A BIOMIMETIC PERSPECTIVE ON (RETRO)FITTING OF BUILDING ENVELOPES

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ABSTRACT

A BIOMIMETIC PERSPECTIVE ON (RETRO)FITTING OF BUILDING ENVELOPES

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The starting point of the research is the problem of (retro)fitting in architecture. Existing buildings are constrained by their fixed and static materiality and limited life span. Yet they often require interventions due to changes around them. In practice, these interventions are commonplace, yet very little attention is devoted to preparing buildings to these changes before they require interventions. Therefore, current understanding of (retro)fitting in architecture implies turning the building back to its original state, after it becomes retro. Unlike this, living beings do not become retro, rather they aim to fit the best condition of their current situation through adaptation strategies. To this end, the buildings share much in common with organisms in nature and can borrow a number of information from them with biomimetics.

This research focuses on the design of the building envelope, as it is very influential with regard to retrofitting. Revisiting the analogy between the skin and building envelope, the thesis aims at redefining (retro)fitting with a new design approach named as "adaptive fitting**”**. The early design phase is particularly important, as decisions taken during this stage can determine the “fitting” of the design. With adaptive fitting, building envelopes can act like the skin in nature since they will be coded with the ability of fitting. Taking nature as a measure and learning from the fitting modes of nature, the infrastructure of change will be integrated to the genes of the design from the beginning. With this, the building will be ready for possible mutation scenarios and adaptively fit into changing conditions.

Keywords: Preliminary design phase, biomimetic design, retrofitting, nature as a measure, building envelope.

ÖZ

YAPI KABUKLARININ (RETRO)FİTİ ÜZERİNE BİOMİMETİK BİR BAKIŞ AÇISI

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Bu tezin başlangıç noktası mimarlıktaki retrofit problemidir. Mevcut yapılar sabit ve durağan maddesellikleri ve sınırlı ömürleri ile kısıtlanmışlardır. Fakat bu yapılar çoğu kez etraflarındaki değişimlere bağlı olarak müdahaleler gerektirmektedirler. Pratikte bu müdahalelerin çokça karşımıza çıkmasına rağmen yapıların müdahale gerektirmeden bu değişimlere hazır olması konusuna çok az önem verilmektedir.Bu sebeple, (retro)fitin mevcut anlayışı yapılar eskidikten/ retro olduktan sonra onları orjinal haline geri döndürmeyi işaret eder. Bunun aksine canlılar eskimezler/ retro olmazlar, bunun yerine adaptasyon stratejileri ile mevcut durumlarının en iyi haline uyum sağlamaya çalışırlar. Bu bağlamda yapılar, doğadaki canlılarla birçok ortak nokta paylaşırlar ve onlardan biyomimetik ile bir dizi bilgi ödünç alabilirler.

Bu araştırma, (retro)fit konusunda çok etkili olması sebebiyle yapı kabuğunun tasarımına odaklanır. Bu tez, deri ve yapı kabuğu arasındaki analojiyi yeniden ele alarak, (retro)fit kavramını 'uyarlanabilir uygunluk' adında yeni bir tasarım yaklaşımı olarak yeniden tanımlamayı hedefler. Erken tasarım süreci, bu aşamadaki kararlar tasarımın uygunluğunu

(fit olma) belirlediği için özellikle önemlidir. Uyarlanabilir uygunluk ile yapı kabukları uygun (fit) olma becerisi ile kodlanacakları için deri gibi davranmaları beklenir. Doğayı bir ölçüt olarak ele alarak ve ondan uygun olma yöntemleri öğrenerek değişimin altyapısı tasarımın genlerine en başından entegre edilmiş olur. Bununla birlikte yapı, olası değişim senaryolarına hazır olur ve değişen koşullara uyarlanabilir (adaptif) bir şekilde uyum sağlar.

Anahtar Kelimeler: Ön Tasarım Aşaması, Biyomimetik Tasarım, Retrofit, Ölçüt Olarak Doğa, Yapı Kabuğu.

To my dear husband and my little angel with love,

Aydın and İpek Öztoprak

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CHAPTER 1

INTRODUCTION

This chapter describes the main scope and structure of this research. The research field of this study emerges from the symbiosis of architectural design and biomimetics.

While the idea of nature-inspired design has always been prevalent throughout the history, especially with the discovery of microscope, the ability to learn from the form, function, behavior of the living beings, from their molecular compositions to their environments, has significantly advanced in the last century. After the 19th century, with the interest in biology as a discipline, the tendency of imitating nature gave way to scientific knowledge and laws explaining nature. Due to advancements in computer technologies and growing interest in the paradigm of complexity and complex systems, processes and relations of nature came to the fore. This led to a close examination of natural and man-made processes and revealed that they are more similar than previously thought (Brownell & Swackhamer, 2015, p. 19). As Brownell and Swackhamer (2015) explains, this is partly due to the fact that "*more advanced human creations, such as a city, a building, tend to resemble the inherent complexities and behaviors of natural systems and must adhere to natural principles in order to endure".*

As Bar-Cohen (2006) points out, *"through evolution, nature has "experimented" with various solutions to its challenges and has improved the successful ones"*. The experiments of nature involves principles of many different fields that we recognize as science and engineering, such as physics, chemistry, materials, science, mobility, control, sensors, etc.(Bar-Cohen, 2006) . Further, they involve all scales, from micro to macro. Therefore, in many examples the technologies that are similar to those invented by humans are being used by the organisms in nature in a more intelligent and efficient way. Biomimetics basically aims to translate this intelligence of nature to human beings for solving the problems we are struggling to solve. Different from nature inspired design prevalent throughout the history, biomimetics introduced the systematic approach of knowledge transfer from biology to other fields. As Mazzoleni (2013) points out, biomimetics exceeds an analogy, performing on diverse levels, such as the organism, behavior and ecosystem.

With the growing impact of biomimetics, a new direction is found for many fields, such as engineering, manufacturing, material science and even for medicine and fashion. In architecture also, many current approaches are trying to transfer strategies from natural systems. However, in most of the studies, nature architecture relationship is still on a more form-based level. In this sense, finding a biomimetic method is still an ongoing discussion since architects are trying to go beyond form-based relations and to learn more from nature.

The mind shift brought by biological knowledge and computational thinking, together with the advancements in digital fabrication technologies, signal a shift in architecture's relationship with nature. In the last 30 years, many of the developed computational theories and methods have been inspired by biological principles. Contemporary architecture is now intensely engaged with these theories and methods. Over the past decade, as Imperiale (2006) mentions, *"significant digital research has emphasized the development of smooth, voluptuous architectural objects with attention to topological surfaces and skins"*. Contemporary architectural culture is suffused by concepts like smooth exchanges, flows, continuousness, performative surfaces, skins, membranes (Imperiale, 2006). The extensive use of these concepts bear a closer relationship with nature, that requires considering complexity of nature through its processes and patterns, from which its properties and performance emerge.

The building envelope is at the heart of these issues, as the first architectural element that is perceived from outside and that interacts and engages with the environment. The term envelope implies wrapping and surrounding the space people live in, in a similar manner organisms are surrounded by their skins in nature. Recent architectural trends, which are mentioned above, brought a new understanding in the building system hierarchy, as such the strict differentiation between roof and façade can often not be made. For this reason, the term envelope has become extensively widespread.

The envelope includes additional functions such as loadbearing, active or passive environmental control and individual expression. Different from traditional approaches, today, the envelope is not seen as an isolated building component but as an integral element with considerable importance in terms of the building's performance. Further, with today's technologies, building envelopes can be created from a series of braided surfaces visualized on computers, and machine instructions can be sent straight to the factory to enable full size fabrication.

With the increased use of the skills of digital design and fabrication tools in architecture, the issue of skin has been magnified (Imperiale, 2006, p. 270). Over the past decade, significant digital research has emphasized the development of smooth, voluptuous architectural objects with attention to topological surfaces and skins (Imperiale, 2006, p. 270). The concepts of smooth exchanges, flows, continuousness, performative surfaces, skins, membranes have suffused contemporary culture (Imperiale, 2006, p. 270). The extensive use of the analogy of the skin can be traced through many built and unbuilt examples of building envelopes and researches and experiments in the field. Despite the growing impact of biomimetics in architecture, without a systematic method to transfer biological knowledge, the application of the term skin cannot go beyond a mere metaphor.

At this very point, this study claims that it is worth revisiting the analogy[1] between the skin and the building envelope. Further, it suggests that building envelopes share much in common with natural skins and can borrow a number of information from them with biomimetics. Skin can be described as the outer layer of the body of organisms. In this study, the term skin is used on a general level to refer to any animal covering, including fur, feathers, scales, exoskeletons and shells.

In architectural discourse, today, another source of confusion is related with the handling of the current topics of efficiency, performance, adaptiveness and responsiveness. Contemporary architecture is intensely engaged with these topics, across multiple realms, from spatial, social, cultural to purely technical such as structural, thermal and so on. These topics are all driven by the search for new solutions to create buildings with responsive performances to varying functions, user needs and climate conditions. There are two main directions in these ongoing discussions: improving existing buildings and designing new buildings with these ideas. As noted earlier, the building envelope is the interface of interior and exterior environments through which we perceive, interact and engage with the building. Therefore, it is at the focus of these ongoing discussions.

The hypothesis of this study is predicated on the assumption that with a biomimetic perspective, the idea of "fitting" encapsulates the terms efficiency, performance, adaptiveness and responsiveness. Seen in this context, the conception of these terms bears a much closer comparison with the biological idea of fitting, such as it is seen in the natural skin. It is the application of the biological analogy of the skin that makes it seem more appropriate to describe the enveloping membrane of the building as "fitting". In this study, performance is considered as *a moment of fitting*. Adaptation is one of the most

[1] Analogy and metaphor both compare a situation in one domain with the situation in another. Considering their use within the design context, the key difference between them is whereas metaphors assist the designers to define the define problem, analogy maps the causal structure between a source and a target domain. For further information, see Hey, et.al. (2008).

encountered terms in biomimetic studies and within the context of this study, it is considered as *a function of fitting,* while adaptation is *a function of fitting.*

Currently, since the existing buildings comprise the largest segment of the built environment, the idea of "retrofitting" has achieved a certain currency around these discussions. In this study, (retro)fitting is used as a broader term which comprises all the updates required to extend the life span of buildings. In nature, organisms have the ability to become and remain fitting before they become retro. This is achieved by adapting to current conditions. Unlike this, in order to be fitting, buildings are aimed at turning back to their original state, which is considered as the optimum. In other words, when the design is finished, it is considered as the best fitting condition of the building and it is permanently frozen. Therefore, in most cases, the design does not involve *future-proofing scenarios*.

The analogy of skin and building envelope provides a great potential to redefine (retro)fitting in architecture as fitting in nature. Developing an understanding of the building envelope analogous to the skin requires a holistic viewpoint, as Allen and Starr (1982) indicate, *"which seeks to find the smallest number of explanatory principles by paying careful attention to the emergent properties of the whole as opposed to the behaviours of the isolated parts"* (as cited in Reap et. al., 2005). Recently, there had been some significant attempts to develop a biomimetic approach to the building envelope (Badarnah-Kadri, 2012; Gruber & Gosztonyi, 2010; Mazzoleni, 2013). These studies are mostly concentrated on learning lessons from nature in order to increase energy and resource efficiency of the envelope. In these studies, nature is taken as a model and mentor, yet nature should also be taken as a measure. In a similar vein, since skin can be used as a measure for the design of the building envelope, further studies can also be discussed in this realm.

In this study, protective covers of architectural constructions, whether named as the envelope/façade/surface/roof, are to be discussed as analogous to the skin in nature. To this end, all the discussions along the study will be held by taking the natural skin and its functions as a measure. Rather than searching for finding specific formal or functional analogies, this study attempts to focus on the nature of the skin and to develop a new biomimetic approach for the design of the building envelopes. In doing this, first and foremost, a holistic biomimetic perspective is required for two things: mapping successful strategies of nature in a systems understanding[2], and thus learning from it, and integrating the natural processes to the whole of the building. Particularly adaptation principles in nature, which makes natural organisms fitting, will be taken as a measure of fitness in building envelopes. It is proposed that developing such an approach in relation with nature is important for transforming the envelopes to the skins for buildings.

1.1.Problem Statement

The contemporary debate in architectural discourse on the topics of efficiency, performance, adaptiveness and responsiveness are related to two main expectations from buildings: 1. buildings need to fit to existing conditions, 2. buildings need to sustain their fitting state. It can be observed that the underlying reason of the deep influence of these topics in contemporary architecture is the need for “fitting”. While the natural skin is always fitting, in building envelopes, fitting is still an elusive term; questions of ‘fitting’ do not have a simple yes/no answer and assessments of ‘fitting’ in building envelopes is still arguable. In order to understand what fitting really means to architectural design, extend the use of buildings and thus increase their fitting capacity, there is no need to look further than nature, where fitting is a question of survival.

In nature, organisms are able to respond to changes in their environment, either immediately, involuntarily or purposefully, and develop adaptation strategies based on the information on their genes and their ability to change. Adaptation is required to

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[2] Systems understanding requires a special way of looking at a thing, focusing attention on some particular holistic behavior in a thing that can only be understood as a product of interaction among parts. For further information, see Alexander, (2011).

achieve a fit between the system and the environment and to maintain the quality or state of being fit. Natural organisms become and remain fit by short term and long term adaptations (evolution). In this sense, adaptation is a process of becoming fit to changing environment over and over again. In this regard, it became crucial to redefine the idea of (retro)fitting in architecture in relation with nature. A biomimetic perspective fits well to the current argument, since above mentioned conceptions like efficiency, performance, adaptiveness and responsiveness are all encapsulated by the idea of fitting in nature. In this line of thought, (retro)fitting in architecture also becomes a question of fitting.

Natural organisms adapt in order to increase their fitting capacity. Adaptations are the *"differences among the organisms in nature which enables them to live in different kinds of environments and adopt different lifestyles"* (Purves, Sadava, & Orians, 2004). Adaptation enables the organism to cope with environmental stresses and pressures, and survive. Thereby, natural organisms do not need to develop new strategies to be future-proof. Rather, there is already available strategies coded in their DNA, which contain genetic information about the organism. In nature, fitting is a result of the internal forces of functional integration, together with external forces of environmental adaptation. The DNA is the driving force of these functions that in turn drive the response of the organism to environmental conditions. This study proposes that buildings can be designed similarly, made up of genes which are including the infrastructure of change and thus encapsulating fitting from the very beginning of the design.

Among the systems of the building, the envelope faces most of the changing conditions around the building. In this regard, the envelope does not merely provide shade and protection from the external environment, rather it has a multitude of functions to perform and a range of conditions to adapt and respond to. Today, there are many systems in architecture that respond and adapt to changes, adaptive, responsive, dynamic, kinetic, smart, living systems. Most of these systems are active, so that they can respond real-time changes with feedback systems. In most cases, this process performed by changing specific properties of a building within a specific time frame in order to manage changing environmental conditions or occupants' demands (Badarnah-Kadri, 2012, p. 12). For this reason, in buildings, responsiveness and adaptability are often considered as real-time reactions to identified parameters. Although responsiveness and adaptation are terms that are borrowed from nature, their application in architecture is very different from nature. Unlike architectural examples, adaptation in nature involves a progressive modification. Further, adaptation in nature is both a state of being and a process. Due to these major differences, buildings cannot use all potentials of adaptive and responsive systems as natural organisms do. Therefore, in most cases, they cannot sustain their fitting state and do require (retro)fitting.

Currently, the fitting of building envelopes is structured around the need for *"better management of energy flows, both from the exterior environment into the buildings and from the interior spaces of the building to the outside, with the goals of the improvement of the building's performance and the user comfort inside the building"* (Kolarevic & Parlac, 2016). In line with this, the transfer of adaptation principles to the building envelopes mostly focus on actively seeking equilibrium with mimicking specific features from nature. Since the constraints of that specific feature will not be exactly the same as those in the design problem, it is hard to achieve the adaptive quality of the imitated natural system. For instance, while nature-inspired, motor-based systems commonly seek to achieve energy flow control, they produce a large amount of energy when reacting, thus they increase overall energy load of the building. In such cases, the buildings require updates with methods such as new energy-efficient appliances or latest smart energy controls etc. In conclusion, the idea of abstracting and transferring strategies from nature requires a broader perspective.

In nature, all organisms change to be fitting. For instance, the bodies of human beings are changing from birth to death. Those changes in human bodies are also reflected over much longer time scales, in evolutionary time spans, where species change their form to adapt, to survive. But we also see changes occurring in organisms in real-time. For instance, in order to grab little fish, an octopus changes its size, shape, color and texture.

While the population changes in evolutionary adaptation, individuals change in short time adaptations. Within the scope of this study, short term adaptations will be discussed, since they better serve the purpose of the research.

Adaptation is achieved by the change in a characteristic that affects the organism’s survival or reproduction (Futuyma, 2009, p. 279). These changes in organisms are due to the massive amounts of information that is contained by the cells. If the DNA is stretched, it can be observed that it contains a lot of code. This genetic code, as Alicia Imperiale puts it, is an invisible energy or information that affects material (Imperiale, 2006, p. 282). In a similar manner, algorithmic code has a capacity to create very complex geometries with small amounts of data. It corresponds to the way nature constructs its designs using cellular components. But the code in nature is embedded in the cell itself and cells organize themselves to adapt to changes around them. Whereas the algorithmic code has been shaped by a designer, the information in DNA has been shaped by a historical process of evolution.

To this end, in natural skin, fitting is a result of environmental conditions on the one side and metabolism and energy and resource balance on the other side. Further, with response and adaptation strategies which are coded in organisms’ genes, the skin fits into existing conditions and sustains its’ fitting state. Currently, in building envelopes, performance driven architectural design aims to set a similar framework to our buildings, emphasizing on integrated and comprehensive optimization of various quantifiable performances of buildings. In this regard, even though there had been a number of different approaches to the idea of performance in architecture, it is in most cases limited to the performance with respect to physical environment of the building. For a long time, the idea of performance is considered as a post-rationalization and correction method. Currently, with the developing algorithms, increasing use of Building Information Modelling (BIM) as a design tool and changing understanding of biology, performance becomes both a state of being and a process. In other words, it becomes related with the idea of being a building and sustaining its function.

This study takes this point further, with taking nature as a measure and thus redefining the idea of performance as a problem of fitting. In nature, fitting is a question of survival. Organisms in nature need to achieve and sustain a fit by adapting their shape and function in real time to environmental changes. Similar to this, fitting of a building refers to its state of being appropriate for a particular environment, at the same time meeting comfort requirements of its' users. Fitting of a building is a multi-layered problem which can be defined across multiple realms from spatial, social, cultural to structural, thermal, environmental etc. A configuration of a building may be called fit if it is able to maintain given the specific configuration of its environment. Adaptation is required to achieve a fit between the building's systems, users' demands and the environment and to maintain the quality or state of being fit. Learning adaptation strategies from nature and taking nature as a measure to set fitness criteria in buildings would open up new perspectives in performance driven design in architecture which can foster sustainable development in architecture.

In order to explore this point further, the research focuses on the fitting of the building envelope. Building envelopes can be designed to prevent, to hide, to symbolize, to represent, to commemorate etc. In order to help buildings, survive and function for a long time, building envelopes need to become and remain fitting. In nature, fitting of the skin results from interactions between programmed instructions and environmental conditions and triggers. In most cases, this is achieved efficiently through economic handling of material and energy. For instance, in the eggshell the thinnest possible shell is enough to fulfil the purpose, which is a very efficient use of material. These fitting strategies of nature can guide us to redefine fitting in architecture and extend the life span of buildings by increasing their fitting capacity.

As Baumeister (2014, p.162) mentions: "A *well-adapted* biological strategy must meet the *functional needs* of the organism in the *context* in which it lives in order to contribute its survival". In essence, the basic strategy of survival is the concept of meeting functional needs in context. Baumeister then transfers this lesson from nature to human designs as:

"A *well-adapted* DESIGN must meet the *functional needs* of the DESIGN CHALLENGE in the *context* in which it MUST EXIST in order to contribute its SUCCESS" (Baumeister, 2014). In this manner, at urban scale, in order to be fitting in, the design of the building envelope needs to be integrated into the nature, rather than just imposing them on nature-fitting on. At building scale, building envelope needs to be integrated with the other parts and systems of the building on the level of shape, processes or interactions within the building as a whole.

This study addresses the importance of building envelopes and their fitting capacity in extending the life spans of buildings. It focuses on the fitting of the building envelope at building scale. Architectural constructions and biological systems for protective covers are exposed to the same environmental conditions and needs. Therefore, the requirements of the skins in nature and envelope of buildings are comparable. This study aims to learn lessons from nature to increase fitting capacity of buildings with designing future-proof building envelopes. With a biomimetic perspective, fitting requires to be coded in the genes of the design, interacting and co-evolving with the building from the earlier stages of the design until the demolition, even re-cycling of the building. With this, similar to nature, the idea of fitting becomes integrated to the design as a life-long and multi-layered process, which involves all systems of the building. Such a perspective not only enables designing long-lasting buildings but also extending the life of existing buildings.

Life spans of buildings are specific. Regarding a sustainable approach, it is desirable to extend that period as long as possible. In order to extend their life span, the buildings require updates which are referred with a number of terms such as refurbishment, restoration, renovation and repair. In order to avoid vagueness, in this research, "retrofitting" is used as umbrella term. If we examine the term "retrofitting", "fitting" means meeting requirements of a purpose or situation[3], while 'retro' refers to reminiscent

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[3] Accessed from: https://www.merriam-webster.com/thesaurus/fitting. Retrieved at: 25.12.2017.

of an earlier time.[4] This is to say, time is the factor that makes something to become retro. Since, conventionally, time is not considered as a design parameter from the beginning, the buildings do not develop instant reactions to new conditions. From this point of view, it can be stated that buildings are designed to fit at a certain time and to a certain range of conditions. Retrofitting seeks to overcome this problem by fitting the existing (already retro) buildings to changing (existing) conditions.

At this point, it is important to understand a building as *a system of systems*. In Refurbishment Manual, Giebeler et. al.(2009, p.23) describe buildings as *"summary of parts with different life spans"*. According to their life-expectancies table, building envelope as a whole might require its first retrofit after 20 years. This means that buildings from 1997 are now possible candidates in terms of envelope retrofits. In fact, the lifetimes of buildings typically are long, but many of the technologies as well as the activities they shelter and support are changing. In many instances, accommodating these changes has been a costly and resource insensitive process of alteration, reconstruction or outright replacement.

Since buildings are assets with different life spans, under a new use, with a transformation or customization they could be considered reborn. If the possibility of living several lives is integrated into the genes of the design from the very beginning of the design process, the buildings can be born again and this creates possibilities to improve their efficiency. This concept of several lives is one of the sustainable approaches that should be taken for architectural design. Without an extensive construction and demolition, it will also bring a new understanding of material use and historic preservation of buildings.

Unlike architecture, organisms in nature do not become retro, rather they become fitting. They are programmed to adapt and become better suited to changing conditions. Yet, the term retro implies turning back to original conditions, while searching for a language to

[4] Accessed from: https://www.merriam-webster.com/thesaurus/retro. Retrieved at: 25.12.2017.

do this. In most cases, this requires an extensive construction and transformation. In nature, the changes to adapt and become fit are always newer. Further, fitting process in nature aims at better adapting to current conditions, not to the original state. This is done with different time intervals. In this study, the notion of retrofitting is discussed through the skin analogy and the term "fitting" is used instead of "retrofitting" in architecture.

It can be claimed that fitting is a question of survival in built environment, as it is in nature. When we look at the history of architecture, from iconic buildings to the anonymous ones, we will see that the idea of fitting exists in many examples. If architecture's relationship with nature is reconsidered with a biomimetic perspective, it becomes crucial to rethink fitting in nature and retrofitting in architecture. Buildings are designed for long and useful life, to fit its users' needs well, to cope with environmental conditions. Buildings need to serve to a variety of functions through their life cycle. Therefore, it is necessary that they respond to different fluctuating parameters. If these parameters are considered from the beginning of the design process, buildings may not need retrofitting. For this purpose, it is required to consider fitting in a similar manner with nature, as better suiting to existing conditions rather than the original ones. With this, buildings will be designed as *future-proof* and which are considering possible future needs and requirements, can function longer and increase their life-span.

1.2. Hypothesis

Within this framework, the hypothesis of this research can be defined as follows: Building envelopes/surfaces/façades can act like the skin in nature if they are coded with the ability of fitting. The designer should employ *fitting* from the very beginning of the design process rather than *(retro)fitting* the envelope during the life span of the building.

There are two research questions in this study: 1. Can we redefine retrofitting/ adaptiveness/ responsiveness/ performance/ fitting in architecture in terms of biomimetics, learning from the functions and performance of skins in nature? 2. How can we encapsulate the idea of fitting in building envelopes from the very beginning of the design?

1.3. Objectives and Scope

The central focus of this study is not really the change in shape, size, color or other design parameter but the process of change itself as a design issue. With this, the buildings can adapt before they become retro. The issue at hand is to increase fitting capacity of building envelopes and extend their lives with adaptive fitting. To this end, there are two ways to follow in this study: improving the fitting capacity of existing buildings and re-rethinking architectural design with the idea of adaptive fitting. Existing buildings constitute an important part of the problem. However, due to the difficulty of assessment and monitoring of existing buildings, the scope of the study is limited to new designs.

The research is carried through an analogy between protective covers of buildings and biological systems. This analogy will reveal how the knowledge gained from the proposed biomimetic approach is to be reflected to the design process. Rather than exemplifying the proposed approach with a specific design problem, this research aims to give a general understanding of how adaptive fitting approach will be reflected in design. Thereby, it is not aimed to give a detailed explanation of each step of the proposed biomimetic approach.

The aim of this research is to uncover the potential of the analogy on the *nature of the skin* and building envelopes. The subject of the research is very broad and, thus, certain boundary conditions are need to be set. The research could have been carried with a specific focus on different covers from nature: animal skins, shells, outer covers of plants etc. Since they better serve the purpose of the research with their diverse fitting strategies, animal skins are chosen as the biological models to explore.

The main objectives of this study are:

- To explore and construct relationships between skin in nature and building envelope in architecture.
- To reconsider architectural design process with a biomimetic viewpoint.
- To explore potential of biomimetics and its implementations in architectural design.
- To identify fitting modes in natural skin and building envelope.
- To explore the potential of redefining the idea of fitting in architecture with a biomimetic viewpoint.
- To propose a holistic approach to develop the analogy of building envelop and natural skin.
- To propose a design approach to increase fitting capacity of building envelopes.

1.4. Significance

When buildings are designed for both present requirements and future change, their life spans will be extended. To this end, as a result of the proposed design approach, this research can contribute to the sustainable development of the built environment. Further, it will bring a new understanding to the material use and preservation of buildings. Eventually, all of these can provide a new perspective for both architectural design and practice in general.

1.5. Methodology

Biomimetics in a multidisciplinary field. Therefore, it cannot be approached with conventional architectural research methods. Due to this complicated multidisciplinary nature of the field, biomimetic studies are mostly searching and discussing appropriate methods. There are attempts to develop biomimetic design methods but establishing a general method for the generation of design concepts still remains arguable. There is a need for a specialized method to engage related field and this method needs to be reconsidered in every design problem.

In this study, an empirical research is conducted to identify the factors and levels that are relevant to solve the current research problem and to choose the appropriate design approach. In general, biomimetic design methodologies are set based on two major phases: the preliminary design phase and emulation phase[5]. Basically, the preliminary design phase involves the exploration of the problem and natural systems and organisms' investigation, leading to a design concept. After the first phase, transformation of the gained knowledge from nature into solutions for building envelopes is a complicated multidisciplinary process, which needs to involve technological and industrial knowledge. Therefore, the design approach developed in this research aims at the preliminary design phase.

In order to develop the adaptive fitting design approach, first of all, the research problem is defined in the domain of architecture. Even though a concrete problem is defined, a problem formalization was not yet identified. Second, the problem and its environment is transposed to biology in order to understand how nature has achieved the solution to the problem. The biological models are identified by searching through literature and using web engines and databases. Eventually, solutions provided by nature to design problem are categorized and mapped in order to suggest a particular way to look at nature. This mapping allowed the combination of several biological models and, thus, principles and processes in order to propose a solution to the initial problem. Further, this mapping also

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[5] Existing biomimetic design models can be explored in two main phases: the preliminary design phase and emulation phase. The preliminary design phase results in generating a design concept through the investigation of natural organisms. It includes identification of the problem in the source domain, then reframing the problem, alternative generation. The emulation phase includes implementation and testing of the design concept.

served the base for the formalization of the problem. Third, a deeper understanding of initial problem is developed with findings from nature in mind. This led to another mapping which includes both fields and provides a new perspective to the initial problem. Last, with this new perspective a new design approach is developed.

1.6. Limitations

The current study provides a selection of representative processes and factors based on the analysis of a rather modest number of biological models, which can be considered as negligible compared to the number of samples exist in nature. Generating a reliable database requires an extensive research on natural systems and various resources and collaborators from numerous disciplines. A refined selection of optimized processes and factors can be achieved by consideration of a wider number of biological models. Yet, the sample size and number of processes and factors to be considered and their mapping remain a great challenge at this stage. It is worth to note that, even if such an extendable database is created, there would still be a need of a continuous investigation and update, since nature is continuously updating itself.

Another limitation is the fact that proposed design approach does not consider current technologies as potential inputs. Therefore, the generated design concepts might provide good scientific solutions, but their implementation might pose serious challenges in engineering, availability of technologies, etc. To avoid this, the architect needs to consider these limitations and filter the relevant biological models and solutions accordingly.

CHAPTER 2

LITERATURE REVIEW

Man always observed nature and tried to find solutions to his problems through his experience. Until the very end of 19th century, man has learned shapes and forms from nature through the observation of natural structures. Since the mid-19th century chemistry, later molecular biology and recently systems biology have begun to contribute to the accumulation of knowledge on natural organisms. After the industrial revolution, development of new technologies and advanced tools for observation, particularly electron microscope, and then the scanning tunneling microscope, enabled analysis of nature at atomic level. The alteration of the scale that we look at organisms made way for new discoveries, such as the first DNA profiling in the 1980s[6], and thus brought new insights to biology. This is followed by developments which are mostly exploring how organisms encode, store, reproduce, transmit and express information. Eventually, today, biologists are trying to find out how to map genomes, edit DNA sequences and how to map self-signaling pathways. All these developments have given access to a whole new worlds and gave birth to the *"biology revolution"*.

[6] The modern process of DNA profiling was developed in 1984 by Alec Jeffreys. For detailed information see Panneerchelvam & Norazmi, (2003).

Starting from the 1970s, the way disciplines learn from nature was redefined.[7] With the growing interest in biology as a discipline, the tendency of imitating nature gave way to scientific knowledge and laws explaining nature. Some aspects of nature, which are undetectable to the human eye, have been discovered by science. This triggered new approaches to transfer this knowledge and to develop a new biological perspective. These approaches have been given a number of names in different disciplines, such as *bionics, biotechnics, biotechnique, biognosis, biomorphism, biophilia, bioinspiration, biomimesis, biomimetics and biomimicry*. All these synonymous or related concepts are rooted in the same idea that *"nature herself is a prodigious inventor and has already produces through natural selection all kinds of devices, structures and materials"* (Steadman, 2008, p. 260).

The first one to be coined among these terms, bionics, is defined as "*the science of systems, which have some function copied from nature, or which represent characteristics of natural systems or their analogues"* (Vincent et al., 2006, p. 471). As Senosiain (2003) explains, rather than simply tracing or copying, bionics is based on the idea that *"every model can potentially provide ideas for the design of new methods and mechanics that will improve those currently existing"*. In the 1950s, there was another word, which was coined by Otto Schmitt, "biomimetics", for the transfer of ideas and analogues from biology to technology. Schmitt's biomimetics was broader in meaning, beyond the medical and robotic focus of the term bionics, embracing fields such as engineering, design, chemistry, and electronics and so on. Indeed, there are simpler definitions for biomimetics that are explaining what the young discipline is about. For instance, German Biokon network defines Bionik (German equivalent to the biomimetics) as the *"decoding of inventions of animate nature and their innovative implementation in technology"* and The Centre for Biomimetics at the University of Reading defines biomimetics as *"the abstraction of good design from nature"* (Gruber, 2011, p. 14). At present, a broader term, biomimicry, is making its way into many of the most important areas of research. Pawlyn

[7] *A New Biology for the 21st Century* by Committee on a New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution, National Research Council, 2009.

(2011) denotes that appearance of the word 'biomimicry' in scientific literature dates back to 1962. Nevertheless, the word is mostly known by the work of biologist Janine Benyus, whose work specifically intends to focus on sustainable solutions (Pawlyn, 2011).

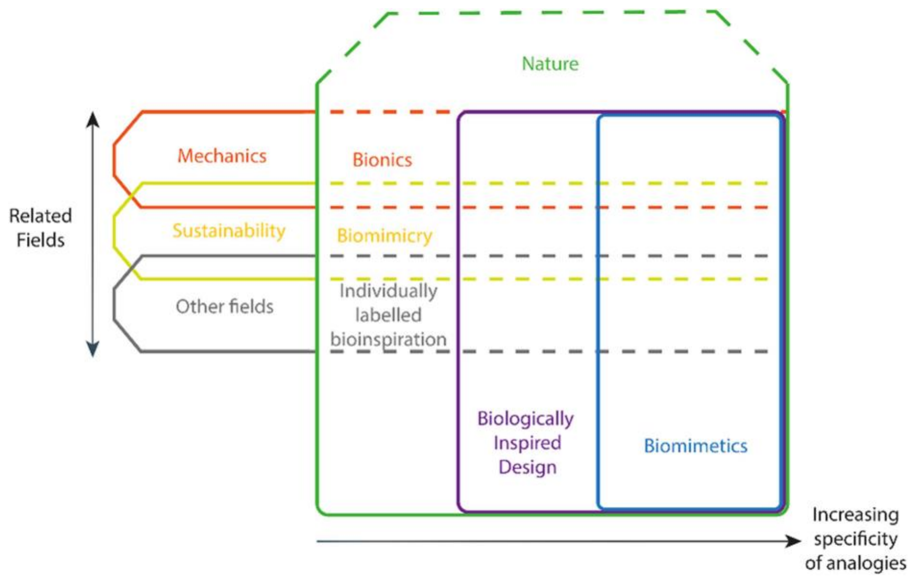
In order to avoid ambiguity and due to its emphasis on biological processes and interactions, the term biomimetics is adopted in this research. Biomimetics basically aims to map the patterns and translate the processes of nature to human beings for improving the quality of our lives. To this end, biomimetics represents a new way to look at the nature. Rather than learning *about* nature, biomimetics offers learning *from* nature.

As Hanks and Swiegers (2012) denotes, mimicry of biological processes is crucial in first progressing toward understanding them and then going beyond. To achieve this, it is important to go beyond models and implement the knowledge gained through mimicry on the wider scene. At this point, it will be useful to address the key distinction between biomimicry and biomimetics. In brief, biomimicry is an idea that is more inspiration oriented, whereas biomimetics is based on the idea of reverse-engineering. Hanks and Swiegers (2012) explains the distinction between these terms as follows:

> *"Biomimicry offers tremendously powerful strategies, but also demands responsible development in order to provide benefits while mitigating potential damage. The biomimetic approach does, however, inherently encourage an examination of how a particular structure or process fits into its surroundings and may thereby assist in the development of sustainable approaches to technological and industrial development"* (p.7).

As shown in the following table, Fayemi et. al. (2017) illustrates the difference of these terms due to their specificity of analogy and an axis of related fields.

Table 1 The field of bio-inspiration. (Fayemi et. al., 2017)



Within the last few decades, different biomimetic approaches have been described and specific process models are presented by a number of researchers in order to embed biomimetic information into their research areas.[8] In biomimetic studies, first of all, a multidisciplinary approach is essential. Second, a general framework cannot be applied to all design problems since the scale and the requirements, and the involvement of other disciplines is different for each problem. Therefore, existing frameworks of biomimetic design need to be specified around every design problem and in the way that they engage disciplines. For this reason, most biomimetic studies attempt to find a methodology that can be specified around the design problem.

Nature provides a large database of adaptation strategies which makes natural beings always fitting. Until now, a number of researchers and designers aimed to transfer adaptation principles of particular organisms into architectural domain. Yet describing

[8] For detailed information about examples of these process models see Fayemi et. al. (2017).

this highly effective and selective database and understanding the functioning of its' systems is still a challenge for architecture. It involves designing mimics which help to unravel how these systems work. As important as this is to go beyond models and implement on the wider scope the knowledge gained through mimicry. Then, it is required to explore on the one hand how similar functional features may be implemented to different structures and, on the other, to present that novel functions of similar or even higher efficiencies and adaptivities may be evolved in artificial systems.

Before moving on, it should be noted that in the literature review presented in this chapter, the term building envelope is considered with a broader perspective due to the scope of current research question, including all different approaches around the idea of enveloping membrane of buildings. For this reason, it may seem arguable whether the given examples fits well to our current understanding of building envelope. This confusion is due to different approaches to the building envelope in architecture in terms of scale, material, technique and understanding. In fact, there is no universally applicable definition of the term "building envelope". Instead, there are a number of different understandings and approaches that share the same intention of enclosing the building. Investigating these different approaches is out of the scope of this study. Therefore, this research presents its argument through a variety of different examples of the building envelope in the literature.

2.1. Solutions Inspired by Nature: Biomimetics in Architecture

> *"We learn important things from imitating animals. We are apprentices of the spider, imitating her in the task of weaving and confecting clothing. We learn from the swallows how to construct homes, and we learn to sing from both the lark and the swan"* (Democritus, 400 BC as cited in Senosian, 2003, p. 3).

Nature has always assisted man and helped him tackle a variety of life's challenges. People started looking nature for inspiration and development of various devices many centuries ago. Among these efforts, engineering examples are remarkable due to their methodical approaches. However, except Leonardo da Vinci, it was not until the 19th century that people made the leap from mere observation to application. In this regard, as Mazzoleni (2013) points out, Leonardo da Vinci could be considered as the first biomimetic designer (p. 7).

In the context of the wide range of architectural discourses, the outer cover of the buildings has always had a major importance. If architecture is explored since the industrial revolution, the evolution of the outer cover from the façade to the envelope can be observed at different scales, forms and systems. Thinking the outer cover as an envelope implies approaching it as a whole, rather than the sum of individual components, in a similar manner with nature. Looking at the last century, the first example of this evolution can be considered as the structures of Antoni Gaudi. Second example is the shell structures of the 1950s, which are profoundly inspired by the structures in nature. Last, the structures of Buckminster Fuller and Frei Otto, which were also developed with lessons from nature. Further exploration on these examples will follow in this chapter.

The last century has witnessed a remarkable change in the nature of the building envelope. In the 19th century, industrial revolution introduced new building materials, products and techniques, reshaping components of the buildings and leading to the possibility of lightweight and transparent structures. Until the development of the steel frame in the early 20th century, almost all buildings of any size had depended on their walls to hold them up. In other words, the exterior walls were forming the structure of the buildings as well as keeping the weather out. With the development of steel frame, the walls were no longer required to bear any weight, instead the interior frame held up the building and the exterior walls kept the weather out.

According to Del Grosso and Basso, the idea of *building skin* originated only after these developments introduced by the industrial revolution that are liberating the exterior walls from their load-bearing task (Del Grosso & Basso, 2010). When the traditional load-bearing wall constructions gave way to frame structures, a new metaphorical comparison appeared in architecture, of the skeleton of the animal with the structural framework of columns and beams. In his “theory of structure” of 1851, Horatio Greenough stated that *“the principles of construction can be learned from the study of skeletons and skins of animals and insects”*(as cited in Steadman, 2008, p. 39). Later, in the steel frame structures of the late 1800s, the separation of building’s skin from its structural bones is made complete, “*making the metaphor especially apt”* (Steadman, 2008). Steel beams and girders allowing for wider interior spaces also provided flexibility of plan and façade, which was later named as “free plan” and “free façade” by Le Corbusier in the mid-1900s. This new structural understanding and structural possibilities brought their own problems and complexity. All these changes made architects to search for new sources of inspiration. In this regard, particularly in structural domain, nature appeared as a major source of inspiration.

The highlight of this was Joseph Paxton’s Crystal Palace, built for the Great Exhibition of 1851. For the design of the structure of the Crystal Palace, Paxton, who was a botanist, took nature as a model. He designed the roof of the Palace based on his studies of the water lily, *victoria amazonica*, that could hold the weight of a small child (Eggermont, 2007; Eryildiz & Mezini, 2012; Margolius, 2002). He observed the underside of the lily leaves, where the primary ribs act as cantilevers and thin cross ribs between them reinforce the main members. Then he designed ribbed iron support structure for large glass panes. In this way, he created a light yet strong roof, covering an area of eighteen square meters. In this context, Crystal Palace can be seen as the first methodic biomimetic approach to the design of the building envelope.

In the early 1900s, Antoni Gaudi was another important figure who explored nature and natural structures in a methodic way. The importance of Gaudi’s work comes from his aim to develop a holistic understanding of buildings, and thus envelopes, and from his explorations of how force and environment effects the shape, as in nature. Gaudi conceived of nature as his model and he did experiments to develop his idea of structural integrity and economy. In this regard, efficiency of the structure was the central point of his work and shape. Gaudi explored animal skeletons and the dynamics of mollusks and plants and used them as a guide. Then he developed his own method based on his observations on natural forms and he invented advanced structural systems. His hanging chain models were among early examples of experimental methods of form finding (Oxman, 2013). Besides, his models were the early examples of the search of efficiency and fitting as a result of the compromise between material and energy.

Figure 1 Gaudi’s hanging model for Colonia Güell (Source: http://upwards.the3doodler.com/gaudis-sagrada-familia-with-cornelia-kuglmeier/. Retrieved at: 25.12.2017)

In the turn of the 20th century, with the potential offered by the *formless or form-finding qualities of plastic-liquid concrete* (Pedreschi, 2008), a new era has started in architecture and construction. This has made possible the realization of shell structures, which are profoundly influenced by the geometry and efficiency of shell structures in nature. Severud (1945) pointed out the relevance of natural models in the design of shell structures as follows: *“..it is a fact that contemporary architect and engineer faces few problems in structural design which nature has not already met and solved”* (p. 149). Engineering pioneers of the mid- 20th century such as Max Berg, Eugéne Freysinnet, Robert Maillart, Pier Luigi Nervi, Félix Candela and Edouardo Torroja have pushed reinforced concrete to its limit and made experiments with shell structures to achieve strength and lightness. Among them, Nervi and Candela took nature as a model to create their structures (Arslan Selçuk, 2009). They aimed to span even wider spaces with less material, leading to light structures, similar to the combination of strength and lightness found in nature. Looking models for this in nature, they aimed to understand how natural laws are related to form and force. The shell structures they created can still be considered as notable examples of stiffening in architecture.

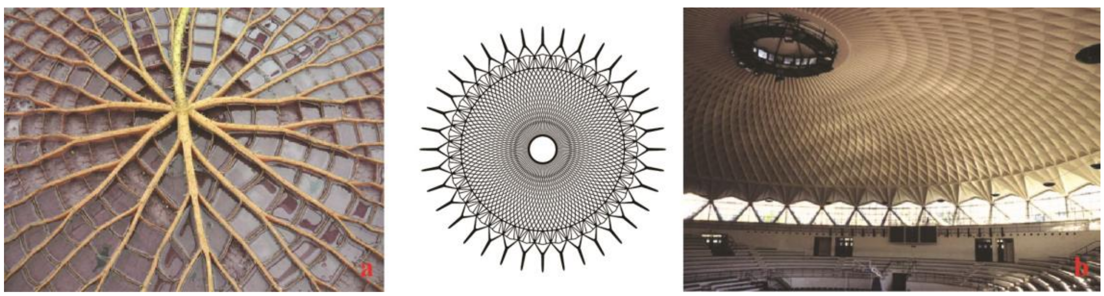


Figure 2 a) Amazon water lily, **b)** Plan and view from Palazzetto dello Sport in Rome by Pier Luigi Nervi (Sources: a) https://asknature.org/strategy/leaves-given-structural-support/, b) www.pinterest.com, c)https://arqteoria.wordpress.com/2013/09/23/aula-2-expressionismo-estrutural/. Retrieved at: 25.12.2017)

Architect and inventor Buckminster Fuller was another important figure who dedicated his studies to explore principles found in nature as a structural rationale. He sought to understand nature's geometry, how natural organisms came into existence and how they maintain themselves. Driven from the principles he found in nature, such as material efficiency, structural integrity and modularity, Fuller created structures which he thought as a whole. In this sense, Fuller's structures point out a departure from the understanding of the exterior of as façade and surface to the envelope. Further, he drew inspiration from the structure of radiolarian (Brayer, 2013) and created one of the first automated climate adaptive envelopes in his design of the US Pavilion at Expo '67, which had a computer-controlled solar responsive system (Velikov & Thun, 2013, p. 81).

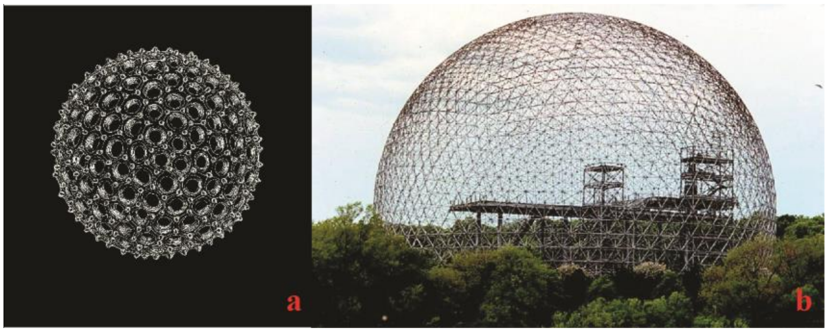


Figure 3 a) View from radiolarian, **b)** The US Pavilion in Expo 1967, Montreal, Canada (Sources: a) http://www.microscopy-uk.org.uk, b) https://www.pinterest.co.uk/pin/291889619575810269/. Retrieved at: 25.12.2017)

In the 1950s, German architect Frei Otto was also exploring structural principles in nature for his constructions, *"created through a dependency on physical forces, the constraints of materials and the effect of spatial boundary conditions"* (El-Ali, 2008, p. 15). He developed light tensile and membrane structures inspired by the spider webs, and proposed new innovative structural types and building envelopes such as the cable net structure he designed for the German Pavilion at Expo '67 in Montreal (Coineau and Kresling as cited in Vincent et al., 2006). He was building physical models, which were similar to chain modeling technique Gaudi used, in order to determine the optimum shape of a form and to test its behavior. He spoke of *"finding form"* as his models were restructured over a certain time span, through material interactions (Otto, 1996). In this sense, it can be argued that, while Gaudi originated the idea of form-found envelopes in architecture, Otto developed the process with using shape and information to reduce the use of material and energy to enclose spaces. The importance of Otto's work comes from his understanding of building as result of environmental forces and as a whole. This enabled him to think of designing building envelopes rather than individual components to enclose spaces. As Kolarevic (2005) mentions, "*the form finding techniques he used in his tensile membrane structures are still considered as the nearest example of* *performance-driven architectural form generation, in which the form of the membrane is dynamically affected by changing the forces that act on the model"* (p. 199).

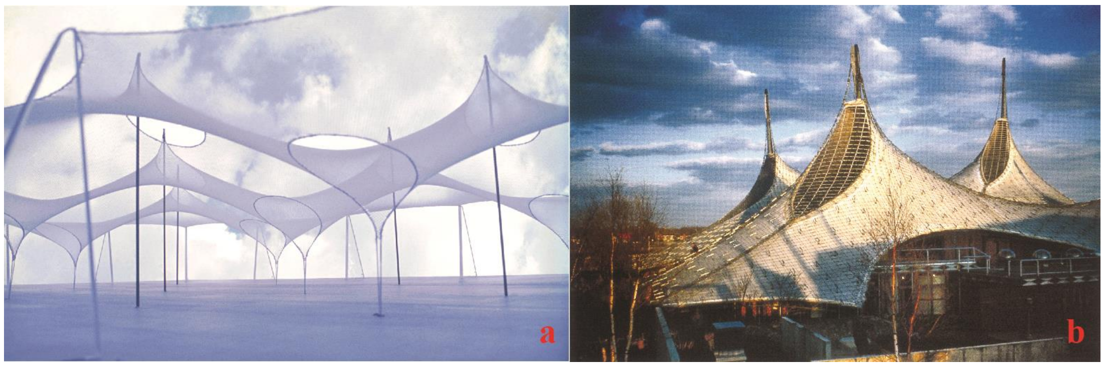


Figure 4 a) Structural membrane form finding study by Frei Otto, **b)** German Pavilion in Expo 1967, Montreal, Canada (Sources: a) https://formfindinglab.wordpress.com/2016/12/22/how-to-describe-the-esthetics-of-structural-surfaces-12/. b) https://www.archdaily.com/623689/ad-classics-german-pavilion-expo-67-frei-otto-and-rolf-gutbrod. Retrieved at: 25.12.2017)

Another importance of Otto's work, together with Gaudi, is that they are considered to be the classical basis for computational models of form-finding and emergence (Oxman, 2013). As Oxman puts it, their experiments introduced the concepts of force simulation as a process of design, and physical design models in which variables can be modified. Their experiments introduced an understanding of nature as a set of processes. More importantly, these were the early attempts to find a medium between animate and inanimate, through *interactive experimentation of the integrated relationship between form, structure, material in a form finding process* (Oxman, 2013, p. 109).

In the 1970s, the quest for structural efficiency has continued to dominate the relationship of architecture with nature. In the late 1980s, energy efficiency came out to be a main topic in architecture due to recent developments in technology and the emergence of sustainability issues. This has shifted the focus of inspiration from structural efficiency of nature to its energy efficiency. The building envelope continued to have a major importance, since it defines the boundary conditions of the enclosed space and energy systems. Later on, with the aim of increasing efficiency of the buildings, green building standards such as LEED, BREEAM, CASBEE etc. are developed and began to be applied to the building envelopes.

In the 1990s, there had been an interest in the idea of performance as a design paradigm, largely due to sustainability issues, together with the recent developments in technology (Kolarevic, 2004, p. 45). The idea of performance was not new in architecture and it can be defined very broadly, across multiple realms, from financial, spatial, cultural to purely technical. However, it is mostly considered as a response to the movements of green and sustainable design. Without a broader perspective, the idea of performance in architecture is still remains as an elusive concept. In this study, with a biomimetic perspective, it is claimed that performance is a question of fitting. Nature provides the best standards to evaluate the fitting of our buildings. In order to survive, nature needs to fit in, while buildings need to achieve the best performance. Fitting is a direct consequence of the metabolism in nature; it fits the form to function in an efficient way, as a whole. Seen in this light, integration of performance in architectural design with a broader and holistic perspective provides a potential to understand the building and thus its behavior as a whole.

While the idea of performance has been discussed widely in architecture, in the late 1990s, Benyus defined biomimicry as a new direction in science that links nature with sustainable solutions and innovation. To date, biomimicry has received increasing attention in architectural discourse. One of the first built examples of the application of biomimicry in architecture is the Eden Project Biomes by Grimshaw Architects. The Eden Project Biomes can be considered a promising example of biomimicry in architecture since it attempts to take nature as a model to create sustainable solutions, such as using responsibly sourced materials, being energy efficient and constructed with minimal waste (Eden Project, 2017). However, the sustainable dimension of the project came forward up to a point and the model it took from nature remained as a metaphor. In brief, the initial intention of the design was partially achieved.

Figure 5 The Eden Project Biomes by Grimshaw Architects in Cornwall, UK. (Source: https://grimshaw.global/projects/the-eden-project-the-biomes/. Retrieved at: 25.12.2017)

Nature operates on systems, and thus, without mimicking whole systems, the use of biomimetics in architecture will be limited to being either a form-finding process or a way to provide sustainable solutions. In nature, form, function and structure are interrelated and indistinguishable. Without a whole-systems perspective, the transfer of morphology and form can seldom go beyond imitation of a few features of a particular organism, since these features hardly match the function of the imitated natural systems. By consequence, the designed system cannot succeed and fit in as the imitated one in nature. There are examples in other disciplines that goes beyond the mimicking of form alone. For instance, the nose of Concorde jet imitates the motion of a swan when landing. In brief, to solve our problems like nature, biomimetic design needs to consider the whole system and the process, how something is made and how it fits into a living system.

In this regard, the Eastgate Centre, built in Harare, Zimbabwe by Mick Pearce exemplifies the attempt of systematic application of biomimetic principles in architecture. The design of the Eastgate Centre drew inspiration from African termite towers, which provide natural cooling of the interior by maintaining 31 degrees Celsius, allowing a continuous harvest of fungus alive. The building is passively cooled by mimicking this sophisticated ventilation system in section diagram and cooling function. For the scope of this study, even though the model from nature is not directly used for the design of the envelope, Eastgate Centre still constitutes an important attempt of systematic application of biomimetic principles in architecture.

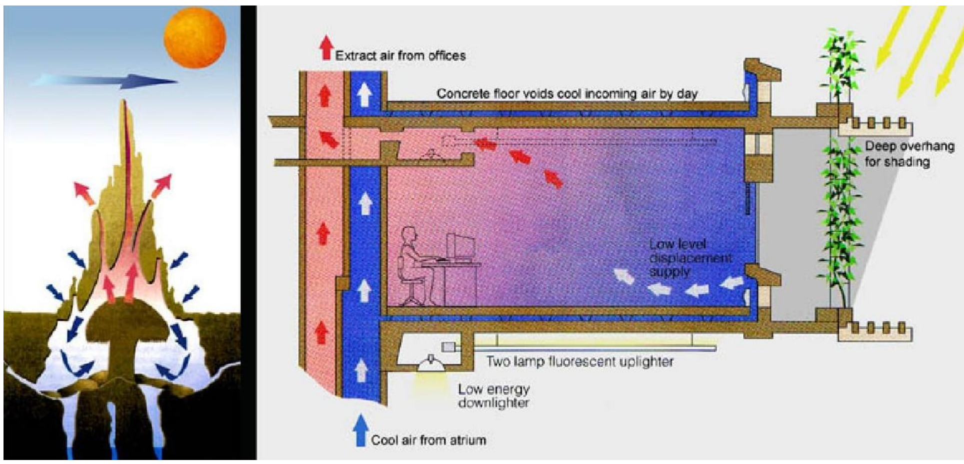


Figure 6 Section from a termite mound and the passive ventilation and cooling system of The Eastgate Centre in Harare by Mick Pearce (Source: http://www.mickpearce.com/Eastgate.html. Retrieved at: 25.12.2017)

It can be claimed that the main promise of biomimetic design is learning from the systems and processes of nature to solve our problems. For this purpose, in the realm of architecture, the notion of generative design is a particularly a promising one. Today, biologists can use a number of techniques to model the form generation and growth processes of natural organisms or to simulate their behavior. These techniques are barrowed by architects and integrated into their form-finding processes, yet in a partially metaphoric way. For instance, in the last few decades, growth has been explored in architecture through rule based computational systems by the creation of algorithmic growth scripts for the development of a “morphogenetic” architecture (Imperiale, 2006, p. 277). Yet, in these scripts, nature is used as a metaphor since the process is directly imitated in the virtual world. For instance, the Embryological House by Greg Lynn integrates growth and development to the design process in the virtual environment (Lynn, 1999). However, if the project is thought to be implemented to the real world, the concept of change is lost.

It is important to acknowledge that the potential of generative design does not lie in the form-finding methods, but in its process based logic which is holistic and repetitive. Due to that fact, generative design is a useful method for addressing complex systems and patterns in nature. Moreover, generative design also has a capacity to address most of the contemporary issues in architecture such as fitting, performance, efficiency and optimization with a biomimetic perspective. More importantly, generative design shifts the emphasis from the design of individual elements and layers in the building envelope to the thinking of the envelope as a whole.

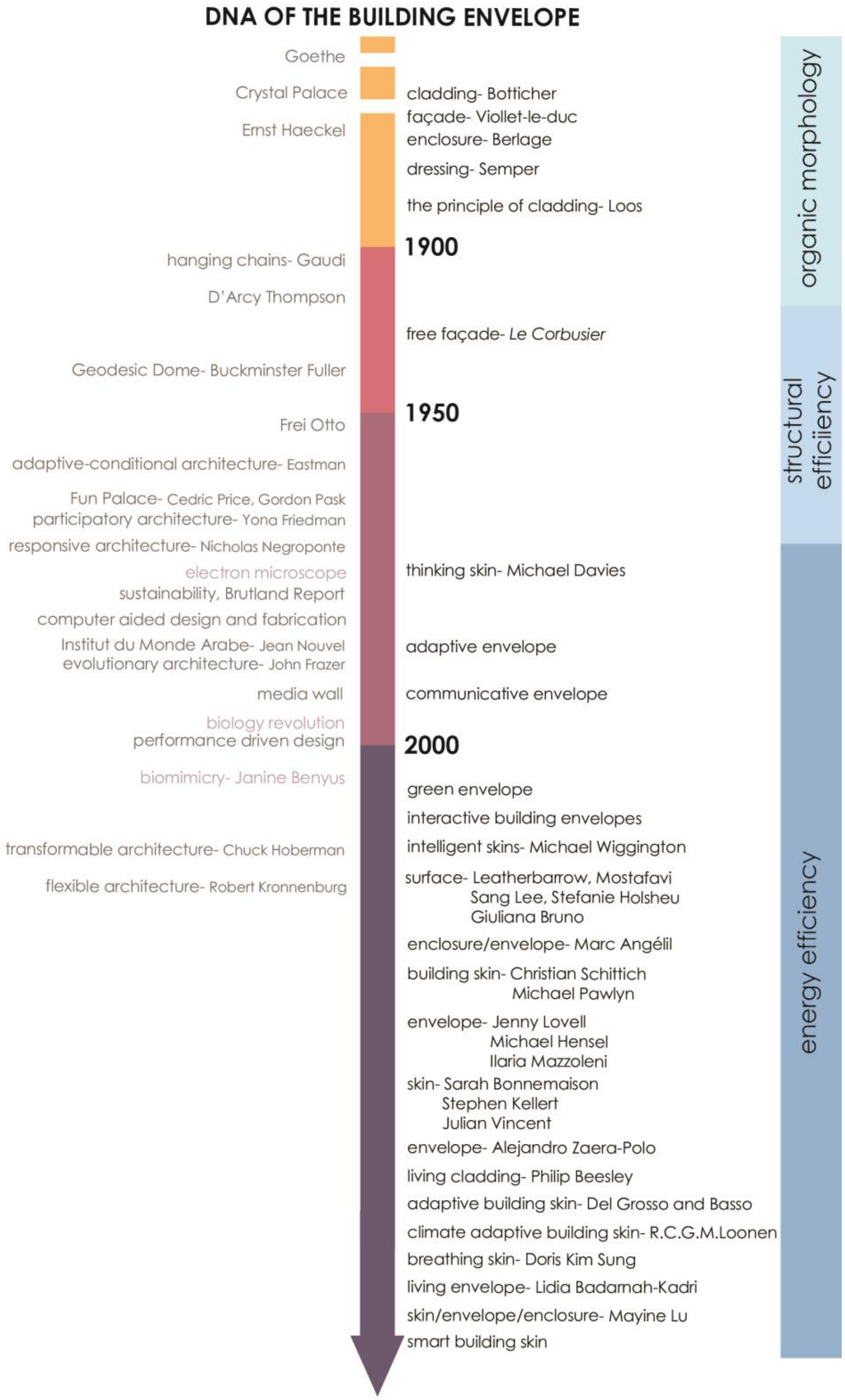
The envelope of Beijing National Aquatics Center exemplifies the use of generative design methods. Like Frei Otto’s structures, design of the envelope is inspired by the structure of soap bubbles, yet organized and optimized with computational procedures. Here, the intention is to develop a methodical approach to nature. In the end, a large-scale bubble-like structure which satisfied aesthetic and performance requirements is generated (Roudavski, 2009). However, as a cellular structure, the design has a capacity to include a lot more information. For instance, cellular structures in nature are highly adaptable. By consequence, in this example nature is taken as a metaphor rather than a model.

Figure 7 National Aquatics Center (Water Cube) in Beijing by PTW Architects (Source: http://www.ptw.com.au/ptw_project/watercube-national-swimming-centre/. Retrieved at: 25.12.2017)

In concluding, it could be stated, over the last century, that there had been three benchmarks in nature-architecture relationship. First, the 20^{th} century introduced new complexities and problems with new materials and construction methods in architecture. This, in turn, shifted the attention to the structural solutions in nature, which achieve stiffness with the combination of strength and lightness. Second, the increase in environmental problems in the second half of the 20^{th} century pointed out the responsibility of the discipline of architecture in taking precautions and developing sustainable solutions. This resulted in reconsidering issues such as efficiency, performance and optimization in architectural design and looking at nature for its efficient solutions. The last benchmark was the emergence of biomimicry, which has redefined the relationship of architecture and nature towards a methodical way. Reconsidering nature with contemporary opportunities of technology has influenced architectural design thinking and thus, biomimicry turned out to be an appealing source of inspiration for addressing complex problems of architecture. In effect, there had been significant attempts to transfer biological knowledge to architecture. However, the idea of biomimetics in architecture requires further exploration, since there is still a need for a comprehensive, systematic and holistic methodology.

The following table marks above mentioned benchmarks and reveals the changing relationship of nature and architecture through the evolution of the building envelope.

Table 2 From the cladding towards the skin: a biomimetic perspective (developed by the author).



2.2. Why and How Biomimetics Works in Architecture

In the 20th century, the advancements in science and technology enabled '*the abstraction of laws of life and apply them elsewhere'* (Kelly, 1994, p. 7). As the knowledge of natural systems is developed, the understanding of the properties borrowed from nature has also evolved. Nature's genius has begun to be been extracted to solve the problems of mankind. Today, as Kelly (1994) declares, it is becoming increasingly difficult to distinguish the things of the nature and the things of mankind. Kelly points out that the metaphors between the machines and organisms are as old as the first machine itself. Yet, currently, these metaphors are becoming real. First, as Kelly (1994) explains, the materials in nature such as food, fibers and shelter was taken. Then, the ways to extract raw materials from nature's biosphere was developed to create synthetic materials. Presently, nature's logic is being extracted and taken (Kelly, 1994). The emerging change is twofold: the logic of Bios is being imported into machines, while the logic of Technos being imported into life. In other words, *"human-made things are behaving more life-like and life is becoming more engineered"*(Kelly, 1994).

Like other disciplines, this has changed the relationship between architecture and biology, with the deep interest of architects in the developments in biological sciences, particularly in the works of scientists such as Goethe, Ernst Haeckel and D'Arcy Thompson. As in other disciplines, in architecture, together with the advancements in computer technologies and growing interest in the paradigm of complexity and complex systems, processes and relations of nature came to the fore. Reconsidering nature with computational tools and principles paved way to innovations and improvements.

Meanwhile, advancements in technology brought digital design and fabrication tools to architecture, first as a tool for representation then as an extension of mind and thinking. This has changed architectural design understanding, shifting the attention from the end product to the process. By consequence, as a process based and data driven domain, digital design has a potential to relate architecture with nature in a different way through computational design models.

While there are many historical examples that fit the idea of learning from nature, the formalization of the concept occurred only in the late 20th century with the work of Janine Benyus. The idea has been linked to sustainability with Benyus and Biomimicry Institute's work, in which biomimetics turns out to be *"a strategy for not only taking advantage of nature to produce novel structures and processes, but also as a way to combat the negative environmental impacts of current practices"* (Hanks & Swiegers, 2012, p. 6). However, it is arguable if a particular focus on sustainability is required in biomimetic studies. The current research claims that these studies should be concentrated on processes and systems in nature with a broader perspective. In corollary, the produced structures and processes will inherently be sustainable. The main potential of biomimetics is not offering sustainable solutions but providing a methodical approach to nature. In this vein, it can be claimed that biomimetics aims to abstract principles that lie behind organism's and species' capability to sustain itself by adapting and evolving itself in relation to the habitat over time.

Benyus proposes *"three fundamental ways to learn from nature in order to solve a specific problem, considering nature as a model, as a measure and as a mentor"* (Benyus, 2002). Firstly, nature as a model for design implies emulating nature's forms, processes, systems and strategies to solve human problems. Secondly, as a measure of design, nature is taken as an ecological standard to judge the rightness of man-made innovations. Lastly, nature as a mentor offers a new way of viewing and valuing nature, for not only what can be extracted from the natural world, but also what can be learnt from it (Benyus, 2002). Based on this framework, it can be argued that, while *nature as a model and mentor* are design methods, *nature as a measure* is an evaluation method which ensures that *"the design passes a sustainability test, as well as an audit to check for missed limits and opportunities"* (Baumeister, 2014, p. 187).

Each of these three ways could be seen as potential entry points but all three ways together describe the experience and the approach to emulate nature's successful patterns. Nature should be understood with a systems perspective. In this regard, nature's rightness and standards, cannot be taken without its' forms, processes and systems. In other words, viewing nature as a mentor requires taking nature as a model and measure. It should be noted that, from this perspective, these three ways eventually become indistinguishable. Seen in this light, biomimetics can also be considered as *"a test of our understanding of nature, in which every experiment is a measure of our understanding"* (Hanks & Swiegers, 2012, p. 4).

In architecture, even though there are attempts to take nature as a model and mentor, there is rarely an example of using nature as a measure. Without using nature as a measure, taking it as a model or mentor has a risk of becoming an incomplete process. The idea of taking nature as a measure implies a comparison of the performance of our designs with nature. If nature is considered a measure, principles found in nature can be used for evaluating the fitness and appropriateness of our designs to existing conditions. In fact, utilizing nature as a measuring tool leads us to performance driven design. If nature is taken as a measure, then architecture can explore its boundaries in a broader way, not only limited with energy but also function, aesthetics etc.

2.3. Building Envelope-Nature Relationship

If we look at the evolution of life on earth, we will see that life is made possible by membranes. The function of the membrane is twofold: "*to provide a surface on or from which interactions and reactions can occur and be controlled, and to provide selective barriers to keep reactants together and rest of the world out"* (Vincent, 2009). Within the hierarchy of the organism, these membranes can occur at any level. The nucleus, the cell, tissues, organs are all surrounded by a membrane. In all cases, all levels, whether the membrane, cell wall or the skin, the enclosure is specialized not only as a covering but also as a selective barrier to control the movement of substances in and out of cells.

In architecture, the idea of providing a membrane has started from the textile structures, evolved into the cladding, façade and eventually today's skin-like building envelopes.[9] This radical change can be seen in the Table 2, in Section 2.1. In historical terms, as Herzog et al. (2004) mentions, the primary reason for creating an effective barrier between interior and exterior is the desire for protection against hostile outside world and inclement weather (p. 19). Later on, other requirements for control and regulation functions have been added to these protective functions such as light in the interior, an adequate air change rate, a visual relationship with the surroundings but, at the same time, a boundary between private sphere and public areas (Herzog et al., 2004). In this part of the study, referring to three periods of the evolution of the protective cover is important for understanding the transformation of the façade to the envelope.

Earlier, nomads built transportable tents, which are made of cloth, in order to protect themselves from natural forces. From the textile structures of the primitive times to contemporary period, there has been a great shift in building envelopes. One of the most considerable periods that affected the building envelope design was Gothic architecture, which was based on a load-transferring structure. Since the walls in Gothic architecture were no longer load-bearing, it allowed for the creation of large windows on the external walls. In the Renaissance period, *"façades became completely detached from the body of the building itself, for the first time becoming an independent architectural element within the overall structure"* (Herzog et al., 2004, p. 64). The outward appearance of the building became important and façades started to hung over the front face of the building, expressing aesthetic intentions. The idea of designing the exterior walls as *"the expressive face of the street"* continued throughout the 17th and 18th centuries. In the 20th century, the traditional load-bearing wall constructions gave way to frame structures. It was only

[9] The 19th century architect Gottfried Semper, claimed that architecture has evolved from these tents of the nomadic peoples. For detailed information see Semper, (2004).

after the second half of the 20th century that the exterior walls of the building, together with the roof are referred as the building envelope.

In architecture, the idea of the envelope fulfils the role of the membrane. The term envelope emphasizes the close comparisons with the skin in nature and it also highlights the intrinsic and integrated quality of the whole building fabric, rather than the layered characteristic associated with the ‘wrapping’ approach to building design. In this manner, the envelope has a potential to perform as part of a holistic building metabolism and morphology which is deeply connected to other parts of the building and environment.

2.3.1. Building the Analogy

The building envelope is not limited to the actual space it occupies as part of the entire structure, but also influence the space in and around the building. It is the key feature when observing a building from the exterior and has impact on the interior. Like the natural skin in organisms, the envelope is where the building meets with the environment. The envelope may need to address both aesthetic, physical, architectural and comfort objectives. To this end, it is an integral part of the entire building with direct relation to design, use, structure and other building services.

The analogy between the outer covers in nature and buildings can even be seen between the human skin and the envelope, as it is presented in Table 3. In the following chapters, the analogy will be broadened with skins of other organisms.

Table 3 Analogies between the human skin and the building envelope (developed by the author).

FUNCTION		SKIN	ENVELOPE
	technical	protection	support (to resist and transfer mechanical loads)
		thermoregulation sensation vitamin D synthesis immunity excretion	control (the flow of matter and energy of all types)
	spatial	space defining interacting with other systems	space defining interacting with other systems
	formal	-	domain of the visual

As it is seen from their similar performance expectations and requirements, skin in nature provides a prominent model for the design of the building envelope. The primary function of both the skin and the envelope has always been to provide a shelter and protection. In other words, the main analogy between the skin and the building envelope is the establishment of an internal environment. They both act as a switch that regulates the interaction between inside and outside. The interaction between inside and outside has many levels from total closure and total openness to matter and energy flows. In nature, the grade of difference needed is a result of environmental conditions on the one side and metabolism and energy and resource balance on the other side. In building envelopes, the interaction between inside and outside is defined by the requirements to achieve high performance and energy control on the one side and the formal and visual expression of contemporary culture on the other side.

The skin is in a constant state of evolution, renewing and regenerating itself. Skin varies in thickness due to its changing relationship with skeleton. As it adapts to the particular qualities of the body, it gets thick where skeleton needs some padding to soften contact, hardened in response to friction (Imperiale, 2006). In different parts of the body the skin also varies in other features such as texture, color, scent and temperature. Similar to this, different parts of the building envelope are exposed to different spatial and environmental forces, and therefore have different requirements.

Skin performs with and for the body as well as performing for itself. With a series of exchanges between the skin, the body and external environment, skin responds and adapts to the changing conditions. As a result of these complex and multi-layered exchanges and relationships between these systems, skin types in natural organisms are highly differentiated from the feathers of birds to the scales of the fish, shells of turtles, exoskeletons, tree trunks and so on. Further, as Brandon (1978) mentions, there is also a significant variation in morphological, physiological and behavioral features among members of a species (p. 183).

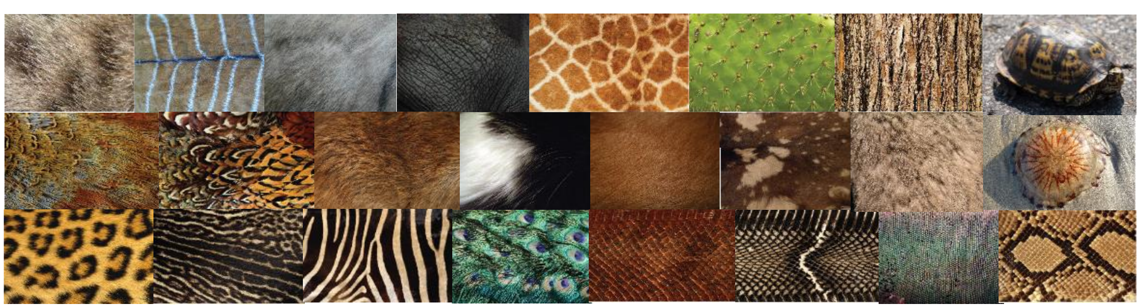


Figure 8 Images of the skins of different organisms in nature.

In nature, skin always fits in as a direct consequence of the metabolism, determined by energy and substance. Skin also fits in environmental conditions, depending on its ability to adjust or resist to external forces. Adaptation enables the organism to cope with environmental stresses and pressures. While adaptation as a state of being refers to changes in individuals, adaptation as a process refers to changes in populations, that is evolutionary adaptation. In evolutionary adaptation, the advantageous traits are passed from older generations to the younger ones. These traits are passed on to next generations and eventually such traits become common in the population. As a result, the population becomes better adapted to some aspect of the environment than it was before.

Table 4 Functional analogies between the skin and the envelope (developed by the author).

SKIN	FUNCTION	ENVELOPE
provides structure	constructive	provides structure
insulation seals/barriers filters-semipermeable storage redirection	protective	insulation seals/barriers filters storage redirection
controlling/regulating responding/changing	regulatory	controlling/regulating responding/changing
signalling appearance	communicative	communication appearance

The skin has several functions, the most important being to form a physical barrier to the environment, allowing and limiting passage of matter and energy of all types while providing protection against micro-organisms, radiation, toxic materials and mechanical injuries. Besides, acting as a protector and barrier, the skin performs as a communication medium serving a critical role in how the body interfaces with the external environment. Similarly, in buildings, the envelope has a key role in determining the building's climate control and performance qualities. The design and position of variety of systems, components and layers constituting the envelope affect the floor plans and the elevations, and respond to environmental and social context.

Together with protecting the body, the skin also regulates body temperature and fluid balance. Furthermore, the skin facilitates the two-way passage of gases through it. Likewise, composition of the envelope has a direct influence on the interior environment affecting comfort, energy and durability of the building. Like the natural skin constitutes our facial features, which make up our identity, building envelope is *"the calling card of a building and its designer"* (Schittich, 2006, p. 9). Both the natural skin and building envelope embody the dialogue between internal and external worlds as they respond to inputs from both environments. They both protect interior environment from the exterior, while keeping connected to it. Moreover, both the natural and architectural skin is made up of a series of layers. In natural skin, these layers are complex, interrelated, and highly differentiated. What lies under the skin affects the surface, the filaments, fibers and bones contributes to the smooth surface of the body. In brief, skin is an interface, which acts as a threshold, allowing for interaction with the elements in multiple directions and scales (Mazzoleni, 2013, p. xxi). Similar to this, building envelopes acts as an interface, adapting to conditions specific to the location at the same time providing interior requirements. To put it simply, like a suit, a building's envelope must be tailored to its specific context of location, from climate to use and inhabitation, in order to get the most adaptive fit (Lovell, 2010, p. 22).

2.3.2. Examples of Skin Inspired Building Envelopes

Nature can be a prominent source of inspiration for the design of the building envelope. Three important benchmarks have changed building envelope's relationship with nature, changed its tectonics and redefined it: computational design, performative thinking of the 1990s, the emergence of biomimetics. For the architects who wanted to use current advancements in their designs, this tectonic change had become a lot more important than understanding the change in architectural design and thinking, and more importantly understanding the potential of biomimetics in architecture. Many contemporary examples are manifesting the amalgam of these three different approaches in different levels. Some of them are more artificial, while some are more data related. Even though the analogy between the building envelope and the skin is conceptually explored in many of these examples, the built examples which propose a systematic methodology for the transfer of biological knowledge from the skin to the building envelope is relatively rare.

Although nature provides many solutions to our problems, the application of the natural model to an architectural design appears to pose great difficulties such as the scaling difficulties. The scales and complexity levels of nature and architecture are different. Therefore, how to compare these two levels of complexity and to transfer knowledge between them poses itself as a major challenge. To this end, mapping of these two different levels of complexity is one of the main objectives of contemporary biomimetic design methods.

Different methods exist for biomimetic design. Gruber (2011) points out that most research groups work in a very narrow field and thus the details of their work are not accessible, but a few considers developing strategies and methods to use biomimetics as a tool for innovation. The developed methods present nature on a vertical scale, either top-down or bottom-up. Yoseph Bar Cohen (2006) puts it as follows: *"In order to approach nature in engineering terms it is necessary to sort biological capabilities along* *technical categories using a top-down structure or vice versa"* (p. 496). These methods will be explained in the following chapter in details.

Scale transfer poses a great difficulty in architecture. Therefore, several contemporary examples of biomimetic design remain in relatively small scale, in pavilions or façades rather than in building level. Climate responsiveness, one of the important functions of the envelope, has been concerned in many examples. To exemplify, a research pavilion, named as the Hygroskin, is developed at the Institute of Computational Design (ICD) of the Stuttgart University. Based on a passive approach that is related to the hygroscopic behavior of timber, Hygroskin aims to explore responsive capacity within the material. The adaptable system is composed of wood cones that open when the relative humidity increases and close when internal moisture decreased (Krieg et.al., 2014).

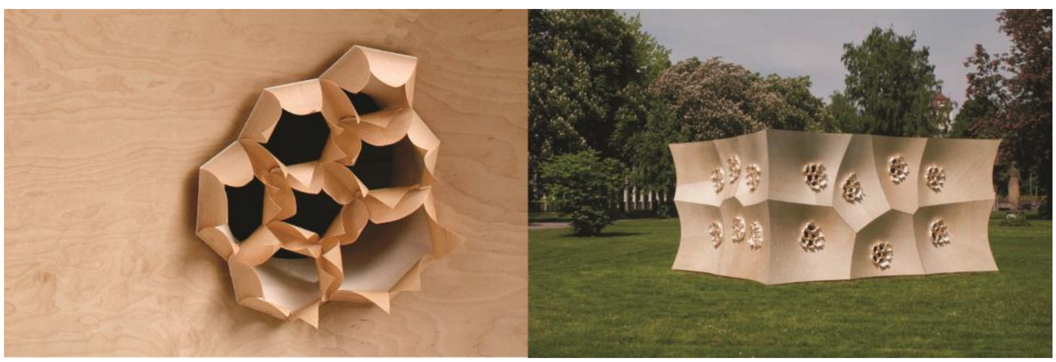


Figure 9 The Hygroskin Pavilion by the Institute of Computational Design (ICD) of the Stuttgart University (Source: Krieg et.al., 2014).

In Hygroskin, adaptive behavior is intrinsic to the design, which is not one of a kind system. Currently, architecture is preoccupied with considerations of design criteria that neglects the inherent material properties. By contrast, all organisms in nature are formed by the interaction of intrinsic and extrinsic forces. As a result of this interaction, shape changes may occur in organisms. Unlike architecture, shape in nature is inherently connected to function. Shape changes, allowing for adaptation of successful strategies, play an important role for survival in natural systems. In plants, some changes are based on intrinsic abilities, triggered by external factors such as changes in external load or humidity (Hoheneder & Gruber, 2016, p. 33). While some of these shape changes are irreversible (e.g. fracture), shape changes induced by humidity change are reversibly cycled as the moisture level varies (Hoheneder & Gruber, 2016). Hygroskin aims to transfer this very biological principle of shape change triggered by humidity to architecture, in order to overcome the problem of climate responsiveness.

In architecture, there is an increasing interest in designing specific building envelopes to match desired functions such as harvesting energy or material (Hoheneder & Gruber, 2016). Among these, Hygroskin's systems design constitutes an important example since it integrates shape change to the function through intrinsic properties of the material used. In other words, fitting ability which is achieved by the shape change, is not an added property, rather it is an integrated part of the system. In a way, this approach is similar to the hypothesis of this study.

Another example of building envelopes which is developed with a similar approach is the Flectofin by ITKE. The fitting ability of the envelope comes from the intrinsic property of the material, inspired by the valvular pollination mechanism of *Strelitzia reginae* (Bird-of-paradise) flower (Schleicher et. al., 2011). In a similar manner with the flower, the fins of Flectofin are able to shift 90 degrees, relying on reversible material deformation rather than the use of technical hinges (López et. al., 2017).

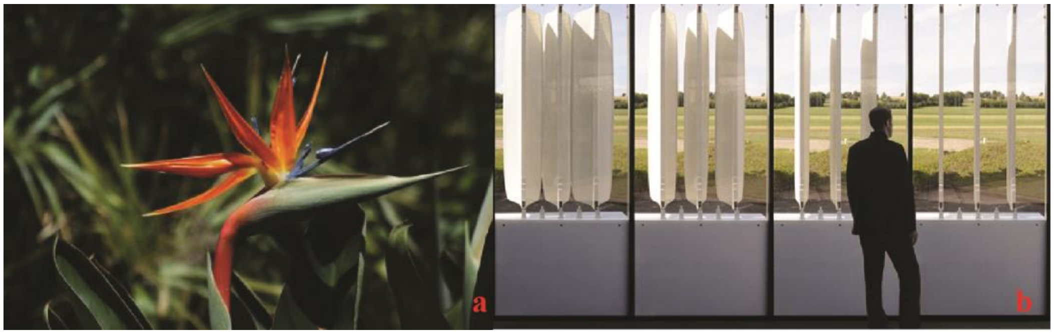


Figure 10 a) The Bird-of-Paradise Flower, **b)** Full scale prototype of Flectofin (Source: López et al., 2017)

In the same line of thinking, the One Ocean Thematic Pavilion for Yeosu Expo 2012, designed by SOMA Architecture, features an external kinetic façade system that is inspired by the research on plant movements and kinematic mechanisms like the Flectofin (López et al., 2017, p. 696). The One Ocean was initially an attempt to scale Flectofin to the size of the building's façade, however, due to the requirements of architectural design and high wind loads, another kinetic system inspired by the research on plants has been developed (Knippers & Speck, 2012, p. 8). In this regard, it exemplifies the difficulty of applying biomimetic principles at building scale. The *kinematic media façade* of One Ocean, developed in collaboration with Knippers Helbig Advanced Engineering, consists of 108 vertical lamellas made from glass-fiber reinforced polymer (Knippers & Speck, 2012, p. 7). This kinetic shading system can adapt to light conditions controlling and responding to changing sun light conditions during the day, as well as allowing the artistic staging of special lighting effects.

Figure 11 View from One Ocean Pavilion in Yeosu, South Korea (Source: http://www.soma-architecture.com/ Retrieved at: 25.12.2017)

Above mentioned Hygroskin and Flectofin are two of the closest biomimetic examples of the idea of coding the ability of fitting from the beginning of the design. However, as mentioned, they have scaling difficulties which makes them hard to apply at building envelopes. There also other examples of searching fitting in building envelopes similar to nature. For instance, another research pavilion that is designed by the same research group with Hygroskin, at the Institute of Computational Design (ICD) of the Stuttgart University, the Sea Urchin, exemplifies the search for achieving structural and morphological performance. The design of the envelope is based on the analysis of the constructional morphology of sand dollars, a type of flat, burrowing sea urchin.

The constructional principles found in sand dollar is transferred to timber plate shells. The design is inspired from the internal structure of the sand dollar which relies on the geometric morphology of its double layered system and the differentiation within the material (Menges, 2017). Another inspiration point for the project was the finger joints and fibrous elements though which the calcite plates of some sea urchin species are connected. This multi-material connection enables the sea urchins’ shell to maintain its integrity during growth and exposure to external forces.

Figure 12 Sea Urchin, 2015-16 ICD/ITKE Research Pavilion (Source: http://icd.uni-stuttgart.de/?p=16220. Retrieved at: 25.12.2017)

Even though the Sea Urchin is also a significant attempt of transferring biological knowledge to architecture, it differs from previous examples given as it does not integrate the idea of fitting to the design. Rather, it focuses on the abstraction of structural and morphological features of the chosen biological model. In doing this, it focuses on different groups of the sea urchin. While the plate growth and fiber and finger joint connection strategy comes from the regular sea urchin, double layered structure and material differentiation strategy comes from the irregular sea urchin. These principles of different groups of the organism vary depending on adaptation strategies in specific environmental conditions. In other words, these principles are a result of the interaction between the organism and its ability to adjust or resist external environments. As such, they are organism and context specific. In this regard, the Sea Urchin, transfers principles developed in different contexts to the same structure. This approach has a potential to provide a pattern to the solution to the problem. However, it is arguable if this potential is used in the design since it is not mentioned by the researchers.

Moreover, the project transfers these biological principles as isolated functions. It concentrates on morphological aspects of the sea urchin, yet largely overlooks other aspects such as functional or behavioral. It is crucial to remember that everything in nature is interconnected, for instance morphological aspects are inherently connected to functional aspects. Therefore, when transforming biological knowledge into design, taking each property individually may result in deficiencies in the properties of biological model since nature operates holistically.

All these points considered, it is worth to remind the need to search for a systematic method for biomimetic design in architecture. In order to create a truly better performing architectural biomimetic model, the design would not only have to mimic specific features of systems found in nature, but the overarching systems as well. Biomimetic design should imitate both the major systems and the minor systems working in unity with them. It is needed to study and understand how the system works, how it is associated with its environment and how it works within the larger scale before applying it to architecture.

2.3.3. Recent Studies on Skin-Envelope Analogy

Similar to current study, in the realm of architecture, there are some researches which also address both method studies, the attempt of taking nature as a measure of transferring the arising knowledge to the system and the idea of reconsidering performance with a biomimetic perspective. In these studies, the skin-envelope analogy becomes more apparent and situated. However, these are mostly unbuilt research studies. To improve the arguments, the question of how to transfer this analogy to buildings is discussed with following researches, both in search for a method and application.

In her academic research, Badarnah-Kadri (2012) proposes a biomimetic methodology, named as the living envelope, for the generation of design concepts. In order to validate proposed methodology and to assess its generality, it is applied on four environmental aspects that need to be managed by the building envelope: air, heat, water and light. In her study, Badarnah- Kadri utilizes adaptation strategies from nature as a key strategy for the design of the building envelopes that can accommodate the environmental changes with less energy consumption. Although her study presents a general methodology for the generation of design concepts, integrating all relevant aspects and systems of the building is still challenging. Her research is similar to this study in approaching the envelope with principles of adaptation in nature, however, it does not focus on integrating these principles to the genes of the design. Further, rather than focusing on the nature of the skin, it addresses specific features of the skin.

Collaborating with a biologist, Mazzoleni (2013) develops a comprehensive body of work on characteristics of organisms at a certain context which solves a building envelope problem in her book titled *Architecture Follows Nature: Biomimetic Principles for Innovative Design*. She explores ways of utilizing animal skins for performative building envelopes. Even though Mazzoleni's findings reveal some unique aspects from animal skins to inform building envelope, developing a general holistic methodology still remains as a challenge. It differs from this study in same aspects with Badarnah-Kadri's research.

In their paper titled *Skin in Architecture: Towards Bio-Inspired Façades*, Gruber and Gosztonyi (2010) also develop a comprehensive study, taking human skin as a model for the design of the bioinspired façades. With this study, they aim to provide a basis for further research aiming at energy efficiency and sustainability. Their explorations provide a detailed analysis on the analogy of human skin and building envelope, with regards to their properties and functions. It has a different scope from current study since it does not aim to provide a methodology to transfer this analogy into an abstraction and a design concept. The analogy of skin and envelope provided in their study is similar to current research, yet narrower in scope. Whereas this study focuses on the nature of the skin with a broader perspective, Gruber and Gosztonyi's study concentrates on the human skin.

Considering nature inspired examples in architecture, it is important to note that a strategy found in nature can sometimes be directly copied, but usually the constraints of that particular natural example will not be exactly the same as those in the design problem, thus *direct imitation seldom represents the best emulation* (Gruber & Gosztonyi, 2010). In order to transfer strategies from nature to architecture, an abstraction needs to be done following profound research in biological model. Here, it is required to reduce complex information and identify relevant parameters and boundary conditions. Without considering these steps carefully, biomimetic architecture cannot reveal all aspects of nature and remains limited to imitating morphological aspects. In many cases, Badarnah & Kadri (2015) denotes, implementing biomimetics include three challenges: "*(1) the search for and the selection of appropriate strategies from the large database found in nature; (2) scaling difficulties; (3) conflicts between solutions of integrated parts of the design concept*".

As it is shown in above mentioned examples, design of the building envelope in the realm of biomimetics requires methodical approach, in a manner that is supporting the interdependence of the envelope with other systems of the building. One problem with current biomimetic building envelope approaches is that they leave other systems of the building intact and only deal with energy efficiency. While designing a building envelope in the realm of biomimetics, it is inevitable to focus on energy, however, we cannot deal with energy consumption in isolation. In fact, systems or aspects of the building should not be dealt in isolation. Further, the concept of biomimetics should be considered more broadly, not to miss further opportunities that are provided by the living world.

To sum up, current literature shows variations in both understanding of biomimetics and in the scale and implementation field. Yet, it can be concluded that, with a biomimetic perspective, evaluating sustainability and performance of our buildings should be a question of 'fitting'. Nature fits the form to function in an efficient way, through coexistence of form, function and material. In this way, nature enhances energy efficiency and optimizes resource utilization. Every time natural organisms face with changes they react by adaptation, which enables them to become better fitted to survive and reproduce in their environment. With these strategies, they always sustain their fitting state. In this regard, the idea of fitting in architecture needs to be addressed in order to take nature as a measure to evaluate efficiency of our buildings.

Before moving on to the next chapter, it will be illuminating to give a glossary of terms that are used in this study. Some terms barrowed from nature and their architectural analogy within this study can be briefly explained as follows:

Table 5 Glossary of terms (developed by the author).

Nature	**Architectural analogy**
Skin	Building envelope
Gene	Infrastructure of change
Metabolism	The sum of processes that take place within the systems of the building
Life	Design, construction, use, demolition and recycling of a building
Species	Building groups in same building standards and codes
Fitting	Appropriateness to the current conditions
Fitness criteria	Variables of fitting

CHAPTER 3

THEORIES AND POSTULATE

Both natural organisms and buildings require to be fitting in order to survive. Like natural organisms, buildings are not monolithic unities but complex systems which constitute multiple and diverse components that operate at different scales and levels. Due to the difficulty of transferring knowledge between these two domains, which have different levels of complexities, this research focuses on the nature of the fitting, to construct a broader perspective.

Although buildings are apparently static, they often require interventions due to changes around them such as the building codes, population growth, environmental conditions, technology or financial issues. In building industry, current activity about the fitting of the envelopes is more concerned with extending the life of existing buildings and upgrade of existing structures rather than with the creation of new structures. It is generally accepted that approximately 50% of construction work involves upgrade projects (Doran, Douglas, & Pratley, 2009).

In practice, the interventions to existing buildings are commonplace, yet very little attention is devoted to preparing buildings to these changes before they require interventions. Therefore, current understanding of fitting in architecture implies turning the building back to its original state, after it becomes *retro*. In other words, it aims to learn from the past, to create the present. Unlike this, living beings do not become retro, rather they aim to fit the best condition of their current situation. For instance, the starfish can regenerate damaged parts or lost arms, but the generated arm is a new one, not a replica of the damaged or lost one. First, it needs to heal the wound and then it begins to generate new cells, which in turn, triggers a new process growth. Unlike buildings, regeneration in starfish is innate and thus it does not need to look at its damaged or lost parts and turn to an original state. Rather it regenerates itself as it develops itself from within.

As noted earlier, existing buildings also become locked in to particular patterns of behavior, energy and resource use and so on, constrained by their fixed and static materiality, limited life span and infrastructure. Understanding how to upgrade these buildings and to overcome lock-in, and then facilitate systems change and plan the reproduction of the next generations will be critical to achieve sustainable solutions. Within the scope of this study, upgrade is not seen solely in terms of repairing and maintaining buildings but as reconfiguration of the behavior and relations of the systems of the building. To put it in another way, upgrade is conceived as a method to design not only the "process product" but also the "process product cycle". Needless to say, this kind of a systemic upgrade requires considering not just isolated parts and systems of the building but an integrated, whole-building process.

With all these in mind, in this study, it is aimed to redefine the concept of "retro" in architecture with a biomimetic perspective through the analogy of the skin and building envelope. For this purpose, this research approach uses the term 'fitting' instead of retrofitting, as in nature. Natural organisms are skillfully and conservatively take advantage of material and energy resources. They meet multiple needs with an optimum solution and select for shape or pattern based on need, such as their growth patterns or limitations imposed by the conditions of life on earth. As organisms' interface with the exterior world, skin plays an important role in their fitting.

In a similar manner with nature, if building envelopes are coded with the ability of fitting from the very beginning of the design, they can act and perform like the skin. The three sections of this chapter are aimed to develop an understanding of fitting in architecture analogous to nature. First, fitting modes in natural skin are explored, then the current understanding of fitting in architecture is clarified, finally, fitting modes in architecture are investigated through new designs and existing buildings. Given the diversity of available fitting modes in nature and architecture, in the last chapter, the analogy between the fitting of the skin and the envelope is built. Based on the discussions in chapters 2 and 3, a new design approach to answer the research question will be developed in the following chapter.

3.1. Fitting Modes in Natural Skin

Similar to buildings, fitting is a question of survival in nature. An organism that is not functioning properly cannot survive in the long run. Adaptation and evolution allow organisms to survive within the constraints imposed by their respective environments. As Reap et al. (2005) put it, adaptation refers to *"the behavioural and material changes organisms make within the period of a lifetime"*, while evolution refers to *"slower, fundamental genetic changes, occurring over the course of many generations"*. Both adaptation and evolution are considered as "*hallmarks of life"* (Solomon, Berg, & Martin, 1993).

Adaptation is required to achieve a fit between the system and the environment and to maintain the quality or state of being fit (Holland, 1992). Natural organisms become and remain fit by short term and long term adaptations (evolution). In buildings, there are examples of short term adaptations, but evolutionary dimension would allow another dimension of adaptation that is yet not available. This could be possible with further developments in the use of building information modelling (BIM) in design.

Together with adaptation, self-organization is also a central attribute of living systems, and of their evolution. In buildings, there is seldom an example of the use of self-organization in a strategic way (Petra Gruber, 2011, p. 124), but could provide a new perspective to building. The self-structuring capacity in nature requires networks, diversity and distribution of structures across scales. Further, it also "*requires the ability to retain and build upon existing patterns*, which is often done *through the use of genetic memory"* (Mehaffy & Salingaros, 2013). Structures that code earlier patterns are re-used and re-incorporated later. As Mehaffy and Salingaros (2013) states, the most common example of this is the DNA, which enables "*the evolutionary transformation of organisms"*. The fitting capacity of natural organisms is transferred through the DNA.

Besides fitting capacity, natural beings are genetically coded with the ability of economic handling of material and energy. Their energy efficiency and optimization of resource utilization, together with adaptive features make them fitting in context. In buildings, energy efficiency has a big and continuously growing impact, whereas management and recycling of resources still needs to be discussed further. Nature can provide a model for developing cyclic production processes in building industry.

Like the envelope in buildings, as the interface between the body and external environment, the skin has a pivotal role in the adaptation processes of natural organisms. Among the ancestors of the earliest reptiles, the adaptation to full time life on land was accompanied by drastic changes in the structure of the skin (Jablonski, 2006, p. 28). These animals evolved scales in order to balance the stiffening effect of the outermost layer of their skin and to retain their bodies' flexibility (Jablonski, 2006, p. 28). Jablonski (2006) explains this further as follows:

> *"Once formed, individual scales cannot grow cell by cell as the animal grows larger. Thus, to accommodate growth, it must form a new set of scales to replace the old set. Lizards and snakes, for example, renew their scaly costume all at once in a cyclical process called shedding. In*

> *a synchronized sequence, the animal forms an entirely new epidermis, the layer of older epidermis separates from the new and the older layer falls away in one piece or several large pieces… Independently, shells evolved in the turtle lineage. The turtle shell incorporates the animal's spine, ribs, dermis and an outer keratinized epidermal layer in a remarkably protective box that grows by slow accretion as the animal's size increases throughout its life"* (p. 29).

In organisms, a wide range of environmental conditions effects self-organized growth. Therefore, the organisms need to be specifically adapted to the environment they grow up in. The degree of variation between genetically identical organisms is the result of this particular relationship with their environment. Besides different organisms, even modular parts of the same organism differ. Fur of the same tiger are not identical. Since these adaptations help them survive in different areas, certain organisms with the same skin color are found in one area, but not in another. Hoheneder and Gruber (2016) compares these adaptation principles of nature to building standards and codes in architecture. As they suggest, "*the buildings that are designed according to the same set of codes yet in different sites generates similar, but not necessarily identical buildings"* (Hoheneder & Gruber, 2016). They are tailored to their specific context of location.

Similar to architecture, in nature, fitting can be found at multiple physical scales and time resolutions. For instance, the chameleon can change its body color through rapid molecular signaling within and between cells when it is frightened and in response to light, temperature and other environmental changes. As Wigginton and Harris (2002) explains, the color change of the chameleon is activated by hormones that affect special pigment-bearing cells in its skin (p. 29). On the other hand, in animals at extreme latitudes, color change happens with seasons, as colder temperatures and shorter days trigger hormonal changes that give rise to dense and white coats (Gonzales, 2012).

Figure 13 Polar bear and Grizzly bear (Source: https://www.theweathernetwork.com/news/articles/climate-change-. Retrieved at: 25.12.2017)

As Louw and Seely (1982) mentions, there are three basic types of adaptations, based on how the genetic changes are expressed: morphological, physiological and behavioral (as cited in Badarnah-Kadri, 2012, p. 19). Morphological and physiological adaptations involve functional features that help organisms to adapt to their environment, whereas behavioral adaptations relate to the actions done by organisms in order to survive (Badarnah-Kadri, 2012, p. 19). Due to these adaptations, the skin of natural beings has become highly diversified. Changes in environmental conditions affects the metabolism and its energy and resource balance, thus skins of organisms of the same species might differ from each other, such as the polar bear and grizzly bear (figure 13). Besides contextual changes, there are many other reasons for skin adaptations. For instance, the male peacock evolved the adaptive trait of the tail feather display to compete for a mating partner. The sea horse is able to change to match the color and surface texture of the coral they live on and thus protect itself from the predators. In sum, these differentiations in the skin help organisms to adapt and remain fitting to enhance their survival. The great diversity of the skin in nature provides a ground to understand fitting patterns of the skin in nature.

Within the scope of this study, fitting modes of the natural skin can be grouped in four functions: regeneration, growth, protection and communication (Table 6). It will be useful to briefly explain these terms in order to establish the biological context of the research.

Table 6 Fitting modes of the skin (developed by the author).

Function	Mechanism
Regeneration	Renewal
	Restoration
Growth	Growth on edge
	Growth of organisms with shells
	Molting
	Addition
Protection	Strengthening
	Coloration
Communication	Signaling
	Sexual attraction

3.1.1. Regeneration

Regeneration is a fitting strategy of the skin which is achieved through the processes of renewal and restoration. Restoration is a response to injury by healing with repair mechanisms. While repair leads to the formation of scar, renewal fully recovers wounds with architecture and functionality of identical to unwounded skin (Gawronska-Kozak et. al., 2014, p. 61). Echinoderms, many reptiles and amphibians are able to regenerate tissues and organs. For instance, if a starfish is cut into two, each of the pieces may regenerate into a new animal (UCSB ScienceLine, 2006). Regeneration also serves as a defensive function, named as autotomy, as the animal detaches a limb or tail to avoid capture. While escaping a predator, if the predator catches the tail, it will disconnect (UCSB ScienceLine, 2006). After autotomy, cells move into action and tissues regenerate (Maginnis, 2006).

The natural skin responds to the injuries with self-repair. Self-repair, which is found at all levels of organisms in nature, can be considered as a prerequisite for life (Gruber et. al., 2016, p. 25). There are several mechanisms of self-repair in nature. In fractured or critically damaged living tissues, an intermediate tissue is formed after the scar tissue, in order to heal themselves. After amputations, in some animals just the wounds are healed yet in others, the lost part is regenerated. While amphibians have remarkable capabilities for regeneration, mammals respond to injuries with a repair process that heals the post-amputated region through a scar (Gawronska-Kozak et al., 2014, p. 61). The moon jellyfish exhibits an exception, as they heal the wound rather than regeneration their lost limbs (Abrams et. al., 2015).

In building industry, regeneration and self-repair still represents a major challenge, in which only few successful examples exist. Unlike nature, currently, detection and repair of the damaged elements in buildings does not usually happen in a self-organized way. Yet there are attempts to develop self-healing asphalt, concrete and metal in material sciences. These smart materials can be used for the optimization of natural sources since they can regenerate themselves over time.

3.1.2. Growth

Another key fitting strategy in the natural skin is achieved by growth. In nature, growth is based on cell division and change of cell volume. It is a gradual increase in physical size and occupying space with an integrated process of self-organization (Gruber et al., 2016, p. 24). In general, concepts of growth in protective covers of animals are growth on the edge, growth of organisms with shells, molting and addition. Growth is such a complex phenomenon, as D'Arcy Thompson (1942) states, that "*for growth to be so uniform and constant in all the parts as to keep the whole shape unchanged would indeed* *be an unlikely and an unusual circumstance"* (p. 35). Rates vary, proportions change, and the whole configuration alters accordingly. Unlike this, in built environment, growth is mostly achieved by the addition of a new structure when extra space or additional function is required. These strategies will be explained further in the following sections.

Growth is an ongoing process in human skin. As Gruber (2011) exemplifies, snails and mussels also grow continuously, owing to the mineral substance that is deposited on the margins of their shells (p. 118). On the other hand, animals some with exoskeletons and some reptiles, such as crabs, spider and insects grow in stages. Some of these animals molt their skin periodically to allow further growth. In the molting process, animals discard their old skin or exoskeleton, meanwhile synthetize and form a new one to match the new body (Gao et al., 2017, p. 1). As the animal grows, its skin becomes stretched. Unlike human skin, a reptile's skin doesn't grow as the animal grows. Eventually, the animal reaches a point where further growth is not possible. When this happens, a new layer of skin grows underneath the existing one. As soon as it is complete, the old skin peels away, leaving behind a replica of itself behind.

Figure 14 Molting examples from nature (Source: www.pinterest.com. Retrieved at: 25.12.2017)

Molting process differs from species to species, depending on the environmental conditions, their nutritional status and their growth rate. The frequency of shedding will change during the animals' life. In general, since younger animals grow at a faster rate than mature ones, they molt more frequently than an adult of the same species. Reptiles shed their skin periodically. Turtles, on the other hand, shed in pieces and slough skin on their neck, legs and old scales located on top of their top and bottom shell. Lizards also shed their skin in pieces and some of them eat their sloughed skin. Iguanas shed their skin in pieces on the outside of their bodies except for their eyeballs. Snakes shed their skin in one piece except for the giant snakes which may tear their skin.

Some animals with hard shells such as silk worm, are trapped in their carapace. They require to destroy this carapace and get rid of it. They escape and then inflate themselves until their outer skin hardens (Otto, 2015, p. 243). As they are particularly vulnerable and sensible in the phase without a hard shell, this is a dangerous period for the organism (Gruber, 2011, p. 118). Strategies of metamorphosis and pupa phases bridge the time of reconstruction (Gruber, 2011, p. 118).

Figure 15 Silk worm metamorphosis (Source: www.pinterest.com. Retrieved at: 25.12.2017)

In the example of silk worm, the cocoon provides thermal insulation, enabling hibernation in a way, as well as keeping the body functions intact. With all these, the cocoon provides a suitable environment for the animal to grow. In buildings, a similar strategy of layering can be observed yet applied in a more static way. In nomadic tents, an additional layer was added to provide thermal insulation and keep interior conditions stable. In modern building envelopes there are second skin and double façade applications. Nature provides useful models to develop this strategy further for contemporary envelopes, in a more dynamic and holistic way.

3.1.3. Protection

Protection is another fitting function of the skin which is achieved through strategies of strengthening and coloration. Like buildings, outer covers of organisms need to cope with mechanical stresses. This is commonly achieved by strengthening through the hardening of the outer layer. For instance, the shell of the turtle developed from its ribs and acts as a shield. This fitting strategy provides enhanced mechanical protection (Jablonski, 2006, p. 29). Similar to this, the envelope provide protection against mechanical damage in buildings. Further, the skin of animals provide protection from radiation, dirt and micro-organisms. The movement of these substances is achieved by semi-permeable characteristics of the skin. The building envelope provide a similar protective cover for buildings, yet it acts more as a border between inside and outside.

There is another protective strategy of the skin, coloration, which is used for protection from predators, sending warning to predators or production of insulation. Coloration strategy also exists in buildings but unlike nature, it is used for communication purposes and aesthetic intentions. In animals, the reason of coloration is that different species and different parts of the body are subject to different selective forces such as concealment, communication and regulation of physiological processes (Caro, 2005, p. 125).

Camouflage and mimicry are two main coloration mechanisms that provide protection from the predators. Camouflage is achieved by *general color resemblance* (Caro, 2005). Animals can remain concealed when their overall coloration resembles or matches the natural background of the environment (Endler, 1978). Camouflage is used when an animal resembles either the general background or specific objects in order to avoid detection. To exemplify, the cuttlefish can dynamically change their appearance to match the background as well as changing their shape to resemble objects like seaweed or stones (Nokelainen & Stevens, 2016). Background matching in animals may change due to seasons or with age (Caro, 2005, p. 125). Mimicry, on the other hand, is when an animal resembles another creature or inanimate object either for defense or to gain other advantages. For instance, some species of caterpillar can inflate its abdomen when it is faced with a predator. The markings on the enlarged abdomen resemble the eye and the shape of a poisonous snake which prevents it from being eaten.

Figure 16 An example of mimicry in animals (Source: http://www.bbc.co.uk/nature/adaptations/Mimicry. Retrieved at: 25.12.2017)

The animals also use coloration for warning, in order to signal that they are harmful or poisonous. Here, the color pattern is used to evade, confuse or deter visually hunting predators (Endler, 1978, p. 320). For instance, a venomous coral snake uses bright colors to warn off potential predators (Forbes, 2009). In architecture, the envelope is the primary element that determines the safety of the building as it provides protection against enemies and storage provisions. Unlike coloration solutions in natural skin, the envelope is expected to be stable and robust, mostly heavyweight constructed.

Figure 17 An example of coloration for warning in animals (Source: http://www.bbc.co.uk/nature/adaptations/Aposematism. Retrieved at: 25.12.2017).

Besides protection, coloration of the skin also provides thermal insulation to animals in extreme environments. Color pattern in animals is adjusted for thermoregulation (Endler, 1978, p. 319). Some animals such as the arctic fox, change their color with the seasons in order to have better insulation properties. For a similar purpose, in building envelopes, the thickness of the insulation material is increased. Current envelopes present a functional layering system, which differs according to the required difference between inside and outside. The bigger the difference, the thicker the layering, like the blubber that prevents heat loss from the body of arctic animals.

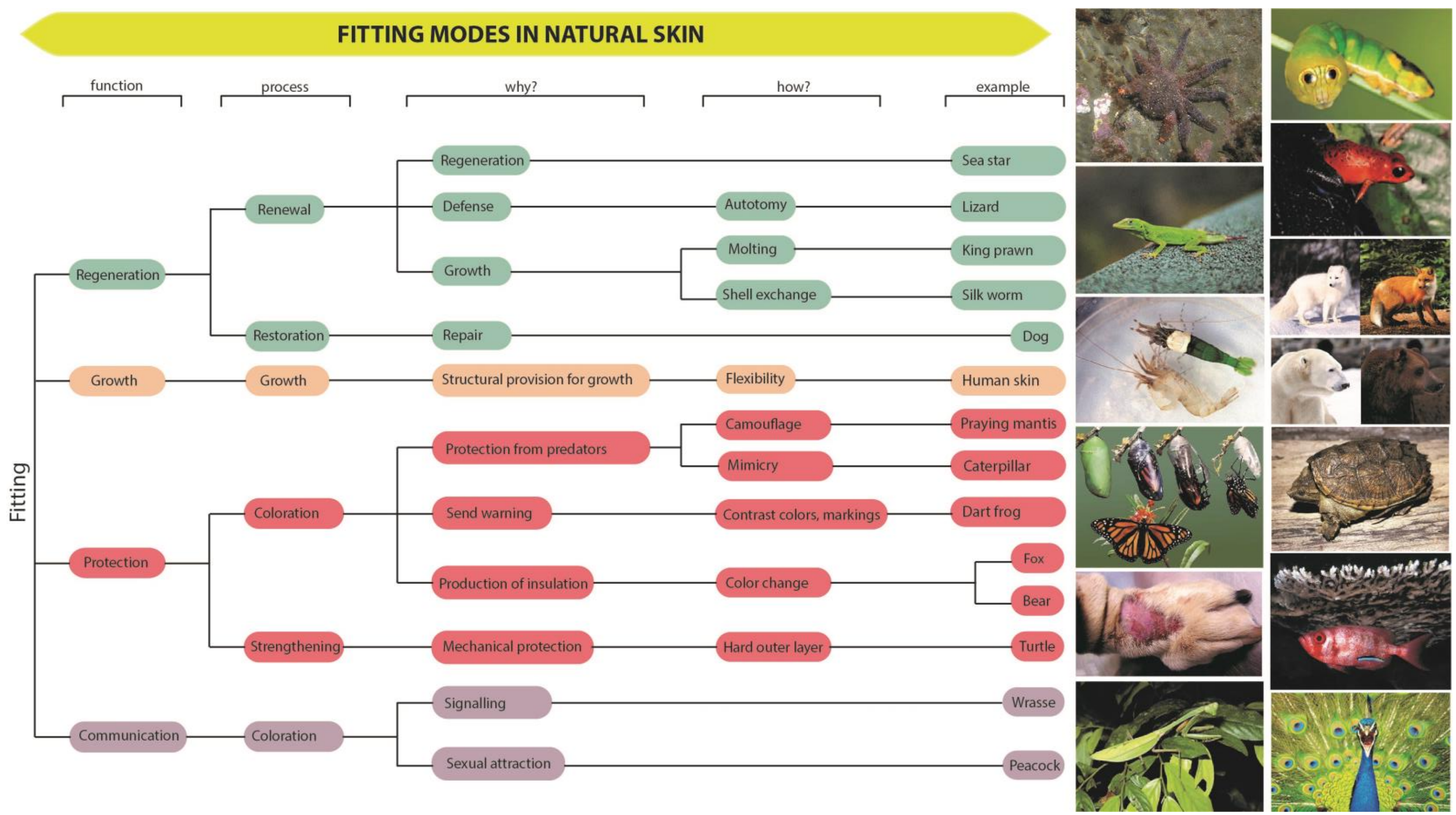
Figure 18 Arctic fox in different seasons (Source: http://www.bbc.co.uk/nature/life/Arctic_Fox. Retrieved at: 25.12.2017)

3.1.4. Communication

Lastly, communication appears as a fitting mode of the skin that is used for signaling and sexual attraction. For this purpose, animals use colors and patterns in order to convey information about their age, sex, mate quality and fighting ability to other individuals (Taylor & McGraw, 2007, p. 592). Color patterns which are used in species recognition and courtship should be as bright and as distinct as possible in order to avoid mistakes and make the process faster (Endler, 1978, p. 320). Like the skin in nature, historically, the building envelope has been used as a main medium of communication, starting from the cave paintings to the contemporary “media façades”.

To conclude this section, a classification of fitting modes of the skin that is generated for the purpose of current research is given below. With this in mind, the following sections of this chapter concentrates on the idea of fitting in building envelopes. Firstly, a conception of fitting and an overview of fitting strategies in building envelopes are given. Then the relationship among fitting strategies in natural skin and building envelope is to be presented to set a base knowledge for further discussions.

Table 7 Fitting modes in natural skin (developed by the author).



3.2. The Concept of Fitting in Building Envelopes

Fitting is one of the main purposes of architecture. In general, buildings are designed for long and useful life, to fit its users' needs well, to cope with environmental conditions. Buildings need to serve to a variety of functions through their life cycle. Therefore, it is necessary that they respond to all fluctuating parameters, some of which are common to all buildings and some others that are specific to the building. Within the scope of this research, fitting in architecture is acknowledged as a relation which defines appropriateness to the current conditions. This relation involves one or more variables (fitness criteria) which are related with common expectations from buildings as well as design-specific intentions and requirements. It is worth to note that even common expectations from buildings are context dependent, including local micro-climate requirements such as natural ventilation potential, acoustic properties and wind comfort. For this reason, every variable of the fitting function needs to be specifically defined in every design.

Like the skin in nature, the building envelope plays a crucial role in the fitting capacity of the buildings. Even though the buildings are essentially static, the environment around them constantly changes. Therefore, the envelope needs to comply with these changes. The factors that are affecting the fitting capacity of both buildings and their envelopes can be grouped in two: exterior environmental factors and users' requirements and demands. First, coping with environmental conditions is one of the main tasks of the building envelope. López et.al. (2017) lists the basic environmental issues that are affecting the building as follows: *"light (solar radiation), temperature, relative humidity, rainwater, wind, noise and carbon dioxide (air quality)"*. These environmental factors are constantly changing and creating new challenging situations to cope with. First of all, seasons bring different climatic environments. One of the solutions to respond to these changes can be thought as the idea of introducing variability into the fabric of building envelope. This can be achieved either with a simple or complex system. For instance, the venetian blind and curtains can be considered as the oldest examples that provide protection from light and heat as well as providing privacy. They can be simply adjusted to changing local climatic conditions.

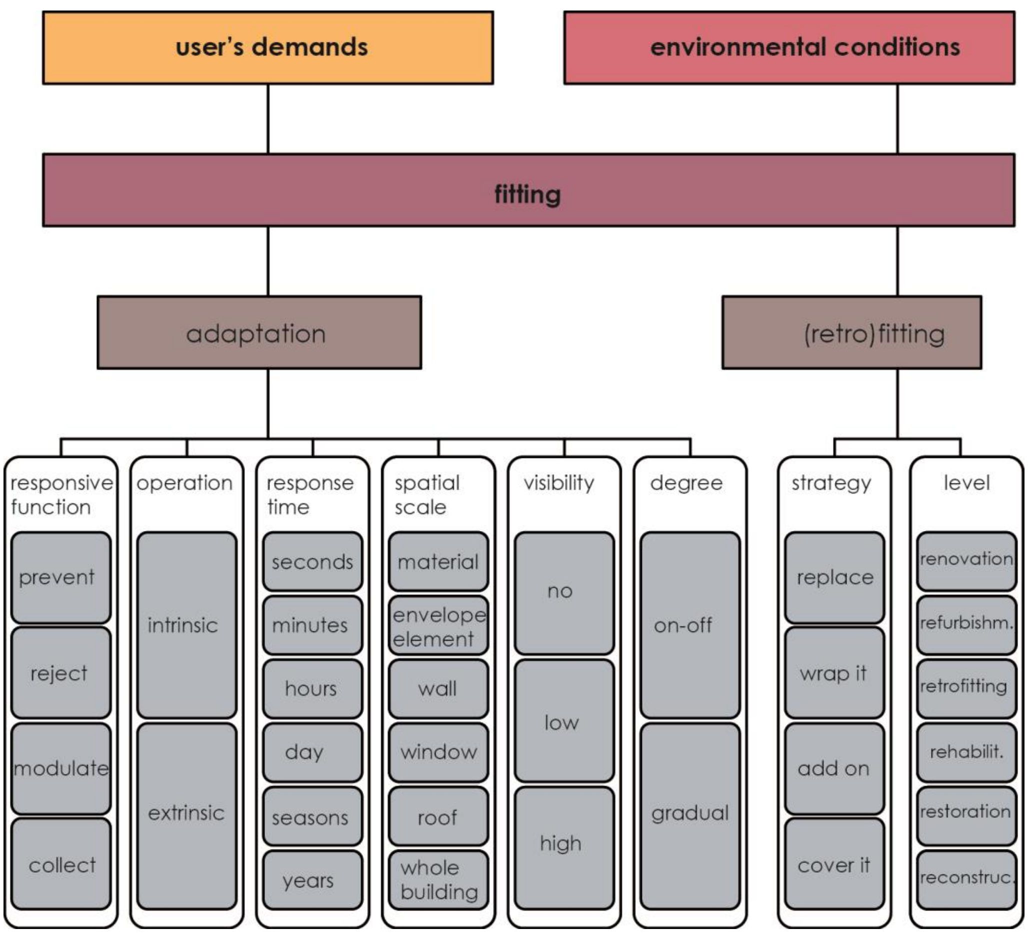
Second point to consider is that the building envelope accommodates many people, each with a different set of requirements, varying time to time. As the user needs and habits vary, the way they interact with the building envelope changes. In general, the users require thermally comfortable buildings. Besides, they have some culturally dependent habits, needs and preferences. These are also affected by attitude to health, safety, risk and aesthetic requirements as well as regulations and organizational and social norms. The building envelope needs to be adaptable to users' changing needs and requirements since they ultimately affect users' health and productivity.

In nature, fitting of the skin is a result of the interaction between the skin, metabolism and the environment. In a similar manner, fitting capacity of the building envelope can be thought at three interconnected and indistinguishable levels: envelope's appropriateness 1) to the requirements that it needs to fulfil- function, occupant's demands, climate control etc.; 2) to the whole building- its integration with other parts and systems of the building; 3) to the context. Through mapping the variables within these levels, they can be further categorized into three types of parameters about design, performance and context.

The critical point where our understanding of fitting in the building envelope differs from that of the natural skin is that the skin becomes and remains fitting in the long run. In other words, the skin *adaptively fits*. In fact, the building envelope also needs to fit adaptively, since it plays a crucial role in the building's fitting capacity as the interface between the building and the external environment. By increasing fitting capacity of the building envelopes and designing them future-proof, buildings can better fulfil their duties and fit in their context.

Within the scope of the technologies of their time, Gaudi and Otto attempted to approach the problem of fitting in a similar manner with nature, by examining the ability of the subject to adapt its structure in order to take a stable configuration under the influence of external forces (Stojanovic, 2013, p. 57). They aimed at achieving efficiency, and thus increasing fitting capacity as a result of the compromise between material and energy, as it is seen in nature. In the following years, with the advancements in technology and computation, and emerging energy issues, there had been a growing interest in exploring the fitting capacity of buildings. Within the scope of this study, these attempts can be examined in two groups: first, the ones that are designed to be fitting, mostly with responsive, adaptive and intelligent systems; second, the ones that are built upon existing structures, which is often done through a process referred as retrofitting. Table 8 presents an overview of fitting modes in architecture.

Table 8 Fitting modes in architecture. Some parts are adapted from (Loonen et al., 2015).



Having considered the conception of fitting in building envelopes and the factors affecting its fitting capacity, some of the fitting strategies will be briefly considered in the next section.

3.3. Fitting Modes in Building Envelopes

3.3.1. Adaptation in Building Envelopes

> *"Survival -the only criterion of success in biology- is largely about adaptation to surrounding conditions and change, both local and global. We need methods –technical or biological- of designing processes of adaptation that can make and maintain successful structures"* (Imhof & Gruber, 2016, p. 2).

The idea of adaptation is often found in the fitting processes of new buildings. Some of these are theoretical, yet potentially applicable. Buildings are by necessity static and fixed elements. However, they are also required to respond dynamically to changes around them. A certain level of flexibility and a capacity for adaptation and change is required in order to comply with changing environmental conditions and users' behaviors and needs (Meagher, 2015, p. 160). As it is explained in previous chapter, this capacity necessitates considering multiple fitting parameters, particularly in building envelopes. Yet, if contemporary examples of adaptive building envelopes are explored, it can be observed that the prominent function of these envelopes is to maintain the stable interior environment and to adapt to current weather conditions.

The term adaptation is barrowed from biology and thus it suggests solving problems with multiple parameters rather than merely adapting to individual concerns. Compared to the concept of responsive, adaptive is a much broader concept since it seeks to optimize functionality and waste reduction (Holland, 1992, p. 3). The word "adaptation" itself, which is consisted of "ad" and "aptare", means "to fit to". With a biomimetic perspective, the frequently used term "adaptive building skin/envelope" refers to *"a morphogenetic* *evolution and real-time physical adaptation of a design in relation to its surrounding environment"* (Al-Obaidi et. al., 2017, p. 1480).

In nature, the tern adaptation refers to both the current state of being adapted and to the dynamic evolutionary process that leads to the adaptation. Every time natural organisms face with changes they react and re-fit by adaptation, which enables them to become better fitted to survive and reproduce in their environment. Similarly, adaptive building envelopes requires accommodating change in multiple ways and systems. Further, it requires various elements such as sensors, actuators and command wires in order to identify, react and adapt to changes.

Natural organisms are coded with genetic information which enables them to constantly adapt to different external and internal stimuli. In other words, adaptation is an organism's natural way of fitting. In a similar manner, in the design of building envelopes that are inspired by adaptation principles found in nature, the issue is not simply how to create a system capable of changing in response to varying environmental conditions, but how to integrate the infrastructure of change into the design of the system.

To sum up, contemporary understanding of adaptive building envelopes has a common focus on the building's relationship with changing environmental conditions. In doing this, these envelopes mostly rely on available standard regulations for buildings to determine the interior comfort demands. In this way, the interaction between the user, the environment and the building cannot be specialized. Thus, the building cannot be tailored to its specific context of location, from climate to use and inhabitation, in order to get the most adaptive fit. While considering fitting parameters of the envelope, the climate conditions are not the only changing parameters. There are other short term and long term parameters of fitting, also changing time to time such as the personal, technological, legal and economic ones. These parameters and their adaptive strategy need to be set specifically for every design, since their importance factor changes from one building to another. These fitting parameters will be further discussed in chapter 4.

3.1.1. Origins of Adaptive Building Envelopes

First of all, in order to understand the emergence of responsive and adaptive systems in architecture, we need to look at the introduction of information technology and cybernetic concepts in architectural space in the 1960s. At these times, encouraged by the developments in cybernetics, the focus of adaptive systems in architecture was based on user-centered interactions. For instance, Cedric Price advocated that architecture was *"a service that should enable its users to reconfigure it according to their individual needs and criteria"* (Kretzer & Hovestadt, 2014). Price was one of the first who conceptualized adaptive environments that could physically move and transform in order to respond changing programmatic and environmental conditions (Frazer, 1995, p. 20).

In the late 1960s, cybernetics tried to synthesize the strategies of biological organisms with technology, with concepts like information feedback, self-organization and adaptation (Yiannoudes, 2016, p. 5). In biology and cybernetics, adaptive systems refer to organisms or mechanisms capable of optimizing their operations by adjusting to changing conditions through feedback. Inspired by these ideas, in 1969, Andrew Rabeneck mentioned the use of cybernetic technologies in buildings, in order to make them adapt to future needs of their inhabitants, and thus aid architects in extending lifespan of their buildings (Rabeneck, 1969). He argued that cybernetic technologies would enable architects to produce completely new types of flexible, and user-centered buildings. In 1972, Charles Eastman presented Adaptive-Conditional Architecture which was very similar to Rabeneck's proposition. With the automated system offered in this model, Eastman aimed to improve the fit between the needs of a building user and the spaces they occupy. According to Eastman, the highest fit could be achieved with the least "effort in physical, physiological, social and economic terms" to execute an activity in a particular surrounding (as cited in Vardouli, 2015, p. 25). More importantly, he pointed out that although many qualitative and quantitative measures are considered to be fit during the design process, they do not respond to future changes of their environment and users' (as cited in Vardouli, 2015). He pointed out the need for adaptation by declaring that "architecture is tuned prior to occupancy" (Vardouli, 2015).

In the same years, Yona Friedman suggested superstructures over the city, which are providing flexibility through allowing inhabitants to construct their own dwellings within the structures. He explains this as follows:

> *"The essential for the spatial town is what I call "spatial structure": a multi-level space-frame grid supported by pillars separated by large spans [….]. This infrastructure represents the fixed part of the city; the mobile part consists of walls, floor slabs, partitions, which make possible individually decided space arrangements: the "filling in" within the infrastructure. Thus all elements which are in direct contact with the user (i.e. those which he sees, touches, etc.) are mobile, as opposed to the infrastructure which serves for collective use and is fixed"* (as cited in Eaton, 2002, p. 221).

Later on, Friedman suggested a new design methodology for architects to evaluate the future changes of buildings more accurately. He wrote that the profession of architecture must respond to the changes that surrounded its practice. To do so, in 1971, Friedman provided the model of 'participatory architecture' which gave users an interface for controlling buildings responsively with the belief that this type of system would provide users with a means for adjusting spaces to meet their changing needs (Sterk, 2006, p. 496). He suggested that this kind of a system would enable buildings to change over the long term, as well as the short term (Sterk, 2006, p. 497).

In following years, architects such as Nicholas Negroponte suggested that the profession of architecture needs to change and they offered systems and cybernetic approach to design provides a tangible model upon which such a change could be based. In fact, Negroponte's work laid the ground for what we call performance-driven architectural design today. In the 1970s, Negroponte developed his "Architectural Machine", which had three notable capabilities: *"1. generation: an environment for rapid design manipulation, 2. evaluation: this is knowledge on various aspects of the design, 3. adaption: a learning mechanism"* (Shi, 2010, p. 513). In this system, *"evaluation is the critical link between generation and adaption"* (Negroponte, 1975). As Shi (2010) denotes, Negroponte's Architectural Machine basically assesses the performance of the design, enabling to adapt or to optimize the design to achieve the best performance.

This system is referred as 'responsive architecture' by Negroponte. In nature, response is how an organism reacts to stimulus. Adaptation is also a response to stimuli but it develops over long periods of time. There are also short term and long term adaptations. Short time adaptations are the ones that happens during the life span of an individual, enabling the individual to fit in the environment confronting it. Long term, evolutionary, adaptations are, on the other hand, inherited characteristics of a species that develop over time in response to an environmental factor, letting the species survive. Generation after generation, advantageous traits help some organisms survive and reproduce, and these traits are passed on to greater and greater numbers of offspring. Depending on the circumstances, after a few generations or after thousands, such traits become common in population. The result is a population that is better suited, better adapted, to some aspect of the environment than it was before. For instance, legs once used for walking are modified for use as wings or flippers. Scales used for protection change colors to serve as camouflage.

These paradigms still guide current models of interactive, smart architecture where interactivity revolves largely around the user. In the 1990s, John Frazer's idea of Evolutionary Architecture opened the way towards natural analogy for computational design processes (Frazer, 1995). Frazer asserts that the concepts of biological growth and form can be applied as the generative process for architectural form. He suggested a new form of buildings, one that is interacting and evolving in harmony with natural forces, including those of society (Parlac, 2002, p. 183). He develops an evolutionary approach with the idea of expressing architectural concepts as a set of generative rules and digitally encoding their evolution and development. By this way, a number of prototypical forms, which are then evaluated on the basis of their performance in a simulated environment, are developed (Frazer et.al., 2002). The key feature of Frazer's evolutionary model is the genetic algorithm, base of the biological evolution. According to him, evolutionary architecture *"...proposes the model of nature as the generative force for architectural form"* (Frazer, 1995, p. 9). The significance of Frazer's evolutionary model is that *"the produced architecture is a participant of natural system, exhibiting 'metabolism' and acting like the mechanisms to which it was formed: in exchange with environment, responsive to feedback and evolutionary in its own right"* (Menges & Ahlquist, 2011, p. 20). Further, the evolutionary model can be used in architecture as an optimization tool which selects solutions that have better performance according to some criteria set by the designer.

More recently, the idea of responsiveness found in these predecessors has engaged with the dynamics of environmental conditions in an attempt to maximize building's performance with respect to climate changes (El-Khoury & Moukheiber, 2015, p. 223). This resulted in the conception of 'environmentally adaptive' building envelopes which are focused on climate control based on daily, seasonal and yearly climate rhythms. In fact, the idea of climate control in building envelopes was nothing new. Within the scope of the technologies of their time, many cases of vernacular architecture had already made optimum use of energy saving potentials. In modern times, glass has been used extensively, increasing the issue of excessive cool-down in winter and overheating in summer (Knaack et.al., 2007, p. 88). In 1929, Le Corbusier proposed a solution for this problem, with his mur neutralisant, which was meant to actively respond to exterior influences (Knaack et al., 2007). In 1981, Mike Davies brought a new perspective with this "wall for all seasons". He formulated the idea of "polyvalent wall" which was a multifunctional skin that could dynamically respond to changing environmental conditions. In polyvalent wall, there were several functional layers within a glass element which provide sun and heat protection, and regulate the functions automatically according to existing conditions. Here, the wall itself was meant to fulfil the energy requirements (Knaack et al., 2007, p. 89). Even though neither Le Corbusier's nor Davies's thoughts were never transferred into an acceptable model, they laid the ground for developing different solutions to the problem of energy saving in modern building envelopes.

Today, there are many examples based on the idea that the envelope can flexibly adapt to changing conditions and needs, such as kinetic, interactive, intelligent building envelopes, that make use of computational systems and mechanical apparatuses. With their unique technological potential, these examples have the capacity to extend building's life cycle as well as enhancing energy and resource efficiency. Following section gives an overview on contemporary adaptive building envelopes.

3.3.1.2. Current Approaches in Adaptive Building Envelopes

In the building envelopes produced after the energy crisis of the 1970s, the use of passive solutions derived from traditional technologies are began to be changed with increasingly active, responsive and kinetic solutions. As a result, these building envelopes tend to be more adaptive to daily and seasonal environmental changes. The dynamic control of energy flows is the key feature of these building envelopes which are mostly facilitated by new materials and the latest advances in sensing, control and actuation systems. Kolarevic and Parlac (2015) explains the key focus of adaptive building envelopes in a similar manner: *"better management of energy flows, both from the exterior environment into the buildings and from the interior spaces of the building to the outside, with the goals being improvement of the building's performance and the user comfort inside the building"* (p. 70). These adaptive building envelopes mostly comprises of layers, such as double skin, corridors and boxed types, where each layer performs a specific function and where their combination can be described by a very complex system (Fiorito et al., 2016).

Loonen et. al. (2013) explains the role of adaptation in building envelopes as *“to have the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and doing this with the aim of improving overall building performance”* (p. 486). The logic of adaptive building envelopes is time based, responsive and dynamic. Furthermore, it is inherently process-based. The temporary state of an adaptive building envelope is a result of the circumstances of the moment on the basis of an activated process and potential for change (Kolarevic & Parlac, 2016).

Even though increasing fitting capacity through adaptive and responsive building envelopes resembles nature, it is completely different from how fitting is achieved in nature. The main difference is that what is adaptive in this approach is not the building’s fitting capacity, but its chosen parts or systems. Thus, rather than achieving a whole-systems fitting, the building partially fits and does not adapt its fitting ability for future changes. Besides, fitting is genetic in nature. The parts of the organism at every level act as a whole to become and remain fitting. Further, as mentioned earlier, the term adaptation suggests solving problems with multiple parameters rather than merely adapting to individual concerns. Current examples of adaptation in architecture rarely considers multiple fitting parameters. Rather they focus on a simple parameter, which is, in most cases, changing climate conditions. Adaptation is inherently context specific, and climate is an important aspect of the context. However, it requires to be considered with other affecting parameters.

Just like the skin in nature, currently there are differing approaches and methods to adaptive building envelopes (Table 9). In nature, variation in the adaptation of the skin mostly relies on genetic information and site-specific conditions. On the other hand, in building envelopes, the difference mostly lies on the method of actuation, in which there are essentially four distinct ways: motor-based, hydraulic, pneumatic and material-based (Kolarevic & Parlac, 2016). The adaptive behavior of the envelope can be passive, without direct control by the users, like material based adaptive systems as it was exemplified in section 2.3.2. Or it can be active, in which components literally move with the use of any external energy sources, controlled manually or automatically. Most examples of the latter approach to date rely on motor based systems such as the mechanical actuation (Kolarevic & Parlac, 2015, p. 71). Today, the most common motor-based actuation system is the mechanized Venetian blind system inside an air cavity, usually in a double skin system (Kolarevic & Parlac, 2015). Recently, there is an increasing use of pneumatic actuation, with Ethylene Tetra Fluoro Ethylene (ETFE) based systems that provide different shading densities. The material based adaptive systems are quite rare, since they require further developments for their large-scale applications.

Table 9 Contemporary examples of adaptive building envelopes and their adaptation strategies (developed by the author).

Building	**Adaptation Principle**	**Natural model**	**Envelope Function**	**Medium/ Technology**
Institut du Monde Arabe	Response to sun's location with changing configuration from open to closed.	-	Control light levels and transparency.	Motor-based
Al Bahar Towers		Leaves, flowers and skin spines	Reduce heat gain and thus energy consumption.	Motor-based
Gardens by the Bay		-		Motor-based
The Media-TIC	Pneumatic sun shading	-	Control light levels and transparency.	Computer controlled pneumatic actuation
The BIQ House	Response to sun's location.	Microalgae	Produce energy, control light and provide shade.	Material-based

The first large-scale example of an active adaptive behavior with mechanical actuation in building envelopes was developed by Jean Nouvel in Institut du Monde Arabe, in 1989. The mashrabiya shaped shading system of the building is sandwiched between two sheets of glass. The system is composed of photosensitive diaphragms which control light levels and transparency in response to the sun's location (Kolarevic & Parlac, 2015, p. 71). As it can be observed in this example, fitting and thus adaptive behavior is based on a simple parameter, in which boundary conditions only affects the envelope. In this example, as in many other contemporary examples, the main focus of the adaptive system is increasing the performance of the building with optimum use of energy.

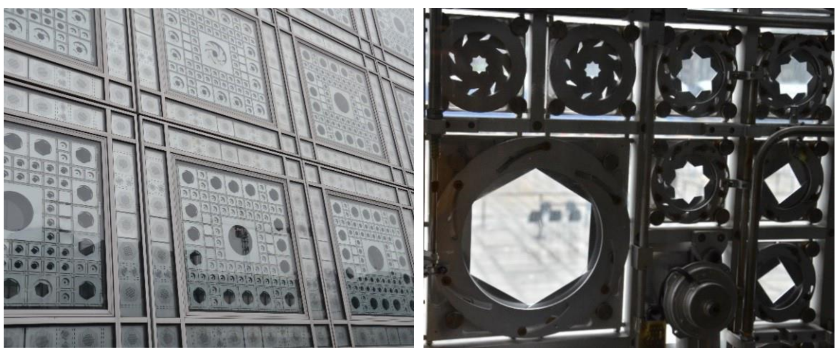


Figure 19 Mashrabiya shadings of Institut du Monde Arabe in Paris by Jean Nouvel (Source: Adriaenssens et al., 2014)

Following Institut du Monde Arabe, due to the advancements in material science and technology, *climate adaptive building envelopes* have gained increasing attention in the challenge of "*harmonizing energy performance within the wider scope of overall building performance"* (Loonen et al., 2013). The 20th century application of HVAC systems resulted in an impermeable envelope that isolated the interior (Addington, 2009). On the other hand, since climate adaptive building envelopes support the use of variability that is available, they allow for a change from "manufactured" to "mediated" indoor climates (Loonen et al., 2013). This aspect of climate adaptive envelopes is similar to the natural skin since it does not alter and reconfigure interior environment, rather it mediates between the exterior and interior to keep the balance.

In building envelopes, new possibilities of double skin shading systems created a higher degree of adaptation and flexibility to adjust in relation to changing solar altitude angle over the course of the day. The use of these systems in building envelopes touch upon building performance in terms of energy on the one hand and aesthetic on the other. As mentioned, energy requirements of the natural skin and the envelope are similar. In most cases, the dynamic effect of adaptive envelopes creates architectural icons and provides a degree of spectacle for the visitors. In this sense, their performance in terms of aesthetics and communication can be compared to mating, courting and communicative abilities of the skin.

To exemplify, the envelope of Al Bahar Towers, designed by Aedas Architects, is representing the cultural elements of Abu Dhabi, while aiming at providing comfortable spaces in extreme weather conditions and temperatures of Abu Dhabi. Similar to Institut du Monde Arabe, the towers feature mashrabiya shaped and intelligent, automated shading components which are opening and closing via centrally located actuators. This intelligent system better distributes natural diffused light, optimizes the use of artificial lighting through dimmers linked to sensors, and reduces air-cooling loads. Eventually, the envelope helps to reduce overall energy consumption, carbon emission and mechanical room size (Fox, 2016, p. 96). The design concept of dynamic mashrabiya system of the envelope is inspired by natural adaptive systems like leaves, flowers and skin spines that are open and close in response to the sun (Fox, 2016). However, the particular reason for this behavior in nature is not the same as the way it is used in Al Bahar Towers. Therefore, it can be argued that the biological model is used as a metaphor.

Figure 20 a) Design principle, **b)** view from the envelope of Al Bahar Tower (Source: Fox, 2016)

Another notable example which addresses energy and aesthetic oriented performance requirements with an adaptive envelope system is the Gardens by the Bay in Singapore, designed by Wilkinson Eyre Architects. The intention of the design was to create an architectural icon, which is addressed with the dynamic "pineapple" pattern of the envelope (Kolarevic & Parlac, 2015, p. 76). Besides aesthetic concerns, the design of the envelope was also challenging in terms of energy since it aimed to create a large, climate-controlled glass house. For this purpose, the envelope features individually controlled, retractable triangle-shaped fabric shades. Each shade can be fully extended or rolled up depending on solar conditions, actuated by the sensors inside the building which monitor the environmental conditions. In brief, similar to the previous example, adaptive behavior of this example aims to increase fitting in terms of energy conservation and aesthetics.

Figure 21 Gardens by the Bay in Singapore by Wilkinson Eyre Architects (Source: Kolarevic & Parlac, 2015)

The Media-TIC building in Barcelona, designed by Cloud 9, employs a network of sunlight, temperature and humidity sensors which triggers two kinds of reactions through ETFE cushions. The envelope adapts to the sunlight that hits the surface, acting as a variable sunscreen arranged in three ETFE layers that are deflated to let more daylight in when needed. Further, in the west side of the envelope, the ETFE cushions are filled with nitrogen to form a vertical cloud that shades the interior by changing the opacity of the envelope.

Figure 22 The Media-TIC Building in Barcelona by Cloud 9. (Source: https://www.designboom.com/architecture/waf-2011-building-of-the-year/. Retrieved at: 25.12.2017)

Recently, several researchers are trying to develop adaptive building materials, mostly looking at nature in which *"the structures recycle their materials, permit change and adaptation and make efficient use of ambient energy"* (Frazer, 1995). These materials are embedded with low-energy responsiveness. The scale is the principal challenge in developing adaptive building material-based systems in full scale. The reason of this is that materials behave differently, for instance non-linear, at different scales (Parlac, 2002, p. 182). This is to say, what works at one scale will not work at another one. One of the rare full scale examples of material-based actuation is the BIQ House in Hamburg, which has a 'bio skin' in its two sides that grows microalgae. The microalgae produced within this bio skin is used to produce energy and also can control light and provide shade (The BIQ Building Project Flyer, 2013). Considering these developments in adaptive building materials, it can be claimed that passive systems that can harvest energy from sun or wind will be increasingly used in the future. Going beyond the focus of energy preservation, these systems focuses on producing energy. However, in the future of adaptive building envelopes, the attention seems to remain in energy related topics.

Figure 23 The BIQ House built for the 2013 International Building Exhibition (IBA) in Hamburg. (Source: Kolarevic & Parlac, 2015)

To sum up, contemporary adaptive building envelopes commonly perform in two ways: energy and aesthetics. The other aspects such as the structural performance is rarely at the focus of these systems. In most cases, these systems are engaged with the dynamics of environmental conditions in an attempt to maximize building's energy efficiency and the dynamic effects that animates the building's form. With transformable surfaces or window mechanisms, these envelopes could respond to daylight, influence occupants' visual perception, change the degree of covering the building in order to control environmental conditions. Thus the key characteristic of these systems is their ability to modify energy flows (manifested as light and heat) through the building envelope. In addition, the adaptive envelopes are also used for spatial effects and aesthetics. They have the ability to engage and interact with their environment through the dynamic effect of the adaptive behavior.

In these examples, the adaptive layer, within the other layers of the envelope, delivers the desired adaptive performance. This is mostly achieved by developing a component based system, where a small actuation can lead an emergent effect. By controlling light levels, solar gain and thermal performance, adaptive envelope systems aim to reduce energy usage, enhance comfort and increase the flexibility of the buildings. However, their contribution to energy efficiency and sustainability of the building in the long run is arguable. First of all, despite all these efforts on adaptive building envelopes there is hardly a holistic example which evolves together with the rest of the building, responding to both interior and exterior environments. In other words, in rare cases the add on adaptive elements become an integral part of the building. Second, as mentioned earlier, most of these systems are motor based actuation systems, consuming electrical energy while trying to decrease energy load in the building. Further, these systems can be broken easily, due to friction problems like the "permanently frozen" façade of the Institut du Monde Arabe building (Kolarevic & Parlac, 2016, p. 230).

In adaptive envelope examples to date, there are inspirations from nature at metaphoric level but biomimetics is hardly employed in above mentioned envelopes, possibly due to the difficulties in large-scale application. Today, in most cases, adaptation process is performed by changing specific properties of a building within a specific time frame in order to manage changing environmental conditions or occupants' demands (Badarnah-Kadri, 2012, p. 12). For this reason, in buildings, responsiveness and adaptability are often considered as real-time reactions to identified parameters. Unlike nature, adaptive features of the building envelope leave the other systems of the building intact; adaptation within one designed system, but unable to cope with the unintended consequences of interactions with other systems. In other words, what is gained in one system is lost elsewhere as the result of other unexpected interactions. With a biomimetic design perspective, the multiple systems and performance requirements of the building envelope can be reconciled in a whole systems understanding, similar to the fitting in nature.

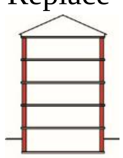
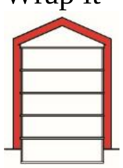
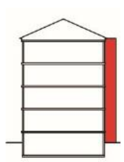
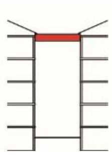
3.3.2. (Retro)fitting of Existing Building Envelopes

Both natural organisms and buildings require to be fitting in order to survive. In architecture, today, *"new buildings only add somewhere between 1% and 5% to the total building stock"* (Wigginton & Harris, 2002). Therefore, besides considering fitting strategies for the design of new buildings, it is essential to consider ways of increasing fitting capacity of existing building stock. As buildings continue to be occupied, they need upgrade to remain fitting. In building industry, current activity about the fitting of the envelopes is more concerned with extending the life of existing buildings and upgrade of existing structures rather than with the construction of the new ones. It is generally accepted that approximately 50% of construction work involves upgrade projects (Doran et al., 2009).

Such projects, born of economy and, resource and material efficiency, are referred to by many terms today: renovation, refurbishment, rehabilitation etc. As can be observed, most of these terms begins with the prefix of re-, which means again. This can be interpreted as these terms aim at turning back to an earlier time, to an original purpose or situation. In other words, they aim at fitting current conditions to a prior state. In nature, organisms do not become “retro”, rather they aim to fit the best condition of their current situation. In this part of the study, (retro)fitting is used as an umbrella term to refer existing design and construction activities which are aimed to extend the life of buildings.

In architectural practice, a variety of different strategies are used for (retro)fitting of building envelopes. For the purpose of this thesis, it is necessary to define these strategies, their motivations and the degrees of their interventions. According to the Façade Research Group at the TU Delft, there are four groups of (retro)fitting strategies of the building envelope. (Knaack et. al. as cited in Riccordo, 2008). These strategies are listed in the table below and will be discussed further in the following section.

Table 10 (Retro)fitting strategies of the building skin. (Adapted from Knaack. et. al.)

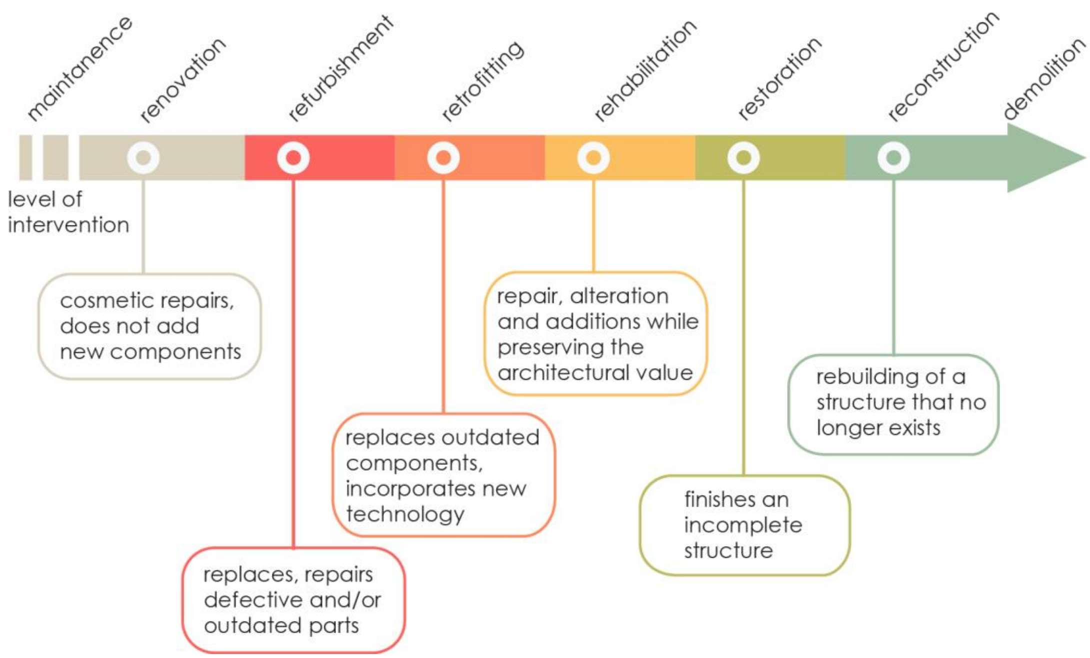
(Retro)fitting strategy	
Replace 	Remove the old façade elements and replace with new ones.
Wrap it 	Add a second layer to the façade, i.e. insulation, cladding of balconies, second skin façade etc.
Add on 	Attach a new structure to the building, i.e. new floor, balconies.
Cover it 	Cover courtyards or atria with new structures, i.e. greenhouses.

(Retro)fitting in building envelopes is carried out for different reasons. The motives of (retro)fitting are often interconnected. On the other hand, they still have different rates of change. For instance, the technical requirements for the envelopes have been increasingly tightened due to increased emphasis on human comfort and the environment (Hendriks & Janssen, 2004, p. 144). The architectural value of the envelope, on the other hand, is changing so fast, so that the aesthetics of the envelope are soon outdated (Hendriks & Janssen, 2004, p. 144). As a result, there might be a gap between the technical and the aesthetical lifespan of the envelope. Unlike this, in nature, the organisms transform as a whole and thus change in one system triggers change in all systems.

The upgrade of the building envelope might have technical and functional motivations, along with financial and social motivations. Buildings suffer from different technical problems which often require repair and upgrade of outdated components. (Retro)fitting to improve the technical quality can be done on grounds of comfort improvement such as reduction of noise or draught. Upgrading of building services can be another measure of improving technical quality. The building can have functional shortcomings like small apartment size, inadequate layout and lack of accessibility for the physically challenged. The upgrades that are done to improve these functional qualities would also trigger changes on the building envelope as well. Financial and social motives for (retro)fitting are also very important. It is important to note that, similar to nature, whatever the motivation, the challenge is to increase the fitting capacity of the buildings, which is the main objective of this thesis.

Another aspect to consider in (retro)fitting of building envelopes is the degree of change, which varies from minor repairs to total refurbishment of entire building (Giebeler et al., 2009, p. 10). There are a number of terms to refer different extents of intervention. The terms applicable to the scope of this study are listed below, which are between maintenance and demolition. Maintenance is limited to the replacement or repair of defective building components (Giebeler et al., 2009, p. 13). Demolition completely eliminates existing structure and components. In nature, there is neither partial replacement nor complete demolition, but rather transformation which is innate, arises from within, in the form of fitting. In this regard, the terms considered in this study addresses the transformation in-between these strategies.

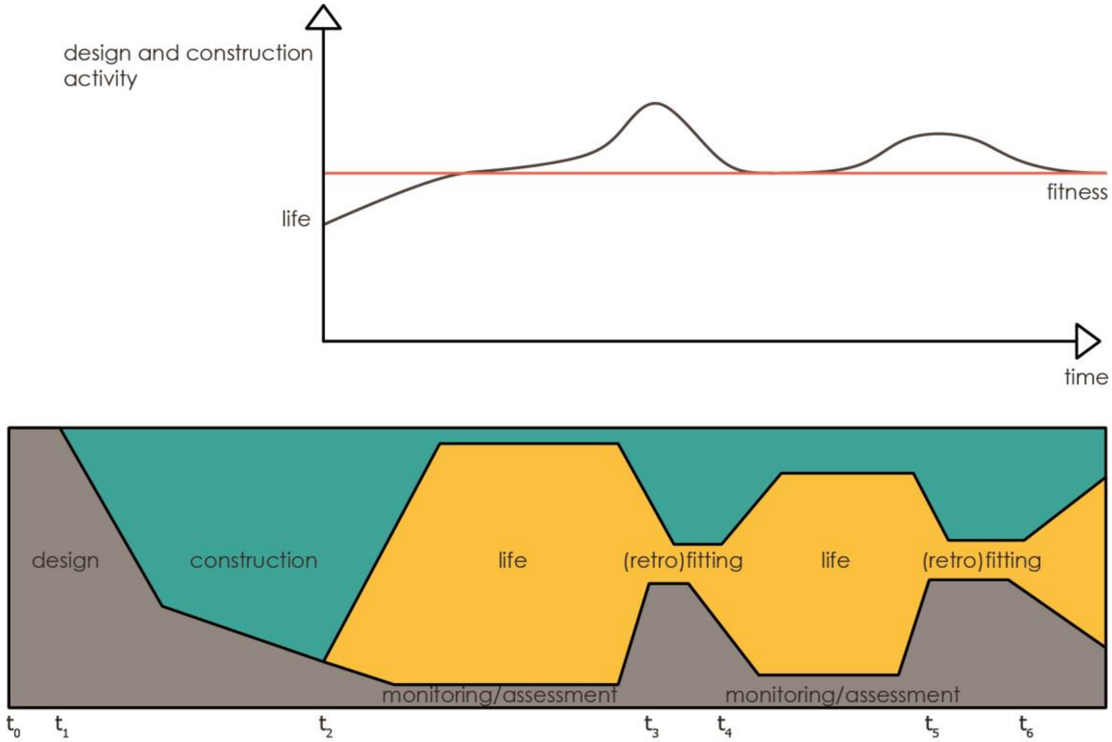
Table 11 (Retro)fitting levels for building envelopes (developed by the author).



In general, the life cycle of a building is linear: it is designed, then constructed, after that, its life starts with operation and maintenance and ends with demolition. The building is monitored and the condition of its systems are assessed through its life for (retro)fitting. While fitting in nature is a life cycle issue, in buildings it is a post-design issue. As it is exemplified in the graph given below, during (retro)fitting processes, design and construction activities increase, suspending the life in the building. There are similar recovery processes in fitting processes of nature as well, like post-molt stage in crustaceans. In the post-molt stage, the crustaceans recover from their previous molt. Since the physical barrier formed by the cuticle is not yet fully functional, the organism needs to mobilize its body reserves in order to harden and mineralize its weak cuticle

(Improving the Molting Periods in Farmed Shrimp in order to Promote Growth, n.d.). As it can be observed, unlike buildings, there is no disturbance of life in this process.

Table 12 A typical example of the life span of a building (developed by the author).



To sum up, even though above explained strategies are acknowledged issues in building construction practice, their theoretical understanding remains arguable. In this part of the study, the existing strategies are examined under an umbrella term: (retro)fitting. There are many individual (retro)fitting examples which are addressing their own set of needs and required methods, yet it is hard to find their precedents. This study proposes redefining (retro)fitting in terms of biomimetics. To this end, to propose a new perspective to the issue, this research approach uses the term "fitting", as in nature. The strategies and motivations of fitting in buildings are similar to nature (Table 13). It will also be possible to apply the processes of fitting in buildings similar to nature, if the idea of fitting is integrated from the beginning, coded in the design like the genes of the organisms. With this, rather than aiming to return to their original states, buildings would aim to fit the best condition of their current situation.

Table 13 Fitting strategy in nature and their architectural analogy according to the degree of change (developed by the author).

Fitting Strategy in Nature	Architectural Analogy
Coloration	Renovation
Autotomy	Refurbishment
Growth	Conversion/transformation
Restoration/repair	Restoration
Renewal/molting	Reconstruction
Shell exchange	Replacement

More detail on the idea of redefining fitting is part of answering the research question and can be found in chapter 4.

3.4. The Relationship Between Fitting Strategies in Nature and in Building Envelopes

Examples given in previous sections have shown that just like the organisms in nature, buildings go through many life stages. Throughout their lives, they are upgraded by fitting modes which are similar to that of nature in order to be continuously adapted to keep pace with changing demands. However, these fitting methods are applied in a different manner than nature. When considering common, state-of-the-art fitting strategies and examples, certain categories of intervention can be identified (Table 14). In this section, these categories are used to provide a systematized approach to present an overview of the relationship among fitting strategies in skin and envelopes. The purpose of the overview is not to present all possibilities, but to categorize them by identifying the basic principle and highlight similarities and differences in each case, in order to increase fitting capacity of buildings, as it is in nature.

Table 14 Fitting strategies of building envelopes with their natural analogies (developed by the author).

Fitting strategy	**Analogy in nature**
Add-on	Growth/protection
Replace	Renewal/metamorphosis/communication
Cover it	Regeneration(healing)/growth
Wrap it	Regeneration(molting)/protection

3.4.1. Add-on

The add-on concept implies adding a new structure to the existing building, usually when a new appearance, extra space or additional function is needed. It can vary from small interventions like adding new balconies to a whole new building as an extension to the existing one. In lateral extensions, the old envelope is no longer part of the building envelope and thus the new envelope can be used to comply with the requirement for improved aesthetical, environmental and functional performance. In vertical extensions, additional usable space is constructed despite the lack of available space in the plot.

A building envelope may be considered as physically obsolete regarding to the deterioration of envelope's physical fabric due to factors such as radiation, water, air contamination, permanent loading etc. When this happens, the envelope is either demolished, replaced or regenerated, mostly transforming into a new face. In some cases, regeneration is achieved by adding-on a new structure, either lateral or vertical, to the existing envelope. This strategy is similar to the regeneration processes of natural organisms. However, different from the building envelope, the natural skin is able to recreate lost or damaged tissues and organs without transforming the old tissue, and does this without demolition and new construction. In regeneration, rather than adding-on a new structure, tissues heal and rebuild themselves through the internal processes of the body. In fact, many animals have an innate ability to rebuilding missing structures lost to injury.

In buildings, many regenerated envelopes feature no longer existing windows passed down from a previous life. These features seem to be blocking light and losing the possibility of increased ventilation. With this, they lose their function and become a scar on the fabric of the envelope. Even though the rest of the envelope is regenerated, these scars remain because they were not designed to be closed one day. In other words, the envelope cannot adapt and heal these scars. For instance, these scars are evident on the envelope of the CaixaForum by Herzog& de Meuron in Madrid. The regeneration of CaixaForum exemplifies the add-on strategy. The old building's envelope is retained and a new corten steel envelope added-on the existing brick envelope, giving the building a new appearance and extra space. While this regeneration gave a new face to the envelope, the older scars remained. As it can be seen from this example, and from many others, regenerated parts add-on to the existing envelope rather than evolving naturally from the old building tissue.

Figure 24 a) Old power station, **b)** The CaixaForum in Madrid by Herzog& de Meuron (Sources: a) https://circarq.wordpress.com/2013/10/21/la-antigua-central-electrica-del-mediodia/. b) https://www.herzogdemeuron.com. Retrieved at: 25.12.2017)

Throughout the world, there are many *post-industrial buildings* like CaixaForum, due to the collapse of the industry era in the second half of the 20th century (Shaoqiang, 2010, p. 5). In Europe, for instance, there are many examples of museums that are converted from old warehouses. These buildings required regeneration or demolition in order to be used in new ways. In the buildings that are regenerated, the envelopes mostly get a new face to comply with the new use of the building. In such cases, regeneration mostly achieved with add-on structures. These new elements of the envelope do not follow the industrial elements from a formal standpoint, but instead fill the new needs and gaps in the old tissue rather than overriding the existing structure (Shaoqiang, 2010). Driven by the needs of the new use, these regenerations are knit into and in-between old structures, *creating a patchwork in the fabric of the city* (Wong, 2016, p. 45).

Existing "historical" buildings provide continuity and form an identifiable, time-specific layer (Zijlstra, 2009). Yet without considering the purpose or organization of the existing structure, the host buildings become simply an economy of means (Wong, 2016, p. 46). Contrary to the stepwise fitting processes of nature that occurs over time is the intentional overwriting of existing structures as an assertion of supremacy. This can be seen particularly in religious buildings which are undertaken on behalf of religious convictions or for the expansion of empire. In such cases, architectural elements of the new religion are added-on to the existing envelope such as the minarets or belfries. The Temple of Luxor in Egypt is a good example of such a regeneration, demonstrating the remnants of a large 3rd century Roman fort, superimposed upon the entry courtyards, a 4th century Christian chapel and a startlingly white 14th century mosque (Wong, 2016, p. 50). Another example is the Mosque at Cordoba, Spain which was originally a Christian church, then transformed into a mosque and later returned to church again.

Figure 25 The Great Mosque of Cordoba in Spain (Source: http://www.readingtree.org/top-10-most-beautiful-mosques-in-the-world/. Retrieved at: 25.12.2017)

In some regeneration projects, the idea of overwriting the existing structure with contrasting additions appears as an architectural concept. The Military History Museum in Dresden and Royal Ontario Museum in Ontario, both by Daniel Libeskind, demonstrate this idea with the new, aggressive geometric forms "*which intentionally interrupts the existing building's classical symmetry"* (Libeskind, 2011).

Figure 26 a) The Military History Museum in Dresden by Daniel Libeskind, **b)** Royal Ontario Museum in Ontario by Daniel Libeskind. (Source: https://libeskind.com/. Retrieved at: 25.12.2017)

In these examples, it is evident that the idea and process of regeneration of the envelope is different from nature. First of all, contrary to the stepwise nature of regeneration in nature, the existing structure undergoes a radical transformation with interventions on the building envelope. Second, the process is top-down since the predetermined form is imposed on the existing structure, not arising from within. As Samuel Taylor Coleridge puts it, transformation in nature, on the other hand, is innate and shapes itself as it develops itself from within (as cited in Adams, 1957, p. 47). Last, unlike natural organisms that transform as a whole, these examples are regenerating existing structures with additions and conversions.

Figure 27 Dovecote Studio in Suffolk, U.K. by Haworth Tompkins (Source: Bloszies, 2012)

The field of conflict into which architect is drawn in regeneration processes is on the one side the existing building with its idea of space created by constructions and materials and on the other side the ingredient seen as necessary, which results from a change in demands or change of use (Giebeler et al., 2009, p. 18). As exemplified above, in contemporary regeneration work, it is a common strategy to adding new elements and separating these two, leaving “old” and “new” easily distinguishable (Shaoqiang, 2010, p. 6). This separation results in a fragmentation and breakdown into layers through adding new to old in a clearly identifiable way (Giebeler et al., 2009). In contrast, nature regenerates without adding a new layer, it evolves from within, as a continuous and homogeneous whole such that it is impossible to differentiate the old and the new.

While this separation aims at preserving the preeminent value of the old in its authenticity, it also prevents evolution of the design from the old building tissue. With this, regeneration does not share the same language with the old design and becomes a new design itself, physically adding-on a new tissue to the old one. Consequently, it has lesser references from the old building tissue and transforms into a new one.

Besides regeneration, another purpose of the add-on concept is growth. Accommodating growth in buildings still remains as a challenge. This is partially because current understanding of design and building has a top-down approach, whereas growth processes in nature have a bottom-up approach based on cellular components. Even though dynamic growth is not yet achieved in buildings, there had been some attempts for additional growth. In the late 1950s the Metabolists, a group of Japanese architects led by Kenzo Tange, began looking at cities and buildings as expandable, flexible structures, capable of organic growth and transformation over time (Mazzoleni, 2013, p. 12). These thoughts of Metabolists are clearly demonstrated in Kisho Kurokawa's Nakagin Capsule Tower, *which embodies an explorative and adaptive design attitude for a building as an organism* (Mazzoleni, 2013).

Figure 28 Nakagin Capsule Tower in Tokyo by Kisho Kurokawa (Source: https://www.archdaily.com/110745/ad-classics-nakagin-capsule-tower-kisho-kurokawa. Retrieved at: 25.12.2017)

Another attempt for growth in architecture was the addition of modular elements, which later became related with a historical movement referred as Structuralism (Petra Gruber, 2011, p. 157). Structuralism proposed coherence, growth and change on all levels of the built environment. This can be exemplified by Aldo van Eyck's Municipal Orphanage, which comprises of clearly defined modules that are structured in a more or less flexible arrangement (Mollerup, 2001, p. 74). Another example is Herman Hertzberger's office building in Apeldoorn. Both these examples are organized like a city with interior streets and markets. In addition, they both contain some kind of built-in openness for future changes (Frampton, 1992).

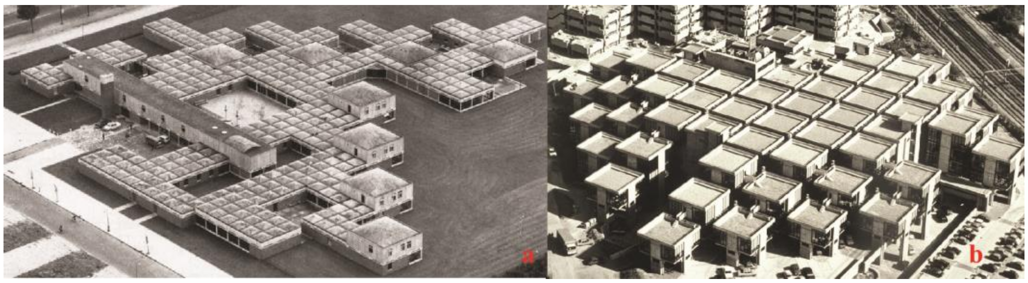


Figure 29 a) Municipal Orphanage by Aldo van Eyck, **b)** Centraal Beheer in Apeldoorn by Herman Hertzberger (Sources: a) https://www.archdaily.com/151566/ad-classics-amsterdam-orphanage-aldo-van-eyck. b) https://www.pinterest.jp/pin/312718767857324032/. Retrieved at: 25.12.2017)

In nature, growth processes are also developed with add on strategies. For instance, a well-known example, nautilus, grows by adding material to its open rim. Nautilus builds its shell in stages, each time adding another chamber to the already existing shell. The shell grows with each new chamber, yet remains similar to itself.

Figure 30 The Nautilus (Source: www.pinterest.com. Retrieved at: 25.12.2017)

In general, biological growth is based on cells which can increase in number and size. In architecture, currently we are far from the technological capacity that enables the ability to generate new modules to achieve increase in size. In terms of material, the principle of addition is mostly used by assembling prefabricated elements on site. In plants, water intake is essential for cell enlargement. The bamboo, for instance, can elongate 90 cm per day due to the uptake of water by already existing cells (Imhof & Gruber, 2016, p. 30). Currently, a similar system in architecture can only be thought of in the form of pneumatic structures that achieve their structural stability through internal pressure (Imhof & Gruber, 2016, p. 30).

In general, in architectural context, growth is associated with the increase in terms of material used or space enclosed. In contrast with nature, this requires extensive planning and construction which are mainly performed top-down. Since the building is not designed to grow, it happens with additions which are not from within and holistic. It is worth noting that self-organized bottom-up processed can be observed in unplanned settlement structures which reveal surprising similarities with nature. Characteristic patterns have emerged in those areas. Yet it is hard to achieve the *"control of growth and the establishment of a top down order"* (Petra Gruber, 2011, p. 149). The houses in these neighborhoods mostly start with simple makeshift cores, continuing with incremental construction and expansion. They often add extra units in order to shelter the growing family or provide rental income to the families. In some cases, the iron reinforcements are left open and ready for expansion with the addition of a new floor. In this mode, the idea of fitting is not adaptive to environmental conditions, but to the social and economic conditions of the user.

Figure 31 Examples of lateral add-on strategy as an example of growth in buildings (Source: http://www.ilkehaberajansi.com.tr/haber/kacak-yapisini-yikim-ekiplerine-birakmadan-yikti.html. Retrieved at: 25.12.2017)

Similar to this, in the 1970s, John F. C. Turner of MIT developed an idea surrounding the concept that housing should be conceived of as an on-going project. Eventually, Turner's premise turned into 'incremental building' development by the architect George Gattoni, who aimed at solving the problem of urban migration, resulting in squatting and huge housing deficits. Gattoni proposed incremental building as an answer to the problem. Three levels of surveys are anticipated in a full understanding of incremental housing: the house, area and the context (Three levels of surveys are anticipated in a full understanding of incremental housing, 2009). For an initial understanding, a data sheet, which summarizes the key issues in understanding the process of incremental housing growth, is suggested (figure 33). The data sheet includes a process graph which links the four elements in the process: time, family size, household income and number of rooms. In this graph, x-axis shows the years, while y-axis shows the number of the occupants. Further, the data sheet includes expansion descriptions for each stage which are achieved with lateral and vertical additions to the envelope.

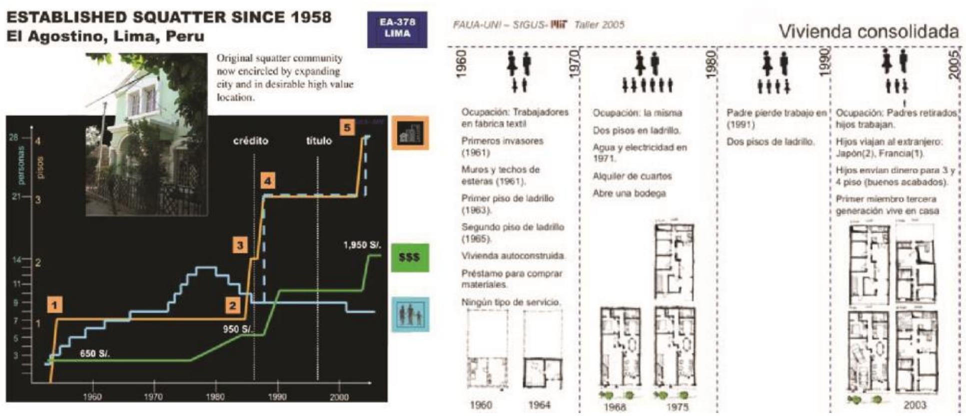


Figure 32 Typical data sheet of incremental housing growth (Source: http://web.mit.edu/incrementalhousing/understandingFormat/level1BasicSurvey.html. Retrieved at: 25.12.2017)

3.4.2. Replace

Replacement of a building envelope implies removing old envelope elements and replacing them with new ones. In this strategy, the loadbearing structure and interior layout is kept while the envelope is replaced. The level of intervention can vary from the entire envelope to parts of it. The replacement of entire envelope in buildings can be compared to the shell exchange processes in crustaceans such as hermit crabs. As hermit crabs grow, they require larger shells and thus they find a new one and abandon the previous one. This is a resource sensitive process, since nothing is wasted. The smaller shells become homes for smaller hermit crabs. Unlike this, replacement of the building envelope mostly involves demolition and new construction. In this sense, it requires starting all over again as opposed to the evolutionary change in nature.

Figure 33 Hermit crab shell replacement (Source: www.pinterest.com. Retrieved at: 25.12.2017)

In most cases, the reason for replacement of the envelope in buildings is not the requirement of growth, since the area around the building allows for limited expansion. Rather, replacement is mostly done within the same or at least similar limits, to eliminate the physical problems of aging components, for providing better thermal and acoustic comfort or for aesthetic concerns. In the Reichstag, New German Parliament in Berlin by Foster and Partners, the replacement strategy is used to represent the character and history of the building, as well as improving accessibility and environmental performance (Foster, 1999). The original cupola is replaced with a new one, which is contrastingly light and transparent, making its activities on view. In this example, the replacement of the envelope is used for fitting current aesthetic, accessibility and energy requirements. In other words, it is used for regeneration and protection.

Figure 34 a) Parliament building before replacement, **b)** Reichstag, New German Parliament in Berlin by Foster and Partners (Source: https://www.fosterandpartners.com/projects/reichstag-new-german-parliament/. Retrieved at: 25.12.2017)

The strategy of replacement is similar to the molting of animals. In this sense, arthropods such as crustaceans suggest important role models since their exoskeleton cannot grow gradually with the organism. For this reason, like buildings, they need to build a new skin to achieve growth. This process, molting, in crustaceans is *"hormonally controlled while it is also significantly influenced by environmental conditions, physiological and developmental stage"* (Skinner, 1985). Chang and Mykles (2011) explains this process as follows: *"Like most other arthropods, crustaceans must initially loosen their connectives between their living tissues and their outer cuticles, escape from the confines of these cuticles relatively rapidly, take up water or air to expand the new, flexible exoskeletons and then quickly harden them for defence and locomotion"* (p. 323).

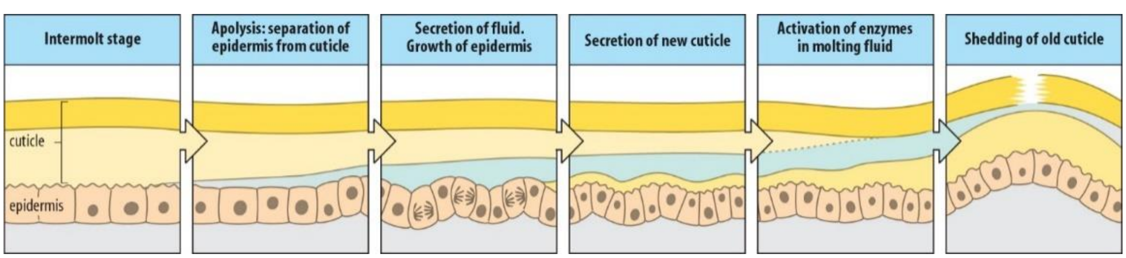


Figure 35 Molting process of arthropods (Source: Drage, 2016)

As Charles Bloszies mentions, a building typically does not molt its skin, but the envelope of 185 Post Street in San Francisco has done so more than once (Bloszies, 2012, p. 132). The original brick envelope was built in the early 1900s, and then in the late 1950s, it was wrapped with a tile and metal framed window system in order to modernize its appearance. Recently, Brand + Allen Architects removed this wrapping to expose the original envelope and then they re-wrapped it with a glass layer.

Figure 36 Fitting phases of 185 Post Street San Francisco (Source: Bloszies, 2012)

Another example that can be compared to molting in nature is the retrofitting of the envelope of Guy’s Tower by Penoyre and Prasad, in London. In Guy’s Tower, the envelope is replaced to improve energy efficiency and sustainability of the building. First, the existing envelope of the tower is over cladded by a new one, then the old envelope is removed from inside. To this end, this strategy reverses a traditional re-cladding solution by over cladding the building whilst in occupation and then removing the existing envelope (Penoyre & Prasad, 2014).

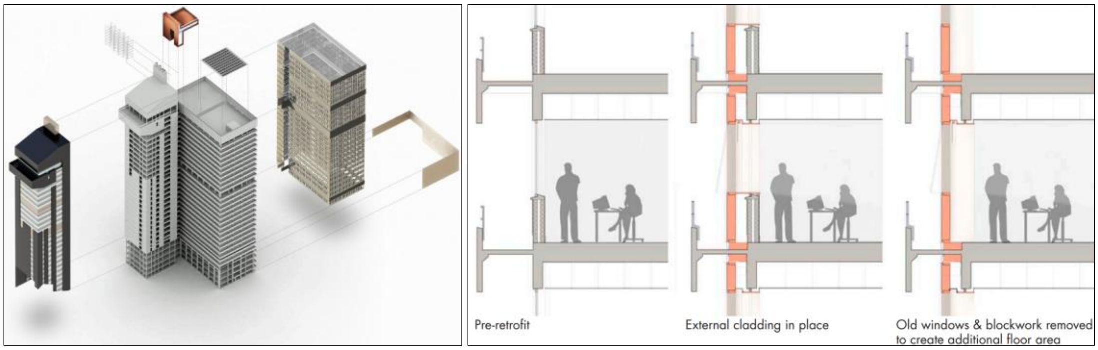


Figure 37 Guy's Tower in London, envelope replacement strategy (Source: http://www.penoyreprasad.com/projects/guys-tower-external-retrofit/. Retrieved at: 25.12.2017)

There are fundamental differences between the ways nature and architecture are thought and designed, yet they are both based on the same requirements, structured with the same mathematical and physical principles. The above exemplified molting process of the skin arises from inside out with the increase of surface area or folds, through cell proliferation and enlargement. The new cuticle is secreted then the old cuticle is split and shed. This process is cyclic, happens when the older cuticle is outgrown. In addition, the information required for this process is integrated to the genes of the organism, and triggered by environmental conditions as well as its own metabolism. In architecture, the introduction of inside out processes and molecular interactions is difficult but could create better performances.

To this end, in architecture, there is still a lack of an envelope system which has modules with pre-coded information that can accommodate inside out processes. At this point, the distinction between modules and pathways is particularly relevant. Carter et al. defines a pathway as "*a specific information-flow conduit, usually a sequence of molecular interactions"* (Carter et al., 2010, p. 2). In contrast, they define module as "*an information-processing unit with a self-contained emergent function"*(Carter et al., 2010). According to this, modules can contain multiple pathways and pathways can operate between modules to structure connections between modules (Carter et al., 2010). In this line of thought, focusing on the pathways, and thus the processes is as important as focusing on the modules to achieve the success of nature.

It is important to note that, holism found in natural processes opposes to the current applications in buildings which are paying attention to the appearance and behaviors of isolated parts, rather than the emergent properties of the whole. In nature, transformation emerges as a whole, within the natural evolution of the organism as a result of the interaction between coded genetic information and environmental conditions and triggers. The skin evolves as the organism grows and the size and needs of the organism changes. The shape change of the organism is inherently connected to function since in nature, specific shapes attract other organisms to help reproduction, provide protection against predators or enable material and energy to be harvested.

In this vein, natural organisms pretend to replace their skin to provide protection. For this purpose, they change their skin color and patterns with camouflage and mimicry, as explained earlier. Further, color change also provides insulation to organisms. In building envelopes, there are examples of color change but they are not used for insulation purposes. Rather, they are used either for aesthetic purposes or to introduce dynamic aspects to the building, like the media façades. The communicative functions of the envelopes have been discussed in the realm of performance in architecture since the 1970s and this has resulted in today's "media façades". With computer controlled light systems, these envelopes are used for massive displays that are communicating with their environment. This approach changes the envelope *from a static monument to a performing actor* (Edler, 2005, p. 152).

This fitting mode of the building envelopes is similar to coloration processes in natural skin that are used for signaling and sexual attraction. For instance, there are white stripes on spotted skunk's black coat which serve as a warning to their predators to keep their distance. On the other hand, one of the earlier media façades, Kunsthaus Graz Museum's envelope also features computer controlled spots on its envelope which are used for communicating with its environment.

Figure 38 a) Kunsthaus Graz by Peter Cook and Colin Fournier, **b)** spotted skunk (Source: https://www.museum-joanneum.at/fileadmin//user_upload/Presse/Standorte/Abbildungen/Kunsthaus/BIX_02.jpg. Retrieved at: 25.12.2017)

In animals, patches of color, rather than overall coloration, may be used to communicate to members within the same species (Caro, 2005, p. 129). As Caro explains, this fitting mode may function as social releasers, such as signals of subordination or devices to intimate rivals, may warn organisms within the same species that predators are close or may signal reproductive condition (Caro, 2005). Between species the signal of markings or bright colors are used to warn predators that the organism is toxic or distasteful. For instance, the spotted skunk which has black and white patches of fur on its body.

It can be argued that, in architectural examples of coloration, the building envelope becomes separated and alienated from its inner programmatic structure with a strong emphasis on aesthetic, dynamic and interactive aspects (Edler, 2005). On the other hand, in nature, coloration of the skin is tightly related with the organism, resulting from the organism’s physiological and physical functions. What is common in both cases is that their skin appears to be replaced.

3.4.3. Cover it

Covering strategy mostly indicates a physical growth, additional functions and protection of insulation in buildings. This can be done by covering parts or entire internal and external courtyards and atria. This strategy has a great impact on the building envelope as it changes the relation between inside and outside as well as adding extra functional space. The earlier examples of this concept was seen in the 19th century which relied on iron and glass coverings: passages or arcades. In most cases, these top-lit alleys were inserted pedestrian paths through building blocks, connecting two streets at the end (Ingersoll & Kostof, 2013, p. 664).

Figure 39 a) The Passage du Caire, Paris, **b)** Vittorio Emanuele II Gallery, Milan (Sources: a) http://parisadele.com/portfolio/passage-du-caire/. b) https://madeinvan.life/italie/. Retrieved at: 25.12.2017)

The courtyard of an earlier inn in historical Ankara, Çengelhan, is covered with glass while the building was transformed into a museum. The Great Court at the British Museum by Foster and Partners in London also demonstrates the same idea with different means and requirements. The design covers the former courtyard with a glass and steel roof, using the state-of-the-art engineering and technology. With this, the courtyard becomes an extension of interior space, overwriting its character.

Figure 40 a) Çengelhan Rahmi Koç Museum in Ankara, **b)** British Museum in London (Sources: a) http://www.mimarizm.com/makale/cengelhan-in-oykusu_113824 b) https://www.fosterandpartners.com/projects/great-court-at-the-british-museum/. Retrieved at: 25.12.2017)

The strategy of covering was implemented in a different manner in Renzo Piano's design of the Morgan Library, New York. There were there historical buildings existed in the site, which were distinct in appearance, representative of different times in which they are constructed. To cover the area between these buildings, Renzo Piano inserted a new element instead of a glass covering.

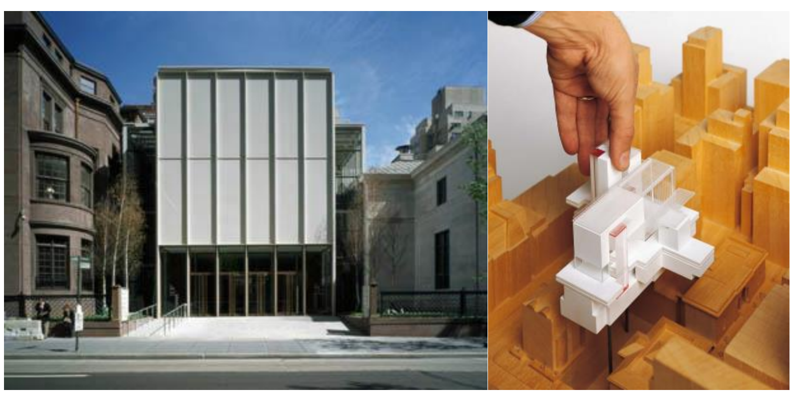


Figure 41 Morgan Library in New York by Renzo Piano (Source: Bloszies, 2012)

The strategy of covering in envelopes can be considered with self-repairing processes of the skin. Self-repairing processes are caused by either natural growth processes or by artificial injuries. As Imhof and Gruber (2016) mentions, *"self-repair is found at all hierarchical levels of living beings from the macromolecule to the entire organism, and can even be considered as a prerequisite for life"* (p.25). There are several mechanisms of self-repair in nature. The reason that the sunburned skin feels hot to touch is that it is infused with blood and mounting a hot and vigorous inflammatory response in order to repair the damage caused by UVR (Jablonski, 2006). In the event of an injury, *"a highly complex and coordinated set of processes is initiated to restore tissue structure and barrier function"* (Walker et al., 2015). In general, this process occurs in three phases: inflammation, proliferation and remodeling, which result in re-establishment of skin integrity (Walker et al., 2015). In fractured or critically damaged living tissues, an intermediate tissue is formed after the scar tissue, in order to heal themselves.

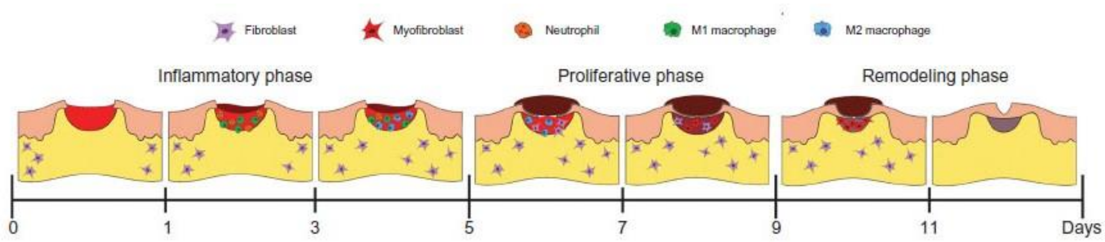


Figure 42 Schematic representation of the phases and timeline process of the skin healing process in mice (Source: Walker et al., 2015)

Unlike nature, in most cases, (retro)fitting processes of building envelopes are not step-wise and inside out. Yet there are attempts in material sciences to develop self-organized healing and repair in building materials, which can lead (retro)fitting processes to become like fitting in nature. For instance, Speck et al. investigated the self-healing characteristics of climbing plants in order to develop a self-healing membrane material for using in pneumatic structures (Speck et.al., 2006). As it can be observed in figure 43, functional model of the generated membrane is very similar to skin healing processes in nature.

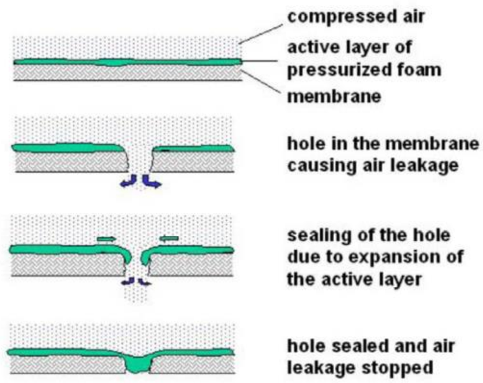


Figure 43 Functional model for a self-repairing building envelope (Source: Speck et al., 2006)

Different from existing coatings, "*self-repair is a function that requires nano-structuring beyond surface coating"* (Gruber et al., 2011, p. 137). For instance, The Natural Process Design Inc. has developed self-repairable durable concrete, with the idea of embedding repair material in ducts in cracking or tension zone before it subjected to damage. When cracking occurs, this repair material will be released from inside and enter in the damaged area, where it penetrates into cracks and rebounds to the original material of structure and structure will be repaired (Kadam & Chakrabarti, 2013).

The design strategy of Elemental, led by Alejandro Aravena also resembles the repair process in skin. Similar to a wound, Elemental leaves space between their structures to accommodate further growth. For instance, their Quinta Monroy development in Iquique is designed to make the most of a tiny budget by building the frame and the essential spaces for each house, leaving the remainder for the residents to complete themselves over time. The main design strategy for these unfinished low-income houses in Iquique was that half of the houses are identical the other halves and left for future uses. The first floor of the finished half is made up of unfinished concrete floors and the second is covered in unfinished plywood. There is only one sink in the kitchen. The main idea is building everything that families would not build themselves, such as concrete foundations, plumbing and electricity (Elemental, n.d.).

Figure 44 Quinta Monroy in Iquique, Chile by Elemental (Source: http://www.elementalchile.cl/en/projects/quinta-monroy/. Retrieved at: 25.12.2017)

Although the space left for future use resembles the wound in skin, their repair process is simpler, without a complete integration to existing envelope. In repair process, the skin is healed from within, sharing the same architecture and functionality of uninjured tissues. In Elemental's proposal, the space in-between requires a new spatial, physical and material quality. The surfaces defining this space do not offer any integration. In this sense, although it is an important attempt to accommodate growth without requiring demolition and leaving some areas unfinished, it is not as effective as unfinished structures in unplanned settlements, that were mentioned earlier.

3.4.4. Wrap-it

Wrapping strategy implies covering the envelope with a second layer. It can include small interventions like cladding of balconies, or big ones like wrapping the whole envelope. Different from replacement, this strategy is less disturbing for users as the interventions are carried from outside. To this end, it does not suspend the life of building. Wrapping can be done for various reasons such as providing better thermal and acoustic comfort or complying changing aesthetic demands.

To exemplify, with aesthetic concerns, Frank Gehry wrapped an existing Californian house in layers of unfinished, frugal materials such as plywood, corrugated metal, chain-link. The wrapping extended the house towards the street and left the existing envelope almost untouched.

Figure 45 Gehry Residence in Santa Monica by Frank Gehry (Source: https://www.archdaily.com/67321/gehry-residence-frank-gehry. Retrieved at: 25.12.2017)

The wrapping strategy, since it is imposed from outside, challenges the way nature operates fitting processes. Therefore, it is hard to find a direct analogy of this strategy. Wrapping, in a way, transforms the existing envelope. A similar transformation can be observed in metamorphosis processes, in which the animals need to destroy and get rid of their carapace in order to achieve growth. In metamorphosis, the transformation starts from within and growth is achieved in stages. For instance, silk worm demonstrates an advanced form of metamorphosis, which eventually produces an adult that does not resemble the larva. In this metamorphosis, the insect passes through four distinct phases. First of all, during growth, the larva of caterpillar goes through 4 molts. Then it spins a cocoon of silk threads around itself. Inside the cocoon, the larva changes into the brown, chitin covered structure called the pupa. Finally, metamorphic changes of the pupa result in an emerging moth (Medhekar, n.d.). In this example, transformation happens as a result of the process. In this process, the skin of the insect transforms as a whole, in a stepwise manner, from within and bottom up.

Figure 46 Metamorphosis of the silk worm (Source: www.pinterest.com. Retrieved at: 25.12.2017)

In contrast with this process based and inside out growth process of nature, glazing balconies in buildings also provides physical growth of interior space. The balcony is a semi-open space which extends from the walls of a building. However, nowadays, it is used as an extension for the indoor living space by enclosing the balcony. In some cases, the walls separating indoor and outdoor areas are removed. This fitting strategy of building envelopes does not happen through interaction that arises from within. Rather, it is implemented to the existing structure, by wrapping the open-space. In this regard, glazing balconies is an inapt fitting strategy which changes the layout and transforms the building envelope without a reference from the prior stage. Recently, this strategy is developed and new apartment blocks began to be designed with already glazed balconies. With this, the glazing system of balcony has become integrated to the building. Here, glazing of balconies is not an adaptive strategy which arises inside out and evolves with the building. However, with this strategy, the designer integrates the idea of mutation to the design and freezes it.

Figure 47 a) Example of glazed balcony, **b)** Lotus, Beytepe in Ankara, (Sources: a) https://balconyideas.co/the-incredible-enclosed-balcony-ideas/enclosed-balcony-houzz-enclosed-balcony-ideas-2/. b) http://www.lotusbeytepe.com.tr/. Retrieved at: 25.12.2017)

In Mediterranean climates, these glazed balconies serve as part of the living space during transitional periods and as part of the climatic buffer during summer (Knaack et al., 2007, p. 11). In this strategy, the intention is similar to that of a *double façade* today which is obtained by adding an extra layer of glazing outside the façade to provide the building with ventilation or additional sound-proofing (Knaack et al., 2007). Another way of applying double façade is referred as the *second-skin façade*, which is obtained by adding a second layer of glass over the entire outer surface of the building (Knaack et al., 2007).

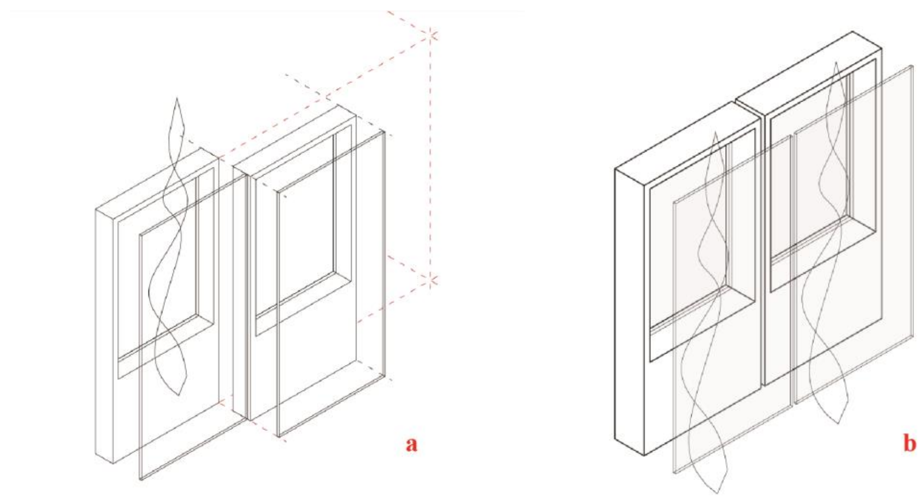


Figure 48 a) Double façade, **b)** Second skin façade (Source: Knaack et al., 2007)

Even though the idea of disconnecting inner and outer layers with an empty space seems similar with nature, it is dramatically opposed. First of all, it is not evolving from within, rather the outer layer is simply mounted on the inner layer, remaining as an addition. The natural skin operates as a part of a holistic metabolism and morphology. Second, the envelope does not transform as a whole. This is also evident in the terminology used to refer the system, since the term façade implies a simple surface rather than a total enclosure that acts as a whole. Further, this system is not resilient, and thus adaptive to changing environmental conditions as it offers limited possibilities of controlling the interior environment.

With all these, it can be understood that the analogy of the skin in second-skin façades does not go beyond simply wrapping the interior space. However, the skin as a biological model offers further possibilities. For instance, the skin of organisms is strikingly resilient to changes in their environment. Thus some animal species can survive in the face of the bitter cold of polar regions with simple but effective strategies such as fur color change. The arctic fox changes the color of its coat as the seasons change. They adapt to the low polar winter temperatures as a result of the their dense and multilayered coat, which is thicker during winter (Prestrud, 1991).

While animals adapt to environmental changes by regulating their thermal conductance and their thermal balance, notably by changing insulative properties of their fur and skin, buildings adapt to changing environmental conditions with active and passive design strategies in building envelopes. The active strategies include systems with innovative technical devices, sensor or motor based systems, as explained in earlier chapters. Passive strategies are the ones that are related with the design of construction, material properties and shape of the envelope itself. For instance, thermal insulation layers are used in envelopes in order to reduce unwanted heat loss and gain, and thus increase the energy demands of heating and cooling systems. These insulation layers are similar to insulative properties of animal skins. However, in nature, these properties are adaptive, therefore fur color and coat thickness of animals in different regions are varied.

In conclusion, as it is seen from the examples, currently, fitting modes are applied to buildings when the building is already not fitting and change is needed. They are not designed to be ready for possible future changes. That is every time fitting is needed, fitness criteria are set around the problem at hand, without considering future changes. Further, every problem is approached in isolation, without developing a systematic and holistic solution and considering the rest of the building. By consequence, current fitting solutions largely remain as a make-up which has little effect on increasing fitting capacity of buildings in the long run.

On the other hand, fitting modes of the natural skin are holistic, iterative and sustainable. Fitting processes in nature arise from within outward, according to the organism's own essential characteristics and its inner identity. Similar to this, fitting in buildings can be derived out of its content, its function and its context. With such a perspective, the required transformation is to be discovered, found, rather than imposed on the existing structure and fitting would be the reflection of the building's inner workings together with its interaction with its users and environment.

Fitting is achieved through different functions of the skin such as regeneration, growth, protection and communication. The idea of learning from the fitting modes of the natural skin is not simply the simulation of the processes of these functions. Rather, it requires understanding the nature of these processes and transferring it to similar fitting modes of the building envelope. In a similar manner with nature, fitting modes in architecture can be seen as a part of the natural evolution process of a building. In order to achieve this, the architect needs to consider possible fitting modes from the beginning and develop his/her design according to this scenario. With this, the architect can integrate the infrastructure of change to the genes of the design. Considering fitting as a design parameter changes the details of the design. As a consequence, a new design approach is needed in order to *fit buildings as nature*

Table 15 Fitting modes of the skin in nature and building envelopes in architecture (developed by the author).

CHAPTER 4

A NEW BIOMIMETIC DESIGN APPROACH

As it is argued, fitting processes of the skin can guide and redefine (retro)fitting processes of the building envelope. Currently, the idea of dynamic fitting is the underlying theme of the widely used terms in architecture, like adaptiveness and responsiveness. Although these conceptions seem to resemble nature, their similarity with the processes in nature still remains arguable. Adaptation, responsiveness, performance and efficiency of natural organisms are all characterized by the logic of fitting and achieved by organism and context-specific processes. In this vein, first and foremost, the terminology that we use for these processes in architecture needs to be re-discussed. In order to construct a biomimetic viewpoint to the issue, terms like (retro)fitting, adaptiveness, responsiveness, efficiency and performance needs to be considered under the theme of "fitting". With this, the idea of biomimetic design will be approached in a different manner, constructed with a broader perspective. Eventually, this perspective will also affect the design approach in architecture.

The idea of fitting is holistic by nature. Therefore, this study claims that fitting processes and patterns in nature can only be transferred to architecture with a holistic approach. As understood in this research, the most important feature of holism is its *inside out* character, from the smallest number of explanatory elements and principles to the emergent properties of the whole. Nature designs fitting processes at a time and integrates it to the genes of the organism. In other words, fitting arises from the smallest element, the DNA.

Architectural constructions should be designed in the same manner, in order to be fitting like nature. Fitting should be arising from inside and the rules of fitting should be integrated to the design from the very beginning.

The *"adaptive fitting"* approach that is presented in this study is developed with this perspective, through emulating fitting processes in nature. It offers an ideal fitting process, as it is in nature, through considering performance criteria and fitting from the very beginning of the design process. As will be seen, this requires a new perspective to the design approach and redefines the understanding of (retro)fitting in architecture. Further, it brings a new material and structural agenda, changing the construction processes and the details of the buildings. In this chapter, first adaptive fitting approach will be elaborated, second the new biomimetic approach will be presented, and last the application of the new approach will be introduced through the design of the building envelope.

4.1. The Idea of Adaptive Fitting

In this study, the notion of fitting in architecture is described with reference to nature, as a relation which defines appropriateness to the requirements of current conditions. As has been noted, such a description of fitting comprises contemporary conceptions dealing with change such as (retro)fitting, adaptiveness, responsiveness, efficiency and performance. These conceptions share the same logic: "to fit to", which can be better learnt from nature. In nature, organisms need to adjust themselves to changes around them in order to get the most *adaptive fit*. In buildings, the type and level of change is planned and implemented when it is needed, whereas natural organisms have the information of change which is "*contained in small units of code that are syntactically connected and interrelated through combinational rules"* (Imperiale, 2006, p. 276).

In buildings, fitting is mechanical since it is imparted through external forces. In nature, on the contrary, fitting is innate; it arises from within, and reaches its determination simultaneously with the development of the organism. Fitting in nature, then, does not necessarily return to a previous condition. It constructs rather the next best condition, regarding to inherited information of change and environmental triggers. Fitting in architecture entails the idea of turning buildings back to their original state. On the other hand, it is hard to talk about an original state in natural organisms since they are in a constant evolution.

Significantly, the aspect of “unfolding from within” of the fitting in nature guides this study in answering the research question and redefining current understanding of (retro)fitting in architecture. With a biomimetic perspective, (retro)fitting in buildings corresponds to the adaptation in nature. Thus, this study claims that (retro)fitting requires to be understood as a problem of fitting. Unlike this, current understanding of (retro)fitting implies turning the relevant aspects and elements of the building back to their original state. The process of (retro)fitting is not a systematic and holistic one, like fitting processes in nature. Therefore, it seldom contributes to the fitting of the building in the long run. It is rather approached as a short term concern, with a “bolt-on” conception as an urgent response to obsolescence.

This study proposes reframing this juxtaposition of adaptation and (retro)fitting with a new conception named as **“adaptive fitting”**. The idea of adaptive fitting implies *“adapting before becoming retro”*. Learning from the fitting modes of nature, in adaptive fitting, the infrastructure of change is integrated to the genes of the design from the beginning. With this, the building will be ready for possible mutation scenarios and adaptively fit into changing conditions. In adaptive fitting, buildings become future-proof and designed so that they can still be used even if the requirements change. It is crucial to note that the central focus of adaptive fitting is not really the change in shape, size, color or other design parameter but the process of fitting itself as a design issue. At its core, therefore, adaptive fitting is integrating the behavior itself into the design.

The conception of adaptive fitting requires a new approach for the design of buildings. Contemporary understanding of the design is locked into particular patterns of behavior, relations, energy and resource use and so on. In adaptive fitting design approach, the designer employs the idea of the mutation of the building as a method from the very beginning of the design phase, processing fitting ability to the genes of the design, as in nature. By doing this, fitness criteria of the building become design criteria. Further, fitness criteria become resilient in the sense that it is open to probable changes and transformations in relation to the steps and conditions of the building's life. In this approach, design, construction and building systems are not distinct entities that develop independently. Rather, they are all integrated in a holistic manner from the beginning and throughout the process.

Adaptive fitting approach aims to move beyond conventional design approaches that see fitting as a domain of repairing, maintaining buildings and upgrading their performance towards an understanding fitting as a survival strategy of existing buildings, similar to that of natural organisms. In this sense, fitting, pursued through biomimetics, becomes a holistic, iterative and sustainable process that provides the resilience of adaptation in buildings.

The characteristics of adaptive fitting design approach can be elaborated as follows:

- **Adaptive fitting arises from within rather than by external addition.** The idea of adaptive fitting triggers development through inner modification. To this end, all the parts of the building and the whole exist for each other, not for the sake of some external purpose. In adaptive fitting approach, although the buildings respond to the outside world, they operate in such a way to counteract outside stimuli in order to maintain the equilibrium inside, like the organisms in nature.

  In nature, fitting of the organisms arise from within. As a general principle, the organisms function bottom-up, capable of assembling materials and structures by manipulating and organizing their individual fundamental building blocks (Reap et al., 2005, p. 5). Unlike this, design and construction are traditionally considered as top-down processes. Therefore, in fitting processes, the predetermined intervention is imposed on the existing structure. Fitting in nature, on the other hand, is innate and evolves itself as it develops itself from within.

In nature, this is achieved with the interaction of components that occurs on all levels. In this line of thought, adaptive fitting approach may require a system in which fitting emerges from the interaction of energy and material within the system that proceeds over through time. In nature, such an interaction also leads to emergent characteristics, which needs to be discussed further in the emulation phase of a biomimetic design and, thus, is out of scope of this research.

- **In adaptive fitting, there is a continuity: the old condition constructs the new one.** What happens to the old when the new is ready and the old is completely obsolete is planned and integrated to the design. Like nature, the old condition of the building has the information for building the new one from inside out. In other words, it knows how to construct the new one but it does not know what will be constructed.

- **Adaptive fitting redefines the buildings' life cycle in a cyclic manner.** Life cycle of a building has often a linear direction in which material systems are running down. This cycle is often defined as a once-through linear system passing through materials processing, assembly, use and demolition. In this cycle one end of life scenario is recognized as the demolition of the building. If we look at nature, we will realize that ecosystems have evolved over a long period into completely cyclic systems. Since it recycles everything, resource and waste is undefined in nature. Waste to one part of the system represents resource to another. Identifying the nature of fitting modes of the skin, searching for patterns of fitting and transforming these patterns into design strategies that can be applied both to existing building envelopes and to the new ones alters life cycle of buildings in a cyclic manner.

- **Adaptive fitting is able to encode capacity of fitting in buildings both in the long term and the short term.** In adaptive fitting, patterns in nature juxtapose with the design process in architecture. On the one hand, adaptive fitting is responsive to momentary change in users' needs and desires, therefore it accommodates change in the short term. On the other hand, adaptive fitting aims at long-term use of the building, therefore it considers long-term change patterns.

- **Adaptive fitting requires identifying spaces that change and do not change.** Natural systems retain and build upon older patterns of information, at the same time they respond to change by adding novel adaptations. In a similar manner, a building that is designed with adaptive fitting approach mutates from the existing situation of the building when change is needed.

- **Adaptive fitting requires a new material and structural agenda.** The standard practice requires specialized and multiple plans and skills for any interventions. In contrast with this, the idea of adaptive fitting relies on techniques that are able to allow additional interventions over the time with simple processes. The most convenient way to apply modifications to an existing construction would be simple and robust construction techniques based on lightness and flexibility principles, with the possibility to obtain reversible and removable interventions. These issues about the material, structural and technical agenda need to be discussed further in possible emulation of the adaptive fitting approach.

- **In adaptive fitting approach, the systems and components that are no longer useful for one building may be re-installed in another building.** For the systems and components cannot be re-used as such, the materials from which they are made can be disassembled and reused for the production of new components or systems. In fact, this latter principle is described by Braungart and McDonough (2002) as the *cradle-to-cradle concept.* This principle extends the concept of building manufacturing towards building re-manufacturing. Furthermore, it implies a material and structural design that considers more carefully the materials used and the way in which components are joined, in order to allow reusability and disassembly. Consequently, the components and materials that constitute an adaptive fitting building have an extended lifetime that may be substantially longer than conventional buildings.

- **Adaptive fitting allows buildings to remain in use longer, thereby preventing costly and wasteful comprehensive demolition and rebuilding.** They become more resilient and less wasteful. Adaptive fitting buildings fit their environment, purpose and inhabitants as they are designed to enable modifications to be made as needed. They are ready to accommodate change in a more responsive manner as they adapt to changing needs. Thanks to this responsive capacity, they can remain fitting to environmental, cultural and societal changes for longer, maintaining pace with what is expected from them. Although all these abilities have operational ramifications that bring economic advantages, it is crucial to remember that they also provide benefits of enhanced sustainability.

- **Adaptive fitting approach is designing alternative future-proofing scenarios from which potential solutions emerge**. Different from hitherto adaptive solutions, rather than being possible endpoints, these possible future-proofing scenarios should be used as a basis for further investigation and elaboration. To this end, it can be claimed that adaptive fitting design approach proposes no specific processes, algorithms or steps. It offers a way of approaching to the fitting of buildings, in a similar manner with nature.

4.2. Developing a New Biomimetic Approach

The endurance and efficiency of natural systems are emergent properties, they emerge from simple units and rules. However, the properties of these systems cannot be deduced from their components. Their complexity emerges from simple set of initial rules, processed from inside out. The success of natural systems is dependent on the processes of their constituent parts, yet their parts do not solely determine their behavior. Thereby, understanding their complexity and transferring strategies from them requires the recognition of the inside out patterns. This demands a new approach for biomimetic design, that is derived from the evolutionary development of living systems, from their material properties and metabolisms, and from their adaptive response to changes in their environment.

In addition, and in fact of wider significance, this study claims that recognizing the inside out processes and patterns in nature enables constructing a holistic biomimetic view. A holistic view of biomimetics involves mapping of patterns in life's general characteristics and processes, and then incorporation and application of these patterns across multiple spatial, temporal and organizational scales of the design. Particularly in architectural design, focusing on the inside out development of the natural systems enables transferring knowledge of patterns and behaviors to buildings.

As mentioned earlier, in developing a biomimetic design method, a holistic view is required for two things. First, looking to nature with a holistic perspective and mapping patterns of successful strategies provides understanding of its systems as a whole, as well as understanding how a particular structure or process fits into its surroundings and may thereby assist in the development of successful solutions. Thereby, it enables understanding the inside out patterns and relations in nature across multiple scales. Natural systems have emergent qualities as a result of the regular interaction or interdependence of items. For this reason, a holistic biomimetic approach necessitates recognizing interconnections, identifying and understanding feedback and non-linear relationships, understanding dynamic behavior and systems at different scales (Arnold & Wade, 2015).

Second, a holistic view can also allow a potential integration of multi-functionality of natural systems and thus multiple aspects in one design concept. Further, this line of thought could be expected to open reasonable approaches to dominant topics in architecture like sustainability, efficiency and performance in a multidimensional manner. In order for a biomimetic design to exhibit the success of the mimicked processes and factors, the relations by which mimicked useful idea is achieved need to be considered and integrated to the building as a whole. In this line of thought, unlike traditional design approaches, an overall design problem cannot be solved with solving individual problems one after the other. In other words, the holistic behaviour of the building cannot be understood in the individual part not can it be seen with the addition of parts.

Another important point of current study is the use of patterns in nature to guide design processes. The potential of a patterns approach is revealed in this study and it is used to develop a new biomimetic design approach for the design of the building envelopes, as it is presented in this chapter. Christopher Alexander defines a pattern as *"a three-part rule which expresses a relation between a certain context, a problem, and a solution"*(Alexander, Ishikawa, & Silverstein, 1977). Based on this definition, patterns can be considered as an abstraction of design solutions that are relevant for a group of design problems (Alexander et al., 1977). They build analogies between observed solutions and problems at hand and are used to transfer knowledge across domains (Hoeller et al., 2007). In this regard, it is reasonable to use patterns when aiming to imitate solutions from nature. Despite the potential of patterns to abstract and transfer knowledge between domains, they have barely been used for biomimetic design (Cohen & Reich, 2016).

4.2.1 Current Biomimetic Approaches in Relation with the Proposed Inside Out Biomimetic Approach

In the last two decades, there had been several attempts to develop a biomimetic approach to transfer knowledge from nature to human problems. Until recently, there had been two different approaches with various terminologies in biomimetics: (1) challenge to biology (Baumeister, 2014), top-down (Speck & Speck, 2008), biomimetics by analogy (Gebeshuber & Drack, 2008), problem based (Helms, Vattam, & Goel, 2009), technology pull (ISO/TC266, 2015) and (2) biology to design (Baumeister, 2014), bottom-up (Speck & Speck, 2008), biomimetics by induction (Gebeshuber & Drack, 2008), solution based (Helms et al., 2009), biology push (ISO/TC266, 2015). Both two approaches have different starting points and differing characteristics as design processes (Goel, Vattam, Witgen, & Helms, 2014). In the first instance, a design problem is identified and then the solutions in nature are searched. Here, the problem needs to be clearly recognized and matched with organisms that have solved similar problems. In the latter instance, a particular characteristic, behavior or function in an organism or an ecosystem is identified and then it is translated into human designs. This approach is based on the previous knowledge of biological research, and then applying this knowledge on the design of the problem that you already have.

Among these two approaches, there have already been attempts in developing specific biomimetic design process models in different disciplines. Regardless of their approach, biomimetic process models involve three different domains: problem, nature and solution. In most of these process models, three general phases, which promotes the transition between one domain to another, are identified: problem definition, exploration and investigation and solution development. The main differences between the presented process models is observed in sub-phases of their methodologies and biomimetic tools that are used. The main differences between the initial phases of these models are relatively minor.

In brief, both top-down or bottom-up approaches mostly employ linear and hierarchical processes. The adaptive fitting approach proposed in this research changes this hierarchical view of biomimetics into an interrelated network system. Recently, there had been attempts to develop non-linear biomimetic design approaches. For instance, Pedersen-Zari (2007) proposed a systems approach based on three biomimicry levels: organism, behavior and ecosystem level. The first one indicates mimicry of a specific organism, the second is the mimicry of how an organism behaves or relates to its larger context and the last one is the mimicry of an ecosystem. Pedersen-Zari indicates, there are further dimensions within each of these levels, such as the form, material, construction, process and function. According to her, for instance, at organism level, material of a specific organism can be mimicked, while at ecosystem level, an ecosystem which is made of structures made from the same material can be mimicked (Zari, 2007).

Pedersen-Zari attempts to develop a non-linear systems approach for the generation of biomimetic designs, yet her approach concentrates on systems separately. It is worth to remind that any system cannot be understood without recognizing interconnections and non-linear relationships, understanding dynamic behavior and systems of systems. This is to say that an ecosystem cannot be understood without recognizing the organism and behavior level. Furthermore, a dimension within a level cannot be understood without recognizing other dimensions. Complexity can be reduced by modelling different parts of a system conceptually and view a system in different ways. However, in architecture, this brings the danger of designing buildings which are stylistically or aesthetically based on nature, but are made and function in an otherwise conventional way.

In the last decade, there had also been some researchers that develop biomimetic design models with cyclic processes. For instance, in her previously mentioned research, Lidia Badarnah-Kadri (2012) proposed a cyclic biomimetic design methodology which is based on two major phases: preliminary design phase and the emulation phase. According to Badarnah-Kadri's research, in order to find design solutions from nature, the requirements of a certain challenge should be defined and then analogical systems in nature that perform similar functions should be identified. She then points out the need for design tools that support transitions between the domains, especially the identification of biological analogies and their abstraction for design concept generation. In this regard, the proposed biomimetic strategy, the living envelope, is aimed to *"facilitate the transitions between the various phases of the design process, with a special attention to biological information representation, principles identification and abstraction, and their systematic selection"*(Badarnah-Kadri, 2012, p. 43).

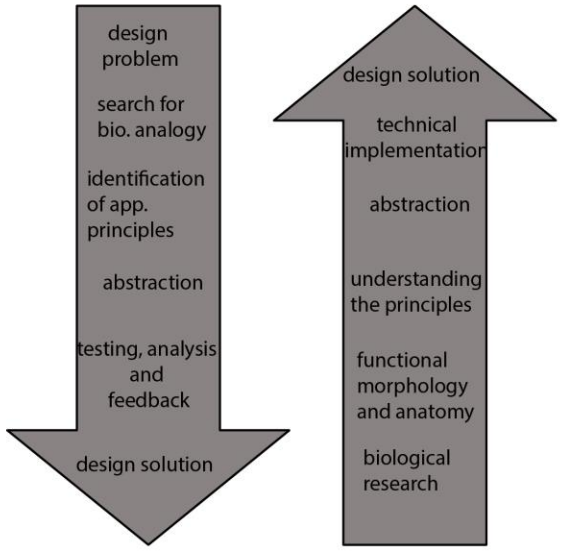
Another recent example is Arslan Selcuk's research which proposes a *"parametric thinking cycle"*(Arslan Selçuk, 2009). In her methodology, first stage is the identification of the real problem based on the observations. Then, a real natural model is selected in order to relate the defined problem to man-made structures. After that, the mathematical model of the defined problem is constructed through appropriate simplifications. Later, this mathematical model is transferred to a computational model and evaluated. Finally, non-dimensional parameters that are set into design problem are to be discussed and compared by the generated design (Arslan Selçuk, 2009).

The main difference of this study that needs to be emphasized is that, it aims to construct an inside out view of nature, regarding its general characteristics. Such a view also entails an *inside out biomimetic approach*, which unfolds from within. The above presented linear approaches include hierarchical phases. The cyclic biomimetic design methods are based on iteration loops of hierarchical phases. Current research differs from existing models in this sense. Rather than linear or cyclic, this research employs an inside out process. It is proposed that, in architecture, the new way of learning from nature might be thinking through the inside out development of nature. The idea of inside out provides a non-linear and non-hierarchical process, which can be diagrammatized with the shape of spiral.

Adaptive fitting design approach presents an interrelated process, where investigation and abstraction goes hand in hand. The investigation goes back and forth through simultaneous mapping of the two domains: biology and architecture. This interaction is due to the fact that a comparison and simultaneous mapping of biology and architecture may lead to a knowledge gain in both domains. In the following table, the adaptive fitting design approach is illustrated along with existing biomimetic approaches.

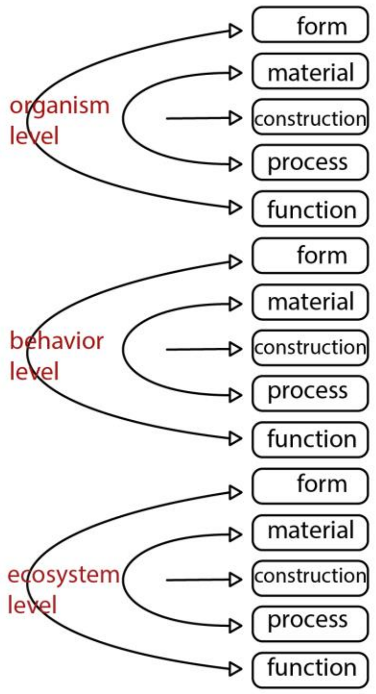
Table 16 Existing biomimetic design methods along with adaptive fitting design approach (developed by the author).

Top-down Bottom-up



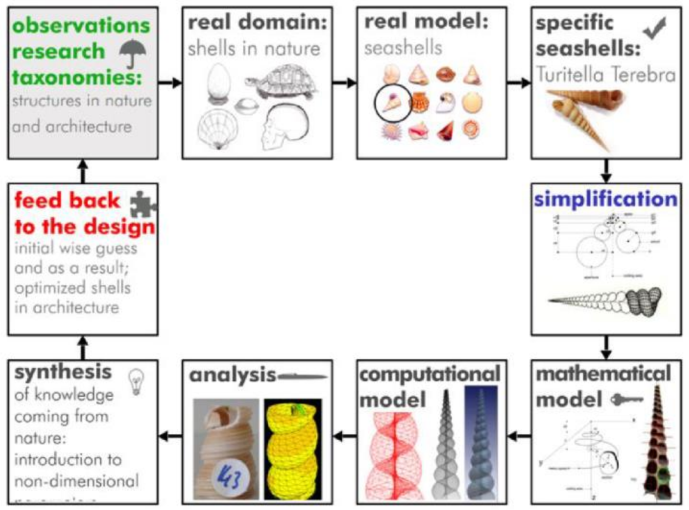
(Speck& Speck, 2008; Gebeshuber& Drack, 2008; Helms, Vattam& Goel, 2009; Baumeister, 2014; ISO/TC266, 2015)

Biomimicry for Sustainability



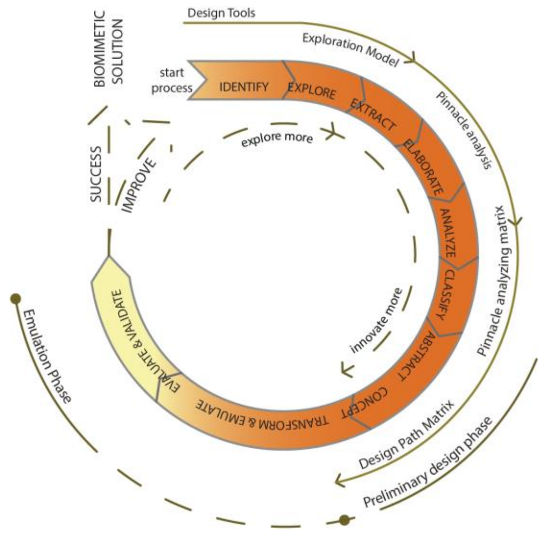
(Pedersen-Zari, 2007)

Parametric Thinking Cycle



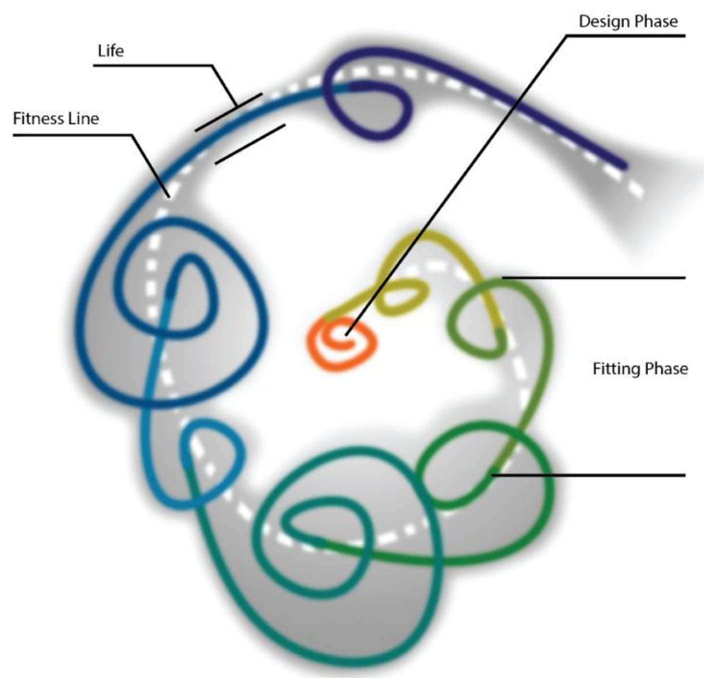
(Arslan-Selçuk, 2009)

The Living Envelope



(Badarnah-Kadri, 2012)

Adaptive-Fitting



the origin: the beginning of the design phase

fitness line: the requirements of fitting

fitting phase: fitting mode and required intervention

life: starting from the design to the demolition and recycling of the building, encompassing all fitting phases

(created by the author)

As can be seen, adaptive design approach has a starting point yet it never comes back to that point. In other words, it emanates from an origin, arises from within and revolves around that point yet does not come back to that point. The point of origin of the proposed approach is the design phase. Every new spiral illustrates a new fitting phase, their color representing the fitting mode and their radius curve representing the level of intervention. Here, the design is optimized between performance and adaptation. The fitting modes are not considered as isolated actions, rather they are continuous in the sense that the curve of the former effects the latter one. With this, intervention and design becomes an integral part of the life of the building.

Another spiral which can be thought as the backbone of fitting modes and required interventions, and shown with a white dashed curve, presents the ‘fitness criteria’. The fitness criteria also determine the performance requirements of the design. There are two main factors that effect this spiral: user’s demands and environmental conditions. This spiral needs to be specifically designed for every building.

Fitting phases include biomimetic stages which can be applied more than once during the life span of the building. In other words, in each phase, the patterns of relevant fitting modes are mapped, abstracted and transferred to the design in order to come closer to the fitness curve again. Further, the relationship between different fitting phases are vague, again not like the one begins when the other ends.

The life of building, encompassing all possible fitting modes and interventions, starting from the design until the demolition and recycling of the building, is shown with a grey cloud. This thickness of this cloud, thus life quality of the building, decreases when the intervention curve increases. Through its life span, the building aims to come closer to the fitness criteria through continuous fitting interventions. In this sense, this approach proposes not only learning specific fitting modes from nature and transferring this knowledge directly into the building. Rather, it proposes searching for the nature of fitting and transferring models of fitting from nature in order to become and remain fitting. Here, the important thing is not the transfer and application of specific fitting modes into the building, rather it is the relationship between these changes, which becomes the infrastructure of change in buildings.

4.3. Adaptive Fitting in Building Envelopes

This research illustrates the use of adaptive fitting design approach in buildings through the analogy of the skin and envelope. This analogy will reveal how the knowledge gained from the proposed biomimetic approach is to be reflected to the design process. Rather than exemplifying the proposed approach with a specific design problem, this research aims to give a general understanding of how adaptive fitting approach will be reflected in design. Thereby, it is not aimed to give a detailed explanation of each step of the proposed biomimetic approach. It should also be noted that mapping appropriate patterns of nature with an inside out manner needs to be discussed further in the emulation phase, thus it is out of the scope of this thesis.

4.3.1. An Overview of the General Qualities of Fitting in Natural Skin and Building Envelopes

The research up to this point showed that the idea of fitting is holistic by nature. Therefore, this study claims that fitting processes and patterns in nature can only be transferred to architecture with a holistic approach. As understood in this research, the most important feature of holism is its inside out character, from the smallest number of explanatory elements and principles to the emergent properties of the whole.

In buildings, fitting is mechanical since it is imparted through external forces. in order to be fitting like nature, aarchitectural constructions should be designed in the same manner. Fitting should be arising from inside and the rules of fitting should be integrated to the design from the very beginning. Significantly, the inside out character of the fitting in nature guides this study in answering the research question and redefining current understanding of (retro)fitting in architecture.

Before moving on, it will be useful to present general qualities of fitting both in skin and building envelope. In nature, fitting arises from inside out, as a part of the natural evolution of the organisms. In architecture, the idea of fitting is not self-contained, but it is implemented. As explored in earlier chapters, unlike building envelopes, fitting in natural skin does not aim to turn back to an idealized original state. Rather, fitting processes of the skin always aim to achieve the optimum condition of their current situation. In nature, fitting is achieved with layered but connected systems. The building envelope is also a layered system but its connection with its sub-systems and the whole of the building remains arguable. There is a dispersed integration in the skin, such as the sensors, blood vessels, ventilation pores etc. which enables it to become and remain fitting. In building envelopes, the integration can be observed in functions, rather than systems and elements.

The general qualities of fitting processes of the skin and building envelopes are listed in the following table.

Table 17 General qualities of the fitting processes of the skin and building envelopes (developed by the author).

Fitting in natural skin	**Fitting in building envelopes**
Iterative	Non-repetitive
Step-wise	Direct
Dynamic/ Progressive	Static/ Non-progressive
Arises from within	Additive
Integrated	Independent
Life-long	Temporal
Holistic	Divided into separate and often disparate elements and systems
Sustainable	Not sustainable

Fitting processes are iterative in nature thus the skin of organisms is able to *"fit n times"*. In buildings, on the other hand, fitting processes are non-repetitive, which are applied once, when needed and only according to current demands. In nature, the repeated transitions over time leads to small random variations in the design, making the organism context specific. A lobster, for instance, requires a bigger shell as it grows. Every time the lobster outgrows its shell, it molts into a new shell. This is a continual process since the lobster grows throughout its live. In every molting, the new shell varies due to environmental factors. In a similar vein, the adaptive fitting design approach should be structured as an iterative process, to continuously adapt and fit the building envelope to changing conditions.

Fitting processes of the skin are step-wise. For instance, as shown in previous chapter, in molting process, the organisms form an entirely new epidermis in a synchronized sequence, in three stages: inter-molt, pre-molt and post-molt. As can be observed in the example of white leg shrimp (figure 50), the inner layer of the older epidermis triggers the molting from inside out. Then, the older layer of epidermis separates from the new and the older layer falls away in one piece or several large pieces. It can be stated that in this process, there is complete recycling rather than waste accumulation: the old cuticle is eaten by either the organism itself or another organism in the environment.

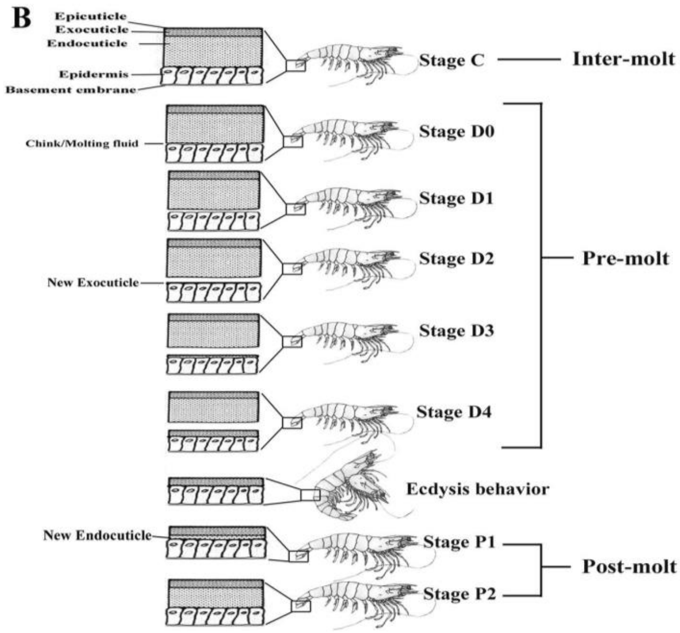


Figure 49 Structure of the exoskeleton of L. vannamei (white leg **shrimp**) during the molting process (Source: Gao et al., 2017)

In the natural skin, fitting processes are dynamic and progressive. The development of constructions and processes for fitting are achieved by trial and error. In this sense, as Richard Dawkins points out, nature resembles *"somebody who makes changes continuously, rather than somebody who creates something new"* (as cited in Vogel, 1998, p. 27). In contrast, in architecture, fitting processes are not guided with embedded information. As exemplified in the previous chapter with industrial buildings, many (retro)fitting examples are done through new additions on the existing structure with the aim of either turning back to the original state or creating an entirely new structure. In the example of 185 Post Street building San Francisco, the envelope is transformed with new materials and gained a new appearance in each fitting phase.

Figure 50 Healing phases of 185 Post Street, San Francisco (Source: Bloszies, 2012)

In fitting processes of nature, the existing structure is remodeled with the embedded information and the effect of related environmental conditions and triggers. As exemplified in the previous chapter, the skin healing processes involve a remodeling phase which creates a new structure that is in a continuity with the original state. This remodeled structure provides optimum functioning in existing conditions.

Figure 51 Human skin healing process (Source: https://thinktechi.wordpress.com/category/self-healing/. Retrieved at: 03.01.2017)

In nature, the principle of fitting is integrated into the organism, incorporating all aspects of the organism and adapted to the existence and interrelation of the organism with the environment. In building envelopes, when requirements and needs change, fitting is applied independently to the obsolete part of the envelope. Further, every fitting process mostly addresses a single problem at a time. Both independent and interrelated systems co-exist in building envelopes. These systems are expected to fulfil multiple performance aspects. Like the skin, an integrated design approach is needed in building envelopes for two things: integration of parts and systems and integration of multiple performance aspects. The envelope needs to integrate multiple systems within itself. An adaptive fitting design approach, thus, requires incorporating all these systems and relevant performance requirements of a building envelope as primary parameter for design.

Fitting is a life-long process in nature, since it is adapted to the existence of the organism, its survival strategies and design principles. In nature, an organism uses its experience to modify its behavior in beneficial ways (Holland, 1992, p. 3), and, thus it continuously changes. In this sense, fitting is both learnt and inherited in nature. Architecture is traditionally almost opposite of continuous change. This is not to say architecture does not evolve or change, but the traditional view of architecture is to "*create a space and preserve it as long as possible*" (Imhof & Gruber, 2016, p. 161). There is a search for a balance between change and fixed structure, as it is in nature. In buildings, we are very interested in allowing novel solutions and innovations that are resilient, but at the same time we want to retain some core structure (Imhof & Gruber, 2016).

For instance, the amount of change that the human skin can accommodate is dependent on the sensory system and its processing of information. This a process where genotype and phenotype work together. In a similar manner, in adaptive fitting approach, building envelopes can be designed with the ability of monitoring changes around them and processing the collected information together with the ability of fitting that is coded into the design. This approach requires identifying spaces that respond to change and do not. In this way, change and fixed structure may be balanced and the building may be able to learn fitting in response to the emerging changes.

Fitting processes of nature are sustainable, resource sensitive and environmentally friendly. In fitting processes, unlike buildings, the organisms use what is available in their environment like energy source, material, cooperation. In the example of shrimp, in the post-molt stage the organism recovers from previous molt. This recovery is related with the water available, since the shrimp requires a large volume of water in order to be able to extend and consolidate its cuticle, as well as to adapt to its new size. A similar strategy of using available materials was only observed in the example of Gehry Residence, given in the previous chapter. However, unlike the organisms in nature, the added envelope was not integrated to the existing structure. Rather, as mentioned before, the new envelope left the existing one almost untouched.

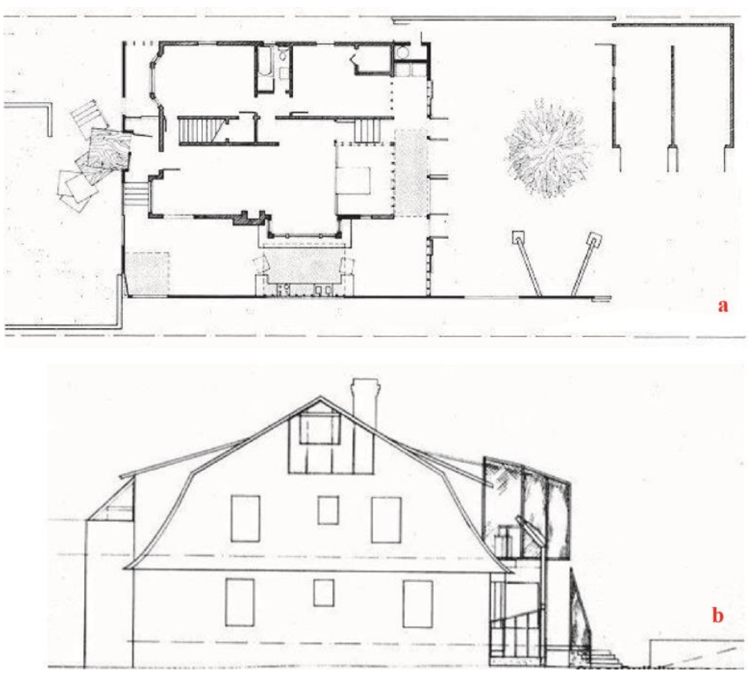


Figure 52 Gehry Residence, **a)** plan, **b)** section (Source: https://www.archdaily.com/67321/gehry-residence-frank-gehry . Retrieved at: 03.01.2017)

In architecture, on the other hand, current fitting modes mostly involve demolition and new construction. In adaptive fitting approach, embedded flexibility enables building envelopes to adapt to different circumstances and be mutable in terms of system-level changes. Similar with nature, adaptive fitting building envelopes become future-proof, designed with the capacity to cope with future changes with minimum demolition, cost and waste, with maximum mutability and efficiency. Considering possible short and long term changes, adaptive fitting building envelopes can become fully adaptable from inside out and across scales. In other words, adaptive fitting building envelopes spatially, functionally and aesthetically accommodate change. This type of architecture can be thought as "long life-loose fit", which is not created around the philosophy of one fit all people and conditions, but with truly flexible intentions that allow specific solutions to be available without recourse to (retro)fitting.

4.3.2. Possible Adaptive Fitting Scenarios

The idea of adaptive fitting is not so much just like something go from a situation to another, but to make a structure where the process of going one situation to another one is actually the subject of the design. Then the challenge appears is how to design the ability of fitting, how to design the process of change within a building envelope? The process of adaptive fitting relies on flows and dynamic patterns. In this sense, it is inherently open to new and often emergent configurations.

In adaptive fitting, possible scenarios for the ability of fitting define the fitness criteria of a building. The designer develops a specific strategy (change/transform/mutate/adapt) in order to optimize these criteria. According to the findings of this study, possible future-proofing scenarios of a building envelope can be grouped in two: changing needs and patterns. Some possible scenarios of change are given in Table 18, not to list all possible change parameters but to give an idea of how to structure these parameters.

Table 18 Possible short and long-term future proofing scenarios of adaptive fitting approach (developed by the author).

Needs		
Short term	Personal	heightening of aesthetic qualities
	Practical	detorioration of building's physical fabric due to factors such as radiation, water, air contamination, permanent loading etc.
	Technological	adapting to technological innovations due to lower operational costs or greater efficiency
Patterns		
Long term	Legal	meeting the requirements of codes and regulations
	Economic	the rise of the rental market
	Environmental	to adapt changes in the character of an area, such as hign pollution, road congestion or urban decay

Changing needs refer to short time parameters, whereas changing patterns refer long time parameters. There are personal, practical and technological needs, which are relatively short term parameters of change. For instance, personal needs such as the expansion of the family and practical ones like the aging of the building structure or technological such as the updating of old services.

There are also legal, economic and environmental needs, which are long term parameters of change. These can be exemplified with legal needs such as the requirements of codes and regulations and economic needs like the rise of the rental market or environmental ones such as the need to update the envelope to respond to climate changes. It is worth to note that, unlike the common understanding, environmental issues not only include climate, but also the availability of space, building material energy, ecology etc.

If these future proofing scenarios are explored in parallel with nature, it can be observed that personal needs can be exemplified by the adaptations of sexual attraction in many mammals, such as the peacock. Most of the fiting modes in nature can be classified as practical needs. Technological and legal needs and patterns do not have a similar fitting strategy in nature. Being economic in terms of handling of material and energy is prerequisite for living beings, so all fitting strategies comply with this category. Environmental changes can be exemplified by physiological changes in seals due to their changing eating habits.

Table 19 Future proofing scenarios of adaptive fitting approach in parallel with fitting modes in nature (developed by the author).

Needs		
Short term	Personal	Sexual attraction in many mammals 
	Practical	Regeneration, growth, protection, communication 
	Technological	-
Patterns		
Long term	Legal	-
	Economic	Handling of material and energy
	Environmental	Physiological changes in seals due to the lack of salmonid 

To conclude this chapter, the mapping of fitting modes of the skin and building envelope is given together with the strategies and reasons of fitting in the following table.

Table 20 Mapping of fitting modes, strategies and reasons of the skin in nature and building envelope (developed by the author).

NATURE	FITTING	ARCHITECTURE	
regeneration growth protection communication	MODES	regeneration growth protection communication	
add-on replace cover it wrap it	STRATEGIES	growth/protection renewal/communication regeneration/growth regeneration/protection	
survival	REASONS	short term	personal practical technological
		long term	legal economic environmental

CHAPTER 5

CONCLUSION

5.1. General Conclusions

It can be seen that biomimetics is the science of new era. The potential that biomimetics offers to disciplines in learning solutions from nature cannot be underestimated. With current advancements, beyond its forms and visual aspects, nature has begun to enlighten disciplines about complex systems, dynamic and integrated processes through computational models. Biomimetics offers a methodical approach to how to consider this biological data and how to transfer this knowledge to other domains.

Today, biological data is creating new paradigms in architecture as well. On the other hand, the studies of sustainable and ecological approaches have been dominating architectural realm as a trending topic and biomimetics is commonly seen as a tool for these approaches, rather than a methodology for how to consider the living environment. Although there are some attempts to develop a methodical approach to transfer biomimetic knowledge to architecture, there is a danger that they also consider nature in the same manner: as a tool for sustainability. In this study, it is observed that a broader perspective is required in order to transfer strategies from nature to architecture. In this way, the provided solution should inherently be sustainable, since the main promise of biomimetics is being and behaving like nature.

In this regard, the thesis provides a platform for discussion on the subject of “how can we go beyond direct imitation of nature and develop a methodical approach to learn from its systems and processes?". This study also presented a parallel reading of nature and architecture in terms of the current research question and provided a mapping of the processes of these two different domains to enable conveying knowledge from one to another.

Before elaborating on the general conclusions of the thesis, it should be noted that this research could not be carried on by focusing solely on the building envelope. Rather, it brought the discussion of *tectonic*, which addresses the relationship between architectural design and its structural and material properties. Further, due to the complexity of knowledge transfer from the domain of nature to architecture, this research could not be carried on with conventional architectural research methods. It required developing a new biomimetic approach, as every research problem does. The proposed biomimetic approach is developed considering the tectonics of the building. In order to answer the research question, this study illustrated the proposed approach in buildings through the analogy of the skin and the envelope.

The research is structured upon a statement that is mentioned in the hypothesis part of Chapter 1, as follows:

"Building envelopes/surfaces/façades can act like the skin in nature if they are coded with the ability of fitting from the very beginning of the design".

Regarding this statement, the life of buildings can be extended by designing them like the natural skin from the beginning. To investigate this statement, the following questions were explored through a literature survey and a theory building, which resulted in the development of a new biomimetic design approach.

- What is the potential of biomimetics and its implementations in architectural design?
- What is the relationships between skin in nature and building envelope in architecture? How can we reconsider this relationship with a biomimetic perspective?

- What are the fitting modes in natural skin and building envelope? How can we map these fitting modes to correlate them?

- What is the potential of redefining the idea of fitting in architecture with a biomimetic viewpoint?

- How can we propose a biomimetic approach to develop the analogy of building envelope and natural skin?

- How can we develop a design approach to increase fitting capacity of building envelopes?

To introduce the potential of biomimetics and its implementations in architectural design, the first step was to review solutions inspired by nature in Chapter 2, starting from a broader context in order to understand the background of the idea of biomimetics in architecture. Then, the reasons and methods of the use of biomimetics in architecture is addressed. After that, the investigation is narrowed in the scope of the relationship of nature and building envelope to explore and construct the envelope’s relationship with the skin in nature. The analogy between the skin and envelope is investigated and then examples of skin inspired envelopes are given. Lastly, an overview of recent studies on skin-envelope analogy in the realm of biomimetics concludes Chapter 2. These studies consist of unbuilt examples, researches and experiments in the field.

Literature review on biomimetics showed that the formalization of the concept and its establishment as a field of science is occurred with Benyus’s work, her view on nature is too fragmentary. It is comprehensible that she suggested classifications and categorizations to provide a framework to look at nature but it is important to note that the nature needs to be understood as a whole. In other words, these categories are indistinguishable.

Throughout Chapter 2, it is observed that the evolution of the protective cover of buildings from the cladding to the envelope is linked with the increasing effect of nature in architecture (Table 2). Earlier, the protective cover of buildings was thought as surfaces, decorated with motives from nature. Later, the shift of focus from organic morphology of nature to its structural efficiency can be read in parallel with the growing interest in shell structures. From this point onwards, the components of the protective cover have begun to be understood as a whole. At last, with energy oriented focus of inspiration from nature, the protective cover has begun to be thought as an interface and its wrapping and breathing qualities came into question. These developments, together with the introduction of biomimetics, resulted in conceptions like the adaptive/kinetic/responsive/living/breathing skin/envelope. Regarding the literature in Chapter 2, there are some difficulties of transferring strategies from nature to architecture due to their different complexities: the mapping of appropriate strategies from nature, scaling problems and conflicts between solutions of integrated parts of the design concept. These difficulties need to be addressed with a methodical approach in order to reconsider the relationship of skin and envelope with a biomimetic perspective.

Another finding of Chapter 2 was that the increasing interest in skin as a model for the design of the building envelope is related with current focus on the topics of energy efficiency, performance and sustainability in architecture. This chapter clarifies that with a biomimetic perspective, evaluating sustainability and performance of buildings is a question of "fitting". This was a starting point to discuss the design of the building envelope in relation with the skin in nature. In fact, in this thesis, the emphasis of "nature as a measure" enabled redefining "retrofitting" as "fitting". Considering the examples in literature, it can be stated that skin has been taken as a model and mentor in the design of the building envelope, but not taken as a measure yet. This can be explained by the lack of a holistic approach that transfers process and behavior based knowledge from nature. This study structured upon the idea that fitting needs to be addressed in order to take nature as a measure to judge the efficiency of architectural designs.

In chapter 3, fitting in natural skin is reconsidered and reinterpreted through a mapping of fitting modes. This mapping is used as a medium to convey fitting strategies from the domain of nature to architecture. In order to find the response of this mapping in architecture, a mapping of fitting strategies of the envelope is generated as well. It should be noted that this part of the research is conducted in a nonlinear manner since the analysis of fitting in architecture went hand in hand with an analysis of fitting of the skin. While investigating the concept of fitting in building envelopes, it is observed that currently there are two main trajectories: designing adaptive building envelopes and (retro)fitting of building envelopes.

Exploring current literature and examples of adaptive building envelopes revealed that there are integration problems at two different levels: integration of the envelope with other systems of the building and integration of multiple change parameters to the adaptive behavior. The former indicates that the adaptive layer, which delivers the desired adaptive performance, is not integrated to other systems of the envelope and thus other systems of the building. Unlike skin, the envelope does not perform with the rest of the building as a whole. In other words, change is accommodated only on the adaptive layer of the envelope. In contrast, natural organisms accommodate change in multiple ways and systems.

The latter indicates that even though they are designed for optimum adaptation to contextual issues and needs, the majority of current researches and projects have addressed a single problem at a time. They commonly focus on energy efficiency and changing environmental conditions. In the design of adaptive building envelopes, although energy is an important topic which is inevitable to address, it cannot be dealt apart from other requirements of the envelope. As explained before, the envelope needs to meet a number of different functions, therefore it is required to perform multiple tasks. Without considering these tasks in a holistic manner, it is hard to achieve adaptation as it is in nature.

The other trajectory of achieving fitting in building envelopes, (retro)fitting, is already an acknowledged issue in the building industry. As Powell (1999) mentions, *"the total number of (retro)fitted buildings are growing over the last few decades, accounting for more than that of new construction"* (p. 10). Regardless of approach, the underlying idea behind (retro)fitting is the upgrade of an existing building to extend its life. When current solutions for (retro)fitting is investigated, it is observed that there are two levels of decisions that are interconnected with each other: (retro)fitting strategies and the level of intervention. Current (retro)fitting strategies are mapped in four groups based on their intervention method: add-on, replace, cover it and wrap-it. This mapping provides a base to develop an understanding of fitting in building envelopes and skin in parallel.

When the levels of intervention in (retro)fitting processes are explored (Table 11), it is seen that there was a significant difference between fitting processes in architecture and nature: fitting processes in architecture commonly aim at turning the building back to its original state, whereas in nature, organisms aim to fit the best condition of their current situation by adapting the changes. To put it another way, unlike nature, buildings become fitting after they become retro. This finding pointed out the major difference between nature and architecture in terms of fitting.

After this observation, parallel mapping of fitting in skin and building envelope revealed more similarities and differences. This mapping is done with a systematized approach based on the proposed categories of intervention in fitting processes. There is a vast number of fitting strategies and examples, both in skin and building envelope. To present all analogies is therefore impossible. In this part of the study, a pattern of fitting processes in architecture is given in relation with nature. These mapping processes and generated patterns led Chapter 3 as a base for the development of a biomimetic design approach which aims to increase fitting capacity of building envelopes.

5.2. Re-visiting Research Questions

1**. How can we redefine fitting in architecture in terms of biomimetics learning from the functions and performance of skins in nature?**

As stated earlier, biomimetics should be taken with a broader perspective, considering multiple performance aspects. The current research highlighted that the process needs to be considered as the key of understanding systems at different levels and domains. Biological forms and their behavior emerge from process. It is process that produces, elaborates and maintains the form or structure of biological organisms and that process consists of a complex series of exchanges between the organism and its environment (Hensel, Menges, & Weinstock, 2010).

It must be stated that focusing on the nature of fitting shall give an understanding of the process itself and enable a methodical approach, rather than a formal analogy. In this regard, the research investigated three questions in order to redefine fitting in architecture in relation with nature: What does the skin do to be fitting? How does nature do this? What does nature do to sustain its fitting state? The exploration of these questions gave an overall understanding about the nature of fitting of the skin and revealed patterns of its functions and performance. Parallel to this investigation, current understanding, strategies and examples of fitting in building envelopes is also mapped. In the end, reading these maps together gave a new understanding of fitting in architecture.

2. **How can we increase fitting capacity of building envelopes with a biomimetic design approach?**

The answer to this research question is given by the adaptive fitting design approach. Adaptive fitting is mainly a holistic approach, viewing fitting as a package of measures working together. In this study, first of all skin-envelope analogy is taken on a broader level. Therefore, different from most of the current biomimetic design approaches, patterns of fitting are investigated, rather than finding an appropriate model from nature. These patterns are used to convey compare two domains and convey knowledge between them.

It should be stated that even though biomimetics provides a methodical approach to learn from nature, each design problem requires its own specialized way of mapping nature, abstracting relevant processes and transferring these into design solutions. In general, Biomimicry 3.8 suggests a linear biomimetic design strategy, either from biology to design or vice versa. Another example, Fayemi et. al.'s unified process model of biomimetic design suggests a cyclic process, yet the analysis and synthesis is clearly separated from each other within two phases: technology to biology and biology to technology. In this study, rather than following current approaches, a new approach is developed to address the research question. Rather than linear or cyclic, this study has a more iterative nature. For this reason, the two domains, architecture and nature is always explored simultaneously. At each step, the findings from one domain reflected to the other one. In other words, analysis and synthesis went hand in hand throughout the study. With this approach, emulation is achieved at different levels.

5.3. Introducing Adaptive Fitting as a Biomimetic Design Approach

This research revealed that to enhance fitting, a building must holistically balance and integrate three principles: sustainable design, economy of resources and life cycle design, from the very beginning of the design phase. The adaptive fitting design approach comprises a conceptual framework for increasing fitting of the building envelopes. This approach is intended to help architects seek solutions from nature rather than giving them a set of solutions. Specific design solutions compatible with a given design problem will arise from this approach.

The adaptive fitting design approach could allow the system to keep the dynamic qualities of constant adaptation. Eventually, this means a new life for existing buildings, a new understanding for sustainability and a new perspective for architectural design. So much of contemporary buildings are created and evaluated as a consumer product, but pursuit of the adaptive fitting approach proves there is a way to shape new in relation to old and achieve continuity. With this approach, fitting of existing buildings becomes more of a process than a product.

Adaptive fitting approach changes the details and thus requires a new material and structural agenda. First of all, a component based design may be required in order to achieve dynamic fitting with emergent properties, as it is in nature. Second, adaptive fitting integrates material agenda to the design from the beginning, and thus addresses environmental issues and waste-management in the design phase. Nature operates on a closed loop system, such that the waste of one is the food for another. For instance, the dead leaves that come off trees in autumn become nutrients for the earthworms on the ground which they fell. The earthworms eat the leaves and, in turn, their waste provides nutrients for the tree, which then produces new leaves in spring. In contrast to nature, demolition and new construction requires highly non ecological methods and has a negative effect on the environment. In brief, with its new material and structural agenda, adaptive fitting can bring a new understanding for sustainability in built environment. Needless to say, designing new buildings with this approach brings a new perspective and redefines the life of buildings.

According to several commentators, the ultimate purpose of biomimetics in not merely to emulate nature or achieve capacities similar to those enjoyed by nature, but rather to go beyond nature into a man-made realm that surpasses nature (Hanks & Swiegers, 2012, p. 4). As it is observed, design in architecture is fundamentally different than the design of fitting processes in nature. Fitting processes design by changing continuously, rather than creating something new. Innovation in architecture is not continuous and conservative, but revolutionary and creative in a sense that phenomena emerge which do not have a predecessor in developmental history. In other words, invention from scratch is possible. In this sense, architectural design exceeds the limitations of fitting processes in nature. On the other hand, fitting processes incorporate more information, is refined to the maximum and conservative, in a positive way. Considering all these, it can be stated that a synthesis of both processes should provide even more possibilities.

5.4. Recommendations for Future Studies

Studying fitting in the natural skin gave insight into some dominant processes and factors for adaptation and provided a start of fitting patterns. It is possible to follow the same rules of classification and categorizations and create an extendable database, for generating new patterns and adaptive fitting building envelope designs.

The validation of the design concept by building and testing scaled and unscaled prototypes was out of the scope of this research. Building prototypes is essential for the realization of emerging innovative ideas, since materials and production methods can be different from the standard, as it is in this study. A multidisciplinary platform is significant for biomimetic innovation in architecture, where researchers and industry collaborate. The arising solutions from such a platform might open up new visions for adaptive fitting building envelopes.

It must be emphasized that in this thesis, skin-envelope analogy has been acknowledged as one of the many possible analogies that can be developed between nature and architecture. Thus, adaptive fitting approach can be examined in the future studies with different analogies. In this study, the biological model skin has been focused due to the research question of the study, which aims to increase fitting capacity of building envelopes. However, it is possible to draw process-based knowledge transfer between any organism in nature and architecture.

Existing buildings were out of the scope of this research since considering them requires an extensive monitoring and assessment work. Fitting of existing buildings encompasses assessing the condition of existing systems and deciding which systems need to be improved, which components need to be replaced, which ones need to be repaired or modified and which ones can be reused. The generated map of fitting processes of the skin and adaptive fitting design approach can be used for the design of fitting of an existing building in further studies.

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