Christina Koukelli_5115736
Theme: Facade & Products_Urban Facades
First Mentor: Alejandro Prieto Hoces_Architectural Facades & Products
Second Mentor: Serdar Asut_Design Informatics
Delft University of Technology
Master of Science Architecture, Urbanism & Building Sciences
Track: Building Technology

P2 Report

S olar hape

M orphing emory

Kinetic Envelope

[Integration of thermo-responsive Shape Memory Alloys in an autoreactive facade system to reduce the building's impact on the Urban Heat Island effect in the Mediterranean climate (case study: Athens, Greece)]

CONTENT

01 INTRODUCTION

1.1. PROBLEM STATEMENT

The urban built environment is one of the main attractors of population shifts from rural to urban areas, creating extreme changes in land use that result in unintended environmental, economic, and social consequences. This growth leads to the development of the so-called Urban Heat Island (UHI) phenomenon, characterized by higher temperatures in the density of built areas than the ones of the rural surroundings and is both directly and indirectly related to serious energy, environmental, health and economic problems [Santamouris, 2007]. This phenomenon is especially intense in the Mediterranean basin with a fast growth of energy consumption in the last years, due to the widespread of air conditioning systems and the increase of cooling demand. This situation is in addition highly associated with the climate change of the last decades and a significant rise of Heat Waves (HW) [Salvati et al., 2017].

Especially in Athens, Greece, UHI has been present already since the 1980s and many research studies have been focusing on the area to identify and evaluate the scale, causes and impact of the phenomenon and to propose certain mitigation strategies. Based on the outcomes of these studies, there has been an increase of the energy building demands, thermal risk and vulnerability of urban population and it has been reported that during the HWs, there is even an intensification of the average UHI magnitude by up to 3.5 °C. This is highly due to the widespread use of air conditioning in residential buildings resulting to a fast increase of electricity consumption over the last few decades. The heat that is dissipated from the buildings to the external environment increases the UHI phenomenon, and therefore, has a strong indirect impact. More specifically, in Athens an average increase of the cooling load of about 13% is estimated, with an annual global energy penalty for unit of city surface and degree of UHI intensity of 0.74 kWh m^{-2} K^{-1} [Santamouris et al., 2017].

Due to the complexity of the UHI phenomenon and the multifaceted factors that are dynamically intertwined, although certain mitigation strategies exist and have proven applications in urban environments, it concerns in general an environmental issue, which is hard to tackle and identify in a precise manner. However, what is evident is that there is a strong connection to the given climatic context, in which it emerges every time. Based on research studies, most of them agree that there is a high indirect impact of the building's energy performance on the increase of the UHI in the cooling-dominated areas, such as Athens, especially given the frequency of HWs. An improvement of the energy efficiency of the building sector might, therefore, reduce the ambient temperature and, consequently, decrease the amplitude of the UHI [Santamouris et al., 2018].

In this direction, a certain level of climatic responsiveness and adaptiveness to extreme heat changes in an energy efficient way can arise as a promising strategy, in order to reduce the building's energy consumption in the present cause-effect relation. This also gives way to the development of responsive technologies, such as passive dynamic adaptive facade systems. Thanks to their adaptive mechanisms and the ability to implement smart technologies and autoreactive materials, they are favored due to the real-time responsiveness to the also dynamic and unpredictable environmental changes, acting as the threshold between building and exterior environment. The above-mentioned framework, composed by problem and promising mitigation strategy, is the direction that is followed in the current thesis and will be further explored and developed with a focus on the incorporation of smart and shape-changing materials.

1.2. RESEARCH OBJECTIVE

In this contextual framework, the research objective aims to investigate the impact of integrated thermo-responsive SMMs in facade components on the reduction of the Urban Heat Island effect in the Mediterranean climate, taking as a case study the city of Athens, Greece.

The main sub-objectives are the following:

- To study the effect of responsive dynamic facade systems in respect to climate adaptiveness and UHI reduction and the relation to potential technologies.

- To research on the potential of thermo-responsive SMM integrated technologies to have an impact on the building's energy performance and contribute to UHI reduction in the Mediterranean climatic context.

- To explore the state-of-the art and the methods to control and pre-determine the SMM's dynamic responsiveness parameters and to identify the potentials of implementation in an adaptive facade system.

- To study the main principles and strategies of natural systems and their relevance to the SMM behavioural ones and to responsive mechanisms in controlling the building's thermal behaviour in a climatic context.

- To design a passive adaptive solar morphing envelope based on thermo-responsive SMMs in an integrated facade system combining autoreactive and bio-inspired responsive mechanisms.

- To achieve motion in an integrated facade system by using latent energy in an energy effective and autoreactive way with optimal use of sensors and actuators, where material, form, function, structure and motion are interdependent in a fit combination.

– To discuss the feasibility of SMM-based facade technologies based on a set of parameters and reflect on the challenges, restrictions and potentials for future facade applications.

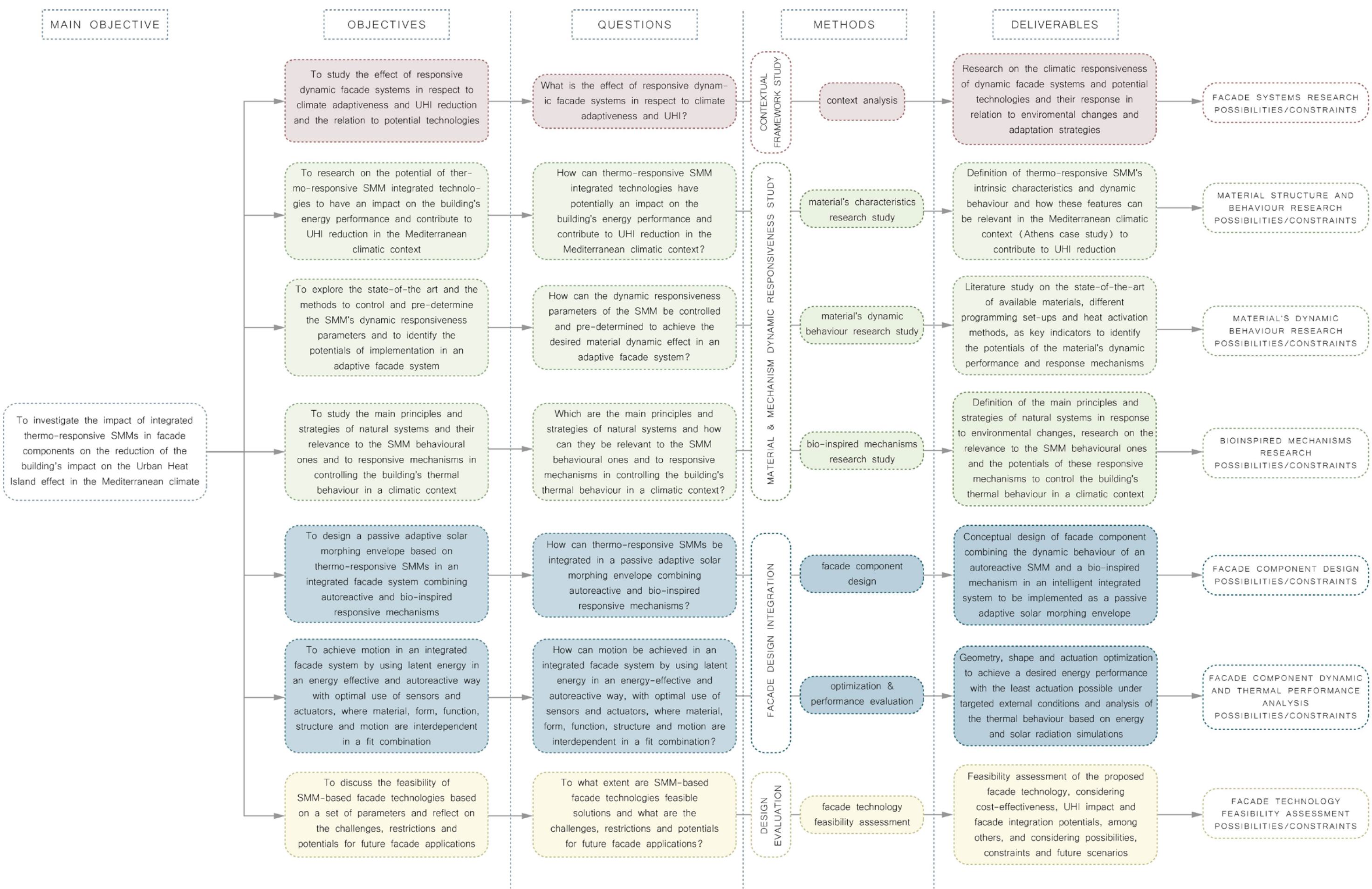


Figure 1: Research objectives and methodology scheme. [own work]

1.3. RESEARCH QUESTION

The above objectives are oriented to provide some insight to the following main research question:

*"How can **thermo-responsive Shape Memory Materials** be integrated in an **autoreactive facade system** to reduce the building's impact on the **Urban Heat Island effect** in the Mediterranean climate, with a focus on the case study of Athens, Greece?"*

1.4. RESEARCH SUB-QUESTIONS

To be able to address the main research question from different inter-linked perspectives, a few sub-questions are identified that answer various aspects which are encountered throughout the research process. These can be grouped in the following clusters, based on the process stage and focus sub-topic:

Theoretical Framework:

Contextual Framework (Problem analysis and Facade System Strategy):

- What is the effect of responsive dynamic facade systems in respect to climate adaptiveness and UHI?

Material and Mechanism analysis:

- How can thermo-responsive SMM integrated technologies have potentially an impact on the building's energy performance and contribute to UHI reduction in the Mediterranean climatic context?

- How can the dynamic responsiveness parameters of the SMM be controlled and pre-determined to achieve the desired material dynamic effect in an adaptive facade system?

- Which are the main principles and strategies of natural systems and how can they be relevant to the SMM behavioural ones and to responsive mechanisms in controlling the building's thermal behaviour in a climatic context?

Design Integration:

- How can thermo-responsive SMMs be integrated in a passive adaptive solar morphing envelope combining autoreactive and bio-inspired responsive mechanisms?

- How can motion be achieved in an integrated facade system by using latent energy in an energy-effective and autoreactive way, with optimal use of sensors and actuators, where material, form, function, structure and motion are interdependent in a fit combination?

Design Evaluation:

- To what extent are SMM-based facade technologies feasible solutions and what are the challenges, restrictions and potentials for future facade applications?

1.5. RESEARCH METHODOLOGY

The main objective of the thesis is to develop a passive adaptive integrated facade system, based on SMM technologies and autoreactive responsive mechanisms in a solar morphing envelope. The aim is to reduce the building's impact on the UHI effect durectly by means of reflecting and dispersing the solar radiation during the heat intensive periods, and indirectly by reducing the building's energy performance and cooling demands.

At the core of the research, a theoretical framework has been formulated, to explore the main aspects of the problem statement and research question. This can be divided into two parts: First, the contextual framework with a focus on the addressing problem, the UHI in its climatic context, impact and strategies, and on the dynamic adaptive facades as the chosen mitigation strategy implementation. And secondly, the material and mechanism analysis, with a focus on the inherent material characteristics and dynamic behaviour, both in a material and a component level, to form a better understanding of the responsive mechanisms.

A contextual research has been conducted to provide a background information concerning the nature of the UHI in the studied area. A research and analysis based on literature reviews from journals and statistical data from related agencies have been realized, to collect the relevant information, which were used as a background to elaborate on the design decisions and strategies for facade implementation. These studies provide information about the causes, impact and existing mitigation strategies of the UHI effect, with a direct connection to the effect of the global climate change and the synergy to the increasing Heat Wave phenomena of the recent years. In parallel, the literature study aimed to collect data about the relevance of the UHI and HWs with the building's energy performance and inner comfort as an indirect impact with increasing influence over the years. For the purposes of the current thesis, the design strategy is also focused on the impact of a passive adaptive facade system to address the UHI. A literature study was conducted in this respect as well, to provide a classification and an overview of the available technologies and dynamic responses and types, both in terms of materiality and systems and to study the several operational systems and purposes of each type. This was used as a guideline for the initial design decisions, to choose the most apt system based on the research's objectives and goals.

Regarding the material and mechanism research, a main objective is to provide a passive adaptive facade system that can realize the change in geometric configuration through the ingrained properties of the material it is made of, without the need for external energy or complex mechanical parts. A large part of the research was, therefore, realized in the existing smart and multifunctional materials, with a focus on the thermo-responsive ones, due to the nature of the environmental issue and climatic context, and the actuation mechanisms that would trigger the dynamic behaviour. In this direction, scientific papers, research studies and experimental lab tests have been consulted to understand the state-of-the-art knowledge and material performance. The available materials were then compared based on their intrinsic features, properties and dynamic performance, as well as availability and implementation potentials, based on existing applications, material experiments and case studies, both realized in the building industry as well as in other fields, such as biomedicine and aerospace. A further subdivision was made between the different material families, as in SMAs, SMPs and SMHs, and an evaluation and comparison were realized, based on the above research and the feedback from experts in the field, which were being consulted in parallel, to be able to opt for the most promising, suitable and feasible one to be implemented in an adaptive facade system.

As for the mechanism, the aim of the literature study was focused on dynamic mechanisms that are based on mostly hingeless movements, minimizing the use of required actuators, with minimum external energy and a real-time climatic responsiveness. Because of these features, there is a relevance between the SMMs' intrinsic characteristics and the principles found in the strategies of natural systems to adapt to environmental changes. This led to the exploration of bio-inspired mechanisms, both in realized biomimetic applications and by directly exploring natural organisms and disassembling the principles behind their response mechanisms for thermal control and heat regulation, to apply the principles in an integrated facade system.

As a mean of evaluating the proposed system, parallel to the design, parametric simulations and design optimizations were realized to fine-tune the selected shading prototype design, assisted by the feedback from performance validation and to provide design variations in conjunction with energy and environmental simulations throughout the design process. This was established by collecting data regarding weather and solar radiation, among others. Software simulation was then used as an evaluation tool to assess the performance of the SMM component under targeted conditions and to additionally perform CFD simulations to evaluate the thermal behaviour of the building envelope. The end evaluation was realized through a feasibility assessment of the proposed facade technology system, to reflect on its efficiency and applicability scenarios. This was based on the energy and environmental performance of the facade system, but also on a set of qualitative criteria, which were defined along the process, such as cost-effectiveness and facade integration potentials, and led to a reflection on the possibilities, constraints and future scenarios of SMM-based facade technologies.

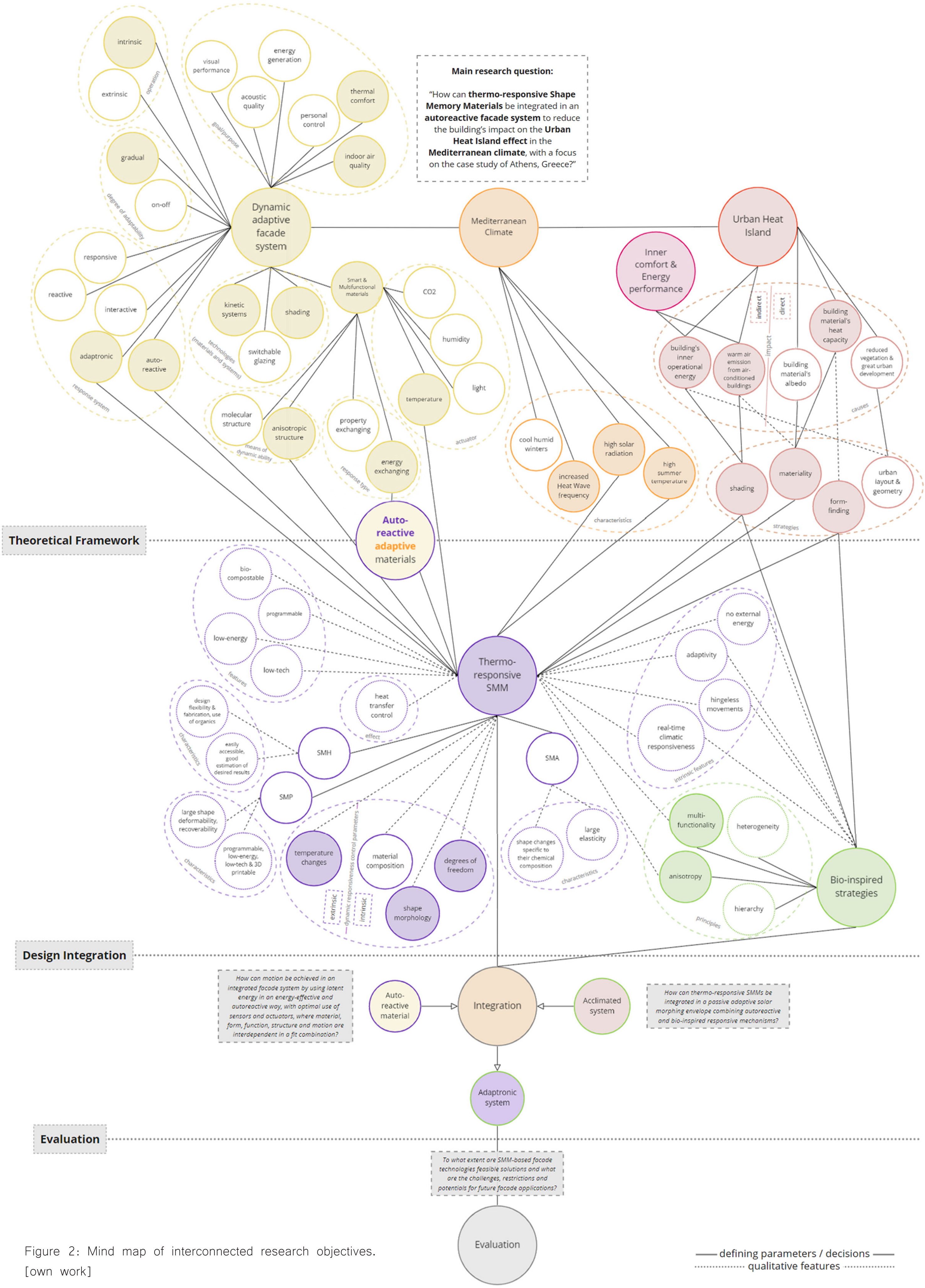


Figure 2: Mind map of interconnected research objectives. [own work]

1.5. THESIS STRUCTURE AND WORKFLOW

The structure of the thesis is comprised of three distinct sections, following the process of the research flow in a chronological order in the available timeframe. The first part includes the preliminary research, composed of the theoretical framework, which includes the environmental problem analysis, the climatic context, the facade system strategy and the material and mechanism responsiveness research study. It is followed by the design integration and facade implementation, where the information extracted from the research would aid and be applied in the facade system integration and design decisions. In the last section, the thesis presents the evaluation of the proposed system, in order to assess its environmental and energy performance. Lastly, it results to a feasibility assessment and a discussion on the level of impact of such a technology to a UHI reduction and to a reflection on the challenges, restrictions and potentials for future facade applications and further development in this direction.

Graduation Timeline

Following the framework of the methodology, the timeline of the thesis is outlined in the Figure below [Figure 3]. The approach is fairly linear with some repetition to allow for redesigning elements, feedback-optimization iterations and system adjustments.

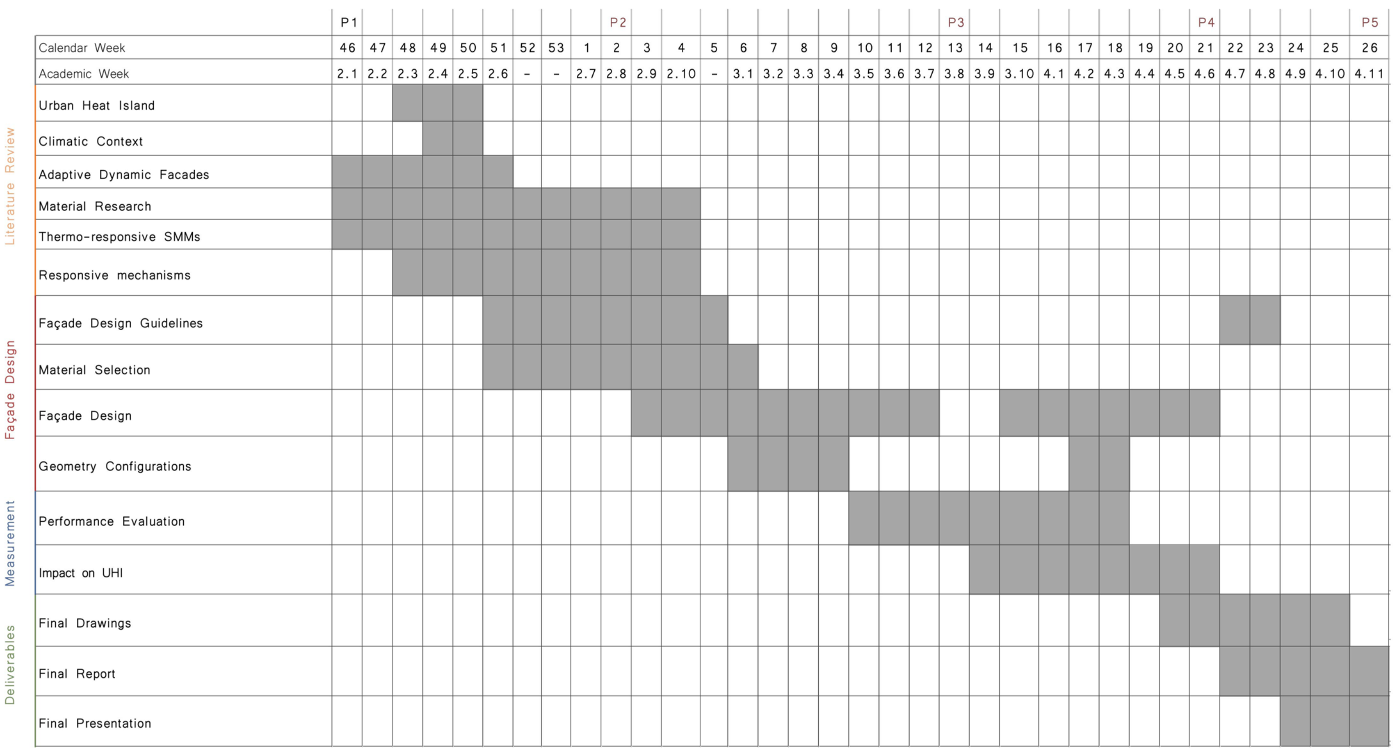


Figure 3: Thesis timeline. [own work]

02 BACKGROUND RESEARCH - CONTEXTUAL FRAMEWORK

2.1. URBAN HEAT ISLAND EFFECT

The urban built environment is one of the main attractors of population shifts from rural to urban areas. As the dynamics of this population shift occur, the 21st century phenomenon of rapid urbanization is creating extreme changes in land use that result in unintended environmental, economic, and social consequences. Urban growth has impacted the energy performance of buildings and human comfort, among others, by changing the landscape, as buildings and other infrastructures substitute open land and vegetation. This growth leads to the development of the so-called Urban Heat Island (UHI) phenomenon, characterized by higher temperatures in the density of built areas than the ones of the rural surroundings ΔT_{u-r}. According to the review by Santamouris [Santamouris, 2007], the UHI intensity varies between 2°C and 10°C [Salvati et al., 2017]. These temperature differences can range from 1°C-3°C in cities with one million or more inhabitants [Guattari, et. al., 2018]. This localized regional effect is in addition to IPCC (Intergovernmental Panel on Climate Change) estimates that put the potential of global warming to be +1.4°C to +5.0°C over the next 100 years, in addition to the 0.6°C temperature increase already observed during the 20th century. [Golden, 2004] Two types of UHI can be distinguished: (1) the canopy-layer heat island and (2) the boundary-layer heat island [Oke, 1979]. The canopy layer consists of air between the roughness elements (e.g. streets) with an upper boundary just below roof level. The boundary layer is situated above the canopy layer, with the lower boundary subject to the influence of the urban surface [Golden, 2004].

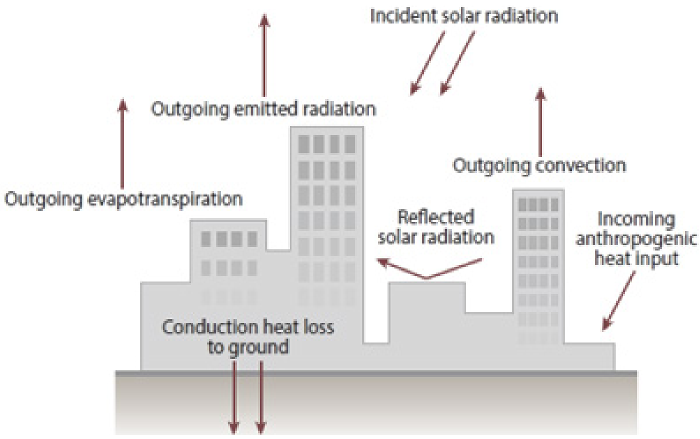


Figure 4: Relevant energy flows for the urban heat island. [Phelan et al., 2015]

2.1.1. CAUSES AND IMPACT

At its core, the UHI effect is governed by an energy balance between the input, generated, lost and stored heat in the urban environment and is a complicated phenomenon that depends on the size, density, building practices, location and season, to name a few factors of the built environment. In a similar way, the impacts are a combination of social, health, energy, economic and other issues, which are difficult to track and assess precisely [Phelan et al., 2015].

In general, urban overheating is caused by numerous reasons, including the thermal properties of the materials used in cities, the released anthropogenic heat, the canyon radiative geometry, the urban greenhouse effect, the reduction of the evaporative surfaces and the reduced turbulent transfer in the dense urban environment [Phelan et al., 2015].

Some of the main causes can be summarized as follows:

- The **urban environment**, with its paved surfaces and reduced vegetation, causes less of the incoming radiant energy from the sun to be reflected from urban areas and, likewise, less of this energy is converted to latent energy associated with evaporation or transpiration of moisture.

- The larger volume of asphalt, brick, concrete, and other materials gives urban areas a much **higher thermal storage capacity** than natural surfaces. One result is that large amounts of energy are stored in the urban canopy during the day and released after sunset – the hysteresis lag effect.

- **Anthropogenic sources** in the urban environment generate additional heat by way of air conditioning, automobiles, and machinery, which indirectly increase the UHI effect. Hence, urban temperatures tend to remain relatively high into the evening hours.

- **Albedo changes** have resulted in a forcing of $-0.4 Wm^{-2}$, about half of which is estimated to have occurred in the industrial era. These changes are mainly attributed to modifications from existing landscape to man-made infrastructure which results in decreasing surface albedo, as a result of roads and buildings.

- **Urban geometry** has changed net radiation and altered convection due to slowing winds near buildings.

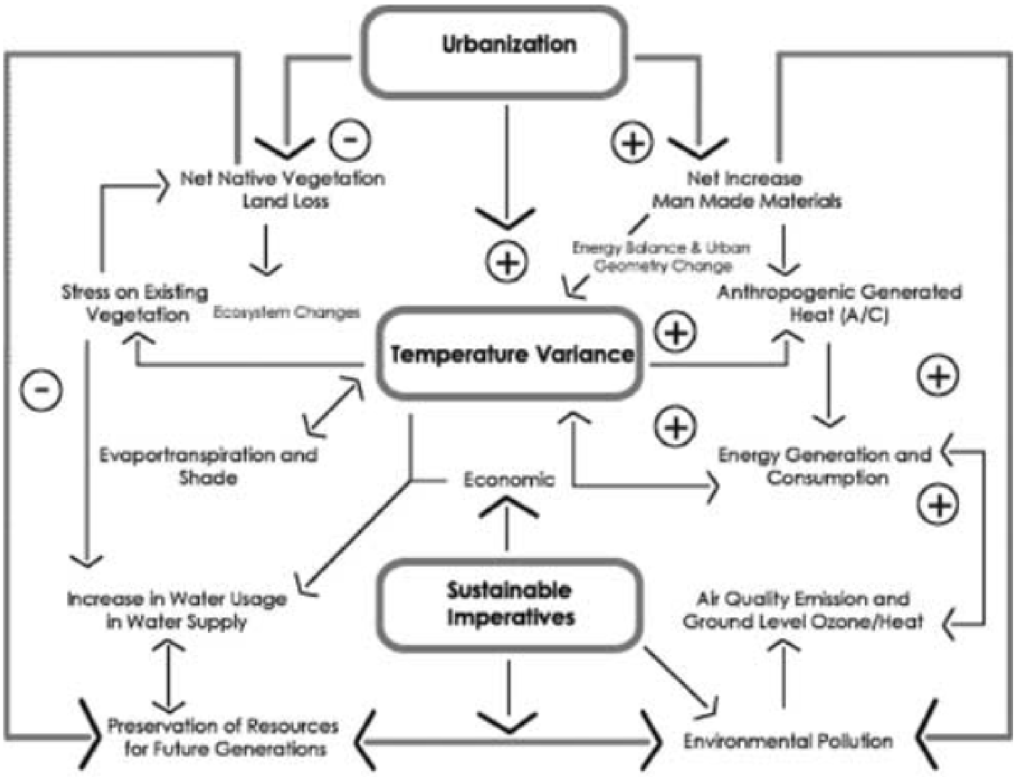


Figure 5: The influence of the engineered environment and urbanization. [Golden, 2004]

This phenomenon is directly and indirectly related to serious energy, environmental, health and economic problems, showing the multitude of its dynamics. The increased ambient temperatures cause a serious impact on the cooling energy consumption, peak electricity demand, heat related mortality and morbidity, urban environmental quality, local vulnerability and comfort.

To name a few, as depicted in the Figure below [Figure 6], with a focus on the ones related to the urban built environment and user's comfort, they can be summarized into the sub-categories below:

- **Commercial / Industry**:
  - o Increased greenhouse gas emissions contribute to global climate change, which can impact the length and severity of the UHI effect.
  - o Increased energy demands increase power plant emissions: CO2, NOx, VOC's.
- **Urban**:
  - o Increased demands for water resources.
  - o UHI increases anthropogenic heat and pollutants from elevated use of air conditioning and use of vehicles as a mode of transportation.
- **Residential**:
  - o Heat related health risks and mortality rate increase.
  - o Increased costs for energy and water demands which affect families and the competitiveness in a region [Golden, 2004].

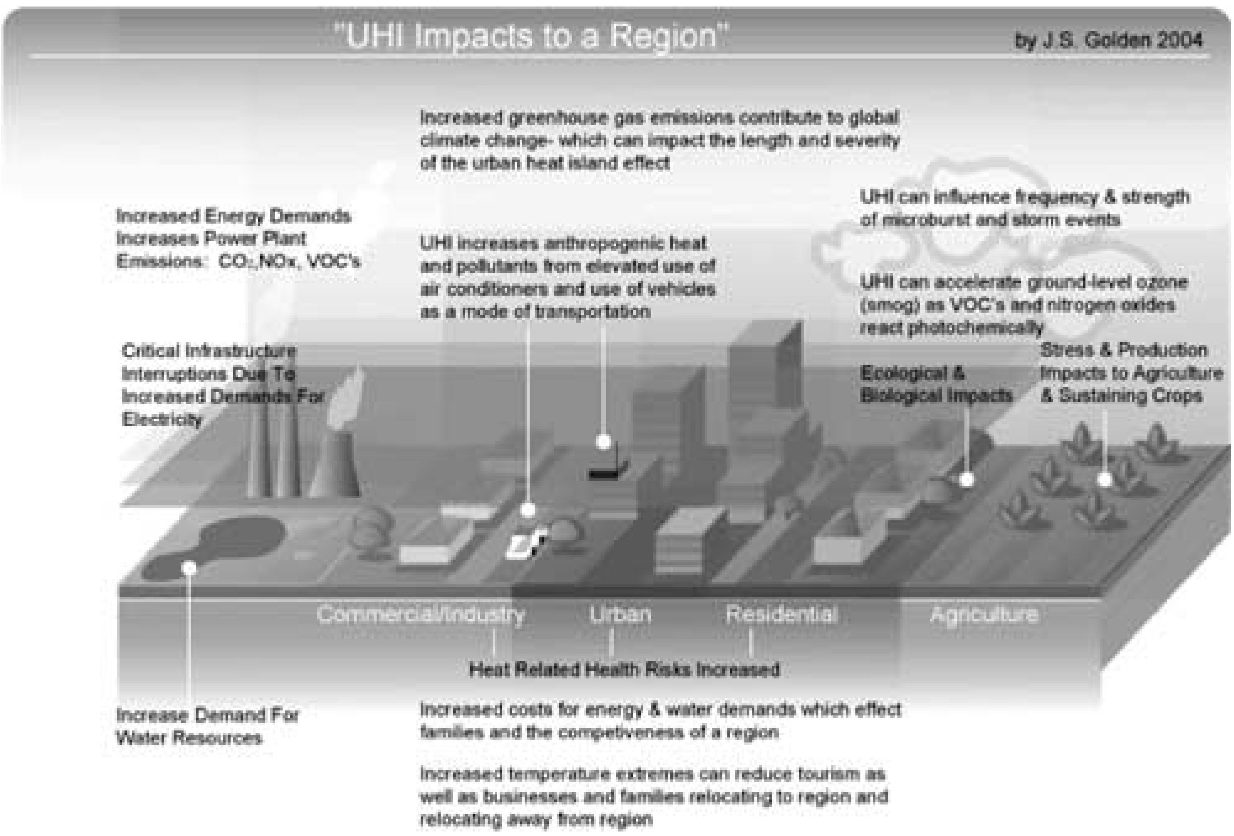


Figure 6: The potential impacts associated with UHI. [Golden, 2004]

2.1.2. EXISTING MITIGATION STRATEGIES

The existing mitigation strategies so far can be roughly divided into two categories: increased vegetation (trees, landscaping, and green spaces) and changes to building practices (materials for higher albedo and/or modified thermal properties, alternative paved surfaces designs, building types, and other materials selections) [Santamouris, et al., 2018]. Other strategies are also common, such as decrease of the anthropogenic heat, solar control of open spaces, use of environmental heat sinks and increase of the wind flow in the canopy layer [Karlessi, et al., 2011].

Here, the focus will be placed on the second category, the strategies related to the building component. These include mainly the implementation of cool pavements and green roofs, controlling albedo with a reflective surface for unshaded areas and shading design for buildings and open spaces. The last one is of the most relevance for the objective of the current thesis, in combination with the increase of the reflective surfaces of the proposed building component to reduce the absorbed and transmitted solar radiation in the building's thermal mass. Apart from that, a strong connection will be added to mitigate the indirect impact of the building's energy performance to the UHI effect, by reducing the cooling demands, by means of shading and, consequently, both decreasing the anthropogenic heat and enhancing the inner comfort levels.

2.2. CLIMATIC CONTEXT – MEDITERRANEAN CLIMATE, ATHENS CASE STUDY

The Urban Heat Island (UHI) effect is particularly concerning in the Mediterranean zone, as climate change and UHI scenarios foresee a fast growth of energy consumption for the next years, due to the widespread of air conditioning systems and the increase of cooling demand [Salvati et al., 2017].

For the purposes of the current research, the city of Athens, Greece, will be considered as a case study for the development of the proposal. Located at the southernmost part of the Greek mainland and hosting approximately 3.8 million residents, it is a densely populated coastal area of the eastern Mediterranean, ranking among the eight largest urban zones in Europe. Athens has been experiencing pronounced warming during the last decades, which in summer amounts to approximately +10°C/decade since the mid-1970s, attributable to both global/regional warming and intensifying urbanization.

The UHI intensity was first investigated in Athens in the early 1980s and since then, the characteristics of the UHI in this area have been the focus of numerous studies based both on ground measurements and satellite observations. These studies have shown that the phenomenon exists during both the summer and winter periods, with its spatial and temporal pattern strongly controlled by the unique characteristics of the area. The UHI phenomenon in Athens is characterized by much higher ambient temperatures in densely built and populated areas compared to the surrounding suburban and rural areas. More recently, Giannopoulou et al. [Giannopoulou et al., 2010] reported a variation of the UHI intensity in Athens between 3.0°C and 5.3°C during the daytime and between 1.3°C and 2.3°C during the nighttime [Salvati et al., 2017] [Papamanolis et al., 2015]. Therefore, it is among the cities, where the phenomenon has a significantly strong intensity and impact and forms part of its climatic context.

2.2.1. SYNERGY OF GLOBAL CLIMATE CHANGE, HEAT WAVES AND URBAN HEAT ISLAND EFFECT IN THE MEDITERRANEAN CLIMATE

As a phenomenon of the recent decades, UHI develops in conjunction with global climate change, resulting in an even greater increase of hot periods in urban areas than in their rural corresponding parts [Santamouris et al., 2018]. At the same time, one of the major concerns nowadays is to reduce the energy consumption and environmental footprint of cities and buildings. In the Mediterranean climate, this issue is more and more associated with the summer season. The widespread use of air conditioning in residential buildings has led to a fast increase of electricity consumption over the last few decades. In effect, the predicted climate scenarios for the next 100 years foresee an increase of tropical nights (>20°C) and hot days (>35°C). In this sense, the combination of global warming with the UHI effect makes the energy issue particularly concerning in the Mediterranean basin [Salvati et al., 2017].

This situation affects the urban environment in a direct and indirect way. Higher urban temperatures act as a catalyst and speed up the photochemical reactions that result in the formation of tropospheric ozone, while the UHI affects the air flow and turbulent exchanges, resulting in higher pollutant concentration. In parallel, higher energy consumption during the summer period causes an increased emission of atmospheric pollutants generated by the electricity power plants, expands the ecological footprint of the cities and results to a higher consumption of resources. In fact, estimation of the additional ecological footprint of the city of Athens necessary to compensate the global impact of the local UHI showed that this is equivalent to 1.5^{-2} times the city's political area and may extend up to 110.000 ha. [Founda et al., 2017].

At the same time, as a result of the climate change, Heatwaves (HW) are becoming more frequent and longer and, based on a recent study [Founda et al., 2017], a synergetic relationship was developed between UHI and HW, taking as an example the heatwaves taking place in Athens in 2012. Based on the outcomes, an intensification of the average UHI magnitude by up to 3.5°C during HWs was found, compared to summer background conditions, leading to increasing energy building demands, thermal risk in cities and vulnerability of urban population. It was also reported that an increase in the mean air temperature is coupled with a simultaneous, vast increase in HW frequency. The last decade has been marked by a number of record-breaking heat related events, as for instance the highest temperature ever measured since the mid 19^{th} century (in 2007), the warmest summer ever recorded (in 2012), and the early heat waves in 2007, 2010 and 2016 [Founda et al., 2017].

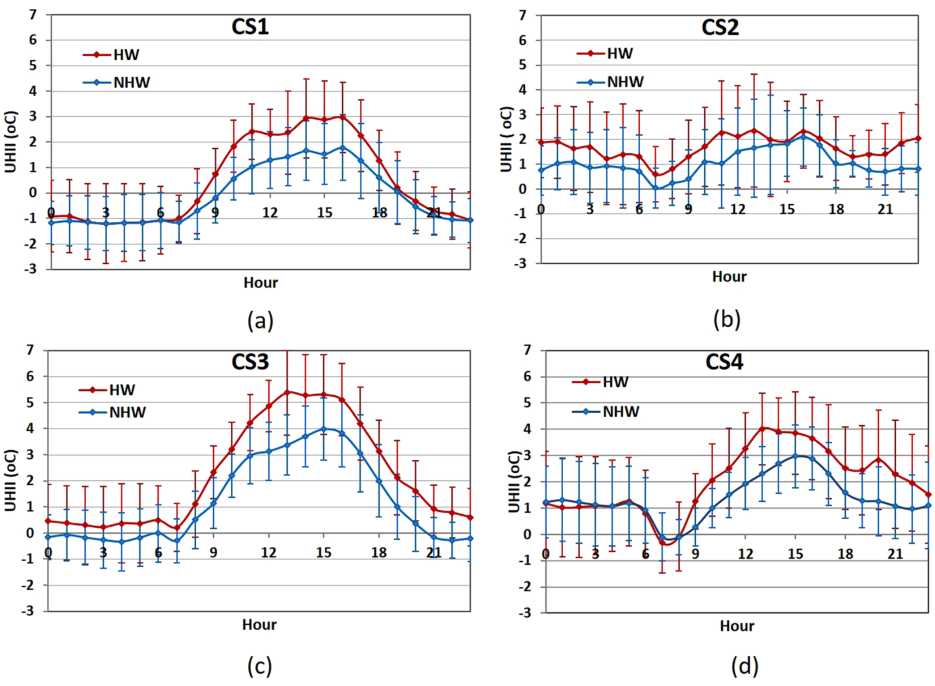


Figure 7: Diurnal patterns of average UHI intensity along with standard deviations at CS1-CS4, under HW and NHW conditions, over the study period (July-August 2012). [Founda et al., 2017]

2.2.2. URBAN HEAT ISLAND AND ITS ENERGY IMPACT ON BUILDINGS

It can be concluded that the combination of UHI and HWs in a continuous rise of temperature due to the global climate change is strongly affecting the energy performance of the built environment, especially in the Mediterranean area. The effects of the UHI on the energy consumption of buildings have been widely investigated, documenting a significant increase of the cooling loads and electricity consumption in the building sector. The heat dissipated from buildings to the external environment by the use of air conditioning systems, in return, increases the UHI phenomenon [Guattari et al., 2018].

More specifically, studies performed by Santamouris et al. [Santamouris et al., 2001] have found that the cooling energy demand of a typical office buildings located in the central area of Athens is almost two times higher than the one of a similar building located in suburban areas, with peak electricity loads almost tripled. Moreover, existing studies correlating the energy consumptions of similar buildings located in urban and rural areas have revealed an average increase of the cooling load of about 13%, with an annual global energy penalty for unit of city surface and degree of UHI intensity of 0.74 kWhm^{-2} K^{-1} [Santamouris et al., 2018].

Through these studies, it can be estimated that a decrease of the magnitude of the anthropogenic heat released in the urban environment may drop down the ambient temperature and decrease the amplitude of the UHI. This may be achieved, among others, with an improvement of the energy efficiency of the building sector in the cooling-dominated areas, such as Athens. As such, the objective of the thesis is focused on those mitigation strategies that can promote a certain level of climatic responsiveness to extreme heat changes in an energy-efficient way, in order to reduce the building's energy consumption and cooling demands in this cause-effect relation. This gives way to the following chapter, which is related to the chosen mitigation strategy as a research field, to study and develop an autoreactive adaptive facade system, which is favored due to the real-time response potential to the above-mentioned also dynamic and unpredictable environmental changes.

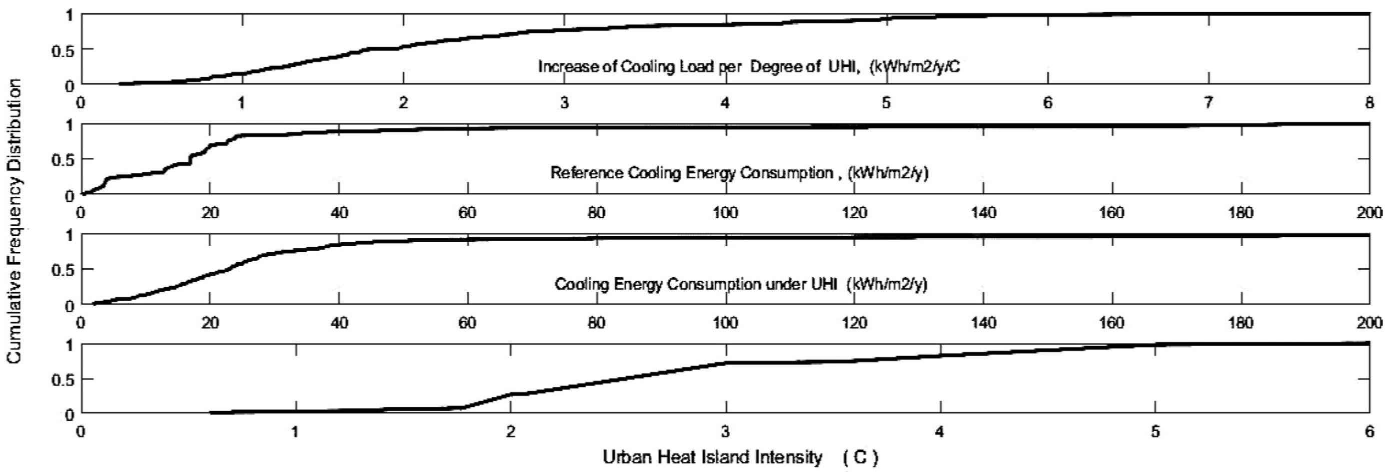


Figure 8: Impact of urban overheating on reference – typical buildings. a) Cumulative frequency distribution of the increase of the Cooling load of the buildings per degree of UHI. b). Cumulative frequency distribution of the cooling energy consumption of the buildings under reference climatic conditions. c). Cumulative frequency distribution of the cooling energy consumption of the buildings under urban –UHI conditions. d). Cumulative frequency distribution of the UHI intensity for all considered cases. [Santamouris, 2020]

2.3. DYNAMIC ADAPTIVE FACADES

The future of the sustainability of buildings is influenced by three challenging factors. From a social perspective, there is a need to achieve a high level of user well-being and indoor environmental quality. At the same time, from an environmental perspective, there is a need to reduce building energy consumption and neutralize building-related environmental impacts. Particularly, the integration of passive and active design technologies in the building envelope is gaining attention as a solution with high potentials to improve indoor comfort conditions and reduce the environmental impact during the life cycles of buildings. In this framework, the dynamic facades or adaptive facades, as defined by the European COST (European Cooperation in Science and Technology) Action TU1403 (Adaptive Facades Network (2014-2018)), have a significant effect on achieving the three performance requirements, by adapting to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles, or seasonal patterns [Luible, 2015].

Another important aspect concerns the potential reduction of energy demand in buildings, heat regulation and CO_2 emissions with the conversion of building envelopes from passive to active regulators of energy balance, which is promoted as part of the Climate and Energy Action Plans (Directive 2010/31/EU). In order to work effectively as a surface-regulator, the building skin must adopt different physical features at different times of the day, requiring different levels of environmental intelligence [Persiani et al., 2016].

In addition to this, what is relevant as well is to contribute with some knowledge as part of the framework commissioned to the Adaptive Facade Network set by the EU COST in 2014. The main aim of this COST Action is to harmonize, share and disseminate technological knowledge on adaptive facades at a European level [Luible, 2015]. By harnessing this knowledge, it will contribute to the generation of new ideas and concepts at a fundamental and product/system development level.

Considering the emergent issue of the UHI phenomenon and its foreseen increasing intensity in the Mediterranean region over the next years, the current thesis entails a challenge with scientific and societal relevance, aiming to achieve sustainability targets in the built environment.

2.3.1. MAIN CHARACTERISTICS AND PRINCIPLES

As a general definition, *"a climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time, either passively or actively, in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building energy performance and/or inner comfort."* [Attia et al., 2020][Juaristi et al., 2020].

What distinguishes this type of facade technologies is the capability of the adaptive facades to adapt physical properties in a reversible way as a response to and/or to adjust to transient boundary conditions (either external, such as climate, or internal, such as occupants' requirements), in order to respond to changing priorities (i.e. minimizing the building energy use, maximizing the use of natural light, etc.). The term 'adaptive' is often synonym to 'responsive', 'dynamic', 'switchable', 'smart', 'active' etc. [Loonen et al., 2016].

Moreover, in the context of nearly Zero Energy Buildings (nZEB) these facades also need to collect and convert available surrounding energy (mainly solar) in an adaptive way, in order to correspond as much as possible to building energy needs. They are thus considered as a viable alternative for achieving low energy building operation with high indoor environmental quality [Loonen et al., 2015].

Adaptive facades are often related to designing dynamic envelope models, which, with the help of sensors, system components and smart materials, contribute towards reducing the building's energy demand and building's environmental impact. They are capable of managing energy flows by altering the properties of fixed devices (smart materials) or by controlling (manually or automatically) moving parts (e.g. sunshades, windows, ventilation outlets, etc.) in relation to the type of user and complexity of the building. This envelope typology is marked by dynamic anisotropy, where a change in the structure modulates the various environmental flows according to the climatic conditions of the place, including external climatic-environmental conditions [Aelenei et al., 2018]].

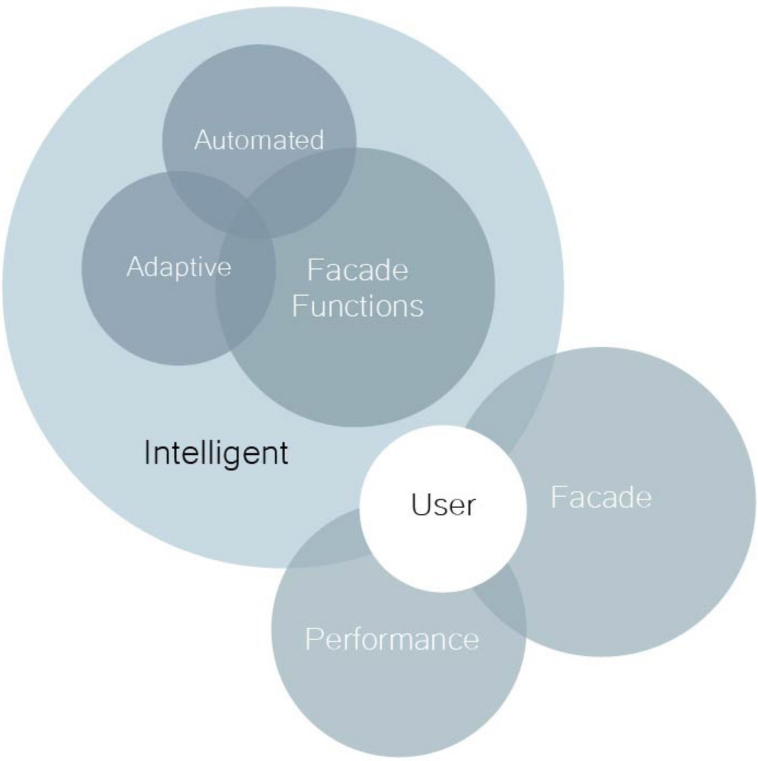


Figure 9: Visualization of the 'Intelligent facades' section context. [adapted from Böke et al., 2018]

2.3.2. CLASSIFICATIONS AND AVAILABLE TECHNOLOGIES

There are several classifications developed from different sources to categorize the available adaptive facade technologies, many of which are overlapping in certain areas, depending on the spectrum of the division each time. As an example, which is based on the collaborative frame of COST Action TU 1403 [http://tu1403.eu], a characterization was carried out in terms of technologies and purpose, depending on different factors, such as the purpose of facade/components with adaptive capacity, which can be related with thermal comfort, energy performance, indoor air quality (IAQ) and visual and acoustic performance, among other requirements, as can be seen in Figure 10 [Aelenei et al., 2018].

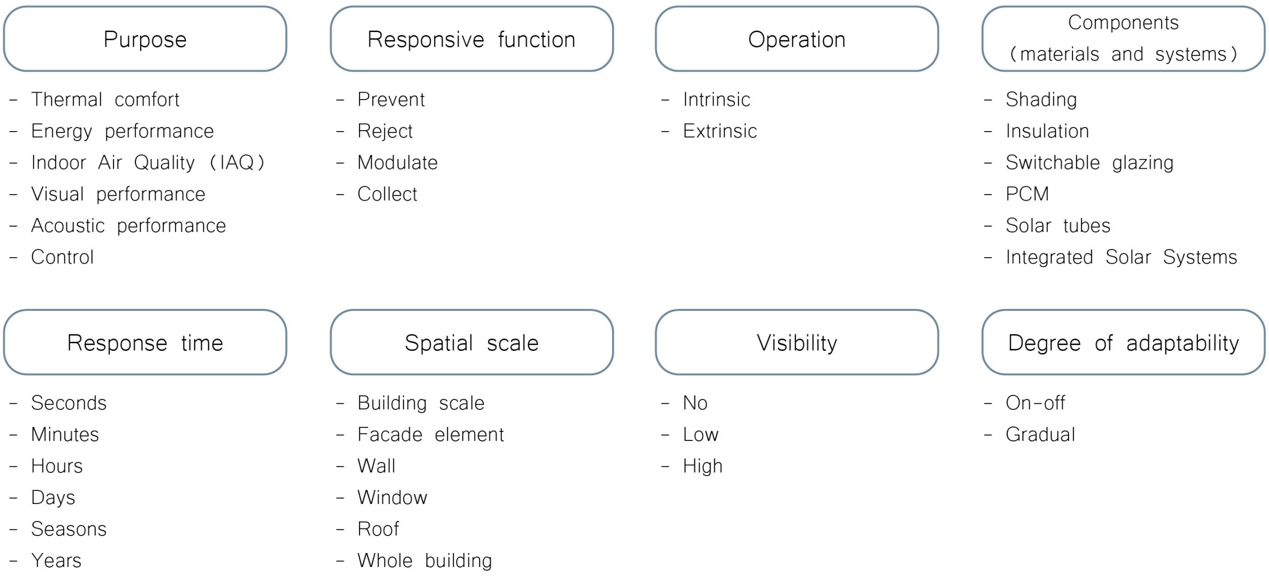


Figure 10: Adaptive facades classification. [adapted from Aelenei et al., 2018]

Apart from that, another classification can be realized by subdividing the facade in terms of system, component and material level, based on the scope of interest and scale of the dynamic mechanism.
This can be seen in the Figure below [Figure 11] [Aelenei et al., 2018].

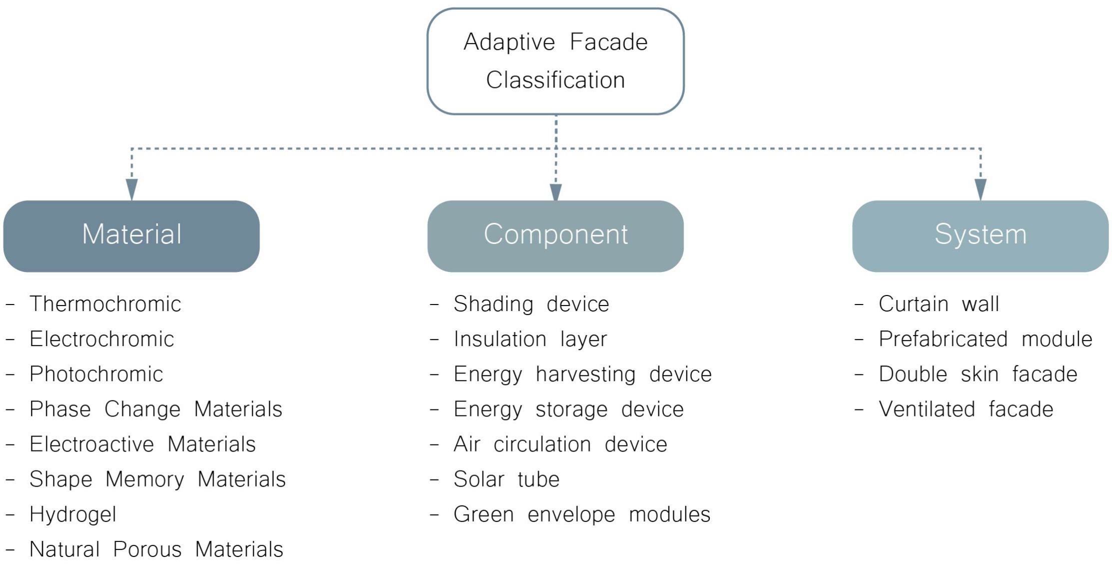


Figure 11: Adaptive facades classification based on material, component and system scale. [adapted from Aelenei et al., 2018]

The above classifications provide a general overview of the possibilities and applications of the available adaptive facade technologies and show the potentials for implementation and the range of parameters that can be exploited to achieve the desired building performance and environmental response. Of particular interest are these technologies that can achieve the dynamic effect at the lowest scale of the facade system, which is the materials themselves, due to their inherent feature to reach significant levels of climatic responsiveness by minimizing external energy resources and complex mechanisms.

2.3.3. RESPONSE SYSTEMS AND TYPES [CASE STUDIES]

More particularly, based on the applied response systems and types, adaptive building envelope systems can be further subdivided into:

1. **responsive** devices: adaptive systems embedded in the core elements of the building's skin that measure the environmental conditions through a system of sensors in communication with a central control system which adjusts the form, shape, colour or character of the building through actuators.

2. **reactive** or **adaptive** devices: decentralized systems with local impact as action-reaction is managed by the one and same device.

3. **interactive** devices: a kind of Artificial Intelligence, having a centralized or decentralized multiple-loop control system allowing it to adjust or "learn" from the precedent experiences giving different output though stimulation might be of the same nature.

4. **autoreactive** systems: an evolution of reactive systems, using latent unused energy from their surrounding environment to achieve physical change through mechanical transmission or use of adaptive materials undergoing dynamic change in response to an external change of specific conditions.

5. **adaptronic** systems: which combine the characters of a centralized and a decentralized system, integrating a conventional centralized sensor-brain system and at least one functional material that allows localized embedded action and reaction to a specific modulus [Persiani, 2020].

The last two response system types are chosen for further exploration and will be analyzed more extensively throughout the research and design implementation.

To provide a better insight on the autoreactive systems, which introduce the next more specific section of the material study, these have the following characteristics:
- autonomous reaction
- kinetic output
- leftover energy
- functional purpose
- reaction to more than one input
- embedded materials with autoreactive properties,

whereas the main parameters of auto-reaction can be divided into:
- System type:
    - o type of change: change in degree and in kind
    - o control center: centralized or decentralized
- Geometry:
    - o structure: rigid or deformable
    - o scale: small, medium, big
    - o symmetry: bilateral, radial, asymmetric
- Energy:
    - o radiant (temperature, light)
    - o potential (humidity and precipitations)
    - o kinetic (atmospheric turbulence and touch)
- Motion: motion strongly depends upon the geometry of the elements it is made of and co-evolves in natural systems as morphology is exploited energetically and mechanically. Furthermore, the material proprieties of a device (especially those of smart materials), can be used for counter-movements when not used as actuators [Persiani, 2020].

No matter how promising these systems are, the search for more dynamic and responsive technology tends to have increased most solutions' dependency on technology and energy rather than their independence. When smart, complex and expensive building technologies are subject to disproportioned amounts of resources in comparison to the achieved performance, the objective to exploit smart technological potentials is undermined. To counteract this downside, the present exploration also includes an effort towards minimizing complexity in mechanisms, actuators and number of mechanical parts of the adaptive facade systems.

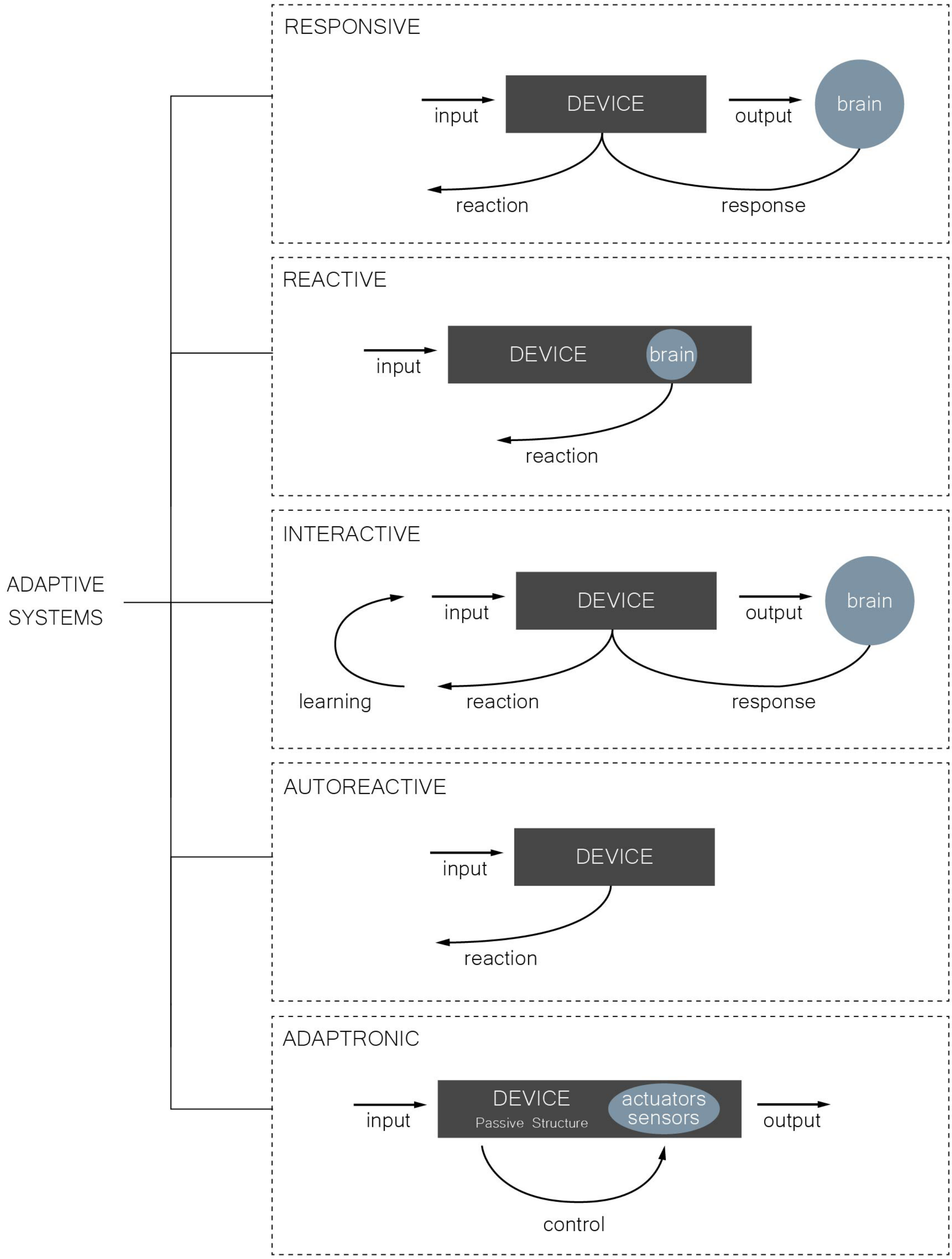


Figure 12: Scheme representing the adaptive systems' family. [adapted from Persiani, 2020]

A few representative examples showing the main principles in practice of some of the systems above are briefly explained below [Persiani, 2020]:

The facade of the Arab World Institute (AWI) in Paris is considered as the forerunner of the family of adaptive facade technologies. The double-glass facade integrates a metallic kinetic sunscreen system that adjusts the indoor light patterns depending on the outdoor light conditions. The kinetic system, which reinterprets the traditional Arabic “Moucharabieh” sunscreens, is realized as a multitude of motor-controlled camera-like metal diaphragms of different sizes and is considered a responsive system.

The “Kinetic Wall” is an interactive installation using kinetic petals that react to the presence of users by opening up dynamic windows on the wall and is triggered by a detection system that reacts to movements.

The “Hygroscope” installation explores the potential of a hygroscopic (humidity-sensitive) material to achieve kinetic response and is therefore considered a fully autoreactive system. The kinetic parts are thin triangular surfaces made of a maple veneer and synthetic composite, which is programmed to react differently depending on the fiber direction, the length, thickness and geometry. Absorption of humidity causes the distance between the fibers of the wood to increase, resulting in a swelling and lengthening of the material in the direction of the fibers.

The “Homeostatic” facade system is made of thin stripes integrating an electro-active polymer (EAP) wrapped around a flexible core, allowing the section of the stripes to bend with the expansion or contraction of the polymer. The actuation of one surface of the plates creates a bending and a deformation effect similar to that of a bi-metal, which is used to gradually shade the facade for light, solar and heat control. The movement in this system is directly controlled through a sensor-brain system integrating a functional material and the system can be considered to be an adaptronic one, with a kinetic mechanism that can also be employed in many autoreactive systems.

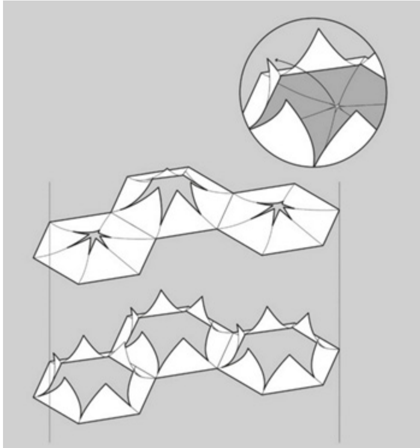


Figure 13: Scheme of the curling veneer flaps in the hygroscope system. [Persiani, 2020]

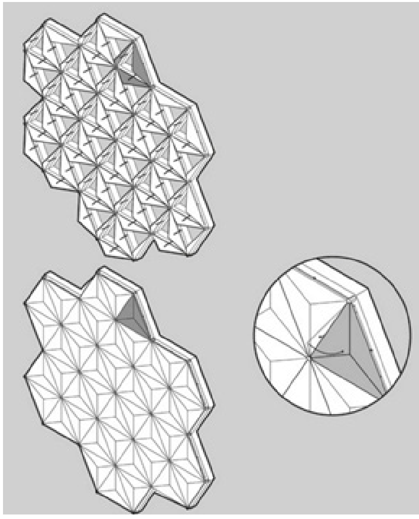


Figure 14: Scheme of the opening and closing of the kinetic wall (left) and a detail of the flaps performing the movement. [Persiani, 2020]

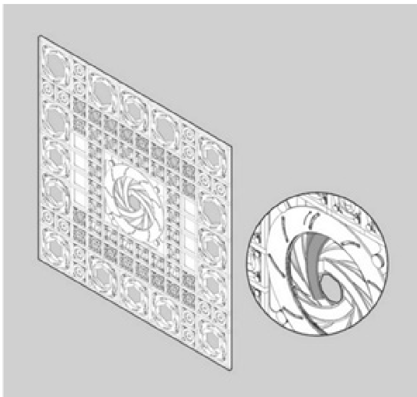


Figure 15: Scheme of the moucharabieh shutters and detail of one of the plates in the shutters that are rotated. [Persiani, 2020]

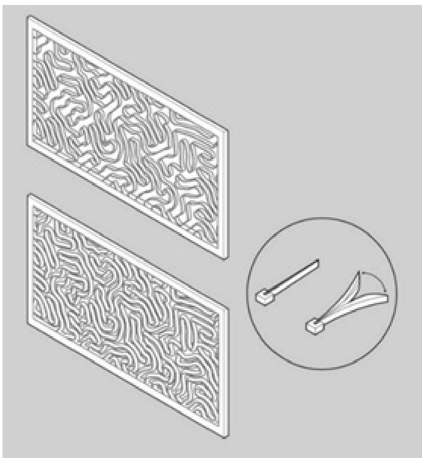


Figure 16: Scheme of the homeostatic facade kinetic transformation (left) and sectioned detail of the strips achieving the kinetic change (right). [Persiani, 2020]

03 BACKGROUND RESEARCH – MATERIAL AND MECHANISM

3.1. THERMO-RESPONSIVE AUTOREACTIVE SMART AND MULTIFUNCTIONAL MATERIALS

At a material scale, smart materials and structures are supposed to be able to respond to environmental changes at the most optimum conditions and adapt their own functions according to the changes, that is, they can respond in a pre-determined manner in an appropriate time with an environmental stimulus and then revert to their original states as soon as the stimulus is removed [Wei et al., 1998]. They are designed materials that have properties that can be significantly changed in a controlled way by an externally applied field value, such as stress, temperature and electric or magnetic fields. This behaviour enables them to fulfill actuation and sensing in one component. An advantage compared to conventional systems is their high integration and reduced complexity of mechanical parts, as they are the system itself combining sensing, actuation and mechanical functions. This favours their application in lightweight structures and development of dynamic systems [Drossel et al., 2015].

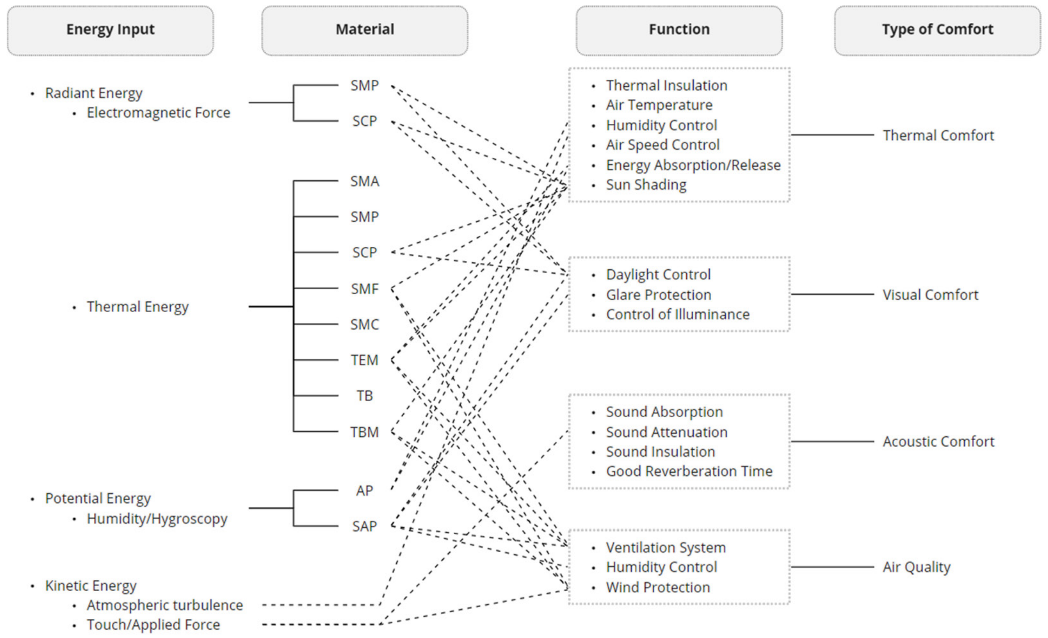
In the case of architecture and dynamic facades, even though adaptive facades show strong potential to exploit environmental resources through their dynamic behaviour, there is still more research needed in this respect. The cost-intensive and mechanical complexity natures of such systems of the past decades directed researchers' interest towards passive material-based actuation systems [SimAUD, 2017]. Aligned to this direction, one of the objectives of the current thesis is to achieve a balance between sophistication and benefit, by employing these innovative facade systems with a high and passive response to environmental changes.

Consequently, to trigger the response of the envelope, no external actuator or complex software management would be necessary. Nevertheless, these materials do not fulfil all the facade requirements by themselves. Thus, they need to be combined with other adaptive technologies and building elements, in order to be functional and feasible. Some of their promising potentials when applied in the external layer of the envelope, include the dynamic temperature change of the external cladding through the solar reflectance change and the enhancement or prevention of thermal losses through shape-changing ventilated facades [Juaristi et al., 2020].

This adaptiveness can be in favour of both reflecting the solar radiation and enhancing the building's energy performance, by reducing its cooling demands, and in both ways contributing directly and indirectly to the UHI reduction in a self-regulating and autoreactive manner. In the current context, the thermo-responsive smart materials are chosen to be studied further and implemented in a facade system design, in order to exploit the increased heat and solar radiation, caused by the UHI effect and HWs, which act as triggering environmental stimuli for the dynamic activation of the material system and its resulting response mechanism. Due to the fact that they are activated by a difference in temperature, these are promising candidate materials for activating smart morphing solar shadings with the thermal effect of incident solar radiation [Fiorito et al., 2016].

Even though their use could reduce the construction complexity in a dynamic adaptive facade implementation, their analysis in the facade industry is still underdeveloped and makes it difficult to retrieve relevant technical information, especially when researching on the properties of the material. Due to the difficulty to estimate the facade's performance well in advance, part of the study is also to reflect on the design implications that possible facade applications of such advanced materials could entail.

3.1.1. STAGES OF INTELLIGENT PROCESS



Legend:

SMP: Shape Memory Polymers
SCP: Shape Change Polymers
SMA: Shape Memory Alloys
SMF: Shape Memory Foams
SMC: Shape Memory Ceramics
TEM: Thermal Expansion Materials
TB: Thermobimetals
TBM: Thermobicomposite Materials
AP: Absorbent Polymers
SAP: Superabsorbent polymers

Figure 17: Mapping of Energy and façade functions' potential relations through the use of Adaptive Materials. [adapted from Persiani et al., 2016]

In a general spectrum, this type of materials belongs to the broader family of smart and multifunctional materials, also known as information materials. "Smart" implies notions of an informed response, with associated qualities of alertness and quickness and also an association with an intuitive or intrinsic response. Smartness in a material or system is determined by one or two mechanisms, which can be applied directly to a singular material, and conceptually to a compound system. If the mechanism affects the internal energy of the material by altering either the material's molecular structure or microstructure, then the input results in a property change of the material. If the mechanism changes the energy state of the material, but does not alter the material per se, then the input results in an exchange of energy from one form to another [Addington, 2012].

The five fundamental characteristics that were defined as distinguishing a smart material from the more traditional materials used in architecture are transiency, selectivity, immediacy, self-actuation and directness. These can be described as follows:

- **Immediacy**: real-time response
- **Transiency**: responsive to more than one environmental state
- **Self-actuation**: internal intelligence to rather than external to the 'material'
- **Selectivity**: the response is discrete and predictable
- **Directness**: the response is local to the "activating" event

[Addington, 2012]

There are various ways to describe the intelligent process of a system, depending on the different points of view and with a strong relevance to studies on natural systems. By using a functional approach, which is based on biological and psychological observations, this process is divided into three main linear stages:

perception → reasoning → action

These steps can be used to enable adapting the creative process of building envelopes to be designed following suitable steps for a given objective, as in this case, high performance through adequate climate approaches.

The first stage, perception, deals with the acquisition of information about the surrounding environment and its transformation into the communication format that the intelligent system uses for collecting such information, in this case the material itself. The information caused by the stimulus is translated, organized and interpreted to be used for the second stage. The second stage, reasoning, is a problem-solving procedure and implies a pre-defined set of actions. Data can be interpreted on different levels, such as environmental data, and logical rules might indicate an almost automatic action. Action, the third step, is the triggering of an activity as response to the initial stimulation that was detected by the perception system. It executes the conclusions reached by the logical system, performing a change in the physical properties of the intelligent system with no external energy for the activation.

As described by the steps and feedback mechanisms, intelligence is a concept with inherent dynamism and long-term adaptability towards maintaining a given goal. Changing conditions are answered by a set of responses which use the least energy possible and are always being adjusted according to information provided by external conditions, and this is one of the core challenges for sustainable design of responsive building envelopes [Capeluto et al., 2016].

Similarly, in the case of the adaptive facades, a certain level of automated self-regulation may also be considered [Macias-Escriva et al., 2013]. Such a self-adaptive and intelligent system involves the recording of information, data processing and control, and its transference in adaptations of the construction. Important component is, therefore, an existing sensing system, which determines relevant information about conditions (e.g. environmental) and other requirements. Furthermore, a control system processes the recorded information and transmits impulses to actuators, which then perform the adjustments of the construction [Böke et al., 2018].

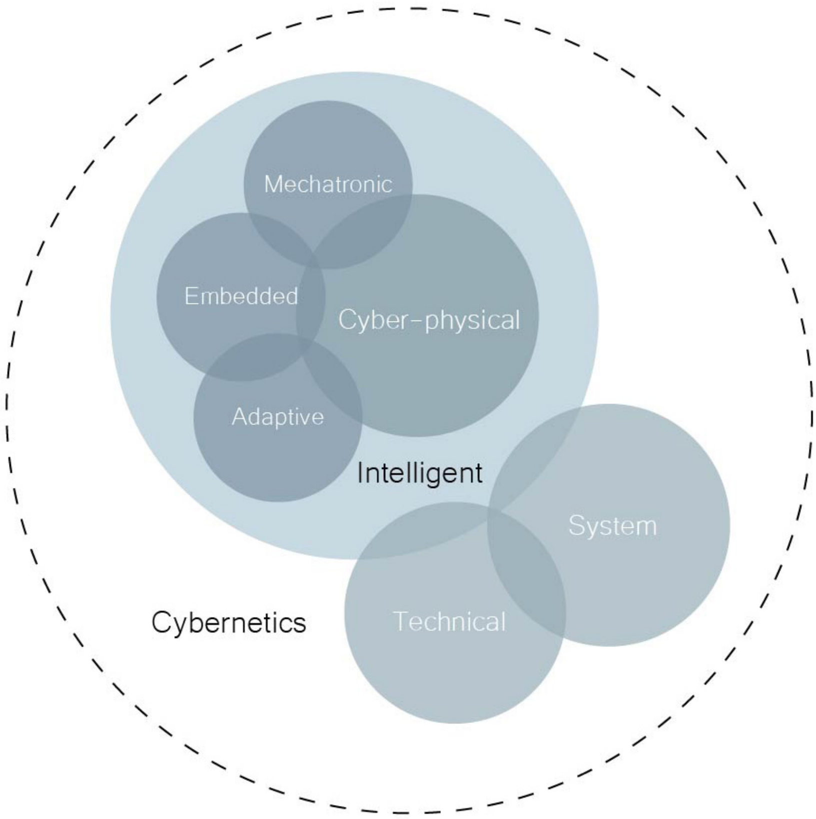


Figure 18: Visualization of the 'intelligent technical systems' section contexts. [adapted from Böke et al., 2018]

3.1.2. THERMO-RESPONSIVE SHAPE MEMORY MATERIALS (SMMs)

3.1.2.1. INTRINSIC FEATURES AND INHERENT DYNAMIC BEHAVIOUR

Narrowing down the focus even further, Shape Memory Materials (SMMs) belong to the energy-exchanging smart materials and are one of the major elements of intelligent composites because of their unusual properties, such as the Shape Memory Effect (SME), autoreactivity, large recoverable stroke (strain) and adaptive properties which are due to the (reversible) phase transitions in the materials. Superelasticity (in alloys) or visco-elasticity (in polymers) are also commonly observed under certain conditions [Otsuka et al., 2018].

More specifically, thermo-responsive SMMs can sense thermal stimulus and exhibit actuation or some pre-determined response, making it possible to tune some technical parameters such as shape, position, strain, stiffness and other static and dynamical characteristics [Wei et al., 1998]. An input of thermal energy (which can also be produced through resistance to an electrical current) alters the microstructure through a crystalline phase change, which enables multiple shapes in relationship to the environmental stimuli [Addington, 2012].

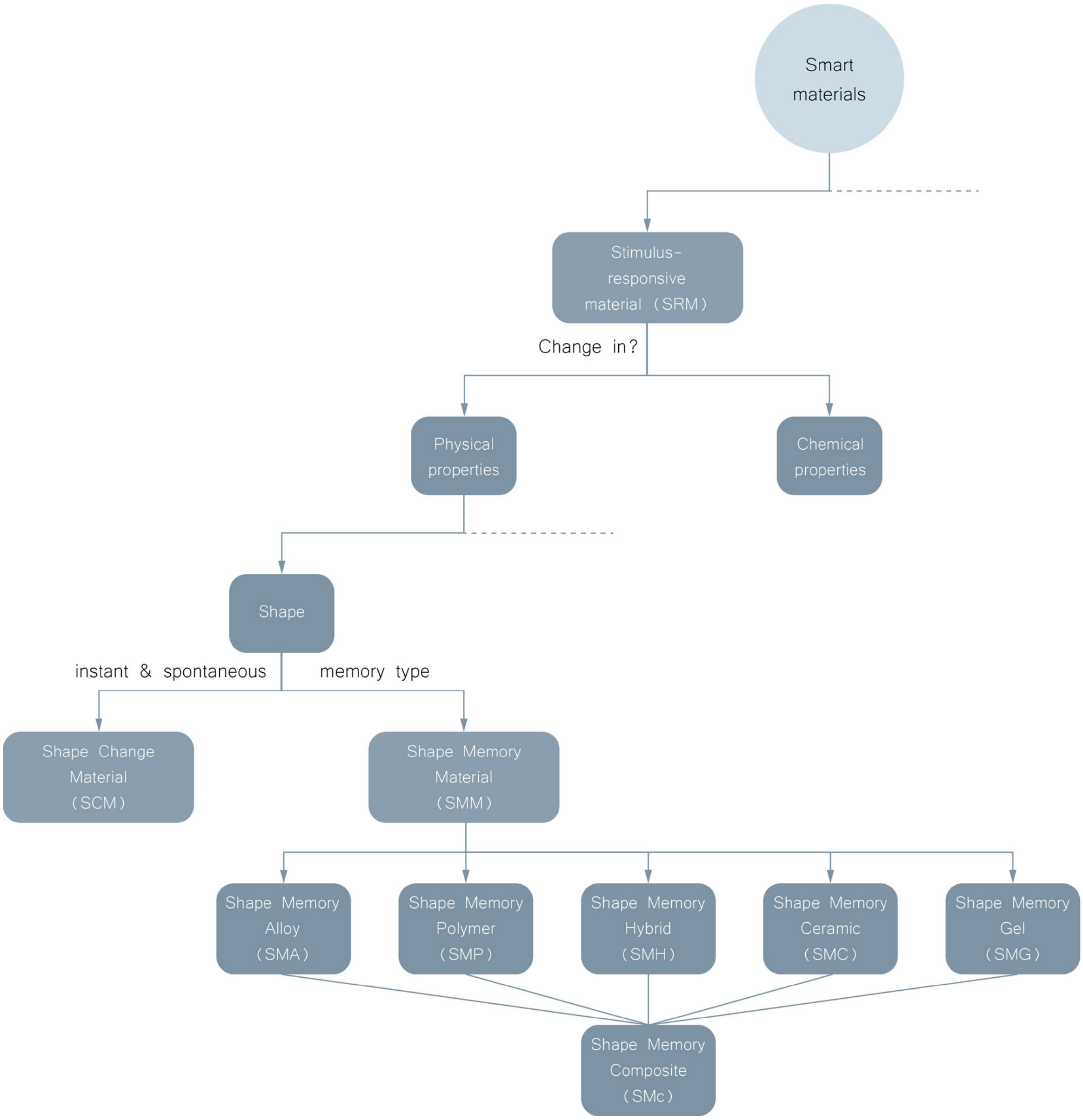


Figure 19: Location of various types of SMMs within the world of materials. [adapted from Sun et al., 2012]

3.1.2.2. CLASSIFICATIONS AND MATERIAL EVALUATION

There is a number of types of SMMs, which have been developed so far. Among them, Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs) are the most developed ones at present, while there is a newly emerging type of SMMs, namely Shape Memory Hybrids (SMHs), which enable non-professionals in materials science to design SMMs with tailored properties/features for a particular application in a "do-it-yourself" manner [Fiorito et al., 2016][Huang et al., 2010].

Shape Memory Alloys

Thermo-responsive SMAs are featured by the four characteristic temperatures, namely austenite start temperature (A_s), austenite finish temperature (A_f), martensite start temperature (M_s) and martensite finish temperature (M_f). Upon cooling from high temperature austenite phase, the martensitic transformation starts at M_s and finishes at M_f. Upon heating from low temperature martensite phase, the reverse martensitic transformation starts at A_s and finishes at A_f. While at low temperatures, SMAs have the SME, at high temperatures, recovery can be achieved instantly and simultaneously upon releasing the applied load [Sun et al., 2012].

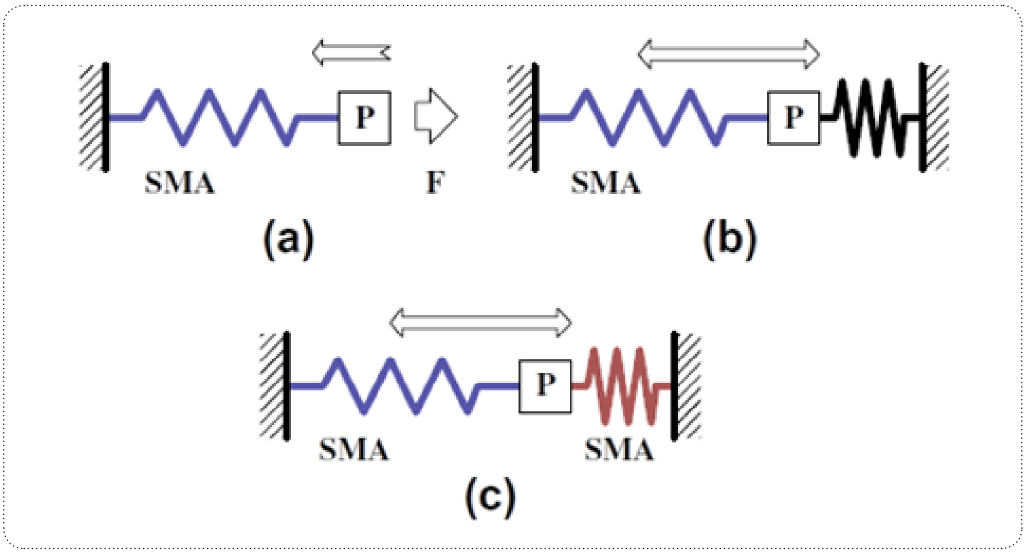


Figure 20: Three basic types of SMA actuators based on the one-way SME. (a) One-way actuator; (b) biased actuator and (c) two-way actuator. [Sun et al., 2012]

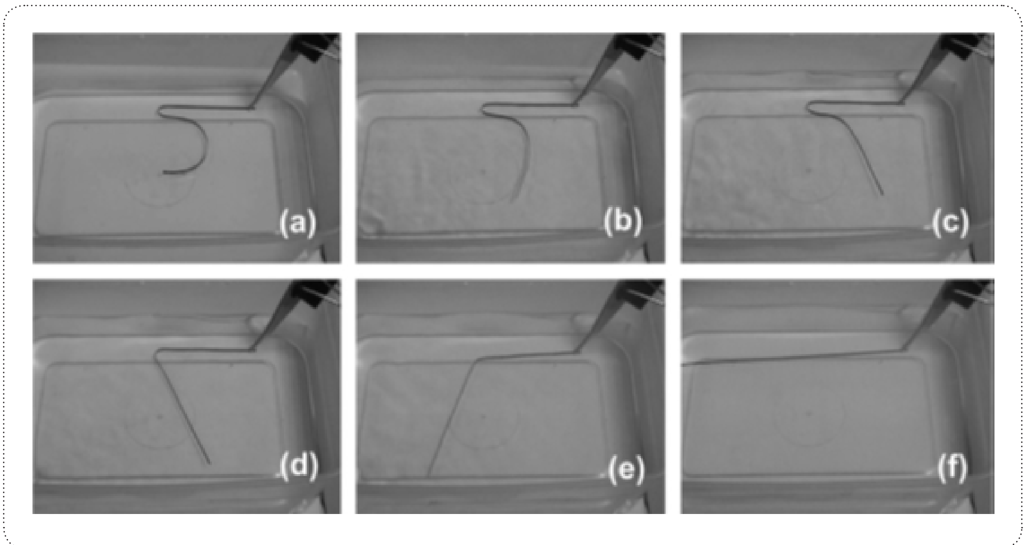


Figure 21: Triple-SME upon heating after local bending to introduce a gradient transition temperature field. [Sun et al., 2012]

Shape Memory Polymers

As a general concept, the Shape Memory Effect is not an intrinsic property of the SMPs, meaning that polymers do not display this effect by themselves. Shape Memory results from a combination of polymer morphology and processing and can be understood as a polymer functionalization [Behl et al., 2011]. The SME in SMPs is based on a totally different mechanism. Regardless of the types of the stimuli, there are two basic segments/domains in a SMP, one is elastic segment, and the other is transition segment. While the elastic segment always maintains high elasticity within the whole SME cycle, the transition segment does change its stiffness significantly at the presence of the right stimulus. SMPs normally are hard at low temperatures and become soft at high temperatures [Fiorito et al., 2016]. Shape memory polyurethanes (SMPUs) remain one of the main classes of SMPs studied. Their attractiveness mainly lies in their ease of processing, low cost and high thermal and mechanical performance [Behl et al., 2011].

There are certain advantages of the SMPs over the SMAs which make their application appealing. To name a few, they have a lower density, lower cost of raw material and fabrication, while they can be easier programmable and 3D printable. Apart from that, the recoverable strain is normally higher, it is easier to tailor the thermo-mechanical properties of SMPs, the shape recovery temperature range can be easily altered within a wide range and even gradient and they have a higher potential for recycle and reuse at low cost. However, they may require a higher level of material understanding to program to the desired dynamic performance.

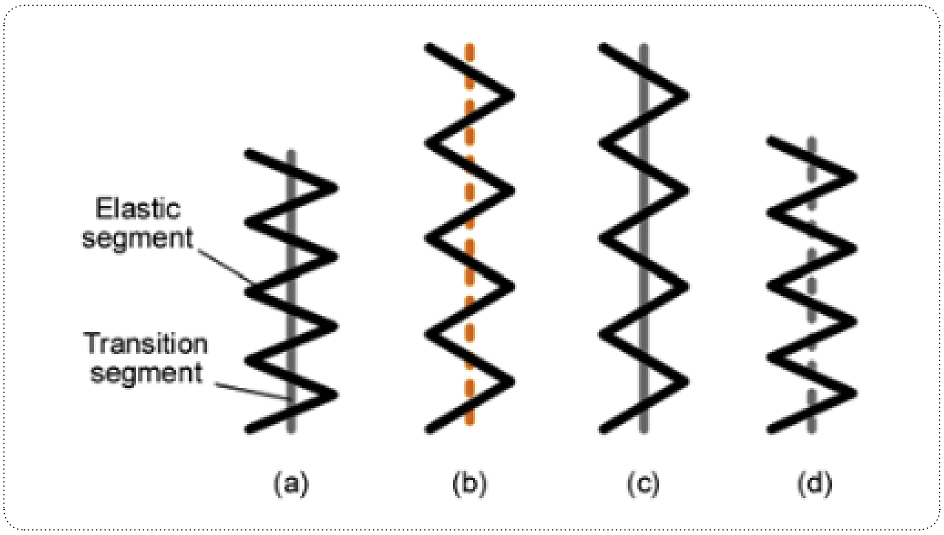


Figure 22: Illustration of the shape memory effect: normal state (a), deformed state (b), preserved state (c), recovered state (d). [Fan et al., 2011]

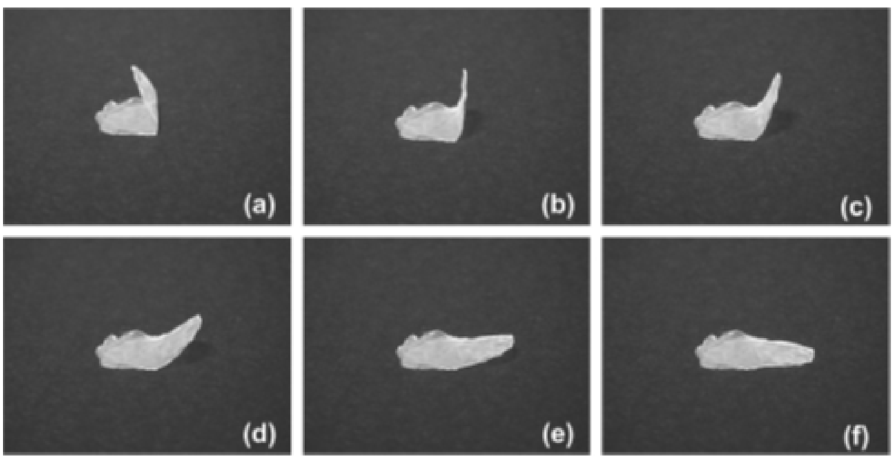


Figure 23: Shape recovery in a 300 nm thick PU SMP film upon heating. [Sun et al., 2012]

Shape Memory Hybrids

Despite the fact that the properties of SMPs can be more easily tailored than SMAs, the successful synthesis of a particular SMP for a special application normally requires strong chemical/polymer background, years of experience and great efforts in trial and error. This is not readily accessible to even every materials researcher. SMHs can provide an alternative solution that is based only on some simple concepts and utilizes only ordinary materials, which have well understood properties but do not have Shape Memory as an individual. Thus, the design of a SMM for a particular application turns out to be a routine which is easily accessible by ordinary engineers and even non-professionals in a do-it-yourself (DIY) fashion.

The mechanism behind the Shape Memory phenomenon in SMHs is the elastic-transition segment/domain system. An example would be silicone and wax, which both are biocompatible, as the elastic matrix and the transition inclusion, respectively. Ideally, in a SMH, there is not any chemical interaction between the matrix and the inclusion, so that the properties of the individual materials are largely maintained. Therefore, the properties of the SMHs can be well predicted from the very beginning. For instance, the transition temperature of the SMH is the softening temperature of original inclusion material. Aging, relaxation, and fatigue etc. can also be well controlled [Sun et al., 2012].

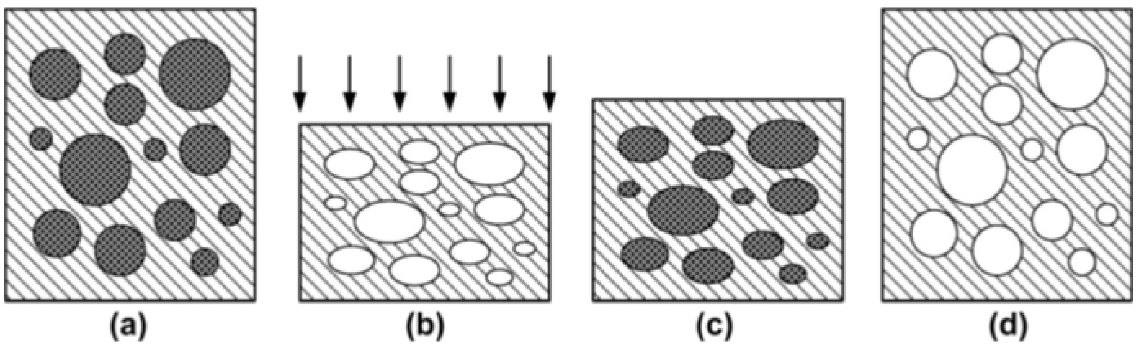


Figure 24: Illustration of mechanism for the SME in SMH. [Sun et al., 2012]

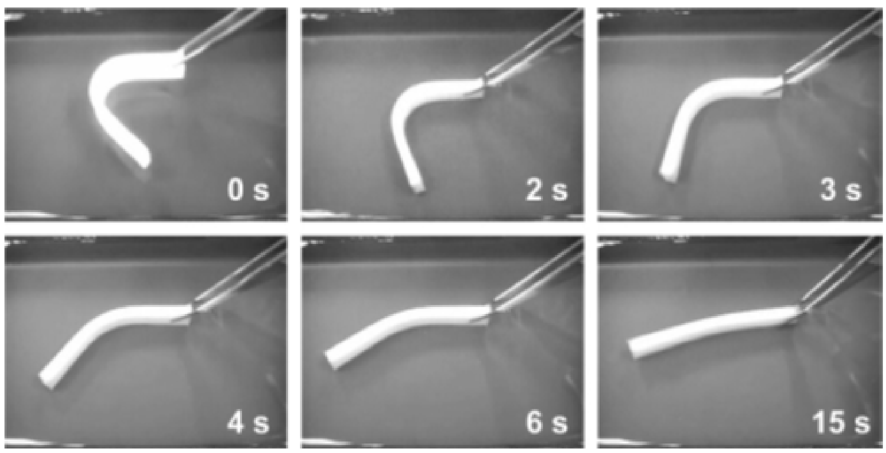


Figure 25: Shape recovery in a silicone/wax SMH upon immersing into hot water. [Sun et al., 2012]

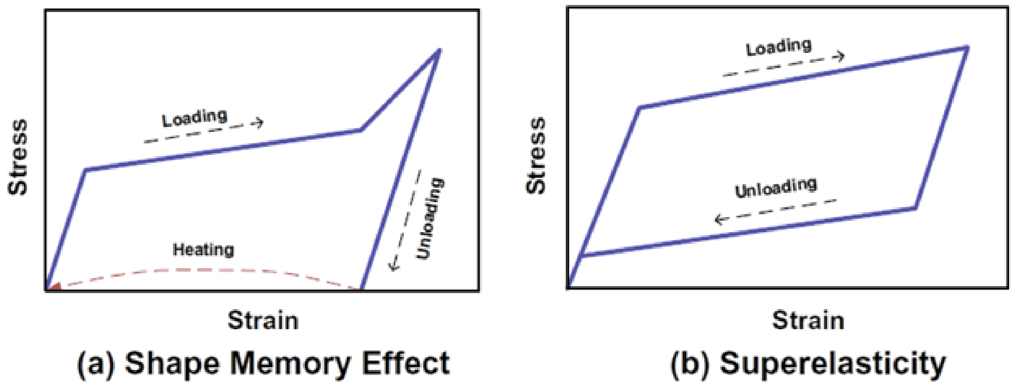


Figure 26: Shape Memory Effect (a) and Superelasticity (b) in SMA. [Sun et al., 2012]

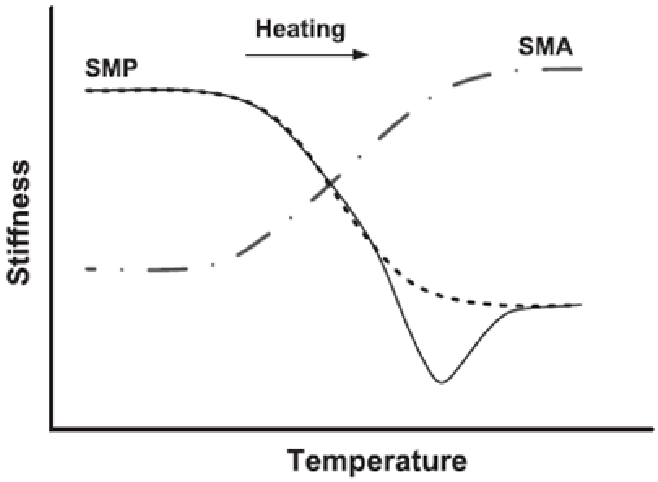


Figure 27: Change of stiffness in thermo-responsive SMMs upon heating. [Sun et al., 2012]

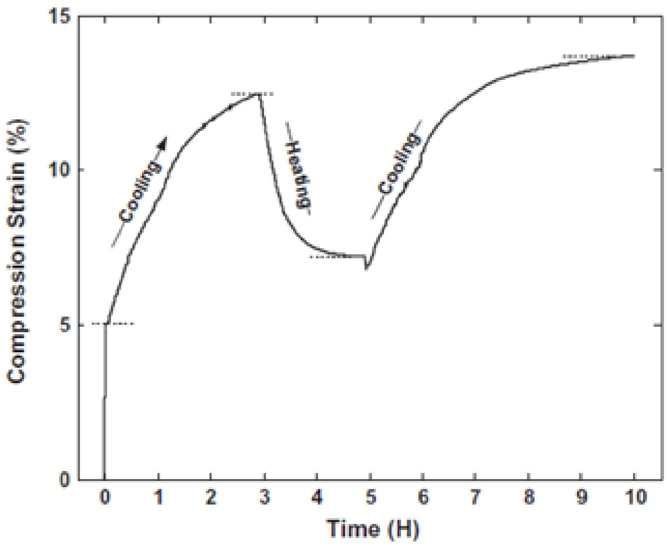


Figure 28: Compression strain against time (in hour) in a SMH during thermal cycling against a constant stress of 176 kPa. [Sun et al., 2012]

A brief overview and comparison of the three available Shape Memory Material families can be found in the tables below (these and some additional tables can also be found in the Appendix):

Table 1: SMA features [information retrieved from Fiorito et al., 2016]

SMA					
+	-	Mechanism	Alloy-based classification		
As an actuation material, SMAs are more powerful than SMPs. The actuation stress in SMAs is 10s MPa and above, while that in SMPs is a few MPa at the most	The difficulties in working with SMAs are related to their different behaviour and characteristics due to many different possible martensitic configurations	Thermo-responsive SMAs are featured by the four characteristic temperatures, namely austenite start temperature (As), austenite finish temperature (Af), martensite start temperature (Ms) and martensite finish temperature (Mf). Upon cooling from high temperature austenite phase, the martensitic transformation starts at Ms and finishes at Mf. Upon heating from low temperature martensite phase, the reverse martensitic transformation starts at As and finishes at Af. While at low temperatures, SMAs have the SME, at high temperatures, recovery can be achieved instantly and simultaneously upon releasing the applied load. This is called the super-elasticity (SE). According to the definition above, the SME is the characteristic of the SMM, while the SE is that of the SCM.	**NiTi based**	Cu-based	Fe-based
Biocompatibility, high corrosion resistance and high electrical resistance	Possible change in the mechanism properties after programming		+ Higher recoverable strain (around 7%), generated force and corrosion resistance		
Super-elastic behaviour			+ High actuation stress (up to 500 MPa)		
			+ High biocompatability		
			- Higher costs		

Table 2: SMP features. [information retrieved from Sun et al. (2012), Leng et al. (2011)]

SMP							Market diffused SMPs		
+	-	Mechanism	Chemical architecture classification				Base Material SMP	Ttrans [°C]	Company / Producer
Lower density PU SMP: 1.25 g/cm3 NiTi SMA: 6.4 g/cm3	More difficult to predict the behaviour of the polymers precisely due to significant relaxation, degradation, etc	The SME in SMPs is based on a totally different mechanism. Regardless of the types of the stimuli, there are two basic segments/domains in a SMP, one is elastic segment, and the other is transition segment While the elastic segment always maintains high elasticity within the whole SME cycle, the transition segment does change its stiffness significantly at the presence of the right stimulus. Carefully examining the mechanism behind the SME reveals that opposite to that in SMAs, SMPs normally are hard at low temperatures and become soft at high temperatures. Therefore, SMPs alone are normally not applicable in cyclic actuation, unless there is a V-shape in the stiffness vs. temperature curve upon heating, which has been found in a couple of SMPs	chemically cross-linked glassy thermosets	chemically cross-linked semicrystalline rubbers	physically cross-linked amorphous thermoplastics	physically cross-linked semicrystalline block copolymers	Styrene butadiene	60-70	Asahi company
Lower cost in fabrication and processing	The SME in SMPs may be affected by the programming conditions						Styrene-based (Veriflex®)	60-70	Cornerstone research group
Easily produced with high quality into almost any specified shapes at different scales using various traditional and advanced polymer processing technologies	Possible change in the mechanism properties after programming						One part epoxy	90	Cornerstone research group
Recoverable strain is normally an order higher than that in SMAs	The successful synthesis of a particular SMP for a special application normally requires strong chemical/polymer background, years of experience and great efforts in trial and error						Two parts epoxy	104	Cornerstone research group
It is easy to tailor the thermo-mechanical properties of SMPs by means of, for instance blending with different types of fillers or varying the compositions	Current understanding of the thermomechanical behaviour of SMPs is limited to one-dimensional deformation						Cyanate ester	135-230	Cornerstone research group
It is possible to be always transparent							Thermosetting epoxy	113	Composite technology development
Shape recovery temperature range can be easily altered within a wide range and even gradient							Thermoplastic polyurethane	40-55	Mitsubishi heavy industry
Damping ratio in particular within the transition range is higher									
The potential for recycle and reuse at low cost is higher									
Many SMPs have excellent chemical stability, biocompatibility and even biodegradability									
SMPs are more flexible in surface patterning for different patterns at different scales, and the resulted surface patterns are more permanent									
SMPs can be integrated into mechanical/ structural design as one part or parts of a structure for load carrying under normal working situation									

Table 3: SMH features. [information retrieved from Sun et al., 2012]

SMH			
+	-	Mechanism	Matrix/inclusion structure
Based on simple concepts and ordinary materials with well-understood properties	Not enough research carried out to beeter understand their thermo-mechanical properties	The mechanism behind the shape memory phenomenon in SMPs is the elastic-transition segment/domain system. For example, if silicone and wax are selected, both are biocompatible, as the elastic matrix and the transition inclusion, respectively. While silicone normally keeps its high elasticity characteristic within a wide range of temperatures, wax melts upon heating to its melting temperature, and becomes very soft. As such, the sample can be easily compressed. The silicone matrix is elastically deformed, so that an elastic energy is stored in it. When the sample is cooled back to room temperature, wax becomes solid again, which can effectively prevent the release of the elastic energy in the silicone matrix. Consequently, after the constraint is fully removed, the sample largely maintains its deformed shape until it is heated again to above the melting temperature of wax.	Silicone/wax
The accessibility, flexibility in design and fabrication of SMH provides an easy access to ordinary people, even without much chemical/ polymer background	Due to the different composition of SMHs, their modelling requires a specific applied study, even if SMHs can be modelled in similar ways to SMPs		Silicone/water
Can be biocompatible			
Both the matrix and inclusions are not limited to polymers only, but can be selected from any materials			
There is not any chemical interaction between the matrix and the inclusion, so that the properties of individual materials are largely maintained			
The properties can be well predicted from the very beginning by means of materials selections and simple estimation			
Aging, relaxation, and fatigue etc. can be well controlled			
They are convenient to be tailored to meet the exact requirement(s)			
Proven ability of silicon-wax SMH for cyclic actuation			
Similar shape memory effect to the SMPs' one			

Table 4: SMM families comparison. [information retrieved from Sun et al., 2012]

	SMAs	SMPs	SMHs
Description / Composition	Most diffused are NiTi-based alloys. Classified in Ni-Ti based, Cu-based and Fe-based	More than 20 different types of SMPs. Most common are thermoplastic polyurethanes and epoxy SMPs	Composed of materials with no shape memory effect on their own. They are "custom made". The most studied are Silicon-Wax Hybrids
Movement / Morphing effect	Stress recover and original shape recover. Small contraction (up to 10%) and deformation. A force is required to re-establish the original shape	Stress recover and original shape recover. High deformation (up to 800%). A force is required to reestablish the original shape	Stress recovery and original shape recovery. Small reversible strain (up to 6-8%). A force is required to reestablish the original shape
Durability issues	More than 200,000 cycles for NiTi alloys. In NiTi alloys high resistance against corrosion and external weather	Up to 200 cycles for SMPU tested. Can be affected by external weather conditions	Currently no experimental data. External weather condition resistance related to composition
Recovery temperature	-10 °C to +200 °C NiTiCu alloys can be tailored for shading devices, As ~ 45-60 °C	+25 °C to +200 °C Can be tailored at lower temperatures Tg ~ 60-90 °C	Vary with the components: silicon-wax hybrids have an activating temperature of ~ 45 °C
Density	6000-8000 kg/m3	900-1100 kg/m3	Variable
Elastic Modulus E above Ts	70-100 Gpa	0.5-4.5 GPa 1.24 GPa (Polystyrene SMP)	Variable
Elastic Modulus E below Ts	28-41 GPa (NiTi SMAs)	2-10 GPa (Polystyrene SMP)	Variable
Transformation strain	6-8%	250-800% 50-100 % (Polystyrene SMP)	~6% (Silicone-Wax)
Actuation stress	150-300 MPa ~100 MPa (NiTi SMAs)	2-10 MPa	Variable
Market availability and shape	Wires (different diameters, already educated in range from few µm to 1 mm) Springs Plates/Sheets	Easily customized shape	Mainly derived from DIY approach User's desired shape
Sustainability	Biocompatible	The potential for recycle and reuse at low cost is higher Many SMPs are biocompatible and even biodegradable	Can be biocompatible Organic materials can be used

3.1.3. APPLICATIONS - CLIMATIC RESPONSIVENESS AND FACADE INTEGRATION

SMMs have been broadly used in a wide range of fields, with a large interest in aerospace and automobile industry, with applications that include hinges, trusses, optical reflectors and morphing skins, exploiting the deformability and elasticity of SMAs the most. In addition, SMPs also present additional potential in the areas of biomedicine, smart textiles and self-healing composite systems due to their autoreactive response mechanisms and shape reversibility in biodegradable ways. In architecture and engineering, the application of SMMs is still in an initial stage, however, there are already developments and interest in this direction as well. Most common examples are self-healing systems, actuators, sensors and vibration control systems, as well as smart and solar morphing envelopes to enhance the building's thermal comfort and energy performance and saving, which is towards where the current study is directing the research scope [Li et al., 2018].

In facade applications, there is still more research needed for the implementation of SMM technologies to be able to exploit the material's inherent dynamic behaviour in a holistic functional system. However, the autoreactive feature of these materials to the environmental changes would enable a low-energy and low-tech control of the thermal behaviour of the building envelope. In the Table below [Table 5] some potential applications are shown with their corresponding principles in SMM integration in the built environment in an energy-efficient way [Li et al., 2018].

Table 5: Potential applications of shape memory polymers in built environments. [adapted from Li et al., 2018]

	Potential application	Principle	Reference
1	Active building facades with self-regulating sun protectors	A broad melting temperature range of temperature memory polymers based on crosslinked copolymer networks	[Behl et al., 2013]
2	Self-shading articulated surfaces	Two-part SMP filaments with different Tg values, forming variable stiffness tiles that respond to different incident solar heat levels	[Clifford et al., 2017]
3	Smart building envelopes	Integrated conventional one-way shape memory(SM), two-way reversible SM, and one-way reversible SM in semicrystalline SMPs	[Zhou et al., 2014]
4	Adaptive building envelopes	Significant reversible elongation resulting from crystallization of crosslinked poly(cyclooctene) films under tensile loads and induced cooling or heating	[Chung et al., 2008]
5	Functional smart architecture	Under various constant stresses, phase-segregated polyester urethanes (PEUs) with two-way shape changes between −20°C~60°C	[Bothe et al., 2012]
6	Convertible roofs	Using a layering technique to combine the SMP and elastic polymer, which forms novel polymer laminates with a two-way shape-memory effect (two-way SME)	[Chen et al., 2008]
7	Interactive kinetic walls	Reversible actuation of ultrathin semicrystalline polymer films	[Stroganov et al., 2015]
8	Changeable architecture	The design and fabrication of polymer particles with two-way SMP abilities between 0°C~43°C under stress-free conditions	[Gong et al., 2014]
9	Thermally comfortable buildings	Copolymer networks from oligo (ε-caprolactone) an n-butyl acrylate that enable a reversible bidirectional SME at human body temperature	[Saatchi et al., 2015]

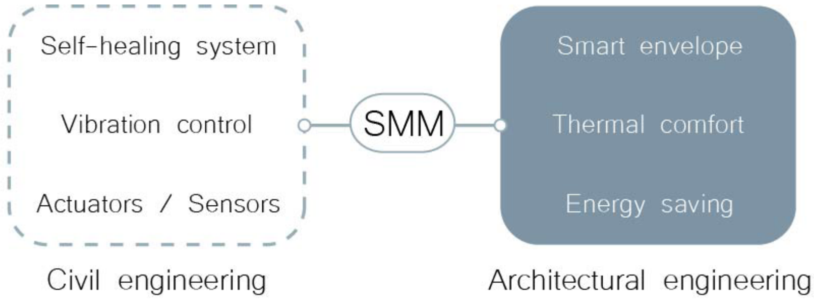


Figure 29: Applications of SMPs in civil and architectural engineering. [adapted from Li et al., 2018]

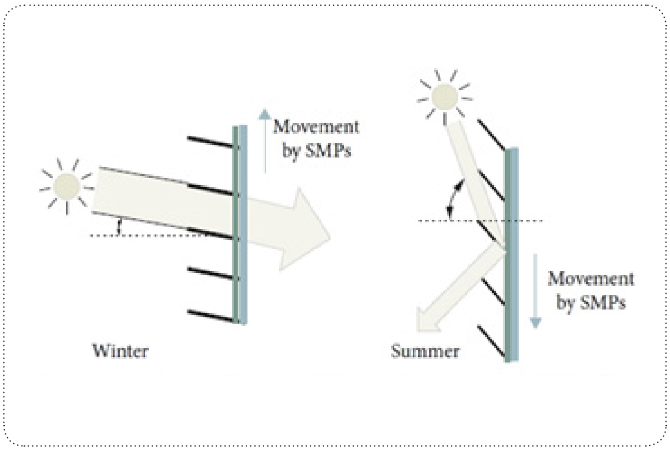


Figure 30: Schematic diagram of thermally responsive SMPs in heat controls of window blinds. [Li et al., 2018]

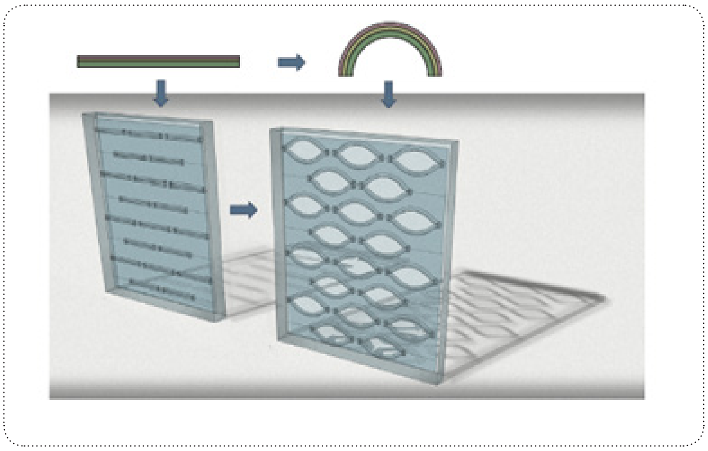


Figure 31: Schematic diagram of composite SMPs in shading controls. [Li et al., 2018]

3.1.4. "SMM FACADE INTEGRATION - UHI EFFECT" HYPOTHESIS

The above research on the material properties and behaviour already highlights some of the advantages and potentials of thermo-responsive SMMs to be implemented in adaptive facade applications due to their high level of direct responsivess and adaptation to real-time environmental changes, while they become attractive thanks to the ability to program their behaviour and, therefore, predict their dynamic performance and deformation. Of special attention are the inherent abilities of these materials, by applying the Shape Memory Effect to control the thermal transmission at the building envelope, increase the solar radiation reflectivity and reduce the thermal transfer. At the same time, some of the applied existing UHI mitigation strategies include reflective and undulated surfaces (either through the material's thermal capacity or through the roughness level of the envelope's surface) with a direct impact on the reflection of the incoming heat and solar radiation, as well as the reduction of warm air-emissions from air conditioned buildings and the reduction of the inner operational energy through means of (self-) shading as an indirect intervention. Within this frame, the thesis' research objective attempts a connection between the two and lies on a hypothesis having both scientific and societal relevance. The hypothesis developed is *"whether, how and to what extent the implementation of SMMs in an integrated passive adaptive solar morphing facade system can contribute to the reduction of the building's impact on the UHI effect in an energy-efficient and autoreactive way".*

3.2. BIO-INSPIRED DESIGN APPROACH

At the same time, during the material literature study on the inherent characteristics of SMMs and their dynamic response mechanisms to external stimuli, there is a relevance and connection found to nature's strategies and principles for climatic adaptiveness. This led to a further exploration of existing bio-inspired mechanisms and their potentials to be interpreted in a facade design, by combining material and mechanism in a passive adaptive system. This gives way to the development of an approach towards responsive, adaptable facade systems by means of hingeless, energy-efficient and bio-inspired systems.

3.2.1. NATURE'S RESPONSE STRATEGIES AND PRINCIPLES FOR CLIMATIC ADAPTIVENESS

Biomimetics is a term coined by Otto Schmitt in 1969 [Schmitt, 1969]. It is known as the science that studies the replication in humans' design of natural methods and processes. Jeronimidis and Atkins defined also biomimetics as *"the abstraction of good design from nature"* [Jeronimidis et al., 1995]. The applications of biomimetics in research follow two different approaches: "bottom-up" and "top-down", with a multidisciplinary approach in both cases [Speck et al., 2008]. In a bottom-up process, research starts from biology and then it is transferred to other disciplines like engineering, whereas in the top-down approach, also known as bioconvergence, research starts from the engineering side of disciplines, where technical problems are accurately defined prior to finding a solution and nature is considered as a source of inspiration for possible solutions to be interpreted to obtain the technical solution.

An important characteristic of natural systems is a multilayered, finely tuned and differentiated combination of basic components which lead to structures that feature multiple networked functions [Knippers at al., 2012]. In relation to architectural applications and the replication of nature's strategies for climatic adaptiveness, Knippers and Speck [Knippers et al., 2012], proceeded to an identification of four main principles by classifying natural systems:

- **Heterogeneity**: characterized by different geometries for different elements and local adaptations of their physical or chemical properties.
- **Anisotropy**: nature shows the use of composite fiber reinforced materials, where the orientation of fibers and their spatial distribution are key factors.
- **Hierarchy**: In natural systems, hierarchy is multi-leveled and present at different scales, each level consisting of similar molecular components, but giving rise to different and, to some extent, independent functional properties and adaptions. This principle has not been already fully explored in architecture and engineering fields.
- **Multifunctionality**: characterized by the integration of monofunctional components into a single element, such as the integration of sensors and actuators in adaptive composite structures or elements for generation, transmission and storage of energy in facade elements.

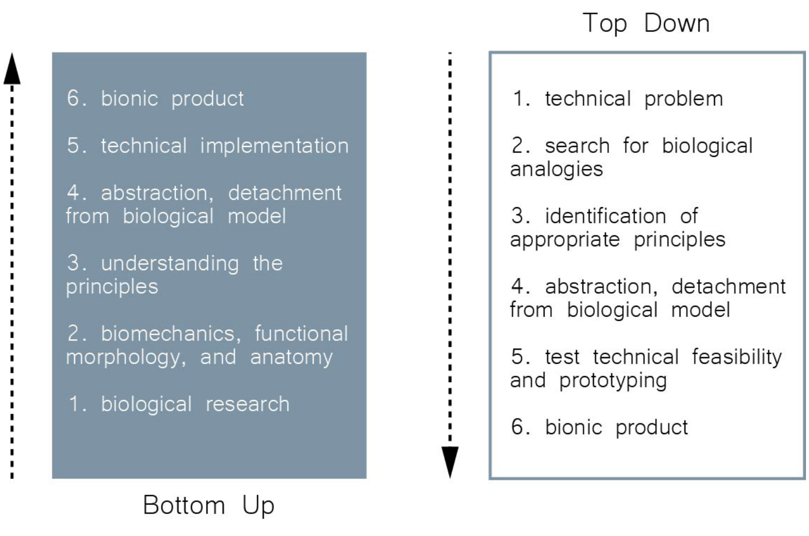


Figure 32: Bottom-Up and Top-Down approaches of biomimetics. [adapted from Knippers at al., 2012]

Table 6: Design path matrix of the biomimicry pinnacles. [Kadri, 2012]

Challenges	Processes	Flow	Adaptation	Scale	Environmental context	Morphological features	Structural features	Material features	Other features
Air									
Exchange	Diffusion	passive	Morphological	micro	Tropical Arid Temperate Cold	Fractals	Valves Conduits	Elastic	Counter-current unidirectional flow enlarged surface area
Move	Pressure variations	passive	Morphological	meso		Funnels Mounds	Conduits	Porous Elastic conductive	contracting expanding unidirectional flow
Heat									
Retain	Increase insulation Counter-current flow Reduce cold stress	passive	Morphological Behavioural	micro meso	Cold Polar	Adjacent Cluster		Conductive	Reduce surface area
Dissipate	Enhance convection Enhance conduction	passive	Morphological	meso	Tropical Arid	Branching Conduits		Conductive elastic	Peripheral flow Unidirectional flow Enlarged surface area
Water									
Gain	Condensation	passive	Morphological	micro	Arid	Bumpy	Channels	Hydrophilic	
Transport	Capillary action	passive	Morphological	micro	Arid	Hexagonal Fractal	Tubes Grooves Channels	Hydrophobic	overlaps folding
Lose	Evaporation	passive	Physiological	micro	Tropical Arid Temperate Cold				Asymmetric expansion Porous
Conserve	Control permeability	passive	Physiological	micro	Arid	Thorns	Grooves	Elastic Waxy	
Light									
Manage intensity	Exposure Inclination		Morphological	meso	Temperate Cold	Dense Monolayer			Elongation Inclination Rotation

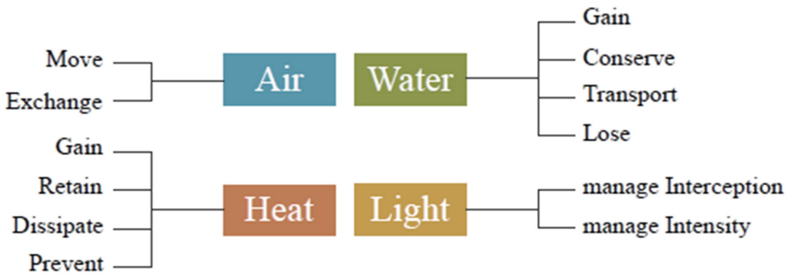


Figure 33: Key functions of adaptive building envelopes and their analogies found in nature. [Kadri, 2012]

3.2.2. NATURE'S INTRINSIC FEATURES AND SMM'S INHERENT BEHAVIOUR

Similarly, smart materials, e.g. alloys and polymers, have intrinsic features that share common features with the nature's responsiveness strategies and homeostatic mechanisms. More specifically, they have shown to possess the characteristics to work as actuators with minimum or no external energy and without the need for complex mechanisms, either separated or integrated, into shading components as an example. Through their Memory Shape Effect and speed of actuation, these actuators are able to produce ranges of movement and responsiveness suitable to be applied in dynamic shading facade systems. Although there are a few examples of applied use of smart materials in shape morphing solar skins, there is much research being developed in this direction for the design of future environmentally responsive facades. The use of shape memory actuators in building sector is still to a limited extent, especially concerning their solar activation, life cycles and resistance to external weather conditions. From the available materials, Shape Memory Alloys have been extensively tested and used, and can be currently considered as suitable materials for shading applications, whereas Shape Memory Polymers and Hybrids can present future interesting opportunities, due to their enhanced dynamic performance and user-friendly customization.

Focusing on architectural applications and the design of shape morphing solar shadings, the principles of anisotropy and multifunctionality are the most relevant ones, if the design is approached following the principles of biomimetics. Anisotropy would define how deformation, and therefore movement, can be achieved through the distribution and orientation of material's fibers. Multifunctionality is then related to the capacity of embedding different functions into one single element (as sensing and actuating functions of smart materials). In this sense, the connection to phytomimetics and the study of nastic structures is of great relevance. Main feature of plants is their flexible movements with high reversibility, which forms the triggering movement and constitutes an inspirational model to reduce complexity of moving parts in buildings and to develop deployable structures. Apart from that, they also show anisotropic arrangement of material and fibers to reduce material stresses in an energy-efficient way.

Nastic structures in general present three important characteristics interrelated with kinetic building systems, which are also present in smart materials. Firstly, movement is triggered by an external stimulus, secondly, motion is carried through volume change (shape) and, lastly, their anisotropy is derived from an unequal distribution of material in the cells. Nastic movements respond to an external stimulus regardless the direction of the stimuli inducing movement and predominantly reversible, for instance the folding/unfolding and raising motion of leaves [Schleicher et al., 2015].

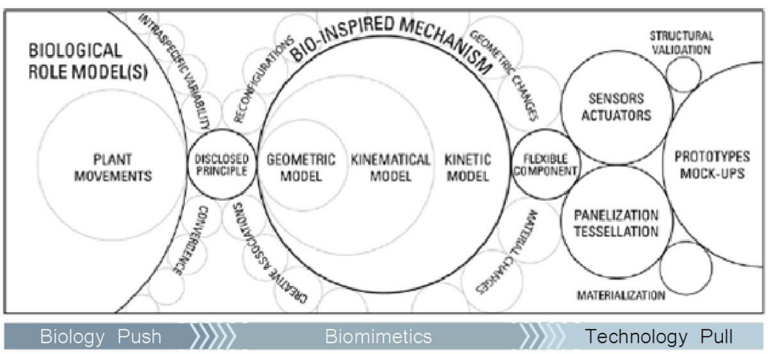


Figure 34: Mapping the key aspects of transferring bio-inspired motion principles into technical kinetic structures. [Schleicher et al., 2015]

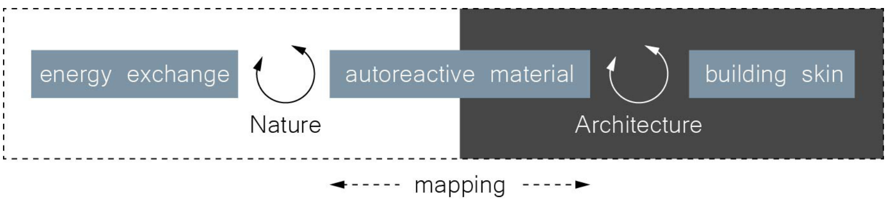


Figure 35: Conceptual mapping pattern between the three topics. [adapted from Persiani et al., 2016]

3.2.3. BUILDING'S THERMAL BEHAVIOUR AND ENVIRONMENTAL RESPONSE WITHIN A BIO-INSPIRED FRAMEWORK [CASE STUDIES]

The abovementioned features and inherent behaviours can be replicated by incorporating material and mechanism in an integrated passive adaptive facade system. In both cases, the aim is to respond to complex but limited ranges of environmental conditions by changes in geometric configuration through the ingrained properties of the material itself, without the need for external energy or complex mechanical parts, and by means of movement which is produced using the elastic properties of the materials working at high strain.

In this direction, architectural envelopes can be designed to move dynamically by reacting automatically as decentralized energy independent systems rather than being controlled by sensor-brain systems [Persiani et al., 2016]. By following nature's priority principles for self-regulation, passive adaptive facade systems can incorporate dynamic material systems and mechanisms with inherent autonomic response. The integration of material systems with intelligence and life features intrinsic in their microstructure can, therefore, produce adaptive functionality to the building envelope and better climatic responsiveness by means of mass and energy regulation.

Biomimicry, after all, attempts to learn from the most fit solutions in nature and borrow ideas for solving many anthropologic issues (technological, social, environmental etc.) As evolution has favoured fit organisms over obsolete ones, these are an enormous inspiration pool for evolving new technologies [Persiani et al., 2016].

Case studies

The inherent directness and climatic responsive mechanisms explained throughout the literature study of materials and response mechanisms are attractive to architects and engineers and there are already some realized projects which have been developed and show promising potentials for further exploration in implementing SMM and/or a biomimetic approach in integrated facade applications. Most of the examples concern kinetic shading systems, while solar morphing shading skins are not broadly explored. Where an actuator is required, this can be completely embedded into the device or strategically located to trigger a specific action [Dakheel et al., 2017]. Some of these applications can be summarized in the overview table below [Table 7], based on the actuator systems, material and mechanism selection and possible relation to bio-inspired approaches.

Table 7: Case studies. [information retrieved from Fiorito et al. (2016), Dakheel et al. (2017)]

	Project name	Motion	Smart actuator	Stimulus	Scale	Biomimetic approach	Reference
1	Flectofin®	Three-dimensional movement (swivel motion - Both in the same axis)	-	External mechanical forces	Component	Bottom-up	[Lienhard et al., 2011]
2	Solar Kinetic	Three-dimensional movement (swivel motion - Both in the same axis)	Shape Memory Alloys (SMA)	Heat source provided through electrical current	Sub-component	Bottom-up	[Suralkar, 2011]
3	Blind	Three-dimensional movement (swivel motion - around a different axis)	Shape Memory Alloys (SMA)	Heat source provided through electrical current	Sub-component	Top-down	[Khoo et al., 2011]
4	Air Flow(er)	Three-dimensional movement (swivel motion - around a different axis)	Shape Memory Alloys (SMA)	Heat source provided through electrical current	Component	Top-down	[Payne et al., 2013]
5	Sun Shading	Three-dimensional movement (swivel motion - around a different axis)	Shape Memory Alloys / Shape Memory Polymers (SMA/SMP)	Heat source provided through electrical current	Component	-	[Lignarolo et al., 2011]
6	Smart Screen	Bi-Dimensional Movement (Translational Movement by overlapping layers)	Shape Memory Alloys (SMA)	Heat source provided by solar radiation	System	-	[Decker et al., 2010]
7	Piraeus Tower	Bi-Dimensional Movement (Translational Movement by overlapping layers)	Shape Memory Alloys (SMA)	Heat source provided by solar radiation	System	Top-down	[Doumpioti et al., 2010]
8	Lily Mechanism	Three-dimensional movement (swivel motion - Both in the same axis)	Shape Memory Hybrid (SMH)	Heat source	Component	Bottom-up	[Schleicher at al., 2015]
9	Kinetic Solar Skin	Three-dimensional movement (swivel motion - around a different axis)	Shape Memory Alloys (SMA)	Heat source provided through electrical current	Component	-	[Pesenti et al., 2015]

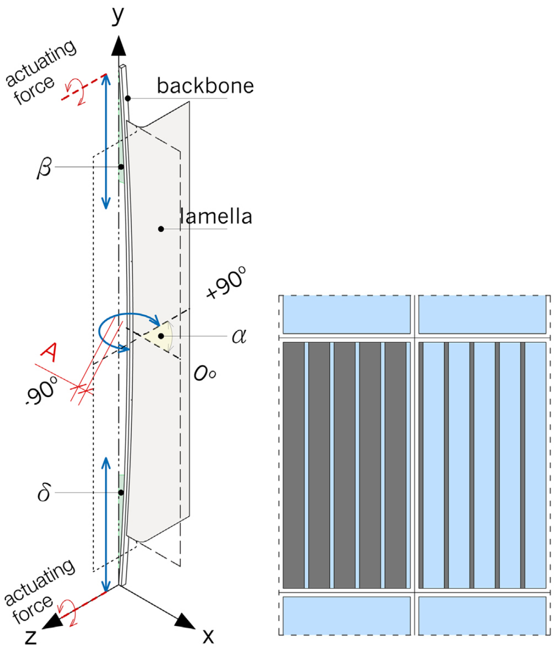


Figure 36: Project (1): Flectofin®. Scheme of operation and example of facade's integration (closed and open configuration). [Lienhard et al., 2011]

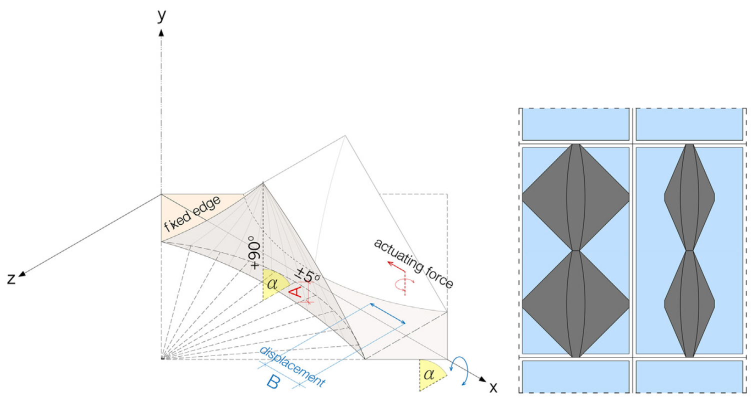


Figure 37: Project (2): Solar Kinetic. Scheme of operation and example of facade's integration (closed and open configuration). [Suralkar, 2011]

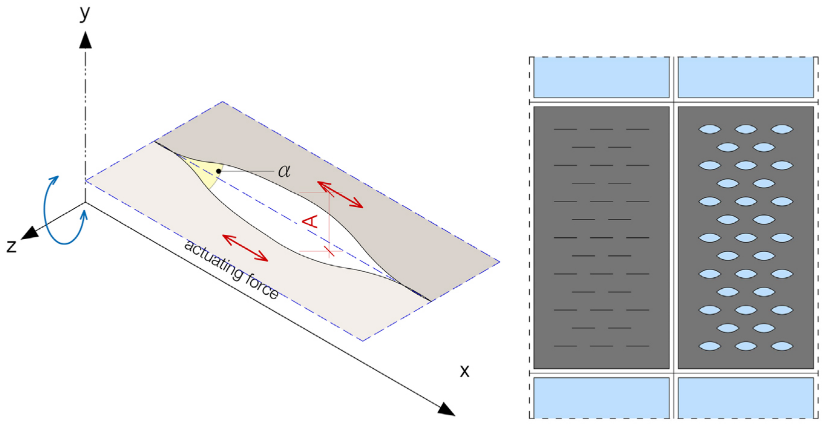


Figure 38: Project (3): Blind. Scheme of operation and example of facade’s integration (closed and open configuration). [Khoo et al., 2011]

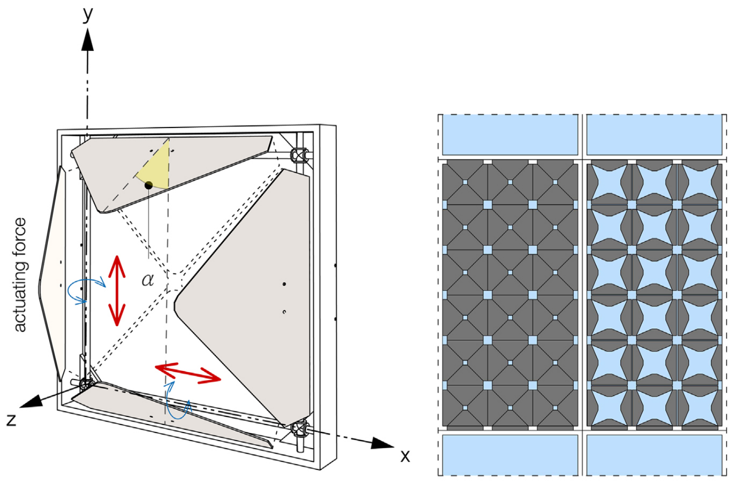


Figure 39: Project (4): Air Flow(Er). Scheme of operation and example of facade’s integration (closed and open configuration). [Payne et al., 2013]

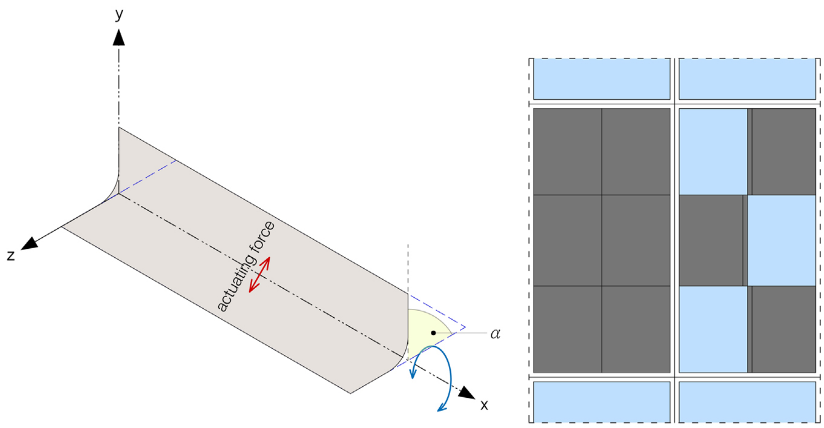


Figure 40: Project (5): Sun Shading. Scheme of operation and example of facade’s integration (closed and open configuration). [Lignarolo et al., 2011]

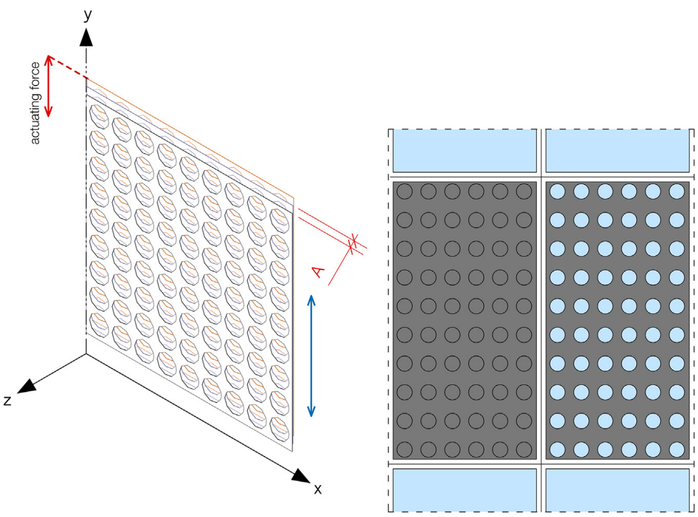


Figure 41: Project (6): Smart Screen. Scheme of operation and example of facade’s integration (closed and open configuration). [Decker et al., 2010]

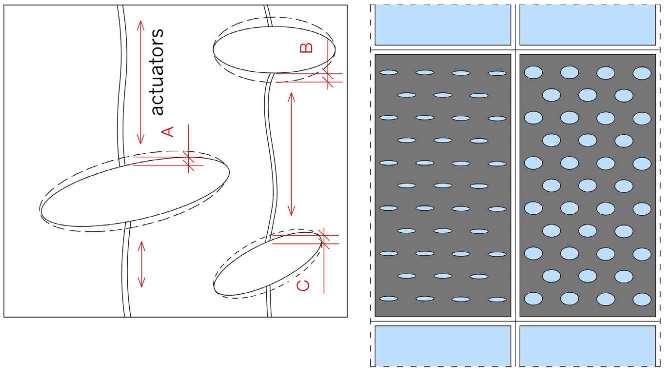


Figure 42: Project (7): Piraeous Tower. Scheme of operation and example of facade's integration (closed and open configuration). [Doumpioti et al., 2010]

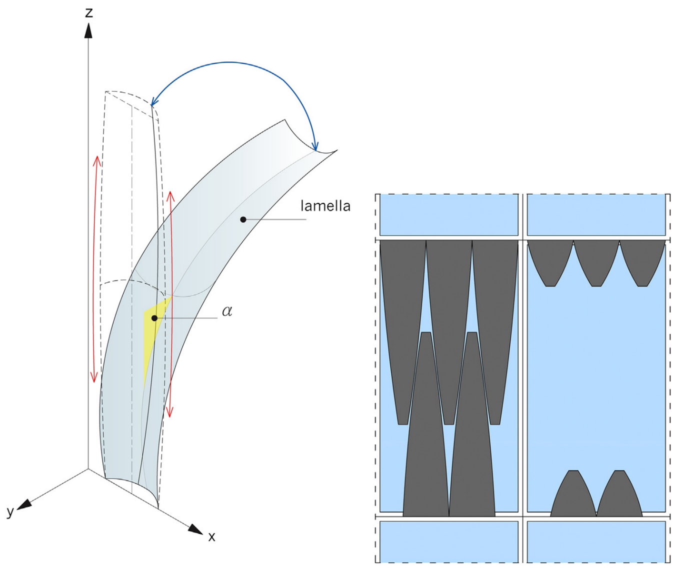


Figure 43: Project (8): Lily Mechanism. Scheme of operation and example of facade's integration (closed and open configuration). [Schleicher et al., 2015]

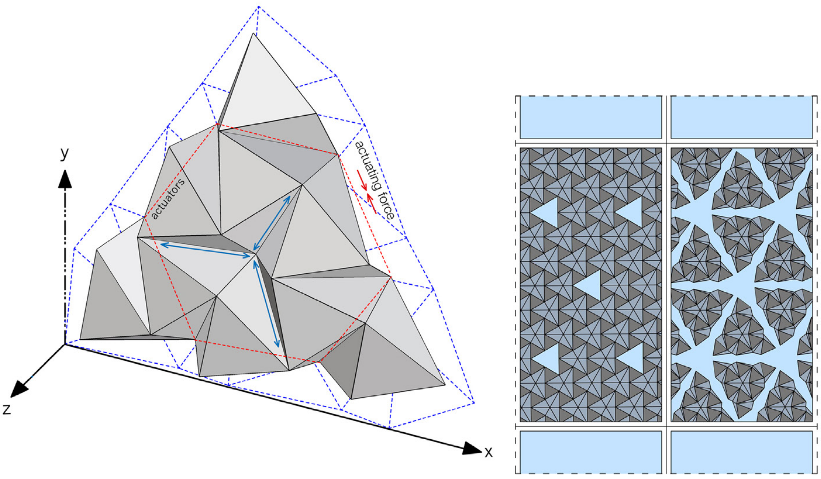


Figure 44: Project (9): Kinetic Solar Skin. Scheme of operation and example of facade's integration (closed and open configuration). [Pesenti et al., 2015]

All the selected projects present one or two degrees of freedom in the desired movement, varying between two extreme positions, open and closed modes, with continuous transition between the two positions. Where movement is three-dimensional, a constrained swivel motion produced by bending and buckling of elastic materials characterizes rotation. An exception is the case of the Air Flow(er) project, in which hinges are used to rotate stiff wings. Most of those performing three-dimensional movements have also been developed either at component or subcomponent scale, due to the discrete sizes and capabilities of smart materials as actuators. On the contrary, translational movements are more suitable for larger scale projects.

As for the biomimetic approaches, anisotropy can be classified as a bottom-up approach aimed at taking into abstraction reversible and repeatable movements found in nastic structures, by means of materials properties and distribution within the component, like in the Flectofin®, Solar Kinetic and Lily Mechanism projects. Movement is produced from the material elasticity and from the fibers' arrangements, while minimizing stress when movement is produced. Based on research following a biomimetic bottom-up approach, they are characterized by means of an iterative process, starting from the reproduction of movement, and followed by the optimization of shape and by the selection of materials. These projects were inspired by existing studies in plant movement, by exploring the nastic properties of *Strelitzia Reginae* flower, *Aldrovanda Vesiculosa* carnivorous plant, and *Lilium Casablanca* flower, respectively. The three examples can perform fast actions and are, therefore, suitable for applications responsive to the continuous changing position of the sun. In the contrary, a top-down approach can be identified in the Blind, Air Flow(er) and Piraeus Tower projects, using analogies from various natural sources, but not related to movement in all cases. However, multifunctionality is considered a predominant feature in all projects, mainly incorporating smart materials for sensing and actuating the systems.

These projects also experiment with the use of polymers as constituent materials for their components, mostly thanks to their elastic properties in tension and low stiffness in bending. Formed and amorphous polymers were used, with layered compositions to reproduce anisotropy of plants. A second material can be found either as protective layer or as actuator, like glass fiber reinforced polymers (GFRP), silicones and elastomers.

In the studied examples, common feature is also the integration of SMM materials as triggering actuators for the shading movements. In most of the cases, thermal triggering has been the most widely researched and developed method for changing shape of the solar shadings, by exploiting a temperature gradient, which is directly provided by direct sunlight exposure. Different activation temperatures have been tested in the analyzed projects. For instance, in the Piraeus Tower project, action would occur between 35°C and 40°C, whereas in the Sun Shading one, SMAs would move when reaching more than 90°C. In the Lily Mechanism project, a Shape Memory Hybrid was implemented, by combining two materials with different thermal expansion behaviors, like GFRP and PMMA, capable to trigger the movement when the materials' temperature exceeds 70°C.

However, one of the limitations of such automated systems, is the dependency on the environmental conditions, where variable external conditions could limit the efficiency of any system intended to produce movement by means of heat and solar exposure. Because of that, it is not always possible to establish a holistic relationship between devices' temperature and solar irradiance. Consequently, sometimes heat needs to be instead generated directly or indirectly from electricity, for example produced by a photovoltaic converter, as in the cases of the Solar Kinetic, Sun Shading and Blind projects. This means that, although control is considered to be automated and responsive to outdoor conditions without any central brain to control the whole facade system, in practice, occupants' control is preferred to be potentially available, mainly for ventilation purposes. However, such applications are not explored in much extent in the built environment, and this highlights at the same time the challenges of such completely automated systems for future facade implementations [Fiorito et al., 2016].

Most of above case studies exploit the dynamic movement for sun-control purposes which can be produced at component scale through lightweight and elastic structures to form solar morphing and shading devices for building applications. The adoption of these materials allows fabrication of components with an anisotropic composition, like differentiated thicknesses and a predominant fiber distribution in a desired direction. The optimization of movement, through the reduction of material's stress and the use of innovative low-energy triggering methods, such as smart materials actuators, are some of the additional benefits [Fiorito et al., 2016]. In those projects, where a biomimetic connection to natural systems' mechanisms is additionally present, this originates by either a bottom-up or top-down approach.

04 FACADE DESIGN INTEGRATION

4.1. ADAPTRONIC SYSTEM: AUTO-REACTIVE MATERIAL & ACCLIMATED KINETIC ENVELOPE

Based on the objectives and research approaches, the thesis aimed to develop a solar morphing kinetic facade system, which can achieve motion using latent energy in an energy-efficient and autoreactive way, with optimal use of sensors and actuators, where material, form, function, structure and motion are independent in a fit combination [Persiani et al., 2016]. The intention was to use the research's background information and study to couple the autoreactive inherent features of the material within an acclimated kinetic system, which provides the desired climatic adaptiveness, by replicating strategies and principles found in nature. As such, the term "acclimated" is from biology and refers to a process in an individual organism adjusting to a gradual change in its environment through its morphological, behavioral or physical changes [Wang et al., 2012]. The end result is a combination of both systems and leads to an adaptronic system, which is able to modify its behaviour to create an envelope of utility and have as objective to instill intelligence in the microstructure to perform adaptive functions [Rogers et al., 1999].

On one hand, the advanced rate of technological advancement can help simplifying the design of moving components through the use of smart materials, reducing consistently the number of operating difficulties. On the other hand, biomimicry can improve the design process by individuating the best combination of geometry, motion type, motion transmission and actuating parameters. [Persiani et al., 2016].

To elaborate further, the adaptronic systems can be defined based upon a technology paradigm as *"the integration of actuators, sensors, and controls with a material or structural component".* Multifunctional elements form a complete regulator circuit resulting in a novel structure displaying minor complexity, low weight and high functional density. However, they can also include the notion of biologically inspired materials and mechanisms by addressing the goal of the material system as follows: *"material systems with intelligence and life features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality"* [Rogers et al., 1999].

The integration of material and systems is holistic in the same way that biological structural systems do not distinguish between materials and structures. The design and development of natural organisms is an integrated process in which component functions are multiple, and result in a cost-effective and durable structure whose performance matches the living system. Likewise, the distinction between adaptronic structures and intelligent structures is vague. Each of the systems requires a hybrid approach to integrating the technologies that synergistically combine life functions and intelligence. The distinction between material systems and structures can then be defined in terms of the scale of their microstructures [Rogers et al., 1999].

Figure 45: Characteristics of mechatronic and adaptronic systems [adapted from Drossel et al., 2015]

4.2. FACADE DESIGN GUIDELINES

The goal is to propose a "living" envelope, a low-energy and low-tech facade system capable of predictably changing in shape in response to heat changes through the ingrained properties of the material it is made of, without the need for external energy or complex mechanical parts and by optimizing the use and number of actuators required to achieve the desired result. In this way, by applying the Shape Memory Effect of the material, a control of the thermal transmission of the building envelope can be achieved, as well as a reduction of the thermal transfer through an optimal dynamic performance of the facade skin.

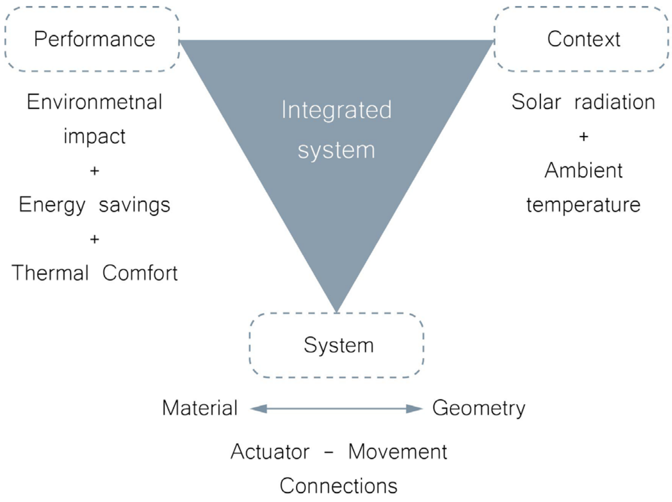


Figure 46: Diagram of integrated design principles [own work]

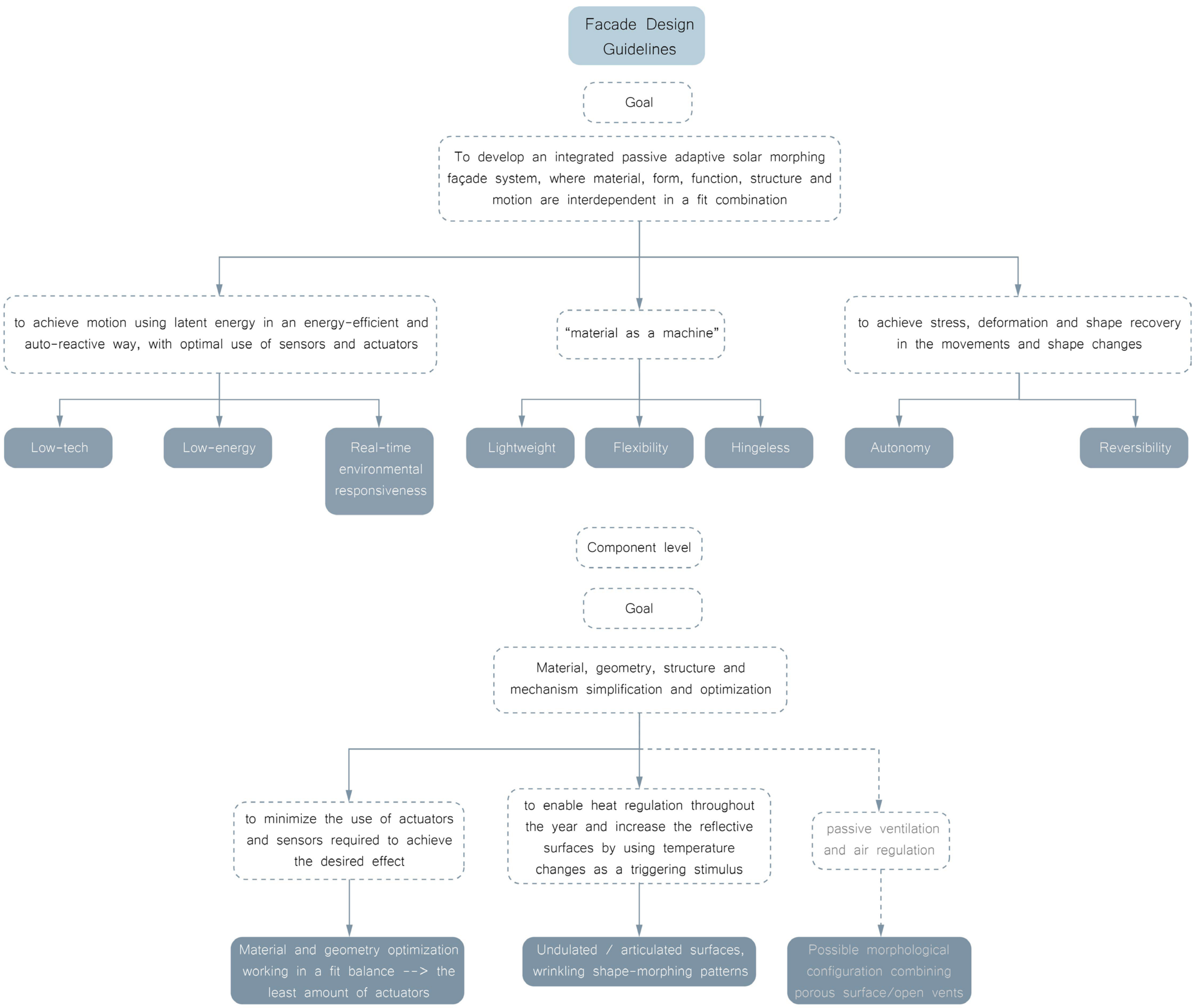


Figure 47: Diagram of facade design guidelines [own work]

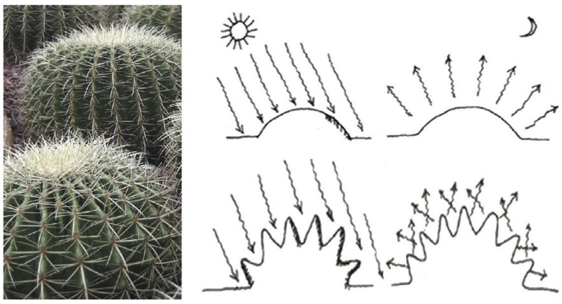
4.3. APPROACH AND PRELIMINARY IDEAS

The facade design proposal concerns the development of a self-shading skin integrated in a exterior facade system, aiming to regulate the heat exposure in both the cooling- and heating-dominated periods. The base of the idea is that the double layer consists of an inner solar absorbing coating layer and the outer SMM-based shape-morphing skin layer, which forms a dynamically responsive and reflective articulated surface. During the summer months, the SMM skin, triggered by the temperature rise, expands and creates undulated and dense surfaces, increasing the reflectivity of the building envelope. In the contrary, during colder periods, the skin retracts to its originally programmed form, revealing the inner heat absorbing layer that is exposed to solar radiation. In both states, the goal is to minimize the cooling demands of the building during hot periods and the heating demands during the cold seasons, acting in an opposite logic than in a regular shading system (covered during summer-open during winter). In the end, the aim is to passively minimize the energy needs and, consequently, the building's footprint on the UHI effect in an indirect way. However, since a fully automated system might not reach the maximum possible effect, the possibility to override the function could potentially be incorporated as a design option to enable the user's freedom of operational control.

Besides that, there has been a research on bio-inspired strategies for heat regulation in natural organisms. The focus was placed mostly on the articulated morphology of the succulent plants' surfaces to reflect the solar radiation by means of their geometry, which is then used as bio-inspiration for the development of an undulated shape morphing facade skin, to increase the angle and area of reflecting surfaces. At the same direction, the layered structure of butterfly wings with their ridges and cross ribs are acting mechanisms to minimize the acceptance of solar heat. As for ventilation strategies, the dynamic opening and closing movement of the "stomata" on the leaves' surfaces to regulate the air intake and exhaust of the plant is an additional strategy used as background inspiration to promote adaptiveness through passive dynamic shape changes.

Additionally, the articulated effect of the self-shading skin depends to a certain degree on the material choice and the origin of the actuating element, which can be a point, a line or a surface. Translated to the facade component, this can result in considering the actuating force acting either in the form of the connecting joint, the edge or the surface of the self-shading skin structure, such as a nodal trigger forcing the movement, a linear elongation-deformation or a surface expansion-shape recovery. This led to various design options, translational movements and degrees of freedom, with SMAs and SMPs having different potentials. For example, SMAs are more commonly used in edge deformations, while SMPs provide mostly surface shape changes. However, SMAs or SMPs can both be applied to control the deformation by control of the joint element, as well. Therefore, the available options could be flexibly optimized based on either a material-driven or a design-driven choice, and therefore, as a starting point, options in both directions were considered to be further evaluated.

Figure 48: Cacti fractal cooling system during day and night and articulated reflecting surfaces. Source: Eastgate. (2017, November 08). Retrieved from https://blogs.uoregon.edu/bioform/2017/11/08/1067/



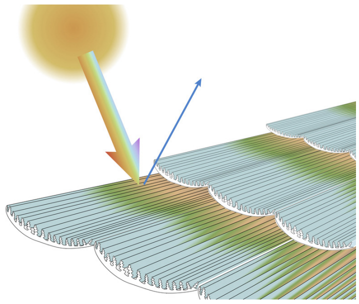
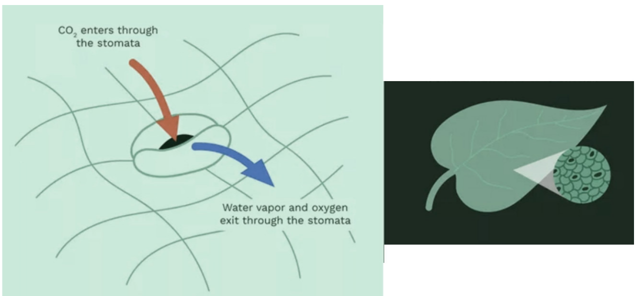


Figure 49: Scheme of butterfly wing's tiny scales covered with microscopic ridges, cross ribs, and other structures. Source: Vukusic, P., Yoshioka, S., Prum, R. O., Vukusic, P., Kinoshita, S., Team, A., & Sherry. (2002, July 26). Wing scales cause light to diffract and interfere : Morpho. Retrieved from https://asknature.org/strategy/wing-scales-cause-light-to-diffract-and-interfere/

Figure 50: Leaves' stomata principal function. Source: Bailey, R. (n.d.). What's the Function of Stomata in Plant Tissue? Retrieved from https://www.thoughtco.com/plant-stomata-function-4126012



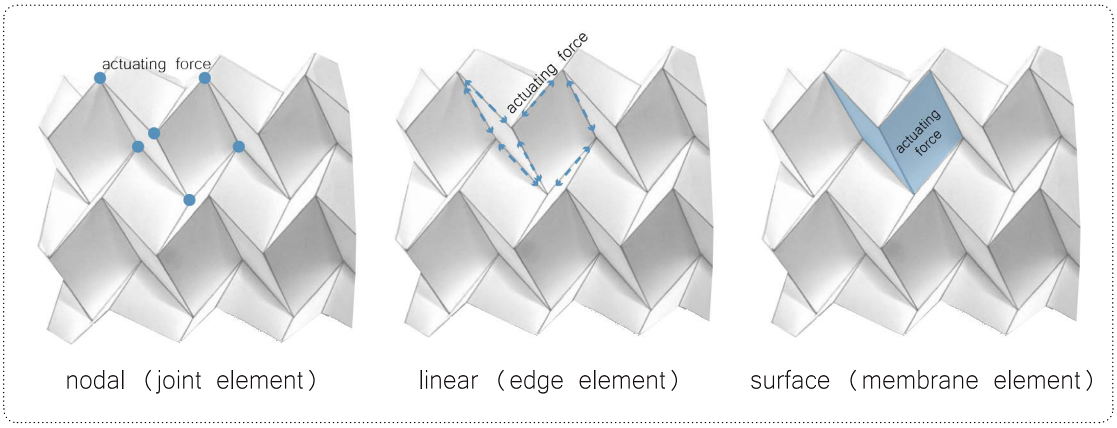


Figure 51: actuation force placement [own work]

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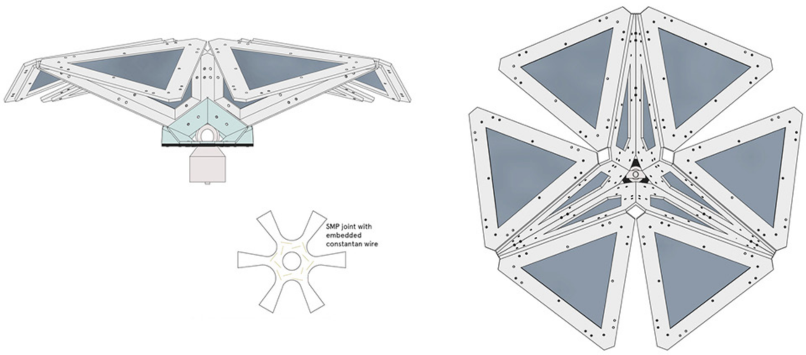


Figure 52: SMP joint [Rawn, 2014]

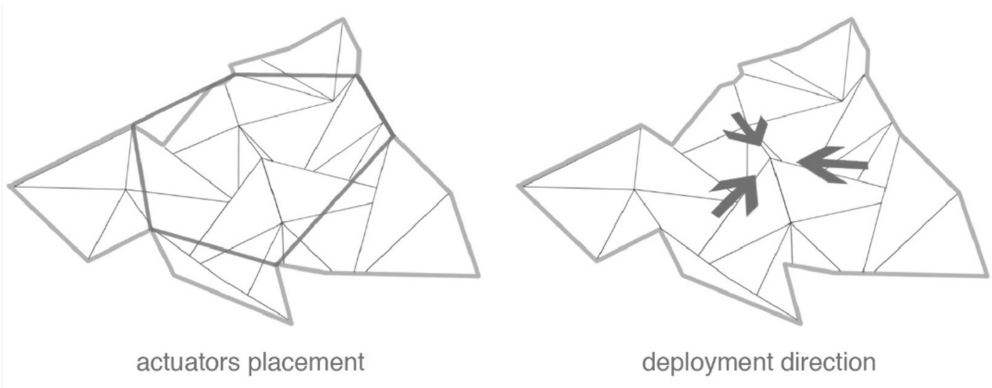


Figure 53: SMA edge wire [Dakheel et al., 2017]

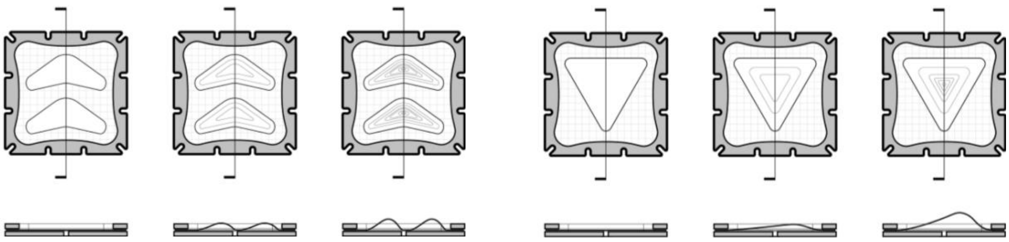
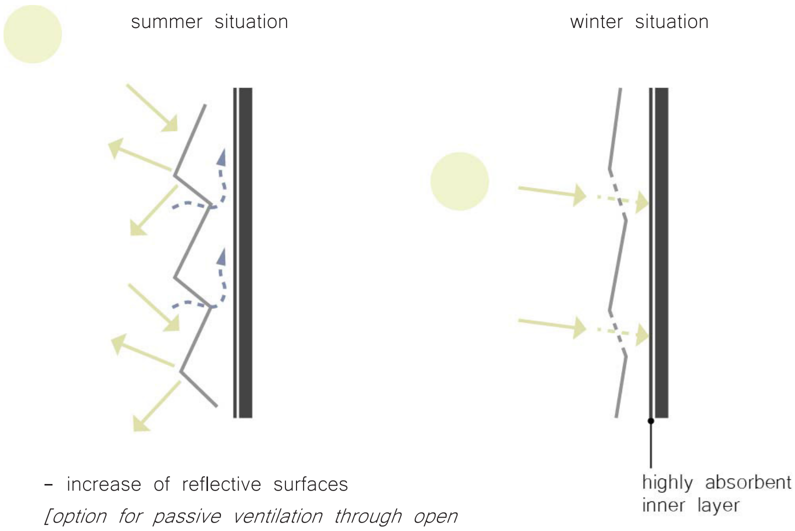
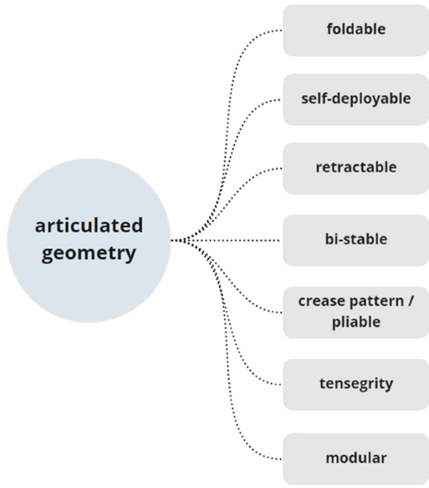


Figure 54: SMP 3D-printed surface tiles [Clifford et al., 2017]

Facade design ideas





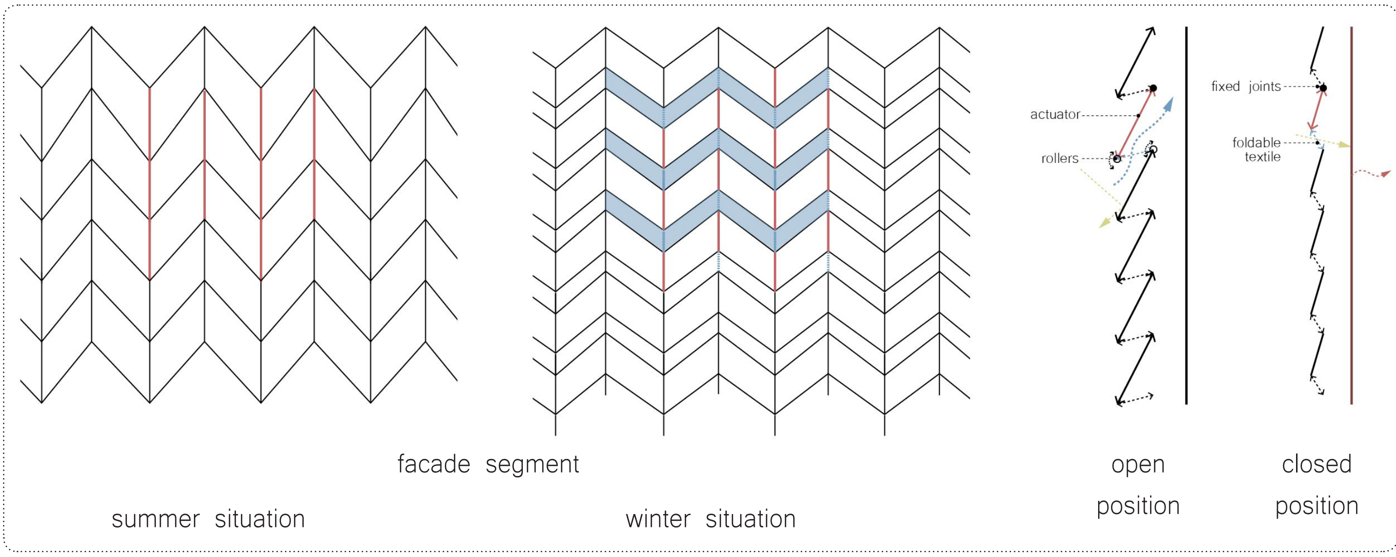
possible geometry features

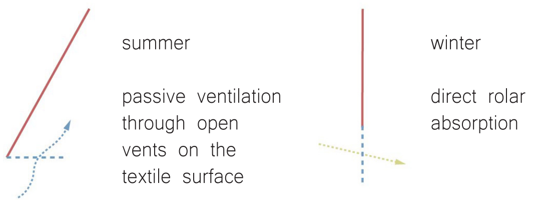
- increase of reflective surfaces

[option for passive ventilation through open vents of the membrane]

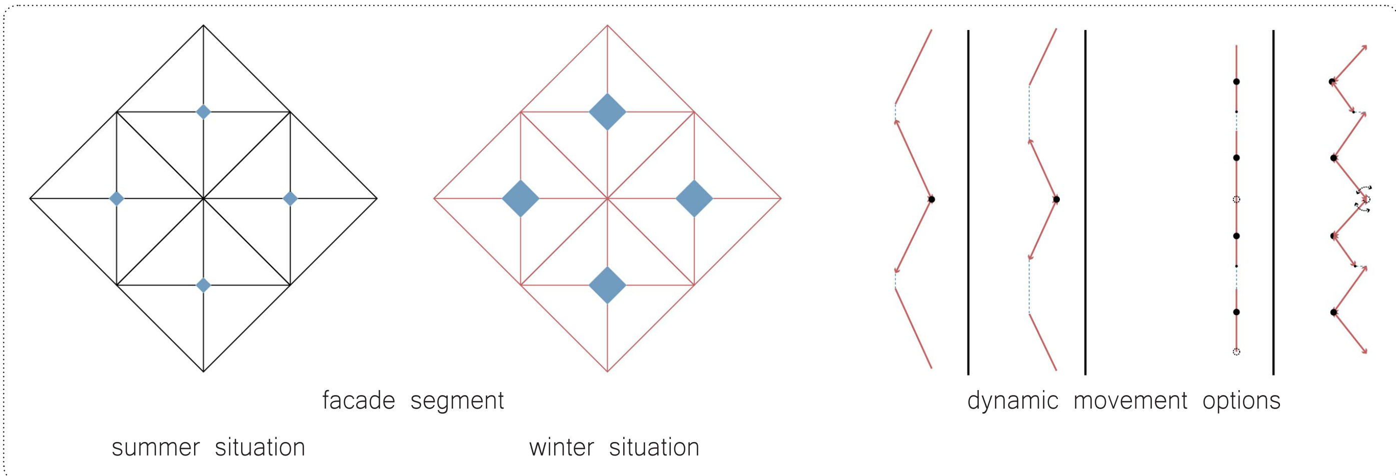
- retractable / foldable membrane or textile as filling "breathing" skin with a translucent and fritted surface

design option # 1

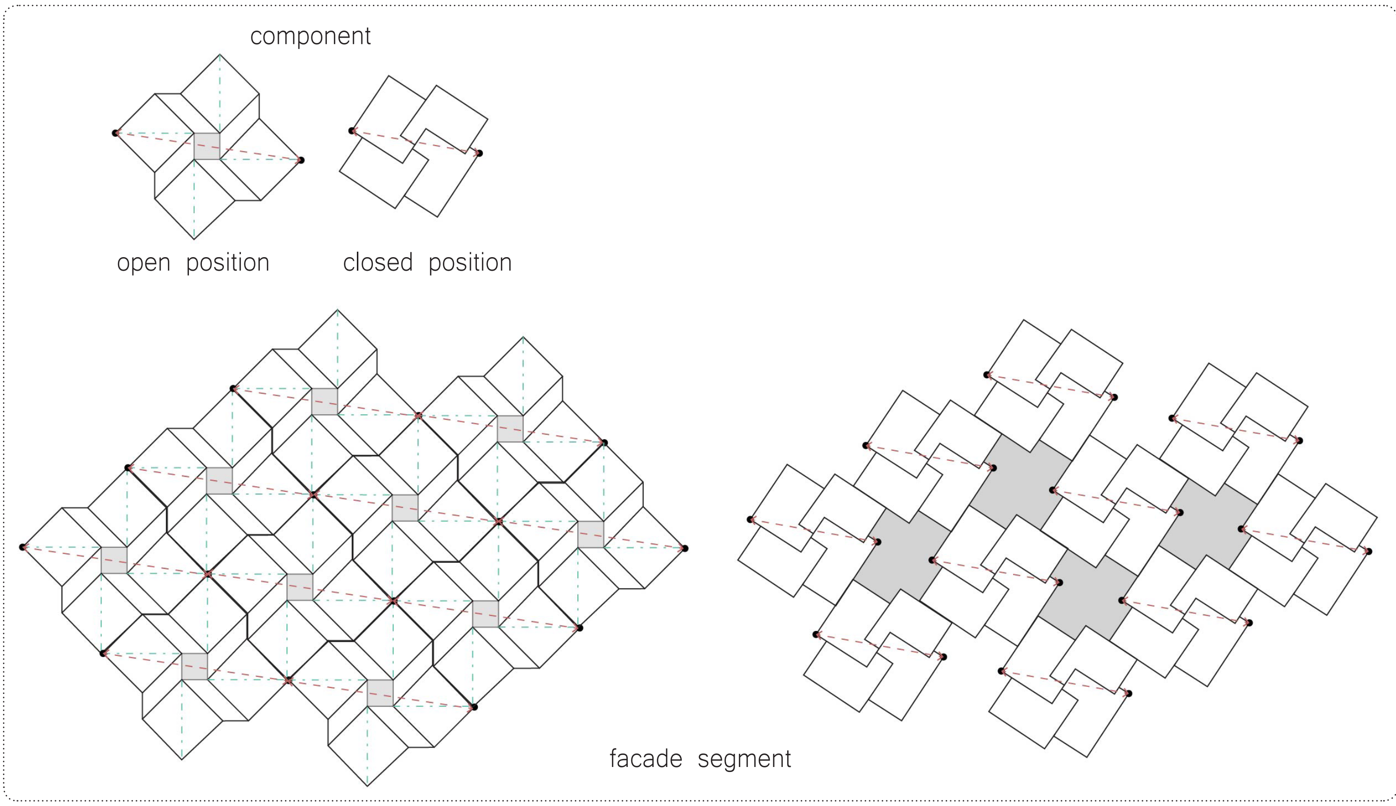




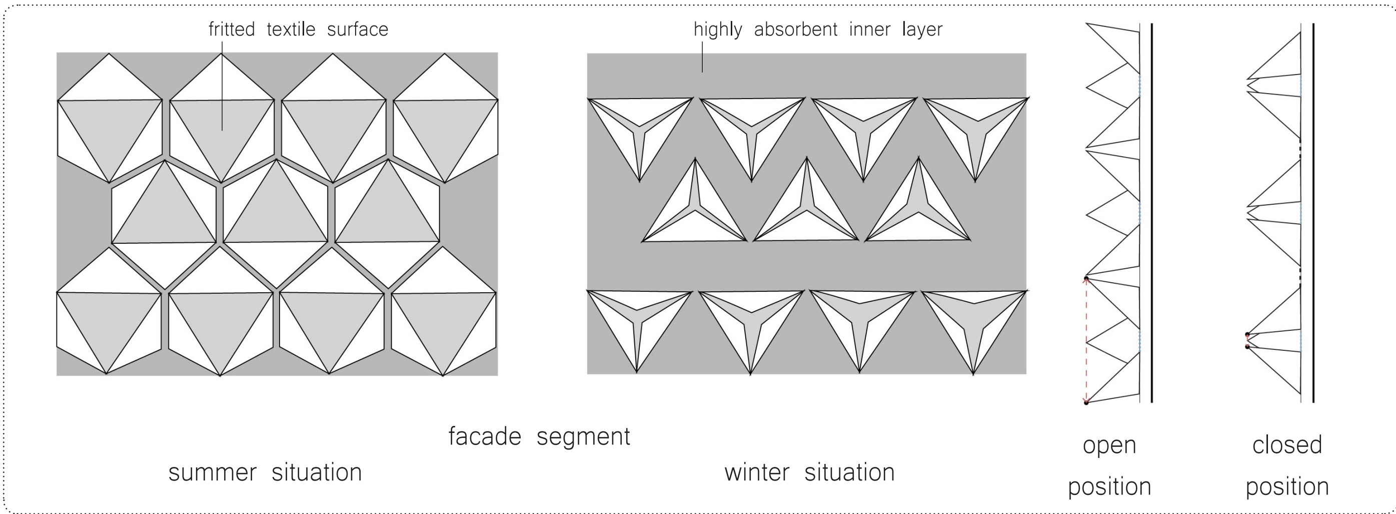
design option # 2



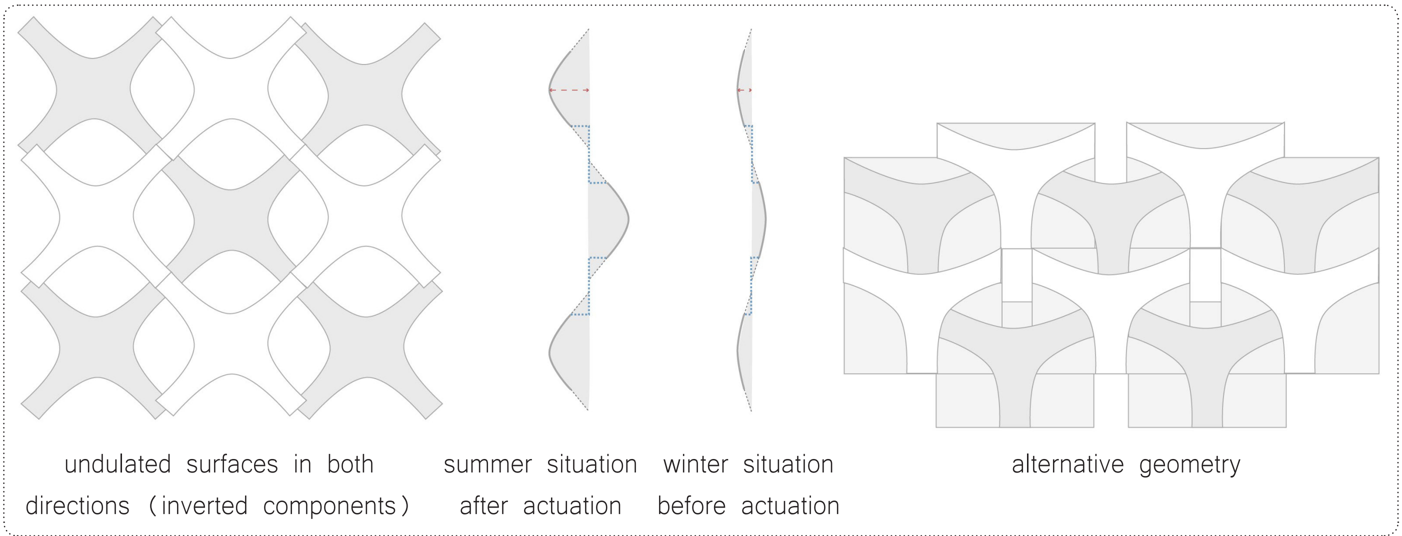
design option #3



design option #4



design option #5 (SMP surface)



4.4. DESIGN METHODOLOGY & WORKFLOW

The design methodology can be divided into three distinct stages, which are realized either in a linear chronological sequence or in parallel. The first phase consists of the literature study, where the background information is accumulated to be applied in the design integration. This includes also studies on the material properties and dynamic behaviour to enable a better understanding of its inherent performance. After setting a theoretical base, the following stage involves the design phase, which will be informed in parallel by research and iterative performance evaluation studies in a feedback-loop process, where material and geometrical explorations will be conducted.

In the performance analysis and evaluation phase, parametric simulations and design optimizations will be realized to fine-tune the selected shading prototype design. This will be assisted by the feedback from the performance validation, to provide parametrical design variations in conjunction with daylight and solar radiation simulations throughout the design process. These simulations receive weather and solar radiation data and attempt a connection to the UHI and its impact on the microclimate and surrounding environment. Besides that, a thermal behaviour modelling under targeted conditions will be realized, as well as energy, radiation and daylight simulations in different operation periods of the SMM-based shading device.

The above iterative process will be based on an interoperability toolchain workflow, with the aim for most of the digital tools to be integrated in the same parametric software environment (Grasshopper). This approach will allow for a better data interchange and modelling compatibility between the various energy simulation engines, a more direct comparison of the different simulations and results, while optimizing the overall workflow in a systematic and comprehensive way. Figure 55 provides an overview of the proposed digital toolchain analyzed for the purpose of each analysis study.

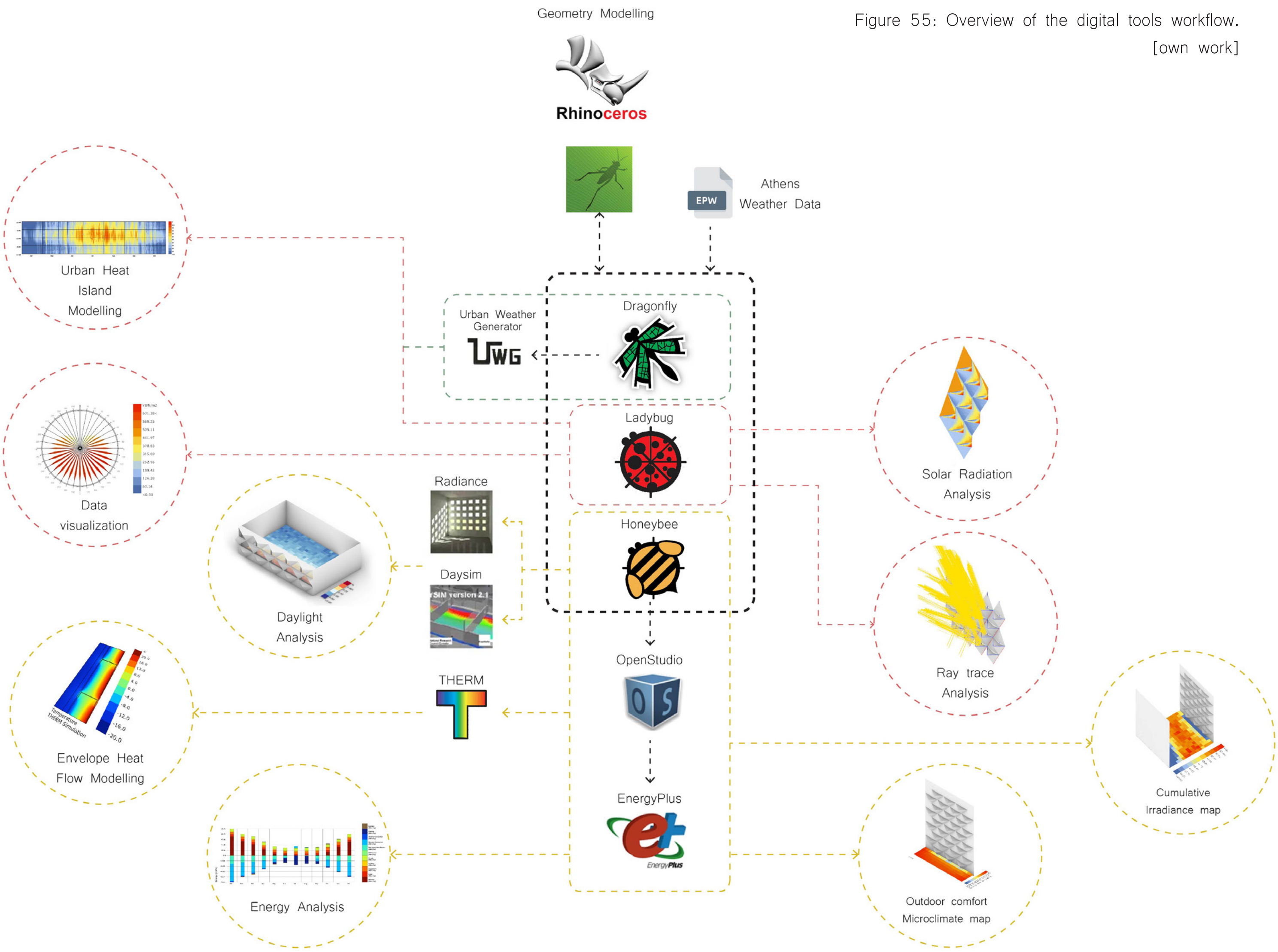


Figure 55: Overview of the digital tools workflow. [own work]

4.5. EVALUATION METHODOLOGY

Based on the above workflow, the evaluation methodology consists of assessing the SMM adaptive facade system's performance, based on the mentioned performed energy and environmental simulations. The objective is to estimate the impact of the system on the urban microclimate from the reflection of the solar radiation, as well as the effect on the reduction of the building's cooling demands. Besides that, a feasibility assessment will be conducted, by evaluating these smart technologies based on certain criteria, involving cost effectiveness, technical feasibility and physical integration, among others, in order to reflect on their potentials for facade applications, also in comparison to similar technologies. These evaluations will provide with both a quantitative and a qualitative overview of the challenges, restrictions and potentials of future SMM-based facade developments, as well as a feedback to the proposed hypothesis of the thesis on the level of contribution, feasibility and consideration of this approach as a UHI mitigation strategy.

05

REFLECTION

Based on the research so far, the background information and case studies, some potentials for the implementation of SMM-based facade components can already be identified. This will give way to further investigation and progress with material and geometry studies and performance of systems of this type of technology to assess its applicability in practice. However, some challenges are also evident from the beginning, as can be seen from similar approaches, feedback from experts in the field and realized projects. One of the aspects that commonly lies in question is the feasibility of the integration of SMM technologies in the building envelope, in terms of scale, cost-effectiveness and energy performance and what is the rate of energy savings with mostly passive systems, as in most of the cases a control system is additionally required for a better monitored performance. This is also due to the fact that it is still a not so broadly used technology in the building sector, especially concerning the SMP family of materials. Another concern is related to the Urban Heat Island approximation. According to researcher Jungwoon Yoon, who has conducted similar studies and provided some help and insight on that matter, there are recalibrations needed to receive more accurate simulation results after comparing with the real heat-island surface temperature. Also, depending on the location of shading installations, the influence by heat island effect would be different. These issues, are, therefore, important to consider during the prototype assessment.

Apart from that, one aspect that is under discussion and requires more elaborate research is the exact choice of material to be used and tested, both in terms of general material family (as in SMA, SMP or SMH) and more precisely on the exact material. As seen throughout the report, there are several parameters that can favour one material choice over the other one. However, the lack of experience and applied knowledge in the building sector makes the decision-making a more complex process. For example, from one hand, SMAs have the advantage of being wider used as actuators for dynamic shading systems and their performance can be verified, but could potentially be overtaken by the SMPs due to their high strain reversibility. On their side, however, SMPs don't offer enough real-size building applications to assess the complications and performance in larger scales, while working with these materials might entail more challenges in the process, since they require more advanced material science background knowledge. In this case, on the other hand, the material processing could also be considered an innovation-driven challenge and be part of the scientific contribution of the project, while the SMAs would allow a more refined and smart facade system as a whole.

Especially in the case of SMPs, after some feedback from researcher Jungwon Yoon, who is working with SMP prototypes in building envelopes, her input is that it is rather difficult and very challenging to apply SMP components in facades. First of all, it is hard to manufacture the SMP components in 1:1 large elements and find the proper processing and equipment, while another issue is to find a method to revert the shape-changing to enable the repetible deformation. If the component is used just in actuator, the load which the actuating component can support also needs to be considered. Based on this feedback, the implementation of SMP technologies in facade systems can be rather complex and not so promising for real facade scenarios and, because of these reasons, may be later discarded as an option, also regarding the time constraints of the Master thesis.

These and some more parameters are being weighed throughout the research process and can be summarized in the table below, where a qualitative assessment is being carried out. This will define the material choice that the current thesis will be based on and a justification for the weight given is also being shortly elaborated in certain cases. Due to the given time frame, one of the decisive parameters is also the accessibiity and availability of the material, as well as its cost. To better evaluate the available options, a market research is being realized at the same time, to be able to reach a decision based on real facts, available products and suppliers, whereas some of the researchers of the case projects shown are being consulted to receive a feedback and recommendations based on their experience. This is intended to act as a guideline to be able to make an informed decision on realistic factors, to meet the needs of the prototype and to overcome complications in the fabrication of the facade component.

Moreover, since the focus of the project lies on the implementation of smart material technologies in the architectural facades, there is a strong relation between the graduation topic, the Building Technology Master track and programme in general. The building envelope is the threshold between the built environment and the urban conditions and as such, the current research aims to reduce the impact of the building on the urban heat island effect and to exploit innovative technologies and materials to mitigate the environmental issue by means of passive thermal self-regulation mechanisms of a shape-changing façade. There is, therefore, a connection between building technology practices that are applied to enhance the building's energy performance and, consequently, improve the conditions of the built environment.

Lastly, as briefly explained through the report, the objective is also to contribute with some knowledge as part of the framework commissioned to the Adaptive Façade Network set by the EU COST in 2014, to share technological knowledge on adaptive facades and contribute to the generation of new ideas at a fundamental and system development level. Apart from that, from a social and environmental perspective, there is a need to achieve a high level of user well-being and indoor environmental quality, to reduce building energy consumption and neutralize building-related environmental impacts. The integration of passive and active design technologies in the building envelope, as studied here, can have high potentials to improve indoor comfort conditions and reduce the environmental impact during the life cycles of buildings. With the UHI phenomenon at its rise and its foreseen increasing intensity in the Mediterranean region over the next years, the current thesis aims to address a challenge with scientific and societal relevance and, by so doing, to achieve sustainability targets in the built environment.

Table 8: Material decision evaluation criteria [own work]

Evaluation criteria for SMM-based façade applicability	SMA	SMP	SMH
Material market availability and accessibility	++	+	++
No background material science knowledge required	++	+	++
Building scale applicability (preceded knowledge available)	++	+ *- Not enough existing building applications with SMPs* *- Applications more extended in smaller scales and other fields (e.g. biomedicine)*	- *Lack of existing building applications with SMHs*
Cost-effectiveness	+	+ *Large amount of raw material might be required and lead to cost increase*	++
Feasibility	++	+ *Lack of knowledge and availability and not broadly applied technologies and materials might hinder its feasibility and extended market applications*	+ *Lack of knowledge and availability and not broadly applied technologies and materials might hinder its feasibility and extended market applications*
Ease of programmability & processing	++	+	+
Deformation level	++	+ *Deformation not tested enough in large scale prototypes to evaluate the possible deformation rate in building scale applications*	+ *Lack of information on possible deformation rate in building scale applications*
Reversibility (as in cycles) / Durability	++	+	- *Currently no experimental data*
Sustainability aspect	+ *Direction of the design focus on minimizing of required actuators and use of more sustainable complimentary façade skin materials*	- *- Even though bio-based SMPs exist, their market availability is limited* *- Large building envelope surface will be covered in polymer-based material*	+ *It is possible to design the SMH with bio-degradable materials*
Possible design implications	*Broader applications of SMA in building shading skins requires a higher level of innovation and originality to add to the technological gap*	*Lack of existing knowledge in SMP-based building applications might lead to design difficulties and dead-ends at an early stage*	*Lack of existing knowledge in SMP-based building applications might lead to design difficulties and dead-ends at an early stage*
Innovation aspect (Technological gap)	*- Material and geometry optimization* *(optimal use of actuators to achieve the desired dynamic effect, material + mechanism in a fit combination)* *- Façade design challenge*	*- Scientific knowledge contribution on the integration of SMP-based technologies on a building scale* *- Prototyping challenge (technological innovation)*	*- Added scientific knowledge on the integration of SMP-based technologies on a building scale* *- Experimentation on non-conventional materials* *- Material and prototyping challenge*

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APPENDIX

SMA features [information retrieved from Fiorito et al., 2016]

SMA					
+	-	Mechanism	Alloy-based classification		
As an actuation material, SMAs are more powerful than SMPs. The actuation stress in SMAs is 10s MPa and above, while that in SMPs is a few MPa at the most	The difficulties in working with SMAs are related to their different behaviour and characteristics due to many different possible martensitic configurations	Thermo-responsive SMAs are featured by the four characteristic temperatures, namely austenite start temperature (As), austenite finish temperature (Af), martensite start temperature (Ms) and martensite finish temperature (Mf). Upon cooling from high temperature austenite phase, the martensitic transformation starts at Ms and finishes at Mf. Upon heating from low temperature martensite phase, the reverse martensitic transformation starts at As and finishes at Af. While at low temperatures, SMAs have the SME, at high temperatures, recovery can be achieved instantly and simultaneously upon releasing the applied load. This is called the super-elasticity (SE). According to the definition above, the SME is the characteristic of the SMM, while the SE is that of the SCM.	**NiTi based**	Cu-based	Fe-based
Biocompatibility, high corrosion resistance and high electrical resistance	Possible change in the mechanism properties after programming		+ Higher recoverable strain (around 7%), generated force and corrosion resistance		
Super-elastic behaviour			+ High actuation stress (up to 500 MPa)		
			+ High biocompatability		
			- Higher costs		

SMP features. [information retrieved from Sun et al. (2012), Leng et al. (2011)]

SMP							Market diffused SMPs		
+	-	Mechanism	Chemical architecture classification				Base Material SMP	Ttrans [°C]	Company / Producer
Lower density PU SMP: 1.25 g/cm3 NiTi SMA: 6.4 g/cm3	More difficult to predict the behaviour of the polymers precisely due to significant relaxation, degradation, etc	The SME in SMPs is based on a totally different mechanism. Regardless of the types of the stimuli, there are two basic segments/domains in a SMP, one is elastic segment, and the other is transition segment While the elastic segment always maintains high elasticity within the whole SME cycle, the transition segment does change its stiffness significantly at the presence of the right stimulus. Carefully examining the mechanism behind the SME reveals that opposite to that in SMAs, SMPs normally are hard at low temperatures and become soft at high temperatures. Therefore, SMPs alone are normally not applicable in cyclic actuation, unless there is a V-shape in the stiffness vs. temperature curve upon heating, which has been found in a couple of SMPs	chemically cross-linked glassy thermosets	chemically cross-linked semicrystalline rubbers	physically cross-linked amorphous thermoplastics	physically cross-linked semicrystalline block copolymers	Styrene butadiene	60-70	Asahi company
Lower cost in fabrication and processing	The SME in SMPs may be affected by the programming conditions						Styrene-based (Veriflex®)	60-70	Cornerstone research group
Easily produced with high quality into almost any specified shapes at different scales using various traditional and advanced polymer processing technologies	Possible change in the mechanism properties after programming						One part epoxy	90	Cornerstone research group
Recoverable strain is normally an order higher than that in SMAs	The successful synthesis of a particular SMP for a special application normally requires strong chemical/polymer background, years of experience and great efforts in trial and error						Two parts epoxy	104	Cornerstone research group
It is easy to tailor the thermo-mechanical properties of SMPs by means of, for instance blending with different types of fillers or varying the compositions	Current understanding of the thermomechanical behaviour of SMPs is limited to one-dimensional deformation						Cyanate ester	135-230	Cornerstone research group
It is possible to be always transparent							Thermosetting epoxy	113	Composite technology development
Shape recovery temperature range can be easily altered within a wide range and even gradient							Thermoplastic polyurethane	40-55	Mitsubishi heavy industry
Damping ratio in particular within the transition range is higher									
The potential for recycle and reuse at low cost is higher									
Many SMPs have excellent chemical stability, biocompatibility and even biodegradability									
SMPs are more flexible in surface patterning for different patterns at different scales, and the resulted surface patterns are more permanent									
SMPs can be integrated into mechanical/ structural design as one part or parts of a structure for load carrying under normal working situation									

Main characteristics of SMPs					
Category	Material	Ttrans [°C]	Rr [%]	Mechanical properties	Comments
Melting transition based	EOC	60-100	>95	-	Opportunity of tailoring Ttrans by a variation of chemical composition
	Natural Rubber	0-45	-	E(20°C) = 6-16 MPa	Stress-induced shape memory effect
	Natural Rubber	75	88-95	-	Commercial rubber band swollen in molten stearic acid
	EOET	45-55	84-85	-	-
	PEG-SMPU	40-50	82-98	-	-
	PU	60	80-100	E' (-75°C) = 2000-2800 Mpa E' (45°C) = 50-385 MPa E' (75°C) = 15-165 MPa	-
	PMMA-SPEG	46-52	>98	E' (0°C) = 682-2740 MPa	-
	PMMA-LPEG	50-53	75-93	E' (0°C) = 958-1465 MPa	-
	PCLU	45-60	94-100	-	Properties could be adjusted
	Radiation cross-linked PCL	54-56	99-100	-	-
	PCL methacrylate	30-50	92-97	E (25°C) = 2.4-72 MPa E (70°C) = 0.7-6 MPa	-
Glass transition based	ZDA Epoxidized natural rubber	20-46	>90	E (25°C) = 1.5-21.1 MPa	-
	Epoxy	31-93	~100	E' (T=Ts) = 1751-3017 MPa E' (T=Td) = 4.5-18.9 MPa	-
	CPU networks	48-66	>99	E (25°C) = 330-600 MPa E (70°C) = 0.77-5.85 MPa	Biodegradable
	PPS	15-45	~100	E (20°C) = 1.8-130 MPa	-
	Hybrid hydrogels	45	~100	E (23°C) = 0.06-0.2 MPa	-
	MMA-co-PEGDMA	56-92	-	E (T=Tg) = 9.3-23 MPa	Biocompatible materials

Continuation of the overview table of the SMP characteristics. [information retrieved from Sun et al. (2012), Leng et al. (2011)]

SMH features. [information retrieved from Sun et al., 2012]

SMH			
+	-	Mechanism	Matrix/inclusion structure
Based on simple concepts and ordinary materials with well-understood properties	Not enough research carried out to beeter understand their thermo-mechanical properties	The mechanism behind the shape memory phenomenon in SMPs is the elastic-transition segment/domain system. For example, if silicone and wax are selected, both are biocompatible, as the elastic matrix and the transition inclusion, respectively. While silicone normally keeps its high elasticity characteristic within a wide range of temperatures, wax melts upon heating to its melting temperature, and becomes very soft. As such, the sample can be easily compressed. The silicone matrix is elastically deformed, so that an elastic energy is stored in it. When the sample is cooled back to room temperature, wax becomes solid again, which can effectively prevent the release of the elastic energy in the silicone matrix. Consequently, after the constraint is fully removed, the sample largely maintains its deformed shape until it is heated again to above the melting temperature of wax.	Silicone/wax
The accessibility, flexibility in design and fabrication of SMH provides an easy access to ordinary people, even without much chemical/ polymer background	Due to the different composition of SMHs, their modelling requires a specific applied study, even if SMHs can be modelled in similar ways to SMPs		Silicone/water
Can be biocompatible			
Both the matrix and inclusions are not limited to polymers only, but can be selected from any materials			
There is not any chemical interaction between the matrix and the inclusion, so that the properties of individual materials are largely maintained			
The properties can be well predicted from the very beginning by means of materials selections and simple estimation			
Aging, relaxation, and fatigue etc. can be well controlled			
They are convenient to be tailored to meet the exact requirement(s)			
Proven ability of silicon-wax SMH for cyclic actuation			
Similar shape memory effect to the SMPs' one			

	SMAs	SMPs	SMHs
Description / Composition	Most diffused are NiTi-based alloys. Classified in Ni-Ti based, Cu-based and Fe-based	More than 20 different types of SMPs. Most common are thermoplastic polyurethanes and epoxy SMPs	Composed of materials with no shape memory effect on their own. They are "custom made". The most studied are Silicon-Wax Hybrids
Movement / Morphing effect	Stress recover and original shape recover. Small contraction (up to 10%) and deformation. A force is required to re-establish the original shape	Stress recover and original shape recover. High deformation (up to 800%). A force is required to reestablish the original shape	Stress recovery and original shape recovery. Small reversible strain (up to 6-8%). A force is required to reestablish the original shape
Durability issues	More than 200,000 cycles for NiTi alloys. In NiTi alloys high resistance against corrosion and external weather	Up to 200 cycles for SMPU tested. Can be affected by external weather conditions	Currently no experimental data. External weather condition resistance related to composition
Recovery temperature	-10 °C to +200 °C NiTiCu alloys can be tailored for shading devices, As ~ 45-60 °C	+25 °C to +200 °C Can be tailored at lower temperatures Tg ~ 60-90 °C	Vary with the components: silicon-wax hybrids have an activating temperature of ~ 45 °C
Density	6000-8000 kg/m3	900-1100 kg/m3	Variable
Elastic Modulus E above Ts	70-100 Gpa	0.5-4.5 GPa 1.24 GPa (Polystyrene SMP)	Variable
Elastic Modulus E below Ts	28-41 GPa (NiTi SMAs)	2-10 GPa (Polystyrene SMP)	Variable
Transformation strain	6-8%	250-800% 50-100 % (Polystyrene SMP)	~6% (Silicone-Wax)
Actuation stress	150-300 MPa ~100 MPa (NiTi SMAs)	2-10 MPa	Variable
Market availability and shape	Wires (different diameters, already educated in range from few μm to 1 mm) Springs Plates/Sheets	Easily customized shape	Mainly derived from DIY approach User's desired shape
Sustainability	Biocompatible	The potential for recycle and reuse at low cost is higher Many SMPs are biocompatible and even biodegradable	Can be biocompatible Organic materials can be used

SMM families comparison. [information retrieved from Sun et al., 2012]