Bio-inspired Passive Kinetic Solar Shading Device for a Responsive Architectural Envelope

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Abstract

In this paper, the authors present research concerning the study of actuation systems in plants. Plants have evolved a multitude of mechanisms to actuate organ movement with neither supply or external energy nor any kind of mechanical or electronic control. The transformation of these strategies into technical solutions for responsive architectural envelopes requires a large number of studies and experiments with new technologies that include smart materials and new capabilities in simulation software. The research field of Programmable matter allows for systems to be autonomously changed according to various factors (water, light, UV ray, heat, touch, etc.). These are basic ideas we have extracted from nature according to development of advanced science and technology. Like in nature, anisotropic changes start at the molecular level, which affect biological structures and mechanics in their entirety at the macroscopic level. Programmable matter is thus linked to the concept of shape memory materials (SMMs), which inherently has the ability to perform information processing that can be significantly changed by external stimuli. The objective of this research is the use of shape memory alloys (SMAs) as smart actuators for the biomimetic translation of actuation systems in plants into an architectural envelope that can adapt and respond to environmental stimuli. Our aim is to develop a new type of passive kinetic solar shading device as a result of biomimetic application. Unlike traditional mechanical activation used for dynamic systems in kinetic façades, this type of responsive architectural envelope requires no complex mechanical parts, electronics or sensors, which can lead towards energy efficient design strategies.

Keywords: Responsive Envelope, Biomimicry, Passive Kinetics, Shape memory alloys (SMAs), Smart Actuators, Energy Efficiency

1. Introduction

The building envelope is the first tool for energy management; it is one of the most important design parameters determining the indoor physical environment, thus affecting energy usages in buildings[1]. The design of the envelope can affect the energy performance of the whole building. In recent years, some promising and innovative building envelopes tend to be more adaptive and interactive with the climate, space functions, indoor environments and occupants[2]. Adaptation is the evolution process whereby an organism becomes better able to live in its habitat[3]. Nowadays, biology is no longer just a matter for biologists, but it is a new inspiration for technical thinking. Some of these studies have looked at nature as a source of inspiration for subsequent application to architecture, this approach is known as biomimicry. Systems found in nature offer a large database of strategies and mechanisms that can be implemented in biomimetic designs.

Plants, much like buildings, are fixed at a place so they cannot move from one place to another. Plants cannot show locomotion but they have various types of movement. The two important types of plant movement are tropic movement and nastic movement. In this article, we are specifically interested in *thermonastic* movements (temperature stimulus). This movement is caused by change in temperature intensity. In regarding to actuation systems in plants, the *Mimosa pudica* is an action plant that closes its leaves when given a stimulus. The plant integrates both sensing and actuating mechanisms, and the distinctive motion is has to do with a hinge-like point, the *Pulvinus*, making the characterization of the motion attractive. The *Mimosa pudica* is well known for its rapid plant movement, its responses to touch and heat stimuli. Like a number of other plant species, it also undergoes changes in leaf orientation termed *sleep* or *nyctinastic* movement. The foliage closes during darkness and reopens in light[4].

To be able to translate elegant mechanical movements in plants into the design of a responsive architectural envelope, one must understand the analogy of 'motion' in architectural design and plants. The term kinetics is originated in the Greek word *κίνησις* (Kinesis) pertaining or associated to movement, motion, and also indicates an organism's response to a particular kind of stimulus in biology[5]. In the context of architecture, in 1970, Professor Zuk[6] described kinetic architecture in his book *Kinetic Architecture* as a field of architecture in which building components or whole buildings have the capability of adapting to change through kinetics in reversible, deformable, incremental, and mobile modes.

Nowadays, responsive envelopes are thus becoming an innovative research topic, due to the necessity of reducing building energy consumption. Kinetic systems are largely integrated in the design of adaptive or responsive envelopes, as it differs from a traditional facade in that it incorporates variable devices whose control adaptability allows the building envelope to act as a climate moderator[7]. But there is a weak point concerning kinetic façade systems: they generally use a large number of moving components connected to each other to perform movement. This makes the system complicated and, above all, consumes a lot of energy to be built and to operate. On the opposite, mechanisms in nature are much simpler, as they produce movement changing one of their intrinsic properties[8]. Such as the movements exhibited by the *Mimosa pudica* responding to external stimuli due to variation of the turgor pressure in the motor cell and the elasticity of the *Pulvinus* actuation. However, the motile mechanism of the plants combines both biochemical and biophysical perspectives. For this reason, the research field of programmable matter has spurred the introduction of biological processes for understanding the behaviour and design of building systems. Programmable matter is linked to the concept of a material, which inherently has the ability to perform information processing or what we call shape memory materials (SMMs) which have the ability to 'memorize' or retain their previous form when subjected to certain stimuli[9].

In this research, we are interested in the biomechanical motions and actuating mechanisms of the *Mimosa pudica* according to thermal stimulation along with the use of shape memory alloys (SMAs), which belong to a class of SMMs, as the biomimetic translation for the passive kinetic solar shading device. We study the Nickel Titanium (Ni-Ti) shape memory alloy to demonstrate its unique properties: the shape memory effect (SME) and super elasticity (SE). Their transformation is instantaneous and completely reversible. It occurs at specifics temperatures. These properties are ideal to interpret actuation systems in plants for bio-inspired devices. Moreover, the use of SMA actuators has been tested in order to perform the shape change without any external mechanical devices. Even though, currently there are not much diffused applications of SMA actuators in the building industry, their intrinsic ability to sense and directly respond to the changing conditions (temperature stimulus) with a range of movements makes these materials attractive for application towards passive systems in kinetic solar shading devices.

2. Adaptive Architectural Envelope: a review

Our buildings' main purpose and especially the purpose of the building envelopes are to protect us from the surrounding climate; but they also need to be able to provide good comfort. The primary design objective for any building envelope is to sustain conditions of thermal, visual and acoustic comfort with minimum energy consumption[10]. The design parameters for thermal, visual and acoustic comfort should respect the local environmental conditions. We have to face the fact that recent years of impact of various environmental conditions, such as climate change, play an increasingly decisive role in the design of new architectural and civil engineering structures. The introduction of adaptive systems into architectural engineering projects allows for a new approach to form finding. Apart from traditional concepts, such as "form follows function" or "form follows force" the amount of energy brought into the system can influence the optimum geometry of the structural system: "form follows energy"[11]. The environment is constantly changing and producing new challenges to cope with. Light (solar radiation), temperature, relative humidity, rainwater, wind (air movement), noise and carbon dioxide (air quality) are the basic environmental issues affecting buildings in general. These issues significantly affect occupant comfort demands as well as building performance. Despite the fact that the climatic characteristics of the area are variable parameters, conventional façades are largely static; so we use large amounts of energy in order to control internal comfort. Energy consumption for space heating and cooling makes up 60% of the total consumed energy in buildings[12].

A new generation of high-performance envelopes have contributed to the emergence of sophisticated assemblies combining real-time environmental response, advanced materials, dynamic automation with embedded microprocessors, wireless sensors and actuators, and design-to-manufacture techniques. This practice has fundamentally transformed the way in which architects approach building design with a shift in emphasis from form to performance, from structure to envelope[13]. A responsive building skin includes functionalities and performance characteristics similar to those of an 'intelligent' building skin including real-time sensing, kinetic climate-adaptive elements, smart materials, automation and the ability for user override. But it also includes interactive characteristics, such as computational algorithms that allow the building system to self-adjust and learn over time, as well as the ability for inhabitants to physically manipulate elements of the building envelope to control environmental conditions[14]. Learning takes place in accordance with changing environmental conditions and inhabitant preferences, such that the algorithm anticipates desirable configurations. A truly responsive building envelope, therefore, not only includes mechanisms for inhabitant sensing and feedback, but is also committed to educating both the building and its occupants. Information is provided to the building's inhabitants so they too can learn over time and modify their actions relative to climate and energy use. This way, both building and occupant are engaged in a continuous and evolving conversation.

The classic design problem-solving contradiction is: how can we profit the most of natural light for visual comfort and free energy from the sun without over heating the interior of the building[15]. Within the scope of this research, the type of responsive architectural envelope is defined as one that responds to changing environmental conditions, both interior and exterior, while managing the indoor environment. Responsive architectural envelopes have the ability to change with time according to exterior environmental variations as well as interior activities and their interactions with inhabitants. We research into responsive architectural envelopes with two main proposals: contributing to energy-saving for heating, cooling, ventilation or lighting, as well as inducing a positive impact on the indoor environmental quality of buildings.

2.1 Advances in architectural envelopes: kinetic façades

Since the last century, different design proposals for more active and less static façades have gradually emerged: kinetic façades as environmental control systems, capable of responding to different changing environmental aspects. Contemporary architecture has adopted kinetic motion as a process of self-adaptation and responsiveness. Responsive façades are expanding and improving thanks to technological enhancement and the use of clever geometries. 'Kinetic architecture' was coined by William Zuk and Roger H. Clark in the early seventies when dynamic spatial design problems were explored in mechanical systems[16]. The Arab Institute in Paris (Fig 1a) completed in 1987, by Jean Nouvel, was one of the first and most widely known examples to employ an active façade based on automatic response to environmental sensors. The automatically controlled shutters are a technical interpretation of the traditional Arabic sunscreens[17]. 25,000 solar cells, similar to a camera lens, are controlled via a computer to moderate light levels on the south façade[18]. In his 'state of the art CABS concepts'[19], Loonen includes this envelope inside the thermal-optical domain; it means adaptation causes changes in the thermal energy balance of the building and, at the same time, the adaptive behaviour influences the occupants' visual perception. Although laboratory tests or scale field tests to demonstrate that the visual comfort and energy benefits can be associated with these kinetic shading systems[20], their considered functionality design has not been validated as a successful adaptive envelope case and it would be more considered as a complex façade system. According Coelho and Maes' studies about shutters[21], the façade panels are noisy, tend to break easily and they are fully automated, not allowing residents in the building to have a high granularity of control over their own space. It would be about an adaptation reached by means of mechanical driven fenestration devices consuming electrical energy.

Also, in recent years, we have seen noted examples of advances in adaptive architectural envelopes, through architectural kinetics and dynamic structures. Two important attributes of kinetic architecture are integrated in the work of dECOi architects: Aegis Hyposurface (1999-2001) (fig.1b) and of Foster and Partners: Aldar Central Market (2006-2011) (fig. 1c). The two attributes are responsiveness and a transformable kinetic building skin. These building skins demonstrated the ability to manipulate the interior spatial conditions using a complex mechanical façade and a roof system. However, these solutions involving complex ‘hard’ mechanical components like multiple pistons to actuate transformation always come heavy and with high-energy consumption.

Figure 1: Some examples of kinetic façades: (a) Arab Institute Paris (b) Aegis Hyposurface (c) Aldar Central Market, Abu Dhabi

We remark that kinetic façade systems use a large number of moving components connected to each other to perform movement. This makes the system complicated and, above all, consumes a lot of energy to work. On the opposite, mechanisms in nature are much simpler, as they move changing one of their intrinsic properties. Several plants have developed a variety of mechanisms able to sense and directly actuate the movement to execute vital functions. Sensors and actuators, through controlled geometry, changes like turgor pressure, cell growth, swelling and shrinking, are able to solve physiological issues. Spatial reorientation, seed dispersal, ingestion and fixation are some of the natural processes activated to preserve the organism and to protect it from environmental changes. The *Venus flytrap*’s leaf folding and the *Mimosa* plant[22] highlight a rapid response to external stimuli. Other natural systems, like tree branches, perform very slow movement to adjust organ orientation. So, learning from nature may be particularly useful for a biomimetic translation into the design of a kinetic shading device[23].

3. Biomimicry

The terms biomimicry and biomimetics come from the Greek words *bios*, meaning life, and *mimesis*, meaning to imitate. Biomimetics is defined as the ‘abstraction of good design from nature’[24] or ‘an emerging discipline that emulates nature’s designs and processes to create a healthier, more sustainable planet’[25]. Biomimicry is an interdisciplinary field that has been developing for some time in other fields, such as engineering or medicine, however in recent years we begin to see how several research works have been developed around biomimicry to look into new solutions in architectural design. In recent years other research works have tried carrying out different methodologies for developing new building envelopes based on biomimetic principles. We compile some of the built projects, always in terms of adaptive envelopes and their interaction with the environment through energy exchanges and improving efficiency. A well-known example of bio-inspired kinetic façade is Flectofin by ITKE[26] (Fig. 2a). It is an innovation in adaptive façade shading systems inspired by the natural elastic kinetics of the *valvular* pollination mechanism in the *Strelitzia reginae* flower (commonly known as the ‘Bird-Of-Paradise’ flower). The flower's inspiration comprises a reversible deformation when an external mechanical force is applied, making it a case of bending kinetics in nature and whose technical implementation result operates in complete absence of hinges and only relies on reversible material deformation. This adaptive behaviour is abstracted and materialised as Flectofin: a hinge-less louver system that is capable of shifting its fins 90 degrees by inducing bending stresses in the spine caused by displacement of a support or change in temperature of the lamina. The kinetic mechanisms of Flectofin has be applied as an adaptive exterior shading system (fig. 2c) in the One Ocean Thematic Pavilion (Fig. 2b) for the Yeosu Expo 2012 in Korea, by SOMA Architecture, in collaboration with Knippers Helbig Advanced Engineering. This bio-inspired adaptive façade shading system shows an advantage of compliant mechanism by gaining motion through the flexibility of the construction, rather than linking multiple rigid parts together. This allows for a significant cost and maintenance reduction. But this elastic kinetic approach to façade shading still relies on external electrical power, similar to a notable and acclaimed example of external adaptive sun-shading is the Al-Bahr Tower in Abu Dhabi (Fig.2b), the 29-storey building presents an adaptive folding shading system inspired by the deployment mechanism in flower petals and Islamic geometric patterns based on ridged link mechanisms, which needs external electrical sources along with linear actuators to activate the elements allowing five different operative configurations, from completely open to totally closed.

Figure 2: Some examples of bio-inspired kinetic façades: (a) Flectofin (b) One Ocean Thematic Pavilion (c) Al-Bahr Tower

A true objective of Biomimicry is sustainability, learning from nature can sustainably innovate design systems. If we look at kinetic structures in biology, for example, actuation and systems in plants are increasingly recognized as models to derive biomimetic principles from[27]. Higher plants evolved a large variety of mechanisms to actuate the movement of their organs without external energy inputs but responding to environmental stimuli. Take an example of a well-known moving plant: the *Mimosa pudica* exhibits a rapid, defensive response to external stimuli, such as the closing of its leaves and bending of its *Pulvinus* -the joint-like thickening of the plant near the bottom of a leaf or leaflet where the plants 'motor cells' reside. Once the plant is activated by external stimuli (touch, heat), it changes the water level in turgor pressure that causes the bending of the *Pulvinus*. Even though the biological phenomena are fruitful processes to observe and learn from, sometimes they cannot be directly interpretable for design tasks; they need biological-technological design analogies to help achieve their biomimetic translation.

3.1 Biomimetic framework in Architecture

The original method of biomimetic architecture is a cross-disciplinary approach between biology and architecture. This method was initially called '*Bau-Bionik*', coined by an architect, Göran Pohl and a biologist, Werner Natchtigall[28]. As a result of a combined effort by the two disciplines, it describes the principles that can be used to compare nature and technology: how biology can be used as a source of inspiration and 'translated' in building and architectural solutions along with current advanced technology. Nature cannot be directly copied to be able to provide architects with a wealth of analogues and inspirations to achieve a true objective of biomimetic design. However, it is not a trivial task to understand the principles that govern the living, especially for architects who need to search for elegant biological analogies and transfer them to solve problem in architectural designs. Practicing biomimetics means learning from nature for the improvement of design and technology in parallel with environmental issues. One must only then be cautious of too direct interpretations. Inspirations from nature for architecture will not function if they are not well abstracted within the context of an interdisciplinary analogy.

In the book '*Bionik als Wissenschaft*'[29], which applies the theory of cognition to biomimetics, signified this process in three-steps: *Research → Abstraction → Implementation*. By observing a cognitive biomimetic design process within the context of interdisciplinary design, 'identification' and 'abstraction' often prove to be some of the most important as well as most difficult steps in a biomimetic project (Speck, 2008) Thus, we have found two common difficulties for architects to apply biomimetic methodology into their design process. We define the difficulties in two transitions: *1.What to look for in nature? and 2. How to interpret natures' principles and transfer them into design tasks?*

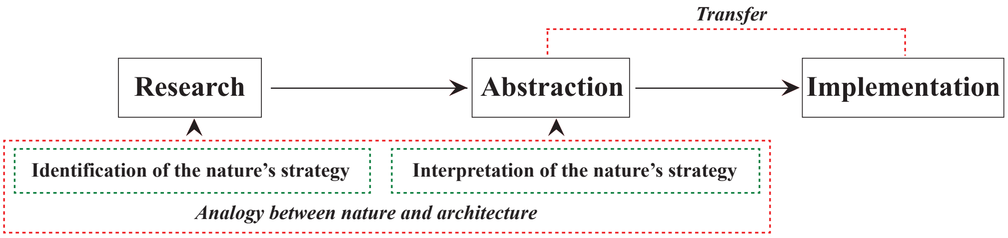

Figure 3: The two transitions of biomimetic design process in architecture[30]

First, one must be cautions when translating inspirations from the living world into world of technology and should not expect the 'impossible': a direct copy never leads to the goal. Second, one must understand that nature represents no blueprints for its structure, and its processes are not always simple to appreciate, let alone to implement. Nonetheless, they are available for our observation[31].

4. Smart materials

The term 'smart material' is widely used and smart materials are recognized as a specific material group. However, no general consensus on the usage of the term is defined. There is an active discussion regarding the linguistics of the term. In general, the following definition is applied: "smart materials are materials capable of automatically and inherently sensing or detecting changes in their environment and responding to those changes with some kind of actuation or action"[32]. This action or actuation is based on a change in the material's intrinsic properties. Takagi[33] explained 'smart materials' as intelligent materials that respond to environmental changes at the most optimum conditions and reveal their own functions according to the environment. With the development of material science, many new, high-quality and cost-efficient materials have come into use in various field of engineering. In the last ten decades, materials became multifunctional and required the optimization of different characterization and properties[34]. Smart materials react to external stimuli, such as light, temperature, pH and magnetic fields. These materials can respond by, for example, changing their colour, shape or transparency. As these materials detect a stimulus and act accordingly, they have both sensory and actuation properties.

Nowadays, technology pushes towards 'smart' systems with adaptive functions and features, it needs the increase of sensors and actuators; thereby resulting in an undesirable increase in weight and volume of the associated machine components, including extra electrical energy to activate the systems in question. The interesting concept of 'smart materials' often mimics biological functions: it describes self-adaptability, self-sensing, memory and multiple functionalities of the materials or structures and properties that react to changes in their environment. This means that one of their properties can be changed by an external condition, such as temperature, light, pressure or electricity. This change can be reversible and repeated many times. There are many groups of smart materials, each exhibiting particular properties, which can be harnessed in a variety of high-tech and everyday applications. These include shape memory materials (SMMs) that are part of programmable matter technologies. SMMs have the ability to change its physical properties (shape, density, moduli, conductivity, optical properties, etc.) in a programmable fashion, based upon user input or autonomous sensing[35]. Programmable matter is thus linked to the concept of a material, which inherently has the ability to perform information processing. Programmable matter allows systems to be autonomously changed according to various factors (water, light, UV ray, heat, touch and etc.) [36]. These are basic ideas we have extracted from nature according to the development of advance science and technology. Like in nature, 'changes' start at the molecular level, which affect the whole and its mechanics at the macro level.

Advances in smart materials have found their way into the architectural practice and experimental projects[37]. Smart material systems are categorized by behavioural aspects, such as structural performance, climate, energy, and architectural performance. One of the great advantages of smart material technology is its ability of integration in existing building components. Due to their intrinsic material performance, smart material systems have generally small dimensions. By embedding smart material systems in building structures, lightweight building components can be accomplished which envision multi-behavioural performances.

4.1 Shape memory materials (SMMs) and Shape memory alloys (SMAs)

Shape memory materials (SMM) are a subject that interests both the academic world and the industry[38]. It is a promising subject, a technological challenge and, moreover, it appeals to the imagination. These materials, exhibiting what is called anisotropic behaviour, have the ability to regain their permanent shape after a deformation that seemed irreversible[39]. The shape recovery is triggered by an external stimulus, which is mainly a temperature that surpasses a critical point[40]. But the type of energy that should be added to trigger the shape recovery depends on the specific material.

Shape memory materials (SMMs) feature the ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied[41]. This is known as the shape memory effect (SME). The reversible martensite-austenite transformation creates the SME mechanism[42]. This is mainly triggered by surpassing a critical transformation temperature, but the same result can be obtained by applying stress as an external stimulus[43]. The SME can be utilized in many fields, from aerospace engineering (e.g., in deployable structures and morphing wings) to medical devices (e.g., in stents and filters)[44].

Shape Memory Alloys (SMAs) are part of SMMs. SMAs are able to 'remember' a shape constituted in advance[45], this shape is the permanent shape. They sense an external stimulus and respond to it by changing their physical properties, which results in a deformation or deflection of the structure[46]. SMAs are known for their excellent memory phenomena accompanied with practical applicability. They use the martensite-austenite transformation to achieve the SME and the super elastic effect[47]. Of all the SMM groups, shape memory alloys exhibit (in general) better mechanical properties. The best-known SMA is a nickel-titanium alloy. SMAs may have two different kinds of SME; these are commonly known as the one-way shape memory effect (OWSME) and the two-way shape memory effect (TWSME). In this research, we are interested in the TWSME for the design of a bio-inspired passive kinetic shading device. Exhibiting the TWSME the alloy is capable of 'learning' to have two stable positions, one above the so-called critical temperature and the other one below[48]. It flips back and forth between these two shapes as the temperature changes.

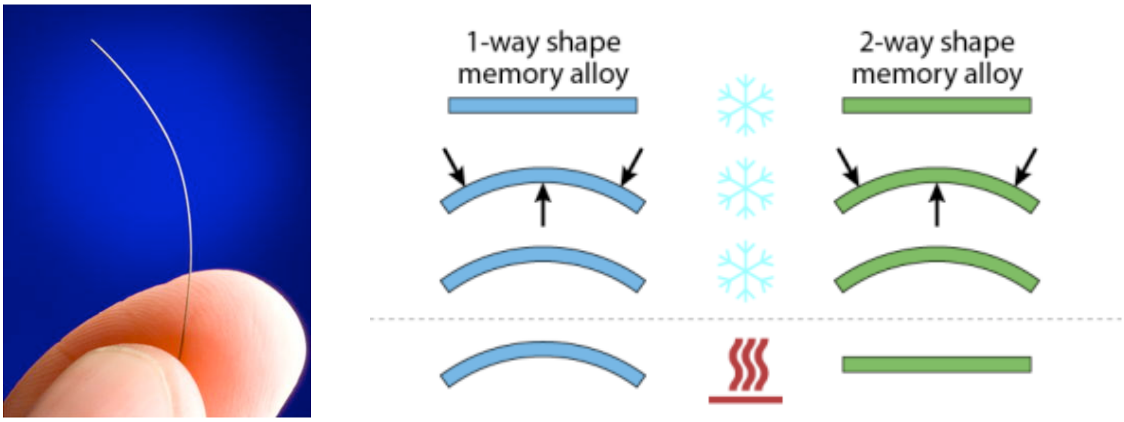

Figure 4: A shape-memory wire, one-way and two-way shape memory effect.

Not until recently, SMAs were not widely used in the field of architecture. The concept of 'adaptive' and 'responsive' architecture has lead to a whole new paradigm of building design and use. Thus, the intrinsic ability of SMAs to sense and directly respond to the changing conditions with a range of movement with low (or without) activation energy makes them interesting tools for the realisation of an adaptive building component[49].

5. Biomimetic Design methodology

How to turn inspiration into a working method?

In this research, as we mentioned above, we are interested in the *nastic* movement of the leaf folding of the *Mimosa pudica*, especially its actuation system, in which the whole organ is actuated by the changes in turgor pressure. The criteria of a successful biomimetic design are included: 1. Choice of biological precedent, 2. Abstraction of principles from biological precedent and 3. Design development and implementation. Thus, the biomimetic design methodology carries on in 3 steps:

1. *Understanding of the organism:* The *Mimosa pudica* is studied with special attention given to the movements exhibited by the plant. The study involved understanding the reactions causing the nastic movements and the processes happening simultaneously at the leaf level.

2. *Abstraction:* Understanding its mechanical means of movement, actuation system, making analogies between biology and technology (actuation methods and material study). This part of the study incorporates simple experiments to generate the collapsing movements similar to the leaflets in comparison with the shape change of (SMA). This phase involves the creation of the working model that could be applied to an architectural function.

3. *Design realization and application*: The prototype is designed to replicate the turgor change at the micro scale, which impacts the kinetic movement of the *Mimosa* leaves at the macro scale according to the stimuli. It is decided that the device would function as a shading device that has the capacity to adjust itself, on its own, for the thermal and visual comfort in the interior of the building according to sun radiation intensity.

5.1 Nature role model: Nastic movement in Mimosa Pudica

Certain plant cellular structures like those in the *Mimosa pudica* (sensitive plant), the *Albizia julibrissin* (*Mimosa* tree) or the *Dionaea muscipula* (Venus Flytrap) all exhibit actuation physiology, which employs turgor pressure manipulation[50]. The *Mimosa pudica* is an action plant that closes its leaves when given a stimulus (touch, heat). The plant's movement is directed by motor cells and tissue mainly in the *Pulvinus*, which is a joint like member at the base of the leaf. These motor cells are driven by phenomena called turgor pressure. The osmotic hypothesis states that the *thigmonastic* movement of the *Mimosa pudica* is powered by a sudden loss of turgor pressure in the motor cells of the *Pulvinus*. The mechanism of this movement can be explained as follows. The *Pulvinus* is a flexible hinge located at the base of the stalk of the leaf. It has a very anisotropic structure. The motor cells are organized in such a way that they allow changes with changing turgor only in length, but not in circumference[51]. As a result, the antagonistic changes in the length of the flexor and extensor cells produce the petiole movements.

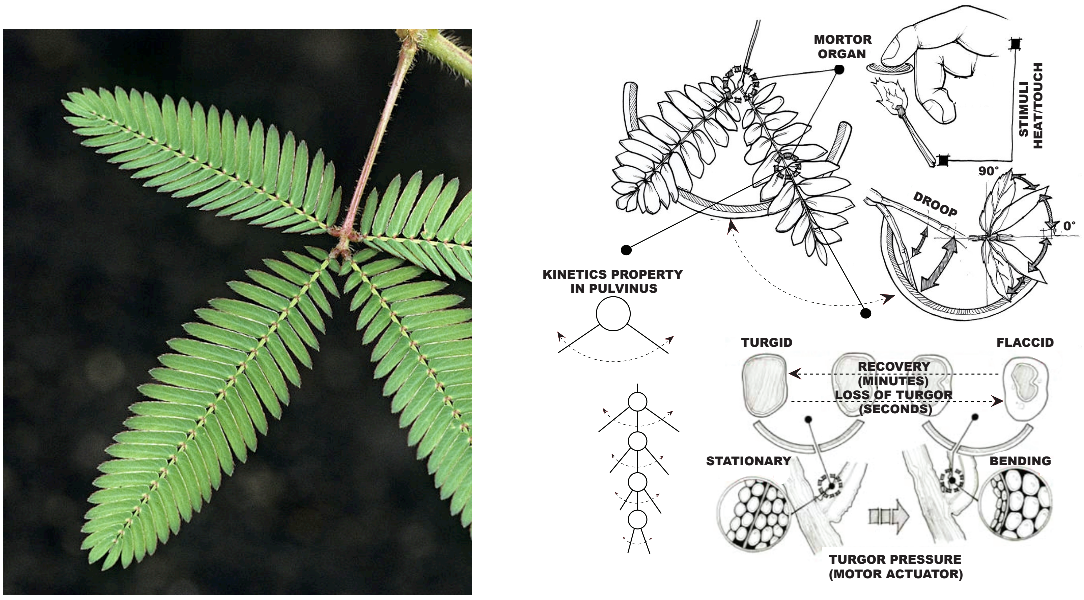

Figure 5: Mimosa leaves, Mimosa pudica leaves mechanism and microscopic scale of Turgor pressure.

The stimuli impart energy into the plant and, as observed, the greater the change in energy the faster the response from the plant. When the *Mimosa* is perturbed, a signal is sent to the motor cells, activating a sudden and sharp increase in membrane permeability, which produces kinetics of volume changes in the upper and lower part of a *Pulvinus* during a petiole bending. Recovery takes roughly fifteen minutes but can only occur during the day. This biological concept refers to the novel concept of 'form follows energy' for a responsive architecture.

5.2 Abstraction

The interesting issue of the *Mimosa* is that it reacts by folding together when stimulated (by touch or heat). We have abstracted the hierarchical shape change and deployment of the *Mimosa* leaves, which is caused by the change of permeability of cell membrane at the turgor pressure in the motor cells of the *Pulvinus* when it senses the stimuli. Just as in nature, where changes at the small scale affect the shape change at the macro scale, similarly, shape memory materials can trigger autonomous actuation systems like that of the *Mimosa*. In comparison, SMMs work in a similar way: it shows the SME when the SMA wire (as shown in figure 6) changes from shape A (contraction) to shape B (relaxation) because of the material's internal crystalline structure change according to the transition temperature. Today, we can commercially buy SMA wires that can be trained at 70°C and 90 °C temperature, but in theory, SMA wires can be trained at any temperature from -20 °C to 110 °C; their transition temperature depends on specific chemical composition and processing. Changing NiTi's composition can change its properties significantly.

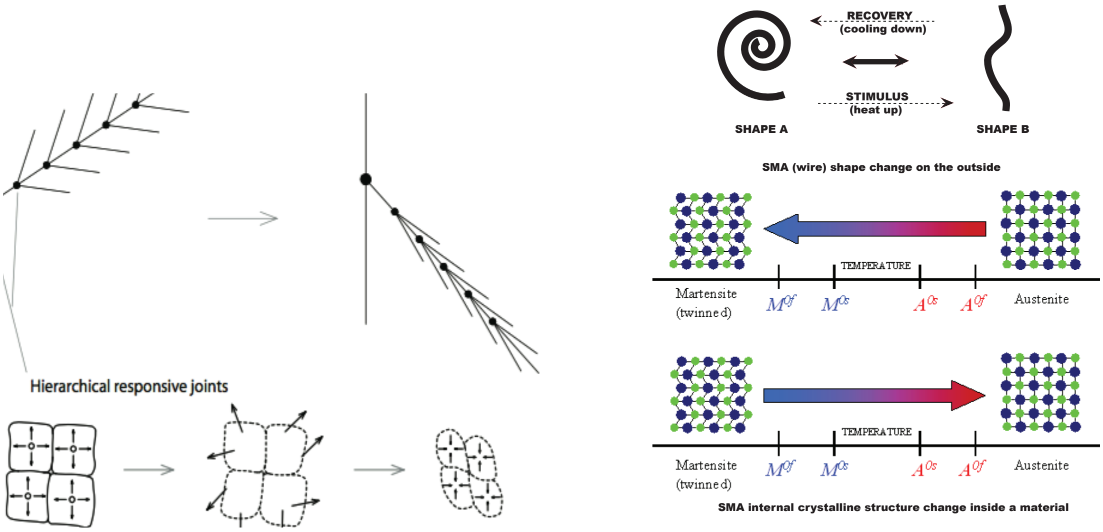

Figure 6: The comparison of mechanical change at macro scale and physical property change at micro scale between Mimosa pudica leaves and the Shape memory alloy wire.

According to our abstraction of the kinetic motion of the *Mimosa* leaves at the macro and micro scale, we've come up with the design of a shading device that has its own capacity to passively react to temperature change, itself a consequence of the intensity of sun radiation. We use SMA wires as actuators and at the same time create a free-form structure of the shading device. It is a kind of soft kinetic system that passively responds to immediate environment's stimuli (in our case, sun radiation). We will also bring the attention to the kinematics potential of origami-folding patterns investigating how those geometries can be modelled so as to optimize the surface displacement. The design development and details will be explained in the next chapter.

5.3 Design development of a bio-inspired passive kinetic solar shading device

This bio-inspired passive kinetic solar shading device is a kind of active system that can perform exhibiting similarity to plant movement. The use of SMAs helps to mimic the characteristics of actuation in plants where their intrinsic physical properties change according to environmental stimuli (in this case heat). Recent trends in shading device design have been trying to replace traditional mechanical systems with integrated multifunctional and smart actuators that are responsible for moving or controlling the mechanism[52]. In our design, the use of SMA as an actuator helps to cut down on the implementation of complex mechanical parts within kinetic envelope components and it is possible make them not require external electrical sources; instead responding to the intensity of solar radiation as a stimulus.

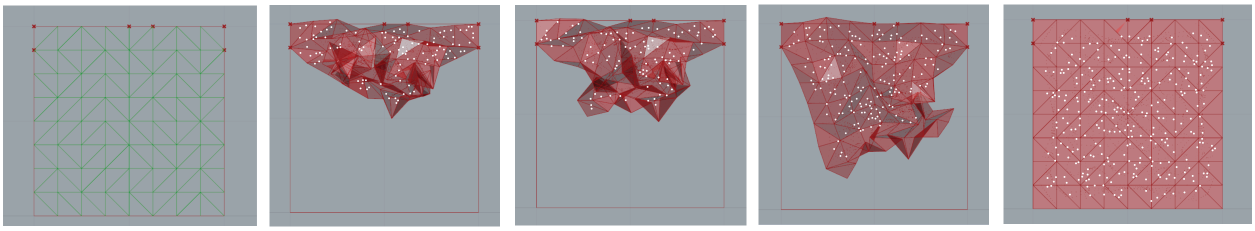

Figure 7: (From left to right): The original origami crease pattern where SMA actuators are placed and the sequenced simulation of the passive kinetic shading device is deployed and activated by the sun radiation stimulus.

As shown in the latter figures, we have created a specific origami tessellation in which to insert SMA wires as actuators within the fabric made surface. The SMA wires are trained to remember both the temporary and permanent shapes so that the wires shrink and fold the fabric towards the top. The fabric that we envisage to use is a kind of sunscreen shading fabric that can protect sun radiation and has light-weight and cardboard-like properties to be able to facilitate the creases arising from the selected origami tessellation. Once the SMA wires interact with the sun radiation, the fabric starts to deploy slowly until it covers the area where sun radiation gets into the building (depending on intensity of the sun). The fabric is perforated with small orifices to provide natural light for visual comfort inside the building while the shading device is closing and totally covering the glazing area.

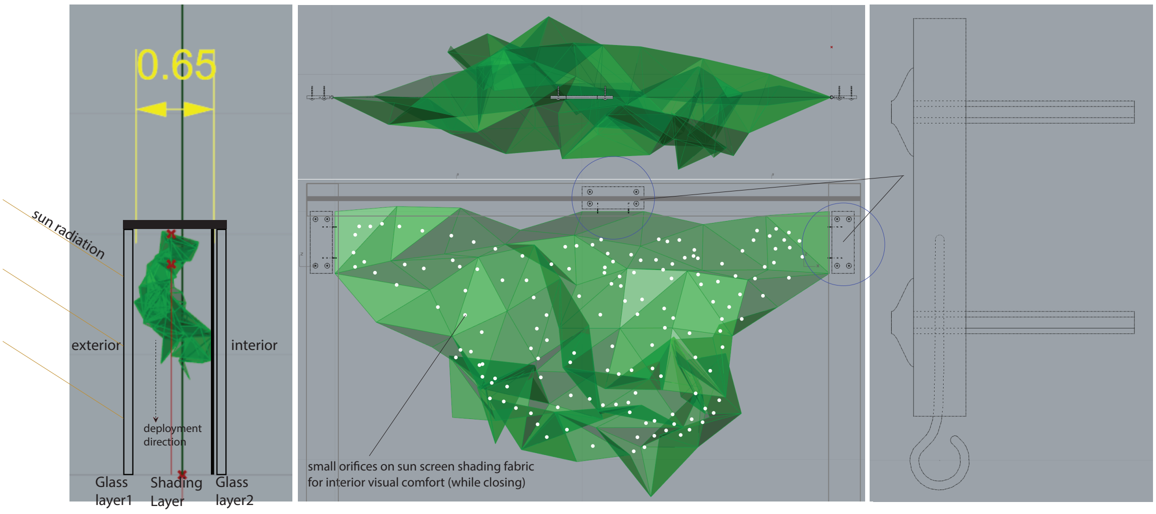

Figure 8: Details of the shading device.

The fabric is located between the double-glazing windows. When the space between the glazing windows starts to heat beyond the transition temperature (70 °C or 90 °C) as a consequence of daily heat gains, the SMA wires start to change shape (shape A to B) and the shading device starts to deploy and cover the glazing window area. When the heat starts to reduce below the aforementioned temperature, the SMA wires start to change shape in the opposite direction (shape B to A), thus, the shading device folds back to the original shape in an autonomously retractable mechanism. The shading device is attached to the building's glazing system through a set of hooks that act like curtain hangers (shown in Figure 8) attaching to the respective wire in their cross section: the anchor system is comprised of three (3) devices, one near the middle top part and two (2) more on each side of the shading device's geometry. This system anchors the fabric/wire material matrix structure to the glazing system and allows it to fold in the specific retractable manner required to act an efficient shading device.

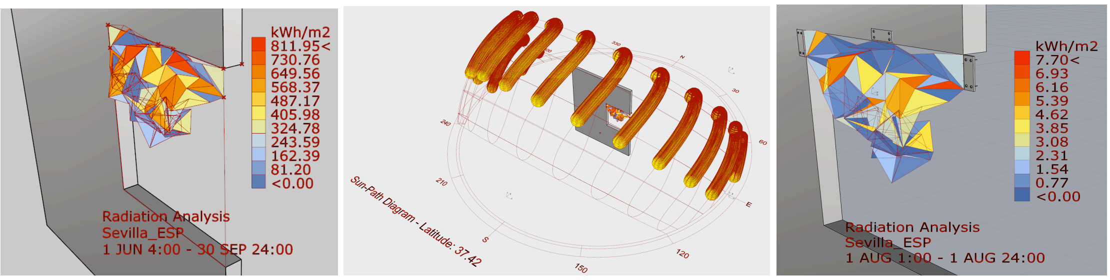

Figure 9: (From left to right) Sun radiation analysis interacts with shading device area, Sun path in Seville, Spain during summer period (June-September), and Sun radiation analysis from 1:00h to 24:00h on August 1^{st}.

We have chosen Seville, Spain as a location for testing the shading device through simulation, while also performing a sun radiation analysis as an integral part of the design process. Seville has a subtropical Mediterranean climate (Köppen climate classification Csa), featuring very hot, dry summers. It is the warmest city in Europe and it has the hottest summer in continental Europe among all cities with average daily highs in July of 36.0 °C (97 °F). Average daily lows in July are 20.3 °C (69 °F) and every year the temperature exceeds 40 °C (104 °F) on several occasions. A historical record high (disputed) of 50.0 °C (122 °F) was recorded on 4 August 1881, according to the NOAA Satellite and Information Service[53]. The location's sun path analysis shows a 76° summer time solar tilt (versus 62° in London, for example). Thus, the shading device is needed in the urban area (e.g. Metropol Parasol by Jürgen Mayer) and also in buildings. We tested the design by placing the passive kinetic shading device on a double-glazing window type, mock-up envelope, similar to the ones typically implemented in skyscrapers or large-scale buildings and then ran physical and environmental simulations to test both the origami pattern and its heat gain performance.

To run the origami physical simulations shown above, we proceeded to write a Python (version 3.6.6) script in the Grasshopper (version 0.9.0076) interface that lets you write automated object oriented programming (OOP) chunks and integrate them into a GH definition as components that have inputs and outputs. OOP is used, in this context, to automate physical approximation calculations concerning macroscopic, mechanical behavior such as rigidity, rest length, stiffness, stress and, in this particular case, Flexinol's heating and cooling resultant pull-forces (Flexinol is a commercially available brand of SMA, made by Dynalloy, a company based in California, USA), proportional to its diameters in the M.K.S. measurement system (weight in kilograms). These characteristics inherent in the material, although they can be modeled using data-flow, work better and are more reusable if implemented in a component that reproduces the material's laboratory tested mechanical data.

To achieve this, we used a previously published formula[54] that integrates proportions between the material's diameter (that, according to the simulation, should be 10.89mm in diameter) and pull force, in accordance with the Dynalloy Technical Data Table and output a scalar resultant ready to be given a vector format. This was realized by making a component of our own authorship called *SMM NiTi Flexinol Mecca* (Fig. 10); a subroutine written in Grasshopper's Python editor and combining the Unit Vector components to turn the values into proper vector form (10mm diameters do not exist in production at Dynalloy, but they can be approximately extrapolated using the *SMM NiTi Flexinol Mecca* component). The general formula was implemented using the following simplified form:

$$\big(2(\mathrm{ax2})\big) * \mathrm{c} = \mathrm{F(x)}$$ [54]

Where "a" is the nominal term, "x" is equal to the wire's diameter, "c" is a constant equal to 100 and "F(x)" equals the resultant pull force. Setting the "a" term to 71 gives the pull force for heating actuation and setting it to 29 gives the cooling actuation pull force, shown below for heating:

$$(2(71\mathrm{x}2)) * 100 = \mathrm{F(x)}$$ [54]

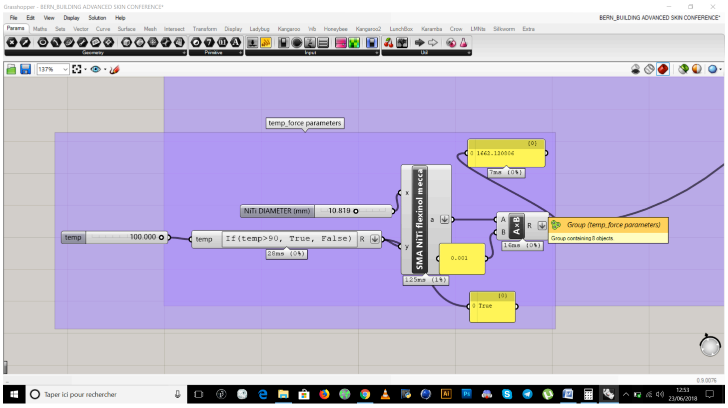

Figure 10: ***SMM NiTi Flexinol Mecca****; our own subroutine written in Grasshopper's Python editor and combining the Unit Vector components to turn the values into proper vector form.*

To run the environmental simulations, we used the Grasshopper plugin Ladybug (version 0.0.65) with which we ran simulations from April to September, the hottest months in the year in Seville; and on August 1st (for a 24 hour span, from 00.00h to 24.00h). The radiation analysis shows the average heat during the summer period (Apr-Sep) in Seville in which heat radiation can go up to 800 KWh/m2, over a 183 day period from, April 1st to September 30th, **slightly over the European average of 752.06 for the same period[53]**. While a simulation ran on August 1st, for a 24 hour period tops at 7.56 Kwh/m2 per day reading, which can provoke a 7.54 °C[55] spike per tessellation unit, just on direct heat collecting alone. This quantity, divided by a third (7.54/3=2.51 Kwh/m2 per unit), gives a conservative, approximate estimate of a 160.85 °C heat gain for the whole device, enough to activate either 70°C or 90 °C Dynalloy SMAs. In theory, these thermal conditions can activate the actuation system without the need for electric input. In this context, autonomous kinetic shading devices can ameliorate interior conditions in large-scale, contemporary buildings.

6. Conclusion

This research focuses on the development and the technical implementation of responsive architectural envelopes based on the investigation of actuation systems in plants. Faced with environmental issues according to overuse of energy and resources, in this context, the energy performance of future building envelopes will play a key role. Today's envelopes are mostly passive systems and are largely exhausted from an energy efficiency point of view. They can neither adapt to changing environmental conditions related to daily and annual cycles nor to changing user requirements. Current energy efficient design strategies like biomimetics and technologies of building envelopes have led to significant building energy saving. In recent years, an increasing number of researchers started to think about smart materials as a way to perform adaptation leading to an environmental responsive envelope. Shape memory alloy wires, springs and plates have been extensively tested and studied in a variety of fields; therefore, on the base of their applications they currently remain within the most suitable materials for shading applications. The combination of a flexible structure with the properties of an active material can embed awareness into contemporary buildings and adapt architecture to its environment. By implementing self regulatory retractable shading systems (aided by a mechanical or electric fail-safe emergency system, which is not addressed in this paper, in case of malfunction or an abrupt change in environmental parameters like disruptive climate pattern fluctuations), weather tightness and heat transmission can both be controlled by buildings themselves with relative ease, especially in hot climates like the one in Seville, the middle east, northern Africa and other desert climate areas around the globe; potentially reducing HAVC and IT control systems related energy consumption which would be of great improvement for current kinetic systems' implementation.

7. References

[1] E. Berkoz and Z. Yilmaz, 'Determination of the overall heat transfer coefficient of the building envelope from the bioclimatic comfort point of view' Architecture Science Review, 1987, Vol. 30, No. 4, pp. 117-215.

[2] J. Wang, L.O. Beltran and J. Kim, ‘From Static to Kinetic: A review of Acclimated Kinetic Building Envelopes’ Conference, World renewable energy forum; 2012; Denver, CO, American Solar Energy Society, Vol. 5, 2012, pp. 4022-4029.

[3] T. Dobzhansky, M.K. Hecht and W.C. Steere, ‘On some fundamental concepts of evolutionary biology’, 1st ed. Evolutionary Biology 2., New York, Appleton-Century-Crofts, 1968, pp. 1-34.

[4] H. Raven, E. Peter, F. Ray and E. Susan, ‘Section 6. Physiology of Seed Plants: 29. Plant Nutrition and Soils’. Biology of Plants (7th ed.), New York, W. H. Freeman and Company, 2005, pp. 639.

[5] http://www.oed.com/view/Entry/103498

[6] W. Zuk and R.H. Clark, ‘Kinetic Architecture’, New York: Van Nostrand Reinhold, 1970.

[7] C. Ben Bacha and F. Bourbia, ‘Effect of kinetic façades on energy efficiency in office buildings-hot dry climates’, 11th conference on Advanced Building Skins, Bern, Switzerland, 2016.

[8] M. Pesenti et al., ‘Kinetic solar skin : a responsive folding technique’, Energy Procedia, Vol. 70, 2015, pp. 661-672.

[9] W.M. Huang et al., ‘Shape memory materials’, materialstoday, Vol. 13, no. 7-8, 2010.

[10] G.K. Oral, A. K. Yener and N.T. Bayazit, ‘Building Envelope Design with the objective to Ensure Thermal, Visual and Acoustic Conditions’, Building and Environment, 2004, Vol. 39, pp. 281-287.

[11] P. H. Kirkegaard, ‘Development and Evaluation of a Responsive Building Envelope’, International Adaptive Architecture Conference, Building Centre, London, March 2011.

[12] H. Omrany et al., ‘Application of passive wall systems for improving the energy efficiency in buildings: a comprehensive review. Renew Sustain Enrgy Rev, 2016, Vol. 62, pp. 1252-69.

[13] www.adaptivebuildings.com

[14] N. Baker, ‘The imitable occupant recent developments in thermal comfort theory’, Architectural research quarterly, Vol. 2, 1996.

[15] N. Chayaamor-Heil and N. Hannachi-Belkadi, ‘Towards a Platform of Investigative Tools for Biomimicry as a New Approach for Energy-Efficient Building Design’, Building Journal, Vol.7 issue 1, Switzerland, MDPI AG, Basel, 2017.

[16] W. Zuk and R.H.Clark, ‘Kinetic architecture’, Van Nostrand Reinhold, 1970.

[17] RCGM Loonen, ‘Climate adaptive building shell, what can we simulate? Eindhoven (The netherlands): Technische Universiteit Eindhoven, 2010.

[18] Arab World Institute, Jean Nouvel, Projects, Paris. http://www.jeannouvel.com

[19] RCGM. Loonen, M. Trčka, D. Cóstola, JLM., Hensen, ‘Climate adaptive building shells: state-of-the-art and future challenges’. Renew Sustain Energy Rev, 2013, issue 25, pp. 483–93.

[20] Es. Lee, SE. Selkowitz, ‘Integrated envelope and lighting systems for commercial buildings: a retrospective’. Paper presented at the ACEEE 1998 summer study on energy efficiency in buildings; 1998.

[21] M. Coelho, P. Maes, ‘Shutters: a permeable surface for environmental control and communication’. In: Proceedings of the third international conference on tangible and embedded interaction, Cambridge, UK, 2009.

[22] L. Burgert and P. Fratzl, ‘Actuation systems in plants as prototypes for bioinspired devices’ Philosophical Transactions of the RoyalSociety A: Mathematical, Physical and Engineering Sciences, 367(1893), 2009, pp. 1541-1557.

[23] R. Suralkar, ‘Solar Responsive Kinetic Facade Shading Systems inspired by plant movements in nature’ In Proceedings of Conference: People and Buildings held at the offices of Arup UK, 23rd, 2011.

[24] J. Vincent, O. Bogatyreva, N. Bogatyrev, N. Bowyer, K. Pahl, ‘Biomimetics: its practice and theory’ J R

Soc Interface 2006, Vol.3, no. 9, pp.471–82.

[25] J. Benyus, ‘Biomimicry: innovation inspired by nature’ New York: H. Collins Pub, 2002.

[26] ITKE. Institute of building structures and structural design, bio-inspired kinematics for adaptive shading systems, Flectofins: a hinge-less flapping mechanism inspired by nature, [Online]. Available: (http://www.itke.uni-stuttgart.de).

[27] I. Burgert and P. Fratz, ‘Actuation systems in plants as prototypes for bioinspired devices’, Phil. Trans. R. Soc. A, 2009, no.367, pp. 1541–1557.

[28] W. Nachtigall and G. Pohl, Bau-Bionik: Natur ← Analogien → Technik, Berlin, Springer; Auflage, 2003.

[29] W. Nachtigall, Bionik als Wissenschaft: Erkennen - Abstrahieren - Umsetzen, Berlin, Springer; Auflage, 2010.

[30] N. Chayaamor-Heil, F. Guéna, N. Hannachi-Belkadi, ‘Biomimicry in Architecture : State, methods and tools, Les Cahiers de la Recherche Architecturale Urbaine et Paysagère, Issue Innover ? 2017. https://journals.openedition.org/craup/309

[31] G. Pohl and W. Nachtigall, ‘Biomimetics for architecture and design’: Nature –Analogies -Technology, Switzerland, Springer, 2015.

[32] Y.libo, F. Angari, M.Qasim, ‘Stress Analysis of Bond for Integrated Optical Fiber Sensors’, Intelligent Civil Engineering Materials and Structures, ed. F. Ansari et al, New York, ASCE, 1997.

[33] T. Takagi, ‘A concept of Intelligent Materials’, Journal of Intelligent Material Systems and Structures, Vol.1, Issue 2, 1990.

[34] S. Kamila, ‘Introduction, Classification and Applications of smart materials: An overview’, American Journal of Applied Sciences, Vol.10, no. 8, pp.876-880, 2013.

[35] W.M. Huang et al., ‘Shape memory materials’, materialstoday, Vol. 13, no. 7-8, 2010.

[36] https://en.wikipedia.org/wiki/Programmable_matter

[37] D.M. Addington and D.L. Schodek, ‘Smart Materials and New Technologies: for the architecture and design professions’, Architectural Press, Elsevier, 2005.

[38] J. De Haan, ‘Geheugenwerking bij NiTi-legeringen’, 1994. Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf

[39] R. Casati, F. Passaretti, A. Tuissi, ‘Effect of electrical heating conditions on functional fatigue of thin NiTi wire for shape memory actuators’ Engineering Procedia, ELSEVIER, 2011.

[40] Detailed Introduction to Shape Memory Alloys. (n.d.). Retrieved 03 2018, from smart.tamu.edu: http://smart.tamu.edu/overview/smaintro/detailed/detailed.html.

[41] K. Otsuka and C. M., Wayman, ‘Mater Sci Forum’, Cambridge University Press, 1998.

[42] J. F. Wakjira, ‘The VT1 Shape Memory Alloy Heat Engine Design’, Master Thesis, Virginia Tech, 2001 http://hdl.handle.net/10919/31196

[43] C. Maenghyo, and K. Sanghaun, ‘Structural morphing using two-way shape memory effect of SMA’ International Journal of Solids and Structures, Vol.42, Issues 5–6, 2005, pp. 1759-1776.

[44] T.W. Duerig, et al., ‘Engineering Aspects of Shape Memory Alloys’, Butterworth Heinemann, London, 1990.

[45] J. F. Wakjira, ‘The VT1 Shape Memory Alloy Heat Engine Design’, Master Thesis, Virginia Tech, 2001 http://hdl.handle.net/10919/31196

[46] A.K.Noor, S. L. Venneri, D. B. Paul and M.A Hopkins ‘Structures technology for future aerospace systems’ 1999, Vol. 1, issue 10 Retrieved 04 2018, from ScienceDirect: http://www.sciencedirect.com/

[47] J. De Haan, ‘Geheugenwerking bij NiTi-legeringen’, 1994. Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf

[48] W. Rottier et al. ‘Shape Memory Materials and their applications’ https://lirias.kuleuven.be/bitstream/123456789/384788/1/

[49] C. Lelievelo, ‘Smart materials for the realization of an adaptive building component’ Phd Thesis, Delft University of Technology, 2013.

[50] I. Burgert and P. Fratz, ‘Actuation systems in plants as prototypes for bioinspired devices’, Phil. Trans. R. Soc. A, 2009, no.367, pp. 1541–1557.

[51] WE.Mayer, D. Flash, MVS. Raju, N. Starrach, E. Wiech, ‘Mechanics of circadian pulvini movements in Phaseolus coccineus L. Shape and arrangement of motor cells, micellation of motor cell walls and bulk moduli of extensibility’. Planta 1985, Vol. 163, pp. 381-90.

[52] D.M. Addington and D.L. Schodek, ‘Smart materials and New technologies: For the architecture and design professions’ Routledge, Oxford, UK, 2005.

[53] European solar irradiation map, annual data in kWh/m2, from Pvshop.eu: http://pvshop.eu/Solar-Irradiation-in-Europe-kWh-per-m2

[54] N.Montás, P. Baquero, E. Giannopoulou, ‘Parametric Modeling Implementation for Kinetic Systems Simulation: Programmable Matter Matters’, Proceedings from the 3rd Conference of Biodigital Architecture & Genetics -Volume 1, Universitat Internacional De Catalunya, Barcelona, Spain, 7-12 June 2017, pp. 102-115

[55] Kylesconverter.com, Convert Kilowatt-hours to Celsius Heat Units, from: http://www.kylesconverter.com/energy,-work,-and-heat/kilowatt--hours-to-celsius-heat-units