build environment for specific human activities, in response to defined environmental conditions. In order to design shape changing architectures, design and fabrication systems must be developed considering specific function requirements and existing climate conditions. In other words, it is important to contextualize the design problem when proposing design methodologies for developing shape-changing architectures.

Andreoletti and Rzezonka (2016) highlight the importance of contextualizing smart or programmable materials in design practice. Contextualizing the design problem is an important first step in any systematic approach to design. Within a design system, Duarte (2018) describes this component as a formulation subsystem, that can interpret the design context, which includes user requirements and physical contextual information. Similarly, to design shape-changing architectures, the interaction of dynamic systems with the environment and the human experience become essential in the definition of the design problem.

Contextualizing means considering functional requirements and contextual information such as climate conditions. When designing shape-changing architectures, function requirements would determine the degree of dynamism that the structures can have. For instance, in designing a shape-morphing skin, designers must establish the desired openness of the system, and how sensible the system should be to environmental changes. These design decisions derive from defining the functional requirements of the space. In addition, specific climate conditions define what activation energy will trigger the shape-change. For instance, in a hot and humid climate, the activation energy would likely be humidity and/or temperature, triggering a reaction in the shape-changing system. Functional requirements and climate conditions define a formulation process that specifies the requirements of the design but occurs prior to designing.

Figure 2 depicts a proposed approach for designing shape-changing architectures, with three components: formulation, design and fabrication. The first component, formulation, defines the functional requirements taking contextual information of the design problem into account. The design component is framed by the principles described in the previous section of material composition, transformation mechanics and activation energy. At this point, computational design tools play an important part in mediating the interdependencies of material and structure. The last component is the fabrication of design solutions, that can be enabled by different manufacturing technologies from automated production methods such as 3d printing to other more traditional manufacturing techniques. The enabling technologies for materializing shape-changing architectures are not discussed in the context of this paper, but it is important to define them as part of the approach.

The first component, formulation, is composed by two complementing processes: Defining the frame of transformation-the parameters of how the geometry will transform-, and the site-specific formulation process of how the system will react to the environment. The first process, the definition of the transformation frame is prescriptive, and should be defined by the functional requirements of use the space has. The second process situates the transformation mechanics in relation to a specific site with defined climate conditions. The thorough understanding of environmental conditions is especially important in the case of designing shape-changing architectures, because the activation energy might depend on specific climate conditions. There are other shape changing materials whose activation energy are not derived from shifting -outdoor- environmental conditions, such as electroactive polymers that change shape with high voltages (Kretzer and Rossi 2012). Nevertheless, the definition of how the system interacts with the environment is crucial in the formulation process as it defines how the system will perform through time.

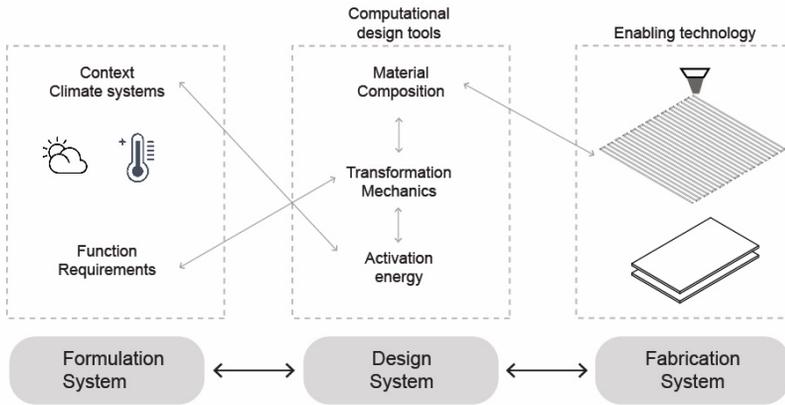


Figure 2: An approach for designing shape-changing architectures

The described approach illustrates the different considerations for designing shape-changing architectures. The subdivisions between the different stages of formulation, design and fabrication are merely conceptual, as these processes often become interdependent, particularly design and fabrication. Nevertheless, the idea is to identify which different components and considerations define the design and fabrication of shape-changing architectures, contextualizing these processes for tailored needs and a particular climate. Furthermore, this approach, at this point, is still theoretical. Further studies need to be carried out in order to validate and/or extend it within the context of designing with shape-changing smart materials.

CONCLUSION

Smart materials and specifically, shape changing materials have already been adopted in other areas of inquiry. The question yet to be answered is how architects can incorporate them into the built environment, to construct responsive and efficient buildings. The competence of architects in developing shape-changing architectures appears to lie in being able to articulate geometry, material properties, and fabrication strategies (Correa and Menges 2017). Discussing the challenges of designing with dynamic materials, we argue for the emergence of a computationally-enabled models of practice that can help overcome these challenges in design.

Kennedy (2012) argues that the implementation of new technologies in design requires new models of practice. The transfer of innovative shape-changing materials technologies from material science engineering to design practice will require the development of a new toolset for architects. Designing for shape-change entails not only a shift in the way we envision architecture spaces but also requires expanding our design-research methodologies. We argue that such design methodologies could rely on computational design tools, adopting a material-centered perspective. Providing an overview of methods and approaches in designing with shape-changing materials, this paper exemplifies how computational tools can help deal with the interdependencies between material, design and shape-transformation.

This paper also discusses an approach for designing with shape-changing materials that starts to systematize design and fabrication processes for dynamic architectures, identifying several parameters that should be considered in constructing such dynamic architectures. Different computational tools for dealing with the interdependencies of those parameters such as material composition and transformation mechanics have been identified. We also identified that design and fabrication processes for constructing shape-changing architectures are strictly conditioned by defined functional requirements and contextual information. This contextualization of the design problem becomes the first step in the approach proposed for designing dynamic architectures.

Shape-changing materials are emerging as a new device to design with in architecture that will ultimately lead to a new architectural language. A language that is dynamic and that questions current forms of representation, traditional forms of design, and changes the way we think about the built environment. This new language requires the development of new techniques and strategies for designing shape-changing architectures, that help deal with the dynamic nature of these new materials, and allow for mediating material properties, structures, transformation mechanics, within a specific context and for a specific fabrication logic. We argue that computationally-enabled design and fabrication frameworks could aid the process of building dynamic and efficient shape-changing architectures.

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