BIOMIMICRY AS A TOOL FOR SUSTAINABLE ARCHITECTURAL DESIGN

TOWARDS MORPHOGENETIC ARCHITECTURE

A THESIS

Presented to the Graduate School
Faculty of Engineering, Alexandria University
In Partial Fulfilment of the
Requirements for the Degree

Of
Master of Science

In

Architecture

By

Salma Ashraf Saad El Ahmar

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In the Name of ALLAH *the Most Gracious the Most Merciful*

I. ABSTRACT

Biomimicry is an applied science that derives inspiration for solutions to human problems through the study of natural designs, systems and processes. Nature can teach us about systems, materials, processes, structures and aesthetics (just to name a few). By delving more deeply into how nature solves problems that are experienced today, timely solutions could be extracted and new directions for our built environments could be explored.

An interesting issue is the development of new design software which enables the writing of scripts and codes, that when coupled to simulations of dynamic structural and environmental loads have the potential to extend design processes from the development and fabrication of a singular static artefact or building to families of variant forms that can respond to varying conditions. Computationally driven design and production processes are enabling the fabrication of complex forms and materials of almost all of the products we use in our daily lives, the complex geometries of many contemporary buildings and the complex typologies of infrastructural and information networks.

This research attempts to investigate new strategies for sustainable design, which are derived from the evolutionary development of living systems, from their material properties and from their adaptive response to changes in their environment. This is achieved through an attempt to link the two emerging sciences; biomimicry and computational design, exploring their potential in developing a more sustainable architecture.

Keywords:
Biomimicry, Sustainability, Computation, Morphogenesis.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Current architectural practice regarding sustainable design and construction is not yet truly sustainable. According to leading biomimetic thinker Bill Reed[1] (who co-chaired the development of LEED standards from the outset), we could "have a world full of LEED platinum buildings and still destroy the planet." These greener designs, though progressive, often stick too close to the existing standard in a way that is simply "less bad." He states that our designs need to be ‘’Regenerative’’, meaning that we need to contribute to biodiversity with our own designs … an approach that not only reverses degeneration of the earth's natural systems, but creates systems that can co-evolve with us, in a way that generates mutual benefits and creates an overall expression of life and resilience. Biomimicry presents a very promising solution to this issue. This is due to both the fact that it is an inspirational source of possible new innovation and because of the potential it offers as a way to create a more regenerative built environment.

In nature this has been well documented through the works of pioneers in the field of biology and evolution. Over many millennia the organisms that inhabit this planet have gone through countless environmental filters that have shaped and continue to inform the shape of organisms today. From early iterations to today’s counterparts the wealth of biological diversity is staggering and is testament to the earth’s testing ground. As supremely motivated and inquisitive creatures, gained from our ancestors. This intellectual base is constantly refined and rethought in an effort to sift through what is deemed unnecessary and excess and arrive at a new level of understanding and ability. Nature has provided this framework of constant improvement for us and it is this feature that is the basis for this thesis. The principle of Biomimetics strives to learn how nature has learned and to not necessarily imitate but distil from nature the qualities and characteristics of natural form and systems that may be applicable to our interpretation of architecture.

One possible way to explore the potential of biological principles present in nature is through their application within a computational design setup. What we are experiencing at this time in design history is one approach for the re-examination of nature using tools of technology and science.

Biomimetics for design is emerging in colleges and universities all over the world. The idea of finding a wide-spectrum method for considering nature is slowly appealing to a

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[1] Bill Reed is an internationally recognized proponent and practitioner of sustainability and an architect. He is also a principal in the regenerative planning firm Regenesis and an associate of the strategic environmental planning firm Natural Logic. He served as co-chair of the LEED Technical Committee from its inception in 1994 through 2003; is a member of the LEED Advanced faculty and one of the first of twelve USGBC trainers of the LEED Rating System and a founding Board Member of the US Green Building Council.

world facing limited resources, nuclear proliferation, and a climate out of synchronization. In such a situation, letting nature take a role as teacher has a logic that crosses academic barriers and suggests that the study of natural processes is a valuable component and potentially an equal partner with traditional biological disciplines researching nature. By automating parts of the design process, computers make it easier to develop designs through versioning and gradual adjustment. New design software enables the writing of scripts and codes, that when coupled to simulations of dynamic structural and environmental loads have the potential to extend design processes from the development and fabrication of a singular static artefact or building to families of variant forms that can respond to varying conditions.

Current development in computer software and technology represents an opportunity to fully explore the potential and benefits of biological principles found in nature, and their application in the process of architectural design, in an attempt to produce a more sustainable or regenerative built environment.

1.1.1 Why choose a biological theme?

There are characteristics of designed objects such as buildings, and characteristics of the ways designs are produced, viewed both at an individual and at a cultural level, which lend themselves peculiarly well to description and communication via biological metaphor. The ideas of ‘wholeness’, ‘coherence’, ‘correlation’ and ‘integration’, used to express the organised relationship between the parts of the biological organism, can be applied to describe similar qualities in the well-designed artefact. The adaptation of the organism to its environment, its fitness, can be compared to the harmonious relation of a building to its surroundings, and, more abstractly, to the appropriateness of any designed object for the various purposes for which it is intended. Perhaps most significantly it is biology, of all sciences, which first confronted the central problem of teleology, of *design* in nature; and it is very natural that of all sciences it should for this reason attract the special interest of designers. (Steadman P. 2008)

A second point is that as a matter of historical fact, it *has* been biology out of all the sciences to which architectural and design theorists have most frequently turned. Indeed it is surprising, in view of the ubiquity of biological references and ideas in the writings of the architectural theorists of the last hundred years, that no work of book length has so far been devoted to the history and theory of biological analogy. The history is certainly a fragmented one, leading into many remote corners and backwaters of the architectural literature. Nevertheless analogy with biology is a constant and recurring theme.
(Steadman P. 2008)

1.1.2 Research questions

In this context, a number of questions are addressed in this research:

- Is there an alternative to the currently prevailing approach to sustainability?
- How could biomimetic design benefit from new design software and technology?

- How could biological principles be applied in computational design?
- What is the potential of such a design approach?

1.1.3 Research Aim & Objectives

Life has had millions of years to finely-tune mechanisms and structures that work better than current technologies, require less energy and produce no life-unfriendly waste. The emulation of this technology is the goal of ‘biomimicry’, the art of innovation & design inspired by nature. Digital technologies on the other hand, are frequently applied to engineering fields resulting in improved solutions. Very few architects actually benefit from such technical advances in the field of sustainable architecture.

Research Aim:

The main objective of this thesis is to research the possibility of linking and applying biological principles in morphogenetic computational design, in an attempt to explore the potential of both emerging sciences in developing a more sustainable and regenerative architecture.

Objectives:

- Explore the potential of biomimicry in architecture.
- Study morphogenetic computational design, by establishing a theoretical and methodological framework for case-studies.
- Explore the possibility of implementing and correlating selected biological principles with morphogenetic design.
- Analyse and evaluate case studies representing such a possibility.

1.1.4 Structure & Methodology

Through an exploratory and analytical research, this thesis is an attempt to establish a link between biomimicry and morphogenetic computational design. It starts by the exploration of the influence of biomimicry on architecture, resulting in a set of selected principles that could be applied in computational design. These principles are then abstracted in order to use them as specific morphogenetic design concepts.

Morphogenetic computational design is then addressed and explored within this context, resulting in a theoretical and methodological framework for selected case studies. Case studies are then analysed in order to evaluate the application of such an approach on future sustainable architectural design, by comparison with conventional design means.

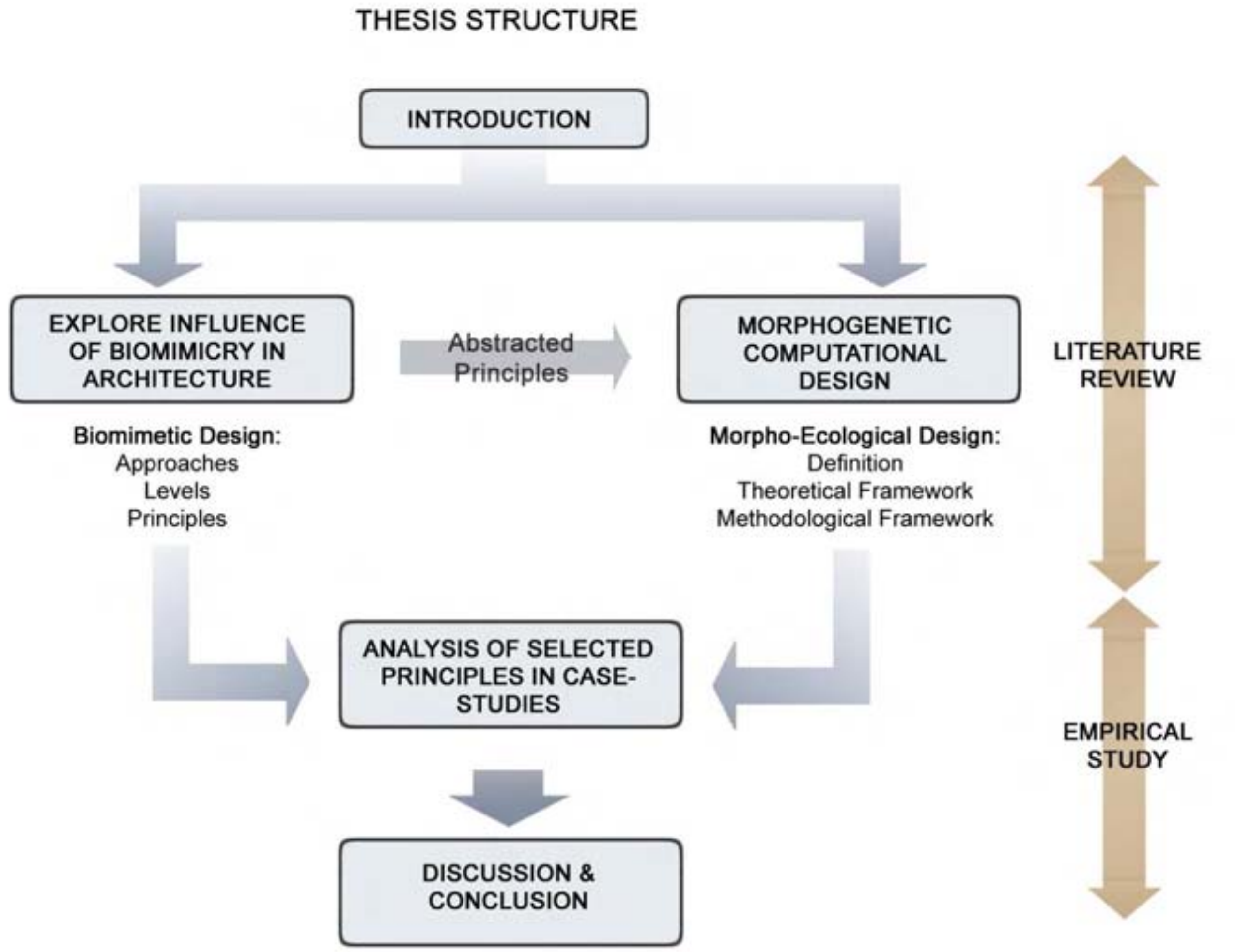

Figure 1: Thesis Structure Diagram

1.1.5 Scope

The scope of this research is the study and analysis of biomimicry as a significant tool for sustainable architectural design and construction, focusing on the possibility of applying selected biomimetic principles in morphogenetic computational design processes, thus highlighting an important link between biomimicry and morphogenesis and outlining its potential for future sustainable design.

This thesis does not deal with the cultural implications of what the formal physical appearance of a holistically designed architecture based on biomimetic principles should be or what cultural values it should reflect.

1.2 Background

Philip Steadman in his book: ‘The Evolution of Designs’ has presented a comprehensive overview regarding biomimicry and computational design; their origins and current research.

1.2.1 Historical Origins

Origins of Biomimicry:

The term *biomimicry* appeared as early as 1982 and was popularized by scientist and author Janine Benyus in her 1997 book *Biomimicry: Innovation Inspired by Nature*. *Biomimicry* is defined in her book as a "new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems". Benyus suggests looking to Nature as a "Model, Measure, and Mentor" and emphasizes sustainability as an objective of biomimicry.

But critics and philosophers since ancient Greece have looked to natural organisms as offering perfect models of that harmonious balance and proportion between the parts of a design which is synonymous with the classical ideal of beauty. The qualities of wholeness, of integrity, of a unity in structure such that the parts all contribute to the effect or purpose of the whole, and no part may be removed without some damage to the whole – these are central concepts in the aesthetics and in the natural history of Aristotle, and are characteristics in the Aristotelian view both of living beings and of the best works of art.

Architects and designers have looked to biology for inspiration since the beginnings of the science in the early nineteenth century. They have sought not just to imitate the forms of plants and animals, but to find methods in design analogous to the processes of growth and evolution in nature. Biological ideas are prominent in the writings of many modern architects, of whom Le Corbusier and Frank Lloyd Wright are just the most famous. Le Corbusier declared biology to be ‘the great new word in architecture and planning’.

The trouble with biological analogy in architecture in the past is that much of it has been of a superficial picture-book sort: ‘artistic’ photos of the wonders of nature through a microscope, juxtaposed with buildings or the products of industrial design. But analogy at a deeper level can be a most fundamental source of understanding and of scientific insight, as many writers on that subject have pointed out.

Although there is much that is completely new in recent ‘biological’ developments in the practice and theory of design, this work does nevertheless often tend to echo or reinterpret ideas in the earlier history of biological analogy. Modern research in ‘biomimetics’ (engineering analysis of organisms and their behaviour with a view to applying the same principles in design) gives a new name and new rigour to what went under the banner of ‘biotechnique’ or ‘biotechnics’ in the 1920s and 1930s.

Introducing computers:

What has happened over the last thirty years is that there has been a great flowering of new theory in architecture and design, looking not just to understand and imitate natural forms, but seeking insights at deeper levels into biological processes, from which designers might derive models and methods. This activity has gathered pace over the past two decades. One reason has been the growing environmental crisis, the rise of green and sustainable design, and a belief that an architecture in closer harmony with nature needs to take lessons from organic forms and systems.

A second major stimulus has been the general introduction of computers into the everyday practice of engineers, architects and industrial designers. Computer-aided design was just 16 years old in 1979 – taking Ivan Sutherland's[2] *Sketchpad* system of 1963 as year zero. The technology in those days was unwieldy and expensive, the users mostly government departments and big companies, and the focus in architecture on prefabricated industrial systems of construction. In terms of method the emphasis was on static representation of finished designs in drawings and virtual 3D models, the automatic evaluation of structural, thermal and a few other aspects of physical performance, and costing. There was much academic interest in methods for the automated generation of architectural form by computer, but little solid progress.

All this changed when computers arrived on every desk in the 1980s, and when powerful new graphics and modelling software gave designers the means to create and explore new worlds of complex, fluid, curvilinear, 'biomorphic' shape. (The equation of 'biological' with 'non-rectangular' could sometimes nevertheless be rather simplistic.) Programs for simulating different aspects of the behaviour of mechanisms and structures allowed engineers to introduce explicitly 'evolutionary' methods for optimising performance. From as

Figure 2: Model of rose campion (Lychnis coronaria) expressed using a context-free L-system generated with L-Studio, a software package developed at the Department of Computer Science at the University of Calgary. (Source: AD Journal volume 78 No. 2, 2008)

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[2] Ivan Edward Sutherland (born 1938 in Hastings, Nebraska) is an American computer scientist and Internet pioneer. He received the Turing Award from the Association for Computing Machinery in 1988 for the invention of Sketchpad, an early predecessor to the sort of graphical user interface that has become ubiquitous in personal computers.

early as the 1960s computer scientists had begun to devise ‘genetic algorithms’ whose mode of operation closely mimics natural evolution, for solving otherwise intractable computational problems and for producing software semi-automatically. Since the 1990s design researchers have been building these algorithms into experimental computer systems that ‘evolve’ the designs of buildings and other artefacts.

1.2.2 Current Research

Janine Benyus (2002) lists three types of biological entity on which technology might be modelled: natural methods of (chemical) manufacture; mechanisms and structures found in nature; and organisational principles in the social behaviour of animals. Centres for the study of biomimetics have sprung up in recent years in universities all over the world, under such names as the Biologically Inspired Systems Lab in Sweden, the Centre for Biologically Inspired Designs at Georgia Tech, Atlanta, and the Centre for Biologically Inspired Materials and Material Systems at Duke University, North Carolina. A new journal of *Bioinspiration and Biomimetics* has started publication in 2007. In Britain there are centres for biomimetics at both Bath and Reading Universities. The Reading group was set up by George Jeronomidis and Julian Vincent, stimulated in part by their Professor Jim Gordon’s book *The New Science of Strong Materials* (Centre for Biomimetics 2007). Research in the centre has concentrated on the properties of organic materials such as bone, collagen, chitin (from which the carapaces of insects are made), cellulose, and the silk of spiders’ webs.

Jeronomidis (2004) has turned his mind to possible architectural applications of this research. Rigidity is created in plant structures by the fluid pressure in cells. Similar principles might be applied in pneumatic or hydraulic structures for buildings, as Frei Otto was the first to recognise. Plants change their forms in response to light – petals open and shut, sunflowers track the sun – providing possible models for environmental controls.

Contemporary architects and researchers are pursuing comparable analogies of design with growth. In some cases they are experimenting with computer systems that first ‘grow’ designs, and then evolve them. One technique that has proved of particular interest to architects in this context is the Lindenmayer grammar or L-grammar (sometimes L-system) due to the botanist Aristid Lindenmayer. The L-grammar is a rule-based system for representing the topology of the branching structures of plants by means of symbols. L-grammars are not confined to describing plant-like forms however, but can be used for generating structures and surfaces that more closely approximate those of buildings. The architect Dennis Dollens uses software based on L-systems to design constructional elements with complex curved forms for an organic architecture that makes explicit reference to animal and plant morphology.

The Genr8 tool for designing ‘interesting’ surfaces resembling natural forms has been developed by Una-May O’Reilly, Martin Hemberg and Achim Menges of the Emergent Design Group at MIT and the Emergent Design and Technologies Group at the Architectural Association in London (O’Reilly *et al.* 2004; O’Reilly and Hemberg 2007). Genr8 allows 3D digital surfaces to be grown using L-systems in response to a simulated environment that mimics *tropisms*, reactions to environmental influences like those acting on plants, such as gravity and sunlight.

Other architects have been generating ‘organic’ doubly curved surfaces with the help of software that has no basis in biological process or structure, as evolutionary algorithms and L-systems have. There may be much talk of ‘morphogenesis’, and a rich stew of other biological concepts invoked, but the truth is that the main analogy with nature is at the level of appearances only, and specifically with the non-rectangularity of nature.

In this thesis one of the main sources of investigating biologically inspired design as well as computational design is the writings of Michael Hensel, Achim Menges and Michael Weinstock of the Emergent Technologies and Design Group at the Architectural Association in London. Their research focuses on a very specific interdisciplinary approach to design that is embedded in technological development and design innovation. They investigate new strategies for design that are derived from the evolutionary development of living systems, from their material properties and metabolisms, and from their adaptive responses to changes in the environment.

CHAPTER 2: INFLUENCE OF BIOMIMICRY ON ARCHITECURAL DESIGN

2.1 Introduction

Biomimicry, where flora, fauna or entire ecosystems are emulated as a basis for design, is a growing area of research in the fields of architecture and engineering. This is due to both the fact that it is an inspirational source of possible new innovation and because of the potential it offers as a way to create a more sustainable and even regenerative built environment. The widespread and practical application of biomimicry as a design method remains however largely unrealised. A growing body of international research identifies various obstacles to the employment of biomimicry as an architectural design method. One barrier of particular note is the lack of a clear definition of the various approaches to biomimicry that designers can initially employ. (Pedersen Zari, M. 2007).

This chapter elaborates on distinct approaches to biomimetic design that have evolved. A framework for understanding the various forms and levels of biomimicry has been developed, and is used to discuss the distinct advantages and disadvantages inherent in each as a design methodology. It is shown that these varied approaches may lead to different outcomes in terms of overall sustainability or regenerative potential.

It is posited that a biomimetic approach to architectural design that incorporates an understanding of ecosystems could become a vehicle for creating a built environment that goes beyond simply sustaining current conditions to a restorative practice where the built environment becomes a vital component in the integration with and regeneration of natural ecosystems. A focus is made on ecosystem biomimicry, highlighting its general characteristics and principles.

Further, specific set biological design principles are selected for further discussion and analysis in the following chapters.

2.2 Design Approaches

A comparative literature review and examination of existing biomimetic technologies was conducted by M. Pedersen Zari at Victoria University in New Zealand in 2007. It is apparent that distinct approaches to biomimetic design exist, each with inherent advantages and disadvantages. These diverse approaches may have markedly different outcomes in terms of overall sustainability. While some designers and scientists employ biomimicry specifically as a method to increase the sustainability of what they have created, biomimicry is also used in some cases simply as a source of novel innovation (Baumeister, 2007b). As demonstrated by Reap et al (2005), a biomimetic design approach does not necessarily mean the resulting product or material will be more sustainable than a conventional equivalent when analysed from a life cycle perspective.

Approaches to biomimicry as a design process typically fall into two categories: Problem-Based Approach and Solution-Based Approach explained in the following paragraphs.

2.2.1 Problem-Based Approach

Throughout literature review, this approach was found to have different naming, such as “Design looking to biology” (Pedersen Zari, M. 2007), “Top-down Approach” (Jean Knippers 2009) and “Problem-Driven Biologically Inspired Design” (Michael Helms, Swaroop S. Vattam and Ashok K. Goel, 2009) all referring to the same meaning.

In this approach, designers look to the living world for solutions and are required to identify problems and biologists then need to match these to organisms that have solved similar issues. This approach is effectively led by designers identifying initial goals and parameters for the design.

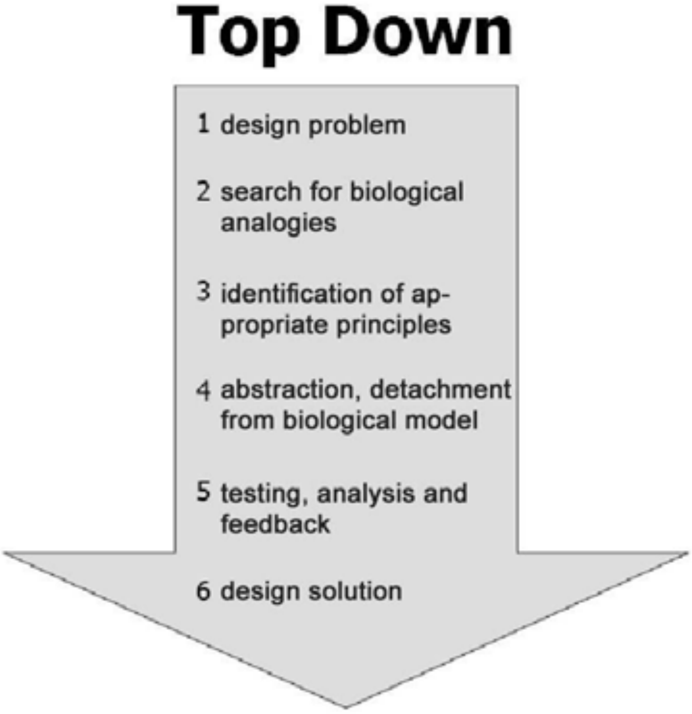


Figure 3: Top-Down Design Approach

The pattern of problem-driven biologically inspired design follows a progression of steps which, in practice, is non-linear and dynamic in the sense that output from later stages frequently influences previous stages, providing iterative feedback and refinement loops. (Michael Helms, Swaroop S. Vattam and Ashok K. Goel, 2009)

An example of such an approach is DaimlerChrysler’s prototype *Bionic Car* (fig.4). In order to create a large volume, small wheel base car, the design for the car was based on the boxfish *(ostracion meleagris)*, a surprisingly aerodynamic fish given its box like shape. The chassis and structure of the car are also biomimetic, having been designed using a computer modelling method based upon how trees are able to grow in a way that minimises stress concentrations. The resulting structure looks almost skeletal, as material is allocated only to the places where it is most needed. (Vincent et al., 2006).

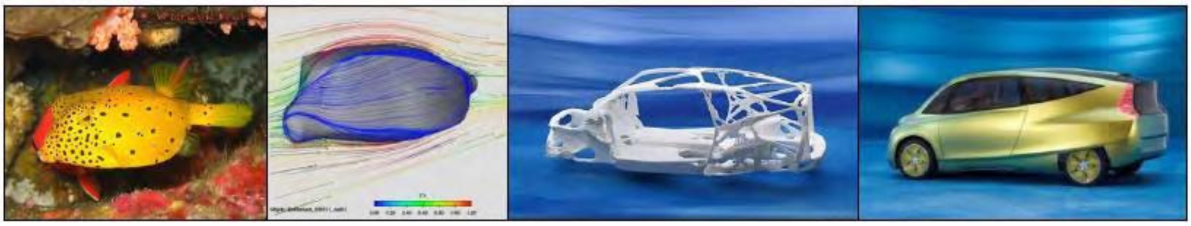


Figure 4: DaimlerCrysler bionic car inspired by the box fish and tree growth patterns. (Source: Pedersen Zari, M. 2007).

The possible implications of architectural design where biological analogues are matched with human identified design problems are that the fundamental approach to solving a given problem and the issue of how buildings relate to each other and the ecosystems they are part of is not examined. The underlying causes of a non-sustainable or even degenerative built environment are not therefore necessarily addressed with such an approach.

The *Bionic Car* illustrates the point. It is more efficient in terms of fuel use because the body is more aerodynamic due to the mimicking of the box fish. It is also more materials efficient due to the mimicking of tree growth patterns to identify the minimum amount of material need in the structure of the car. The car itself is however not a new approach to transport. Instead, small improvements have been made to existing technology without a re-examination of the idea of the car itself as an answer to personal transport. (Pedersen Zari, M. 2007)

Designers are able to research potential biomimetic solutions without an in depth scientific understanding or even collaboration with a biologist or ecologist if they are able to observe organisms or ecosystems or are able to access available biological research. With a limited scientific understanding however, translation of such biological knowledge to a human design setting has the potential to remain at a shallow level. It is for example easy to mimic forms and certain mechanical aspects of organisms but difficult to mimic other aspects such as chemical processes without scientific collaboration. (Pedersen Zari, M. 2007)

Despite these disadvantages, such an approach might be a way to begin transitioning the built environment from an unsustainable to efficient to effective paradigm (McDonough, 2002).

Figure 5: Design Spiral by the Biomimicry Institute

The Biomimicry Institute has referred to this design approach and explained it through the “Challenge to Biology Design Spiral” as illustrated in figure 4.

Research held in Georgia Institute of Technology by Michael Helms, Swaroop S. Vattam and Ashok K. Goel, at the Design Intelligence Lab in 2006, also defined this approach through 6 definite steps, which are very similar to those defined by the Biomimicry Institute:

- **Step 1:** problem definition
- **Step 2:** reframe the problem
- **Step 3:** biological solution search
- **Step 4:** define the biological solution
- **Step 5:** principle extraction
- **Step 6:** principle application

(Michael Helms, Swaroop S. Vattam and Ashok K. Goel, 2009)

2.2.2 Solution-Based Approach

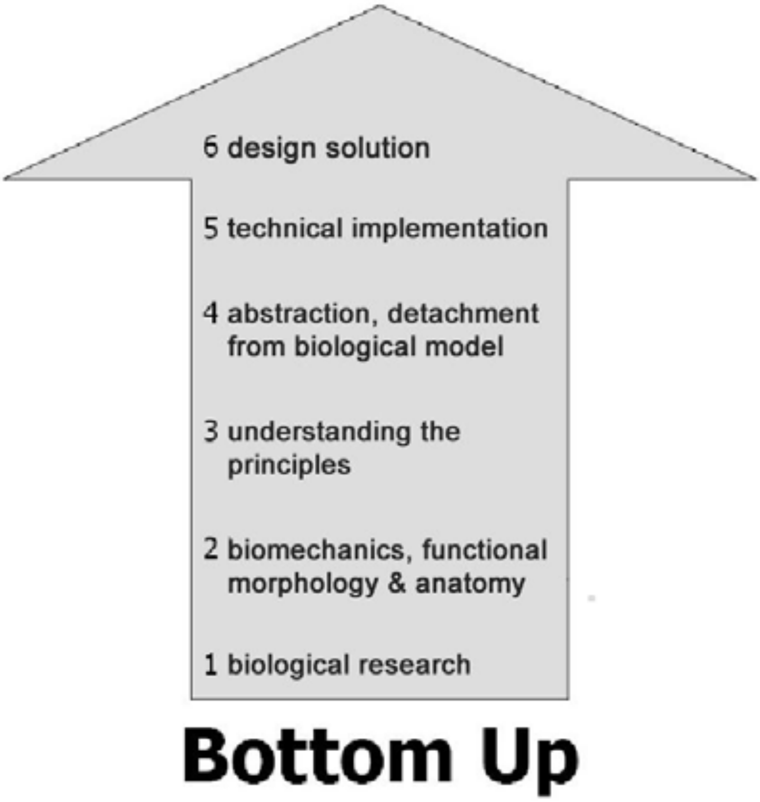


Figure 6: Bottom-Up Approach

As stated in the previous approach, this approach was also found to have different naming such as “Biology Influencing Design”, “Bottom-Up Approach” and “Solution-Driven Biologically Inspired Design”.

When biological knowledge influences human design, the collaborative design process is initially dependant on people having knowledge of relevant biological or ecological research rather than on determined human design problems. A popular example is the scientific analysis of the lotus flower emerging clean from swampy waters, which led to many design innovations as detailed by Baumeister (2007a), including Sto’s *Lotusan* paint which enables buildings to be self cleaning.

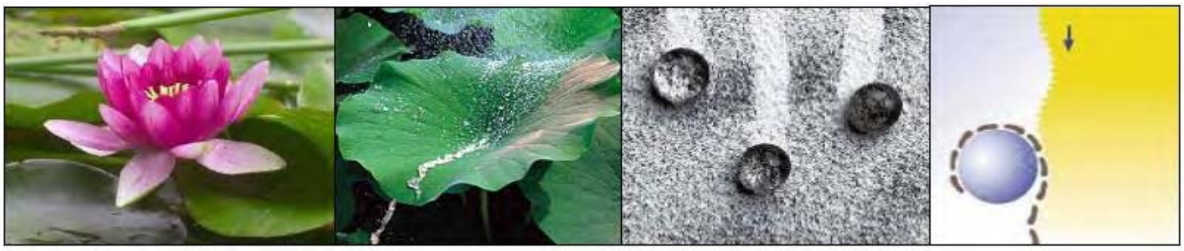


Figure 7: Lotus inspired Lotusan Paint (Source: Pedersen Zari, M. 2007).

An advantage of this approach therefore is that biology may influence humans in ways that might be outside a predetermined design problem, resulting in previously unthought-of technologies or systems or even approaches to design solutions. The potential for true shifts in the way humans design and what is focused on as a solution to a problem, exists with such an approach to biomimetic design. (Vincent et al., 2005)

A disadvantage from a design point of view with this approach is that biological research must be conducted and then identified as relevant to a design context. Biologists and ecologists must therefore be able to recognise the potential of their research in the creation of novel applications.

Research held in Georgia Institute of Technology by Michael Helms, Swaroop S. Vattam and Ashok K. Goel, at the Design Intelligence Lab in 2006, also defined this approach through 7 definite steps:

- **Step 1:** biological solution identification
  Here, designers start with a particular biological solution in mind.
- **Step 2:** define the biological solution
- **Step 3:** principle extraction
- **Step 4:** reframe the solution
  In this case, reframing forces designers to think in terms of how humans might view the usefulness of the biological function being achieved.
- **Step 5:** problem search
  Whereas search in the biological domain includes search through some finite space of documented biological solutions, problem search may include defining entirely new problems. This is much different than the solution search step in the problem-driven process.
- **Step 6:** problem definition
- **Step 7:** principle application

2.3 Levels of Biomimicry

Within the two approaches discussed, three levels of biomimicry that may be applied to a design problem are typically given as *form, process and ecosystem* (Biomimicry Guild, 2007). In studying an organism or ecosystem, *form* and *process* are aspects of an organism or ecosystem that could be mimicked.

A framework for understanding the application of biomimicry is proposed that redefines these different levels and also attempts to clarify the potential of biomimicry as a tool to increase regenerative capacity of the built environment. By defining the kinds of biomimicry that have evolved, this framework may allow designers who wish to employ biomimicry as a methodology for improving the sustainability of the built environment to identify an effective approach to take. The framework that will be described here is applicable to both approaches (design looking to biology, and biology influencing design). The first part of the framework determines which aspect of 'bio' has been 'mimicked'. This is referred to here as a *level*. (Pedersen Zari, M. 2007)

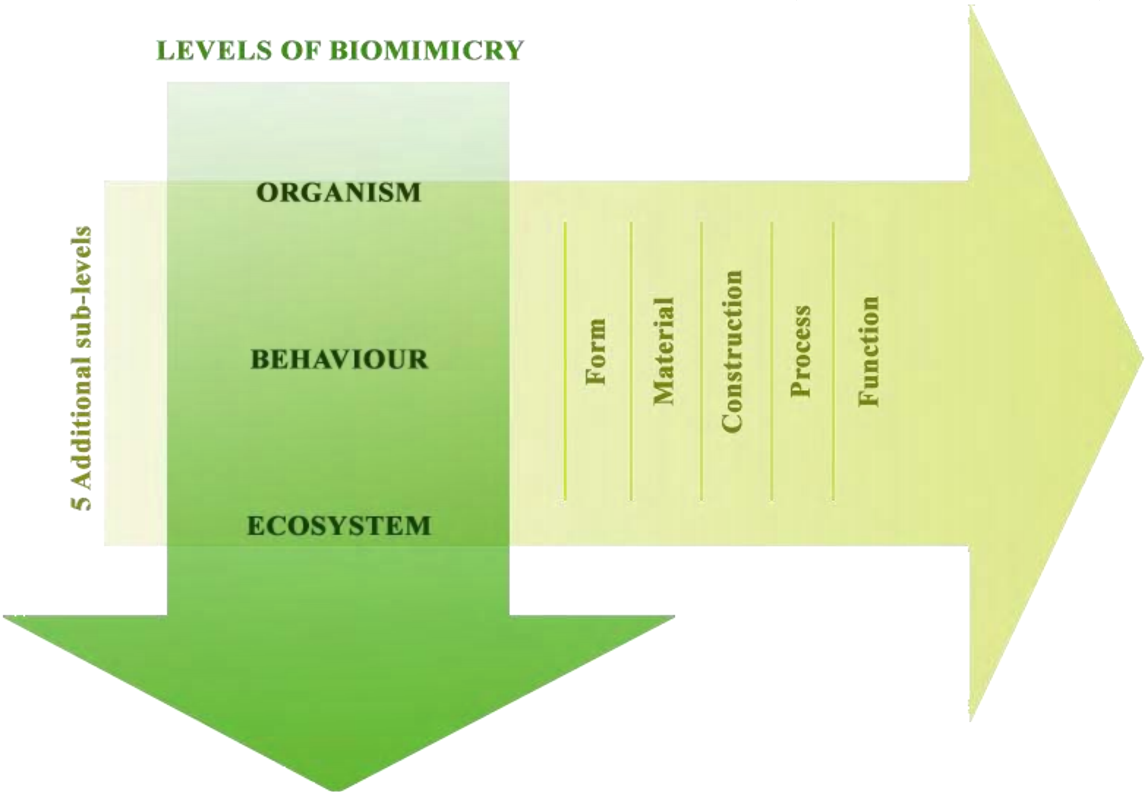


Figure 8: Levels of Biomimicry

Through an examination of existing biomimetic technologies it is apparent that there are three levels of mimicry; the organism, behaviour and ecosystem. The organism level refers to a specific organism like a plant or animal and may involve mimicking part of or the whole organism. The second level refers to mimicking behaviour, and may include translating an aspect of how an organism behaves, or relates to a larger context. The third level is the mimicking of whole ecosystems and the common principles that allow them to successfully function. (Pedersen Zari, M. 2007)

Levels of Biomimicry	Example : Building that mimics termites	
Organism level (Mimicry of a specific organism)	Form	The building looks like a termite.
	Material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	Construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	Function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	Form	The building looks like it was made by a termite; a replica of a termite mound for example.
	Material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	Construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	Process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or the building mimics how termites work together.
	Function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example(fig.12). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	Form	The building looks like an ecosystem (a termite would live in).
	Material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	Construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	Process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	Function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Table 1: A Framework for the Application of Biomimicry (adapted from Pedersen Zari M., 2007).

Within each of these levels, a further five possible dimensions to the mimicry exist. The design may be biomimetic for example in terms of what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function). The differences between each kind of biomimicry are described in Table 1 and are exemplified by looking at how different aspects of a termite, or ecosystem a termite is part of could be mimicked. (Pedersen Zari, M. 2007)

It is expected that some overlap between different kinds of biomimicry exists and that each kind of biomimicry is not mutually exclusive. For example, a series of systems that is able to interact like an ecosystem would be functioning at the ecosystem level of biomimicry. The individual details of such a system may be based upon a single organism or behaviour mimicry however; much like a biological ecosystem is made up of the complex relationships between multitudes of single organisms. (Pedersen Zari, M. 2007)

2.3.1 Organism Level

Species of living organisms have typically been evolving for millions of years. Those organisms that remain on Earth now have the survival mechanisms that have withstood and adapted to constant changes over time. As Baumeister (2007a) points out *'the research and development has been done'.* Humans therefore have an extensive pool of examples to draw on to solve problems experienced by society that organisms may have already addressed, usually in energy and materials effective ways. This is helpful for humans, particularly as access to resources changes, the climate changes and more is understood about the consequences of the negative environmental impact that current human activities have on many of the world's ecosystems. (Alberti et al., 2003)

An example is the mimicking of the Namibian desert beetle, *stenocara* (Garrod et al., 2007). The beetle lives in a desert with negligible rainfall. It is able to capture moisture however from the swift moving fog that moves over the desert by tilting its body into the wind. Droplets form on the alternating hydrophilic – hydrophobic rough surface of the beetle's back and wings and roll down into its mouth (Parker and Lawrence, 2001). Matthew Parkes of KSS Architects demonstrates process biomimicry at the organism level inspired by the beetle, with his proposed fog-catcher design for the Hydrological Center for the University of Namibia (fig. 9) (Killeen, 2002). Ravilious (2007) and Knight (2001) discuss a more specific material biomimicry at the organism level, where the surface of the beetle has been studied and mimicked to be used for other potential applications such as to clear fog from airport runways and improve dehumidification equipment for example.

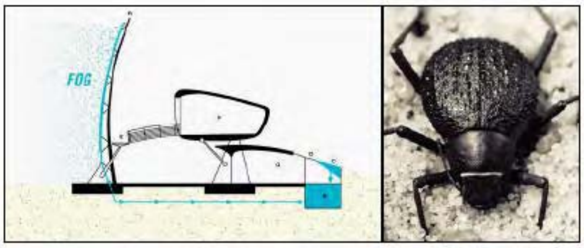


Figure 9: Matthew Parkes' Hydrological Centre University of Namibia and the stenocara beetle.
(Source: Pedersen Zari, M. 2007).

Figure 10: Nicholas Grimshaw & Partners' Waterloo, International Terminal and the pangolin.
(Source: Pedersen Zari, M. 2007).

Nicholas Grimshaw & Partners' design for the Waterloo International Terminal demonstrates an example of form and process biomimicry at the organism level (fig. 10). The terminal needed to be able to respond to changes in air pressure as trains enter and depart the terminal. The glass panel fixings that make up the structure mimic the flexible scale arrangement of the Pangolin so they are able to move in response to the imposed air pressure forces. (Aldersey-Williams, 2003)

Mimicking an organism alone however without also mimicking how it is able to participate in and contribute to the larger context of the ecosystem it is in, has the potential to produce designs that remain conventional or even below average in terms of environmental impact (Reap et al., 2005). Because mimicking of organisms tends to be of a specific feature, rather than a whole system, the potential also remains that biomimicry becomes technology that is added onto buildings rather than being integral to them, particularly if designers have little biological knowledge and no not collaborate with biologists or ecologists during the early design stages. While this method may result in new and innovative building technologies or materials, methods to increase sustainability are not necessarily explored. (Pedersen Zari, M. 2007)

2.3.2 Behaviour Level

A great number of organisms encounter the same environmental conditions that humans do and need to solve similar issues that humans face. As discussed, these organisms tend to operate within environmental carrying capacity of a specific place and within limits of energy and material availability. These limits as well as pressures that create ecological niche adaptations in ecosystems mean not only well-adapted organisms continue to evolve, but also well-adapted organism behaviours and relationship patterns between organisms or species. (Reap et al., 2005)

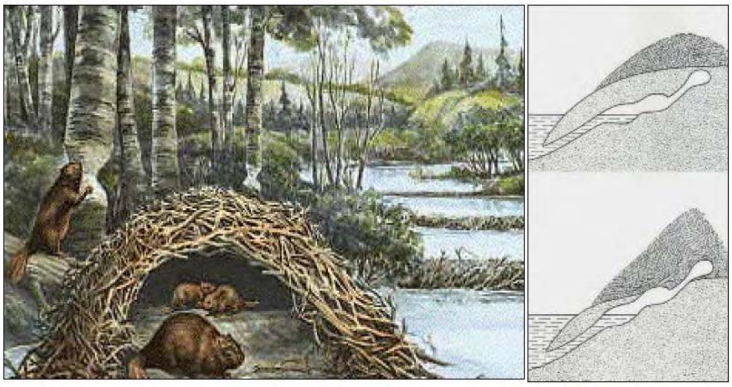


Figure 11: The North American beaver.
(Source: Pedersen Zari, M. 2007).

Organisms that are able to directly or indirectly control the flow of resources to other species and who may cause changes in biotic or abiotic (non living) materials or systems and therefore habitats are called *ecosystem engineers* (Jones and Lawton, 1995, Rosemond and Anderson, 2003). Ecosystem engineers alter habitat either through their own structure (such as coral) or by mechanical or other means (such as beavers and woodpeckers). Humans are undoubtedly effective ecosystem engineers, but may gain valuable insights by looking at how other species are able to change their environments while creating more capacity for life in that system. Several authors provide examples and details of organisms altering their own habitats while facilitating the presence of other species, increasing nutrient cycling and creating mutually beneficial relationships between species. The building behaviour of other species is often termed *'animal architecture'* (von Frisch and von Frisch, 1974, Hansell, 2005) and may provide further examples of such ecosystem engineers.

The famous example of the North American beaver *(castor canadensis)* (fig. 11) demonstrates how through its altering of the landscape, wetlands are created and nutrient retention and plant and animal diversity is increased, helping in part to make the ecosystem more resilient to disturbance. (Rosemond and Anderson, 2003)

In behaviour level biomimicry, it is not the organism itself that is mimicked, but its behaviour. It may be possible to mimic the relationships between organisms or species in a similar way. An architectural example of process and function biomimicry at the behaviour level is demonstrated by Mick Pearce's Eastgate Building in Harare, Zimbabwe and the CH2 Building in Melbourne, Australia (figure 12). Both buildings are based in part on techniques of passive ventilation and temperature regulation observed in termite mounds, in order to create a thermally stable interior environment. Water which is mined (and cleaned) from the sewers beneath the CH2 Building is used in a similar manner to how certain termite species will use the proximity of aquifer water as an evaporative cooling mechanism. (Pedersen Zari, M. 2007)

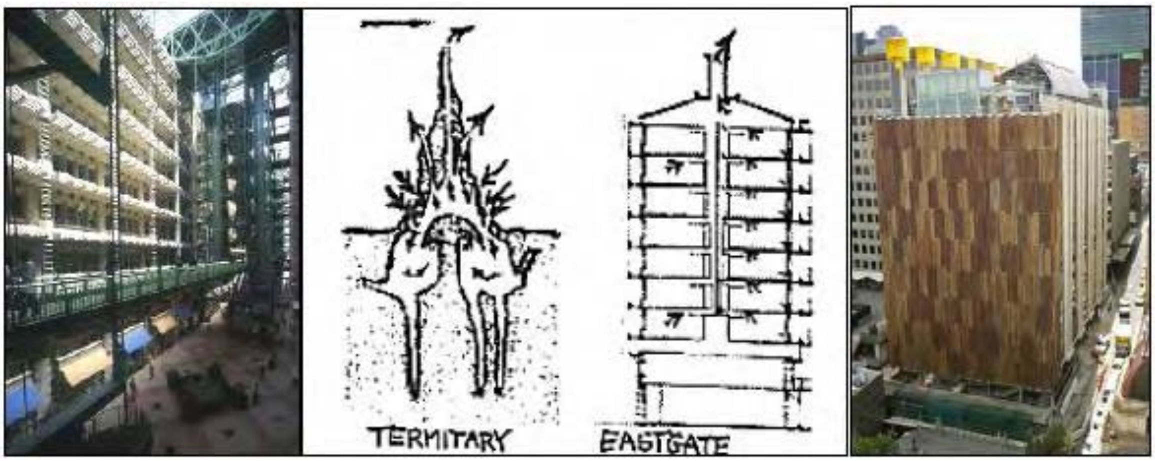


Figure 12: Eastgate Building in Harare, Zimbabwe and CH2 Building in Melbourne, Australia.
(Source: Pedersen Zari, M. 2007).

Behaviour level mimicry requires ethical decisions to be made about the suitability of what is being mimicked for the human context. Not all organisms exhibit behaviours that are suitable for humans to mimic and the danger exists that models of consumption or exploitation could be justified on the basis of how another species behaves. For example, mimicking the building behaviour (and outcome of that) of termites might be appropriate for the creation of passively regulated thermally comfortable buildings. Mimicking the social structure of termite colonies would not be suitable however if universal human rights are valued. It may be more appropriate to mimic specific building and survival behaviours that will increase the sustainability and regenerative capacity of human built environments rather than mimicking that could be applied to social or economic spheres without careful consideration. It may be more appropriate to mimic whole systems rather than single organisms in this regard. An example is Benyus' (1997) assertion that we should *'do business like a redwood forest'*. (Pedersen Zari, M. 2007)

2.3.3 Ecosystem Level

The mimicking of ecosystems is an integral part of biomimicry as described by Benyus (1997) and Vincent (2007). The term ecomimicry has also been used to describe the mimicking of ecosystems in design (Lourenci et al., 2004, Russell, 2004), while Marshall (2007) uses the term to mean a sustainable form of biomimicry where the objective is the wellbeing of ecosystems and people, rather than *'power, prestige or profit'*. Proponents of industrial, construction and building ecology advocate mimicking of ecosystems (Graham, 2003, Kibert et al., 2002, Korhonen, 2001) and the importance of architectural design based on an understanding of ecology is also discussed by researchers advocating a shift to regenerative design. (Reed, 2006)

An advantage of designing at this level of biomimicry is that it can be used in conjunction with other levels of biomimicry (organism and behaviour). It is also possible to incorporate existing established sustainable building methods that are not specifically biomimetic such as interfaced or bio-assisted systems, where human and non-human systems are merged to the mutual benefit of both. An example is John and Nancy Todd's Living or Eco Machines where the process of waste water treatment in ecosystems is mimicked and also integrated with plants (Todd, 2004, Todd and Josephson, 1996). The Australian developed Biolytix® system mimics soil based decomposition to treat grey and black water and again integrates actual worms and soil microbes into the process. (Allen, 2005, Baumeister, 2007a)

A further advantage of an ecosystem based biomimetic design approach is that it is applicable to a range of temporal and spatial scales (Reap et al., 2005) and can serve as an initial benchmark or goal for what constitutes truly sustainable or even regenerative design for a specific place.

The most important advantage of such an approach to biomimetic design however may be the potential positive effects on overall environmental performance. Ecosystem based biomimicry can operate at both a metaphoric level and at a practical functional level. At a metaphoric level, general ecosystem principles (based on how most ecosystems work) are able to be applied by designers with little specific ecological knowledge. Several authors have offered such general principles (Benyus, 1997, McDonough and Braungart, 2002, de Groot et al., 2002). A set of ecosystem principles derived from comparing these cross disciplinary understandings of how ecosystems function is detailed by Pedersen Zari and Storey (2007). If the built environment was designed to be a system and was expected to behave like an ecosystem even if only at the level of metaphor, the environmental performance of the built environment may increase. (Korhonen, 2001)

On a functional level, ecosystem mimicry could mean that an in-depth understanding of ecology drives the design of a built environment that is able to participate in the major biogeochemical material cycles of the planet (hydrological, carbon, nitrogen etc) in a reinforcing rather than damaging way (Charest, 2007). That a greater understanding of ecology and systems design is required on the part of the design team is implicit. Also required would be increased collaboration between disciplines that traditionally seldom work together such as architecture, biology and ecology. Such an approach challenges conventional architectural design thinking, particularly the typical boundaries of a building site and time scales a design may operate in. (Pedersen Zari, M. 2007)

While Kibert (2006) cites a number of authors advocating similar ideas, he criticises this kind of approach to design, because of the difficulty in understanding and modelling ecosystems and asserts that *'…the mimicking of nature in human designs is one dimensional [and] non-complex…'* This is true in terms of realised built form, but does not suggest that mimicking what is known about ecosystems is not a worthy goal in terms of increasing sustainability or indeed that it is impossible, particularly when one takes into account that biological knowledge may be doubling every 5 years. (Benyus, 1997)

As discussed, most examples of biomimicry are organism biomimetic. While biomimicry at the organism level may be inspirational for its potential to produce novel architectural designs (Aldersey-Williams, 2003, Feuerstein, 2002), the possibility exists that a building as part of a larger system, that is able to mimic natural processes and can function like an ecosystem in its creation, use and eventual end of life, has the potential to contribute to a built environment that goes beyond sustainability and starts to become regenerative (Van der Ryn, 2005; Reed, 2006). This does not prevent organism biomimicry at a detail or material level.

The examples provided in table 1 demonstrate the deepening of the levels of biomimicry in terms of regenerative potential from form biomimicry at the organism level to functional biomimicry at the ecosystem level. A building that is exhibiting form biomimicry, which is stylistically or aesthetically based on an organism, but is made and functions in an otherwise conventional way, is unlikely to be more sustainable than a non-biomimetic building. (Pedersen Zari, M. 2007)

A building that is able to mimic natural processes and can function like an ecosystem in its creation, use and eventual end of life has greater potential to be part of a regenerative built environment. It is suggested that if biomimicry is to be conceived as a way to increase sustainability of an architectural project, mimicking of general ecosystem principles should be incorporated into the design at the earliest stage and used as an evaluative tool throughout the design process as described by the Biomimicry Guild (2007), Pedersen Zari and Storey (2007) and Hastrich (2006).

2.4 Principles of Ecosystem Biomimicry

A set of ecosystem principles derived from comparing cross disciplinary understandings of how ecosystems function is detailed by Pedersen Zari and Storey (2007) as follows.

By conducting a comparative analysis of related knowledge of ecosystem principles in the disciplines of ecology, biology, industrial ecology ecological design and biomimicry, a group of ecosystem principles aiming to capture cross disciplinary understandings of ecosystem functioning was formulated. It is intended that this biomimetic theory in the form of a set of principles based on ecosystem function could be employed by designers, to aid in the evolution of methodologies to enable the creation of a more sustainable built environment. (Pedersen Zari, M. and J. B. Storey, 2007)

The following sources were used: Benyus (1997), Berkebile & McLennan (2004), Biomimicry Guild (2007), Copeman (2006), de Groot et al. (2002), Faludi (2005), Hastrich (2006), Hoeller (2006), Kelly (1994), Kibert et al. (2002), Korhonen (2001), McDonough & Braungart (2002), Reap et al. (2005), Thompson (1942), Vincent (2002), Vincent et al. (2006) and Vogel (1998). Additional sources, typically from the discipline of ecology were used to expand upon each principle.

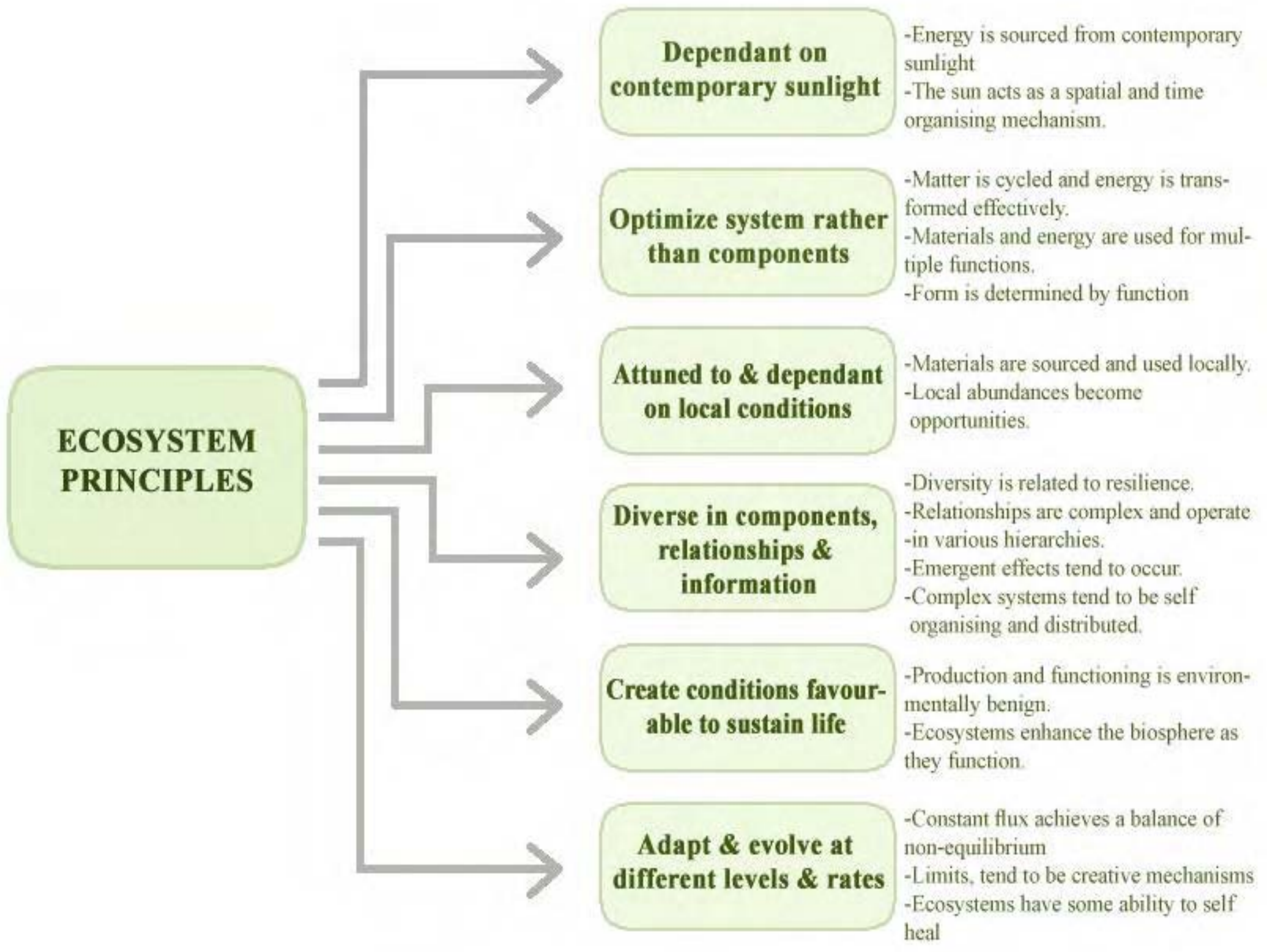


Figure 13: Ecosystem Principles

It should be noted that ecology literature typically does not offer sets of generalised principles but tends to explore the complexities of certain aspects of ecosystems, and that there are a number of controversial theories in ecology, such as the exact process and mechanisms of evolution and ecological succession for example (Kay & Schneider, 1994).

The ecosystem principles provided here are generalised norms for the way most ecosystems operate rather than absolute laws and should be taken as a starting point for further research to fully understand the different and important aspects of each simplified principle. They are in a list format (with a brief explanation following) in order to be an easily usable set of generalised principles that if employed by designers with limited background knowledge in ecology could significantly improve the sustainability of the human built environment.

Ecosystem principles can be applied to the design process by transforming them into a set of design principles that are in the form of questions that are asked of the project at all stages of the design (Biomimicry Guild, 2007, Charest, 2007).

Research conducted by Pedersen Zari and Storey (2007) explains ecosystem principles as follows:

- Ecosystems are dependent on contemporary sunlight.
- Ecosystems optimise the system rather than its components.
- Ecosystems are attuned to and dependant on local conditions.
- Ecosystems are diverse in components, relationships and information.
- Ecosystems create conditions favourable to sustained life.
- Ecosystems adapt and evolve at different levels and at different rates.

2.4.1 Ecosystems are dependent on contemporary sunlight.

- Energy is sourced from contemporary sunlight.
- The sun acts as a spatial and time organising mechanism.

Solar radiation is the only input into the closed loop ecosystem of earth and except for gravitational effects of the moon, is the only source of energy either directly or indirectly available to organisms. The majority of ecosystems exist through utilising contemporary sunlight (recently received from the sun) that has been converted by photosynthesis into biomass, which forms the basis of the food chain (Kibert et al., 2002). In contrast, humans currently source a large proportion of energy from ancient sunlight in the form of hydro carbon fuels.

The sun also acts as a timing and directional orientation or spatial organisation mechanism. Biological rhythms such as diurnal and annual (or longer) cycles are determined by the sun’s gravitational effect and the rotation of the earth. Migration patterns or flowering seasons in some species in response to these cycles are examples of the role the sun (or the earth’s relative position to it) has in timing mechanisms in ecosystems.

If the built environment was based on this one principle alone as is advocated by sustainable design theory in general, where its energy was sourced from contemporary sunlight (including wind, hydro and biomass) and it was sited and organised according to climate, environmental impact would be considerably less and there may be consequent significant positive physical and psychological health impacts (Kellert, 2005).

2.4.2 Ecosystems optimise the system rather than its components.

- Matter is cycled and energy is transformed effectively.
- Materials and energy are used for multiple functions.
- Form tends to be determined by function.

Ecosystems use energy and materials in a way that optimises the whole system rather than individual components (Kelly, 1994). What would appear to be inefficiency in individual organisms can sometimes equate to effectiveness for the entire system (McDonough & Braungart, 2002).

In an example of both materials and energy effectiveness, organisms in ecosystems tend to use materials for more than one function (Benyus 1997). This means less energy is expended and can be used for other functions such as health, growth and reproduction etc.

Reap et al. (2005) describe the characteristic of form fitting to function as 'the use of limited materials and metabolic energy to create only structures and execute only processes necessary for the functions required of an organism in a particular environment.' Geometry and relative proportions found in nature are offered as examples of materials and energy efficiency by various authors (Vogel, 1998, Faludi, 2005).

A built environment that mimicked this aspect of ecosystems through increased communication and organisation to ensure effective material cycles and careful energy flow would challenge conventional attitudes to building boundaries and the idea of waste.

2.4.3 Ecosystems are attuned to and dependant on local conditions.

- Materials tend to be sourced and used locally.
- Local abundances become opportunities.

Species that make up ecosystems tend to be linked in various relationships with other organisms in close proximity (Allenby & Cooper 1994). They typically utilise resources and local abundances from their immediate range of influence, and tend to be well adapted to their specific microclimatic conditions (Reap et al. 2005).

The functions required for an ecosystem to continue and remain in dynamic balance including the cycling and production of materials, are usually carried out by species within the system, existing in specific niches and linked with each other (Benyus, 1997). The ecosystem as a whole is able to be responsive to local conditions through extensive feedback loops created by the relationships between these organisms.

Incorporating this principle into the built environment implies that a thorough understanding of a particular place would be required of the design team and that local characteristics of ecology and culture would be seen as drivers and opportunities in the creation of place.

2.4.4 Ecosystems are diverse in components, relationships and information.

- Diversity is related to resilience.
- Relationships are complex and operate in various hierarchies.
- Ecosystems are made up of interdependent cooperative and competitive relationships.

- Emergent effects tend to occur.
- Complex systems tend to be self-organising and distributed.

A diverse system is often described in biomimicry literature as a robust and stable one capable of adapting to change. In certain levels of ecosystems and in individual organisms there may be a level of redundancy to allow for adaptation to changing conditions at different rates. Some ecologists describe this as the 'insurance effect' (Shear McCann 2000). This concept is usually expanded upon in ecology literature, and it should be noted that there is considerable historical debate about the relationship between diversity, complexity, resilience and stability in ecosystems (Harding 2001). What is clear from the literature is that the number and strength of relationships between species in systems is more important to dynamic stability than actual numbers of species (Shear McCann 2000). Through this kind of cooperative networking, one element (or organism) can fail without disrupting the entire system.

Ecosystems are organised hierarchically (Kibert et al., 2002), and at different scales may be governed by different physics principles (Vogel, 1998, Thompson 1942).

In complex ecosystems both cooperation and competition between individuals and species are important in the creation of ecosystem dynamics (Kibert et al., 2002). Organisms will occupy non-competing niches and species in the same niche may use tactics such as defining territories or having non-overlapping feeding times to avoid competition. Reap et al. (2005) discusses life existing in a cooperative framework as relating to *'the diverse web of interactions that effect populations, facilitate resource transfers, ensure redundancy and generally maintain the biosphere.'*

Emergence in ecosystems is the phenomena of novel and unexpected organisation in complex systems. Allen (2002) asserts that it is through new relationships of control and constraint that emergence appears, allowing systems to become more complex. Ecosystems tend to be made up of distributed and decentralised networks of feedback loops dependant on relationships between organisms, and between the living system and the rest of the environment, making them rapidly responsive and adaptable to change (Vincent et al. 2006, Kelly 1994). Kibert et al. (2002) describe this aspect of ecosystems as *self-organisation.* This kind of organisation, based on multiple feedback mechanisms, tends to have high amounts and transfer rates of information. (Allenby & Cooper 1994)

Translating this into the built environment implies a systems approach to architectural design where considering the relationships between buildings or components is as important as designing the individual buildings themselves.

2.4.5 Ecosystems create conditions favourable to sustained life.

- Production and functioning is environmentally benign.
- Ecosystems enhance the biosphere as they function.

The growth and activities of organisms tend not to damage the ability of the overall system they are a part of to exist and continue (Rosemond & Anderson 2003). Organisms must manufacture or process the materials or chemicals they need in the same environment that they live in and concentrated toxins, such as snake venom for example tend to be used and produced locally (Kibert et al., 2002). This is in direct contrast to the typical human approach towards manufacturing. Allenby & Cooper (1994) point out that chemicals including nutrients are toxic in natural systems if in high concentrations, and that living systems typically do not to have clusters of high energy and materials transformations and avoid high fluxes in the use of energy and materials. Materials (both internal such as organs and external such as shells) are produced at ambient temperature and often use water as the chemical medium (Faludi 2005). Benyus (1997), contrasts this with the human tendency to produce in the energy and materials intensive *'heat beat and treat'* method rather than allowing *'the physics of falling together and falling apart – the natural drive towards self – assembly'* to do the work.

As ecosystems shift from development stages to more complex stages through time and through the combined activities and interactions of the organisms within them, the system tends to become more adaptable to change and is able to support more organic matter and organisms with longer and more complex life cycles. (Odum 1969; Faludi 2005)

Mimicking this aspect of ecosystems would require the built environment to be considered as a producer of energy and resources and designed to nurture increased biodiversity in the urban environment. An understanding of ecology in the creation of the built environment would form the basis of it being able to participate in the major planetary cycles (such as the hydrological and carbon cycle etc) in a way which reinforces and strengthens them rather than damages them.

2.4.6 Ecosystems adapt and evolve at different levels and at different rates.

- Constant flux achieves a balance of non-equilibrium
- Limits, tend to be creative mechanisms
- Ecosystems have some ability to self heal

Adaptation and evolution allow organisms and whole ecosystems to persist through the locally unique and constantly dynamic, cyclic environment they exist in. Reap et al. (2005) describe adaptation as the means by which an organism adjusts (behaviourally and physically) to change throughout a lifetime. Evolution is referred to as the process by which slower genetic changes happen though successive generations in species or ecosystems through the medium of the gene.

Benyus (1997) touches on the idea that nature *'curbs excesses'* from within systems (internal feedback) as well as from external events or changes (external feedback). Feedback mechanisms, or the way that changes in one part of the ecosystem are communicated throughout the entire community are cited as a factor in the ability of ecosystems to adapt and evolve (Allenby & Cooper, 1994). Limits existing in ecosystems are discussed in terms of carrying capacity and intensity of flows of materials and energy. (Berkebile & McLennan, 2004)

The implications of applying this principle to architectural design could range from a redefinition of when a building is considered to be finished, allowing it to be more dynamic over time (applying techniques for additive and adaptable design and design for disassembly for example), to designing mechanisms into building systems to allow for added complexity to evolve over time, increasing the ability of the built environment to be able to respond to new conditions and possibly to become self-maintaining.

2.5 Selected Biological Design Principles

From the previously stated principles of ecosystems, a set of specific principles were selected from some of them. These selected principles provide a basis for further study in the following chapters. Particular selection of these principles was due to a number of reasons such as their current applicability in computational design within the limitations of available technology and knowledge. Another reason is the availability of research and suitable examples to serve as case studies for further analysis. This selection however does not imply the significance of these principles over others.

2.5.1 Adaptation

As mentioned in the principle 2.3.6: *"Ecosystems adapt and evolve at different levels and rates"* they respond to changing environments both by behavioural adjustments of individuals and by Darwinian genetic changes in the attributes of populations.

Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations and is one of the basic phenomena of biology. The term *adaptation* may also refer to a feature which is especially important for an organism's survival. Such adaptations are produced in a variable population by the better suited forms reproducing more successfully, that is, by natural selection.

Figure 14: Cross section through a stem of a geranium revealing the close-packed bundles of differentiated vessels and cells. The geometrical arrangement and close-packed integration produces a complex structure, strong but flexible, and capable of differential movement. All cells have a structural role in addition to other functions, and structural capacity emerges from their interaction. (Source: AD Journal Volume 74 issue 3, 2004)

2.5.2 Material as Systems

From the ecosystem principle 2.3.2: "*Ecosystems optimise the system rather than its components"* it was concluded that ecosystems use energy and materials in a way that optimises the whole system rather than individual components (Kelly, 1994). All living forms are hierarchical structures, made of materials with subtle properties that are capable of change in response to changes in local stresses. Biological material systems are self-assembled, using mainly quite weak materials to make strong structures, and their dynamic response and properties are very different from the classical engineering of traditional man-made structures. (Hensel M., Menges A. and Weinstock M. 2010)

Organisms and natural systems are often composed of a number of interrelated components and materials that act on a continuous scale from the micro to macro structure. At each level of structural organization the cells within the organism perform a function that corresponds to a necessary requirement at that level. (Panchuk N. 2006)

The cells within a tree for example perform this hierarchy of functions at different scales. At the micro level the cells are responsible for the movement of water from the roots to the leaves. Based on weight, the tubular structures of the cells are also stronger than a solid structure that would not be able to act as a transport mechanism. When these cells are grouped together they provide the tree with a high strength lightweight structural system that resists both tensile and compressive forces as well as allowing for flexibility.

(Panchuk N. 2006)

2.5.3 Evolution

The principle 2.3.6: *"Ecosystems adapt and evolve at different levels and rates"* explains that adaptation and evolution allow organisms and whole ecosystems to persist through the locally unique and constantly dynamic, cyclic environment they exist in.

Every living form emerges from 2 strongly coupled processes, operating over maximally differentiated time spans: the rapid process of embryological development from a single cell to adult form, and the long slow process of evolution of diverse species of forms over multiple generations. (Hensel M., Menges A. and Weinstock M. 2010)

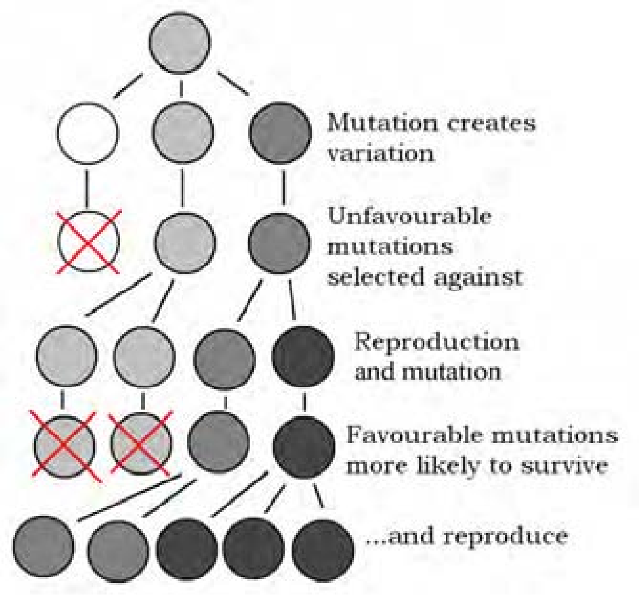


Figure 15: Mutation & Selection diagram
(Source: www.wikipedia.org)

The perfection and variety of natural forms is the result of relentless experimentation of evolution. By means of profligate prototyping and ruthless rejection of flawed experiments, nature has evolved a rich biodiversity of interdependent species of plants and animals that are in metabolic balance with their environment. Analogy of evolutionary architecture should not be taken just to imply a form of development through natural selection. Other aspects of evolution such as the tendency to self organization are equally or even more significant. (Frazer J. 1995)

Nature's complex forms and systems arise from evolutionary processes. In addition, living forms grow, and growth *is* a complex process intertwining contributions of the genotype with the variable contributions of environment and phenotypic dependencies. In nature, the genotype comprises the genetic constitution of an individual, while the phenotype is the product of the interactions between the genotype and the environment. The emergent properties and capacities of natural forms stem from the generative processes that work upon successive versions of the genome. This genome is compact data that is transformed into biomass of complex structural complexity. A compelling goal is to instrumentalise the natural process of evolution and growth, to model essential features of emergence and then to combine these within a computational framework.

(O'Reilly U., Hemberg M., and Menges A. 2004)

2.5.4 Emergence

As discussed in the principle 2.3.4*: "ecosystems are diverse in components, relationships and information"* relationships are complex and operate in various hierarchies, and emergent effects tend to occur.

The dynamical systems of nature, the systems of living beings and the systems of the physical world including climate and geological forms, display a variety of organisational and behavioural characteristics that are central to the study of emergence. There are many definitions of evolutionary and developmental processes that unfold over time. One that is widely quoted is that put forward by Tom de Wolf and Tom Holvoet, who proposed the following working definition of emergence:

A system exhibits emergence when there are coherent emergents (property, behaviour, structure...) at the macro-level that dynamically arise from the interaction between parts at the micro-level. Such emergents are novel with regards to the individual parts of the system. (De Wolf and Holvoet 2005)

The evolution of all the multiple variations of biological form should not be thought of as separate from their structure and materials. It is the complex hierarchies of materials within natural structures from which their performance *emerges*. Form, structure and material act upon one another, and the behaviour of all three acting on each other cannot be predicted by analysis of any one of them alone. (Hensel M., Menges A. and Weinstock M. 2010)

2.5.5 Form & Behaviour

From the ecosystem principle 2.3.2: "*Ecosystems optimise the system rather than its components"* the relationship between form and function is emphasized, and as a result, form and behaviour are equally important.

Biological forms and their behaviour emerge from process. It is process that produces, elaborates and maintains the form and structure of biological organisms (and non-biological things), and that process consists of a complex series of exchanges between the organism and its environment. Furthermore, the organism has a capacity for maintaining its continuity and integrity by changing aspects of its behaviour. Form and behaviour are intricately linked. (Hensel M., Menges A. and Weinstock M. 2010)

The form of an organism affects its behaviour in the environment, and a particular behaviour will produce different result in different environments. Behaviour is non linear and context specific. (Hensel M., Menges A. and Weinstock M. 2010)

2.6 Chapter Summary

This chapter has presented two main approaches in biomimetic design (Problem based and Solution based) and discussed a framework for understanding the different levels of biomimicry; organism, behaviour and ecosystem levels. Advantages and disadvantages of each level were presented, highlighting the different potentials of each level in sustainable or regenerative design.

A focus has been made on ecosystem biomimicry as it has the highest potential for a regenerative built environment, highlighting its main principles. Based on these, a group of more specialized or specific principles were selected, that serve as criteria for the analysis of case studies in chapter 4. The selection of these specific principles was due to amount of available research and literature, in an attempt to link them with current research on morphogenetic computational design as will be presented in the following chapters.

Computational design software and technology present new tools for the investigation of such principles and their underlying potential. The current widespread fascination with nature is a reflection of the availability of new modes of imaging the interior structure of plants and animals, of electron microscopy of the intricate and very small, together with the mathematics of biological processes.

New working methods of architectural design and production are rapidly spreading through architectural and engineering practices, as they have already revised the world of manufacturing and construction. The material practice of contemporary architecture cannot be separated from this paradigm shift in the context within which architecture is conceived and made. The study of natural systems suggests the means of conceiving and producing architecture that is more strongly correlated to material organizations and systems in the natural world. (Hensel M., Menges A. and Weinstock M. 2010)

CHAPTER 3: MORPHOGENETIC COMPUTATIONAL DESIGN

3.1 Introduction

A biomimetic approach to design in architecture (ecosystem biomimicry) requires the development of the currently established and practiced design methods and tools towards a higher level of material, structural and performative integration. Thus it is proposed that integral computational design based on the principles of morphogenetic processes provides such an extension and thus allows for a biomimetic approach in architecture.

Architecture as a material practice is predominately based on an approach to design that is characterised by prioritising the elaboration of form over its subsequent materialisation. In today’s practice digital tools are still mainly employed to create design schemes through a range of design criteria that leave the inherent morphological and performative capacities of the employed material systems largely unconsidered. Ways of materialisation, production and construction are strategized only after a form has been elaborated, leading to engineered, material solutions that often juxtapose unfitting logics. This research presents an alternative morphogenetic approach to design that unfolds morphological complexity and performative capacity from material constituents without differentiating between formation and materialisation processes. This requires an understanding of form, material and structure not as separate elements, but rather as complex interrelations that are embedded in and explored through integral computational design processes.

(Menges A. 2009)

This chapter presents a definition of morphogenesis in both biology and architecture. Another set of definitions is also presented that serves as a theoretical framework for further case-study analysis. The same biological principles selected in the previous chapter are discussed again within the context of computational design. Finally, a methodological framework is outlined that provides further explanation for the presented design approach.

3.2 Morphogenesis in Biology

S. Roudavski (2009) explains morphogenesis in biology, highlighting the general advantages of studying it as follows.

3.2.1 Definition

Morphogenesis is a concept used in a number of disciplines including biology, geology, crystallography, engineering, urban studies, art and architecture. This variety of usages reflects multiple understandings ranging from strictly formal to poetic. The original usage was in the field of biology and the first recorded instances occur in the second half of the 19th century. An earlier, now rare, term was morphogeny, with the foreign-language equivalents being *morphogenie* (German, 1874) or *morphogénie* (French, 1862). Geology was the next field to adopt the term in the 20th century.

In biology the word 'morphogenesis' is often used in a broad sense to refer to many aspects of development, but when used strictly it should mean the molding of cells and tissues into definite shapes.

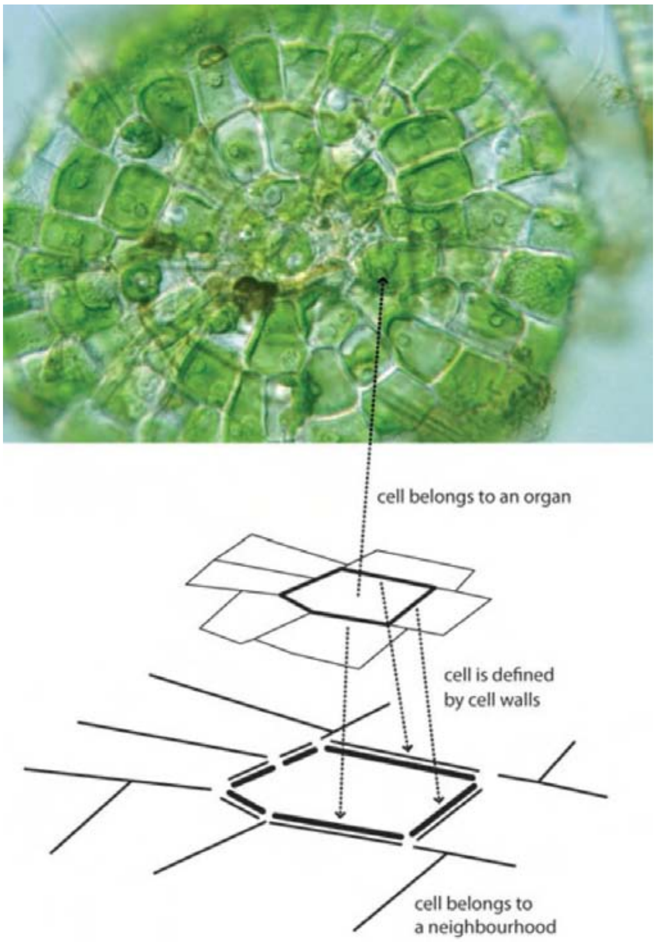


Figure 16: Cellular architecture of plants can be conceptually subdivided into several scale levels represented in this diagram by horizontal planes. This conceptual subdivision helps to formalise the structure and functioning of plants. (Conceptual diagrams based on the work of Dupuy et al. 2008; photomicrograph of Coleochaete orbicularis, top, is by Yuuji Tsukii, Protist. Information Server, URL: http://protist.i.hosei.ac.jp/.)

Furthermore, in biology the word "morphogenesis" can be used to refer either to (i) the structural changes observed in tissues as an embryo develops or to (ii) the underlying mechanisms responsible for the structural changes. Both understandings can be of interest and inspiration for architects, despite the fact that a literal importation of biological structures or processes into architectural design is usually not feasible, meaningful or desirable.

Morphogenesis is one of several processes typical for living organisms. Apart from morphogenesis, these processes include growth, repair, adaptation and aging. Transferring knowledge of these processes into designing might be also productive, especially in relationship to architectural structures with dynamic capacities.

In the biological sciences, the study of forms and their categorization, or morphology, was the first instrumental set of zoology, predating the evolutionary theory. More recently, morphology has outstripped its historical confines, becoming morphogenesis, with an emphasis on the forces that generate living forms, on how forms and environments came into being.

3.2.2 Advantages of studying biological morphogenesis

A better understanding of biological morphogenesis can usefully inform architectural designing because:

- Architectural designing aims to resolve challenges that have often already been resolved by nature;
- Architectural designing increasingly seeks to incorporate concepts and techniques, such as growth or adaptation, that have parallels in nature;
- Architecture and biology share a common language because both attempt to *model* growth and adaptation (or morphogenesis).

3.3 Morphogenesis in Architecture

S. Roudavski (2009) also explains the concept of morphogenesis in architecture as will be presented in the following paragraphs.

3.3.1 Definition

In architecture, morphogenesis (“digital morphogenesis” or “computational morphogenesis”) is understood as a group of methods that employ digital media not as representational tools for visualization but as generative tools for the derivation of form and its transformation often in an aspiration to express contextual processes in built form.

Recent discourse on digital morphogenesis in architecture links it to a number of concepts including emergence, self-organization and form-finding. Among the benefits of biologically inspired forms, their advocates list the potential for structural benefits derived from redundancy and differentiation and the capability to sustain multiple simultaneous functions. (Roudavski S.2009)

3.3.2 Why study morphogenesis?

- A biomimetic approach to architectural design requires the development of novel design methods that integrate both the modeling of behavior and the constraints of materialization processes. This approach presents aspects of the profound changes to the architectural design process entailed by a transition from *Computer Aided Design* towards *Computational Design.*
- It will present the research on computational design tools and demonstrate their application in research based on the abstraction of biological principles for the development of environmentally responsive structures.

- Complex, non-uniform structures are expected to become increasingly common in architecture in response to the growing utilization of parametric modeling, fabrication and mass-customization.
- New challenges and opportunities that the designing of such structures brings are without direct precedents in architecture. Yet, such precedents do exist in nature where structurally complex living organisms have been adapting to their environments for millions of years.

This requires an understanding of form, material and structure not as separate elements, but rather as complex interrelations that are embedded in and explored through integral computational design processes.

3.4 General Concepts

Within the context of this research, a set of relevant concepts are presented and explained since they are important for the understanding and comprehension of the forthcoming theoretical framework and case-studies.

3.4.1 Computational Design

Achim Menges (2009) explains that computational design lends itself to such an approach as it is enables employing complex behaviour rather than just modelling a particular shape or form. The transition from currently predominant modes of *Computer Aided Design* (CAD) to *Computational Design* allows for a significant change of employing the computer’s capacity to instrumentalise materials’ complex behaviour in the design process. CAD is very much based on computerized processes of drawing and modelling stemming from established representational techniques in architectural design (Terzidis 2006). In this regard one of the key differences lies in the fact that CAD internalizes the coexistence of form and information, whereas Computational Design externalizes this relation and thus enables the conceptualization of material behaviour and related formative processes.

In Computational Design form is not defined through a sequence of drawing or modelling procedures but generated through parametric, rule based processes. The ensuing externalization of the interrelation between algorithmic processing of information and resultant form generation permits the systematic distinction between process, information and form. Hence any specific shape can be understood as resulting from the interaction of system-intrinsic information and external influences within a morphogenetic process.

The computational design process that forms the base for this research allows the exploration and development of surface geometries in 3 dimensional space that have virtual environmental conditions. The exploration is enabled by an evolutionary module that produces populations of surfaces in many generations, and the development is governed by an algorithm that mimics organic growth. (Menges A. 2009)

3.4.2 Computational Morphogenesis

Computational form-generating processes are based on “genetic engines” that are derived from the mathematical equivalent of the Darwinian model of evolution, and from the biological science of evolutionary development that combines processes of embryological growth and evolutionary development of the species. Evolutionary computation offers the potential of relating pattern and process, form and behaviour, with spacial and cultural parameters. Evolutionary computational strategies for morphogenesis have the potential to be combined with advanced structural and material simulations of behaviour under stresses of gravity and load. This approach is part of the contemporary reconfiguration of the understanding of ‘nature’, a change from metaphor to model, from ‘nature’ as a source of shapes to be copied to ‘nature’ as a series of interrelated dynamic processes that can be simulated and adapted for the design and production of architecture.

During the short history of so-called digital architecture, the notion of morphogenesis has almost become a cliché owing to excessive referencing to all kinds of design processes that operate most often merely on a metaphorical level. This thesis presents current research on morphogenesis that attempts to investigate the principles underlying natural morphogenesis and step by step transferring them into an integral computational process.

Within this context, computational morphogenesis can be described as a process of perpetual differentiation. The increasing morphological and functional difference of elements enabling the system’s performative capacity unfolds from their divergent development directions triggered by a heterogeneous environment and multiple functional criteria.

(Hensel M., Menges A. and Weinstock M. 2010)

3.4.3 Self-Organization

Complex adaptive systems entail processes of self-organisation and emergence. However, both concepts express very different characteristics of a system’s behaviour. Self-organisation can be described as a dynamic and adaptive process through which systems achieve and maintain structure without external control. The latter does not preclude extrinsic forces, since all physical systems exist within the context of physics, for as long as these do not assert control over intrinsic processes from outside. Common form-finding methods, for example, deploy the self-organisation of material systems exposed to physics to achieve optimisation of performance capacity. Self-organisational systems often display emergent properties or behaviours that arise out of the coherent interaction between lower-level entities, and the aim is to utilise and instrumentalise behaviour as a response to stimuli towards performance-oriented designs. (Hensel, M. 2006a)

Self-organisation is a process in which the internal organisation of a system adapts to the environment to promote a specific function without being guided or managed from outside. In biology this includes the processes that concern developmental biology, which is the study of growth and development of organisms and comprises the genetic control of cell growth, differentiation and morphogenesis. (Hensel, M. 2006b)

Figure 17: The self-organisation processes underlying the growth of living organisms can provide important lessons for architects. Natural systems display higher-level integration and functionality evolving from a dynamic feedback relation with a specific host environment. Coloured X-ray of hyacinth flowers at different stages of growth. Environmentally sensitive growth can deliver a paradigm for architectural design.
(Source: AD Journal, Volume 76 no.4, 2006.)

Self-organising systems display capacity for adaptation in the presence of change, an ability to respond to stimuli from the dynamic environment. Irritability facilitates systems with the capacity to adapt to changing circumstances. The critical characteristics of biological self-organisation are: small, simple components assembled together in three dimensional patterns to form larger organisations that, in turn, self-assemble into more complex structures that have emergent properties and behaviour. (Hensel, M. 2006a)

3.4.4 Differentiation & Integration

When attempting to set forth a paradigm for differentiated and multi-performance architectures, it is interesting to examine available methods for modelling biological growth informed by a hosting environment. Through this investigation it is possible to derive architectural strategies and methods that are informed by environmentally specific conditions and, thus, to achieve advanced levels of functionality and performativity.
(Hensel, M. 2006b)

In biology, differentiation entails the process by which cells or tissues undergo a change towards a more specialised form or function, to become increasingly oriented towards fulfilling specific tasks, to acquire specific performance capacity.
(Hensel, M. 2006a)

Complexity increases when the variety [distinction] and dependency [connection] of parts increases. The process of increasing variety is called differentiation, and the process of increasing the number or the strength of connections is called integration. Evolution produces differentiation and integration in many 'scales' that interact with each other, from the formation and structure of an individual organism to species and ecosystems. (Hensel, M. 2006c)

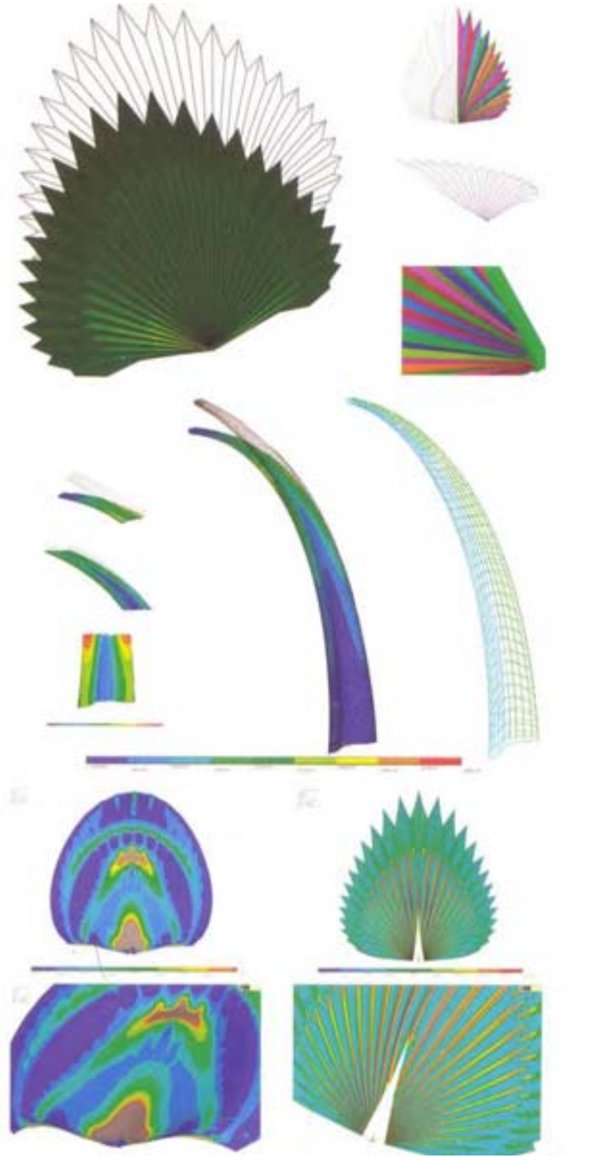


Figure 18: Natural system analysis: palm tree. For the investigation of the palm tree’s exceptional capacity to respond to very high dynamic loading, the morphology of the leaf (top) and stem were accurately modelled. The analysis of the bending stresses occurring at different sections of the palm stem (centre) shows different local bending stresses, indicating the global relationship of bending and torsion stiffness, resulting from the locally differentiated cross section. The structural performance of the leaf was investigated by means of comparing stress patterns developing over the leaf (bottom right) due to wind pressure with the stresses that would occur in a leaf with no folds (bottom left) under the same conditions. EmTech Natural Systems Module, Zoe Saric, Biraj Ruvala, Michel da Costa Goncalves and Jennifer Boheim, 2005.(Source: Hensel M. et al 2010)

3.4.5 Advanced Simulation

Simulations are essential for designing complex material systems, and for analysing their behaviour over extended periods of time. Much of the physical environment can be simulated in the computer: a simple ‘Google’ search will show a collection of sites on the web that have interactive simulations of physics principles, including light, optics, springs and masses, pendulums and waves, harmonics, mechanics and momentum, and even nuclear physics. In such simulations, the parameters of objects can be modified and the resultant change in behaviour observed.

Most architectural design software now includes sunlight modelling for any location in the world, and an increasing range of plug-ins or scripts can simulate the behaviour of chains and springs under gravity. More sophisticated simulations, such as the stress response of structures under imposed loads, or the flow of air and heat through spaces and in materials, are standard modules in engineering software.

Working with simulations requires the development of a logical mathematical description of the performance of a system or process, which corresponds to certain specific parameters of its physical behaviour.

(Weinstock, M. & Stathopoulos, N. 2006)

3.5 Morpho-Ecological Design Approach

Biology is the science of life; it is concerned with the living. For this reason, architecture must go beyond using biology as merely a source of convenient metaphors. Ecology is the study of the relationship between organisms and their environment. This definition also suits the discipline of architecture surprisingly well: in our view one of the central tasks of architecture is to provide opportunities for habitation through specific material and energetic interventions in the physical environment.

Correlating morphogenesis and ecology, a new framework has been developed for architectural design that is firmly rooted within a biological paradigm and thus connected with issues of higher-level functionality and performance capacity. Enhanced context sensitivity lies at the base of this approach. This approach is referred to as **‘Morpho-Ecology’.**

It argues for an ecological model for architecture that promotes an active modulation of environmental conditions across ranges and over time through morphological differentiation. This approach promises both a new spatial paradigm for architectural design and advanced sustainability that links the performance capacity of material systems with environmental modulation and the resulting provisions and opportunities for inhabitation.

(Hensel M. & Menges A. 2008)

3.6 Theoretical Framework

The theoretical & methodological frameworks relevant to this approach concern themselves with intense differentiation of material and energetic interventions that are evolved from:

- Their specific behavioural tendencies in given environment
- Their mutual feedback relationship
- Passive modulation strategies that are sustainable
- Speculation on the resultant relationship between spatial and social arrangements and habitation patterns and potentials.

Morphogenesis is concerned with the processes that control the organized spacial distribution of cells which arises during the embryonic development of an organism, producing the characteristic forms of organs, tissues, and overall body anatomy. This approach takes up the concept of morphogenesis relating to the way the development of material systems is informed by inquiries into scale and size-specific behaviour and related performative capacities. This involves the exposure of the system at each stage of development to a series of extrinsic influences and stimuli provided by a given environment. (Menges A., Hensel M. 2007)

This approach commences from the unfolding of performative capacities inherent in material systems in relation to the specific environment they are embedded within, as well as an intensively empirical mode based on physical and computational form generation analysis methods. Compared with current practice it presents a radically different take on the relation between formal expression and performative capacity of the built environment, as well as a fundamental revision of prevailing approaches to sustainability. (Menges A., Hensel M. 2008)

Performance:

An alternative understanding of performance, one that is based on multi-parameter effectiveness rather than single-parameter optimisation and efficiency, must from the start of the design process include both the logics of how material constructions are made and the way they will interact with environmental stimuli. Computation in analytical and generative modes has a key role in both aspects. The underlying logics of computational processes, particularly when combined with computer-controlled manufacturing processes, provide a much higher level of design synthesis. (Menges A. Hensel M. 2008)

Form-Generation:

Particularly related is the underlying impoverished notion of form-generation, which refers to various digitally driven processes resulting in shapes that remain **detached from material and construction logics**. In foregrounding the geometry of the eventual outcome as the key feature, these techniques are quintessentially not dissimilar to more conventional and long-established representational techniques for explicit scalar geometric descriptions. As these notional systems are insufficient in integrating means of materialisation, production and construction, they cannot support the evaluation of performative effects, and so these crucial aspects remain invariably pursued as top-down engineered material solutions. (Menges A., Hensel M. 2008)

This suggests that the talent, but as yet unused, potential of computational design and manufacturing technology may unfold from an alternative approach to design, one that derives morphological complexity and performative capacity without differentiating between form-generation and materialisation processes. (Menges A., Hensel M. 2008)

The morpho-ecological approach aims for a more integral design approach to correlate object, environment and subject into a synergetic dynamic relationship.
(Menges A., Hensel M. 2008)

3.7 Selected Biological Principles

The previously selected biological principles stated in chapter two are presented here once again within the context of such a design approach. They represent some of the most important features and characteristics of *morpho-ecological design*, and will serve as analysis criteria for case studies in the next chapter.

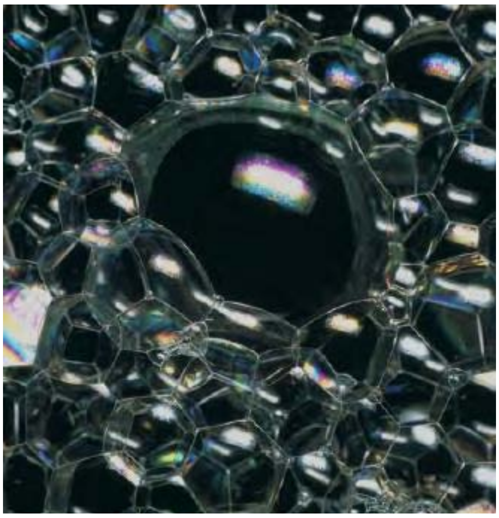
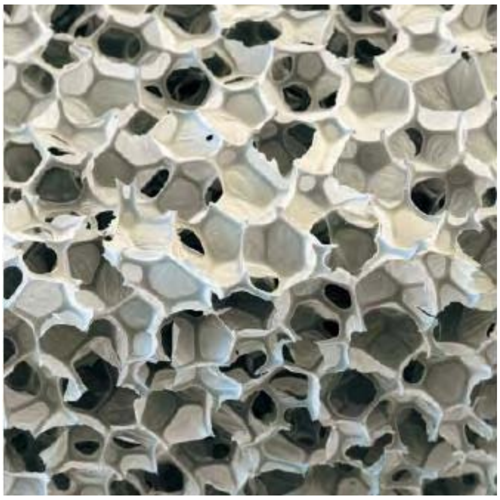


Figure 19: A naturally produced foam of soap bubbles, demonstrating the differentiation of polyhedral cells in an intricate geometry of foam architecture, including the basic Plateau rules for the intersection of three films. (Source: AD Journal, Volume 76 no.4, 2006.)

The selection of these principles was due to the available research and literature on this topic, and does not imply their significance over others.

3.7.1 Adaptation

According Weinstock M. et al (2006), the means by which biological systems respond and adapt to environmental stresses and dynamic loadings are complex, so that responses are nonlinear, arising out of the interactions of multiple material hierarchies. The most important principle of adaptation, not regarded by classical engineering, is small random variation in the ‘design’, repeated over time. It is this stochastic process that produces robust systems that persist through time. In mathematical terms, ‘stochastic’ is often used in opposition to the ‘deterministic’. Deterministic processes always produce the same output from a given starting condition; stochastic processes will never repeat an identical output. It follows that developing processes that include small random mutations over many iterations is a significant ‘evolutionary’ strategy for design, architecture and engineering, and one that will preclude the standardisation of components and members.



F**igure 20**: Scanning electron micrograph of polyurethane foam, showing the porous structure of differentiated open and partially closed cells. Magnification x 20 when printed at 10 centimetres wide.
(Source: AD Journal, Volume 76 no.4, 2006.)

Adapting geometry to changing circumstances throughout the design process can be a time-consuming and costly ordeal or, on the other hand, can be anticipated and tools designed that facilitate the possibility of significant changes right up to the manufacturing stage. Whenever the design requirements and constraints and performance profiles of a design change, it is important that the design can absorb such changes through a modifiable geometric modelling setup capable of retaining geometric relations while being substantially modified. (Hensel M. 2006)

3.7.2 Material Systems

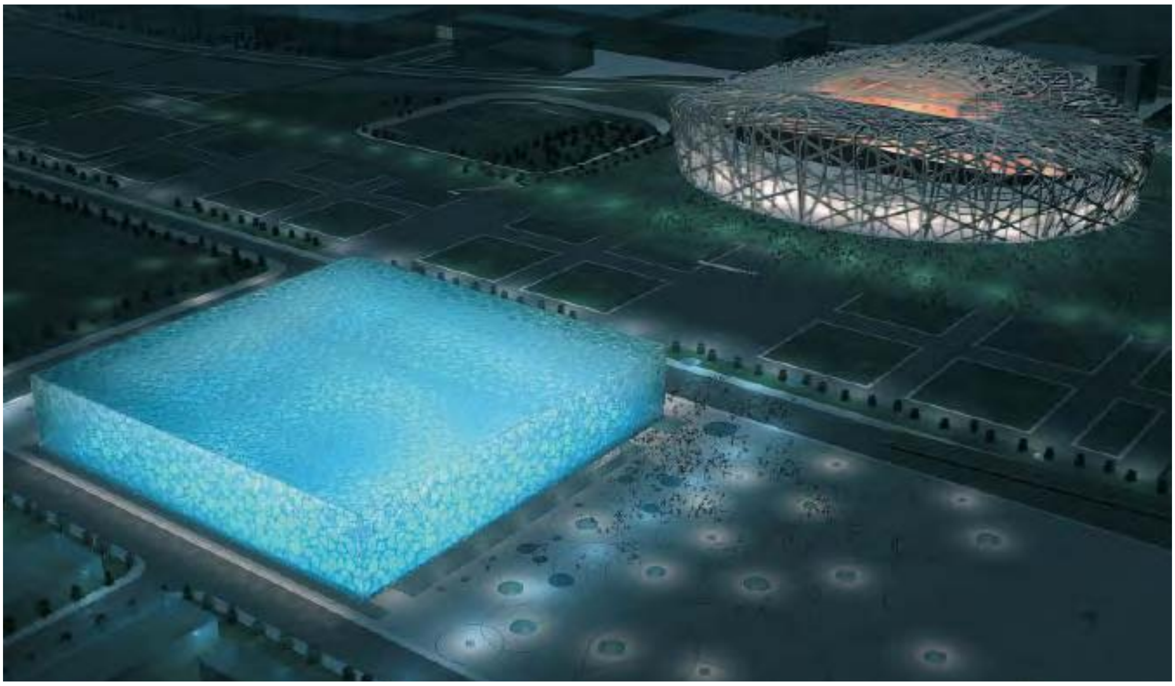


Figure 21: PTW Architects, CSCEG Design and Arup, ‘Water cube’ National Swimming Centre, Beijing, due for completion 2007. Competition model showing overall scale: 177 x 177 metres (581 x 581 feet) and more than 30 metres (98 feet) high, with an entirely column-free interior space.
(Source: AD Journal, Volume 76 no.4, 2006.)

The notion of the material system constitutes one central aspect of the research presented in this thesis. While it may initially seem obvious to consider material systems more or less as the equivalent of construction systems and tectonics, material systems are conceived within this context as a more profound and integral concept. In this way, material system does not refer to the material constituents of a building alone, but rather describes, in a system-theoretical sense, the complex reciprocity between materiality, form, structure and space, and the related processes of production and assembly, and the multitude of performative effects that emanate from the interaction with environmental influences and forces. (Hensel M., Menges A. and Weinstock M. 2010)

Figure 22: Watercube digital structural model. The mathematics of foam geometries are used to produce the structural array, ensuring a rational optimised and buildable structural geometry. (Source: AD Journal, Volume 76 no.4, 2006.)

Interestingly, this conceptualisation of material systems enables the utilisation of the still latent potential of computational design processes. The ability of computational processes to simultaneously do both-to stochastically derive and systematically process complex data sets within a defined or evolving constrained space can be utilised to explore a system's performative capacity within its materially determined limits.

Material and morphological characteristics are derived through iterative feedback loops, which continuously process the material system's interaction with statics, thermodynamics, acoustics, and light and so on. In contrast to the currently predominant modes of utilising computation first for formal expressions liberated from all constraints of construction, and then for the economically driven rationalisation of the resultant, tectonically complicated buildings, this approach utilises computation to recognise and exploit the material system's *behaviour* rather than merely focusing on its *shape.*

(Hensel M., Menges A. and Weinstock M. 2010)

Figure 23: Generative algorithmic definition
Differentiated honeycomb morphology prototype exhibited at the AA Projects Review, July 2004, and digital model of differentiated honeycomb morphology from which the manufacturing data is extracted.
(Source: AD Journal, Volume 76 no.4, 2006.)

3.7.3 Evolution

Architecture is considered as a form of artificial life, subject, like the natural world, to principles of morphogenesis, genetic coding, replication and selection. The aim of an evolutionary architecture is to achieve in the built environment the symbiotic behaviour and metabolic balance that are characteristic to the natural environment. (Frazer J. 1995)

The concept of evolution is explored in computational design processes through the use of evolutionary algorithms. An evolutionary algorithm or EA is a set of rules, embodied in a computer program that starts with a given 'population' of potential solutions to a problem – in our case solutions to a design problem. The members of this population act as 'parents' to a new generation of 'children', passing on their 'genes' with slight variations introduced at random – equivalent to the effects of mutations in natural evolution. In some EAs the children can inherit 'genetic material' from two parents (or maybe more than two!) in a process akin to sexual reproduction. The children are then subjected to a series of evaluations to measure their ‘fitness’ according to some specified criteria. Collectively, these criteria therefore represent the ‘environment’ of the evolving population.

Chromosomes in EAs, then, are encoded representations of features of designed objects: whether the features are present or absent, their size, shape, quantity, position, material and so on. They are, figuratively speaking, the DNA of the world of evolution by computer. In more advanced algorithms, as we will see, the chromosomes, rather than representing the forms and features of objects directly, can instead consist of instructions for building the objects from component parts and sub-assemblies. (The resemblance to DNA is then rather closer.) (Steadman P. 2008)

Figure 24: Generative algorithmic definition.
Algorithmically derived honeycomb prototype in which each cell is unique in shape, size and depth, allowing for changing cell densities and double-curved global geometry, and close-up views showing planar connection tabs between honeycomb layers (left) and double-curved global surface articulation (right).
Source: AD Journal, Volume 76 no.4, 2006.

3.7.4 Emergence

The phenomenon of *emergence was* discovered in the 1970s, it offers a new precision to the study of evolution, complexity and the ‘new’, and it appears to be strangely applicable to a huge range of disciplines and scales, from the micro-biological to the macro-economical. It forces us to reconsider the pervasive atomic, collage-based view of the world, which is concerned with parts, even parts in seemingly complex arrangements. An emergent organization exhibits behaviours or has properties which are not predictable by observing any of the behaviours or properties of its constituent parts. That is, the emergent whole always exceeds its parts qualitatively. The beautiful coherence and dynamics of a swarm of bees can never be traced back to the behaviour of a single bee. Within the realm of architectural practice, an emergent network is more than an arrangement of expertises or an overlapping of spheres of influence. It is a collective which exhibits emergent behavioural patterns that are unpredictable by examining the behavioural patterns of its parts. (Wiscombe T. 2006)

Emergence refers in fact to a very particular scientific phenomenon: the indivisibility and irreversibility of wholes- be they structures, organizations, behaviours, or properties. In particular, emergence refers to the universal way in which small parts of systems, driven by very simple behaviours, will tend toward coherent organizations with their own distinctly different behaviours. (Wiscombe T. 2005)

3.7.5 Form and Behaviour

Form and behaviour emerge from the processes of complex systems. Processes produce, elaborate and maintain the form of natural systems, and those processes include dynamic exchanges with the environment. There are generic patterns in the process of self generation of forms, and in forms themselves. Geometry has both a local and a global role in the interrelated dynamics of pattern and form in self-organised morphogenesis.

Forms maintain their continuity and integrity by changing aspects of their behaviour and by their iteration over many generations. Forms exist in varied populations, and where communication between forms is effective, collective structured behaviour and intelligence emerges. Form and behaviour are intricately linked. The form of an organism affects its behaviour in the environment, and a particular behaviour will produce different result in different environments. Behaviour is non linear and context specific.

(Hensel M., Menges A. and Weinstock M. 2004)

3.8 Methodological Framework

According to Hensel M., Menges A. and Weinstock M. (2010) the methodological framework associated with this approach requires the development of an integral computational setup in which the system evolves. There are two crucial constituents for this setup; one is the definition and inclusion of a set of characteristics and constraints defined through a series of relevant parameters. The definition of the range within which these parameters can be operated, while remaining coherent with other constraints such as construction and fabrication, is a critical task for the designer. The second crucial constituent is the recurring evaluation cycles that expose the system to embedded analysis tools. Analysis plays a critical role during the entire morphogenetic process, not only in establishing and assessing fitness criteria related to structural and environmental capacity, but also in revealing the system’s material and geometric behavioural tendencies.

The computational setup is explained as follows:

- The starting point is the thorough analysis of the project brief and the careful examination of it context in terms of the actual site situation, specific environmental influences, project requirements and limitations of the construction process.

- A material system is then selected by the design team based on project requirements and related influences. A set of physical and digital experiments are performed in order to determine the geometric description of this material system, and to capture and embed its parameters and constraints. Similar to the definition of the elements of the material system, the definition of the relation between these elements is also important.
  The related manufacturing method and assembly techniques are also defined, studied and embedded into the system.

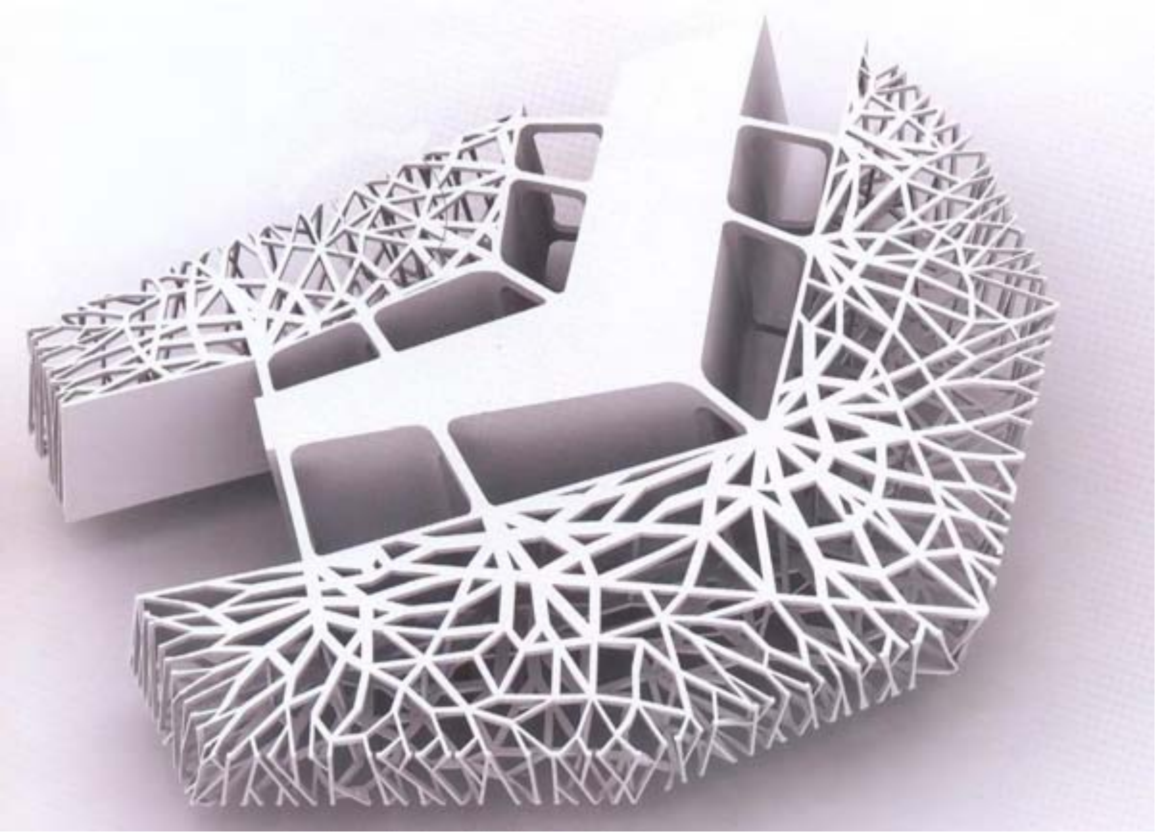


Figure 25: Ocean and Scheffler+Partner, New Czech National Library Design Competition, Prague 2006. The distinctive articulation of the library's cantilevering volumes is developed through generative computational processes driven by spatial and structural criteria. (Source: AD Journal, Volume 78 no. 2, 2008)

- In parallel, research of a specific organism is undergone (if relevant to the project) from which the extraction and abstraction of relevant characteristics is performed. These characteristics are described in terms of rules and parameters in order to implement them in the computational setup. This phase is optional and varies greatly from one project to the other depending on its specific conditions, requirements and available biological research.

- This leads to the definition of performance profiles and related fitness criteria which significantly constrain the design process. For the subsequent steps of initiating the development and differentiation of the system, it is critical to capture and embed its parameters, hierarchies, dependencies and variable ranges in a system-defining genotypic dataset.

- The Danish genetics pioneer Wilhelm Ludvig Johannsen introduced the profound difference between the *genotype* and *phenotype* in developmental biology in 1909 (Mayr 2002:624). The genotype constitutes the unchanging genetic information, whereas the individual actual gestalt emerging from its interaction with the specific environment in which the development takes place is referred to as the phenotype.

- In computational morphogenesis the genotypic definition unfolds a performative phenotypic material system. This takes place through the integrative differentiation of its elements driven by multiple performance requirements. This comprises both the ontogenetic growth process of individual systems and comparative, evolutionary development of system populations across many generations.

- The technical implementation of algorithmic growth processes varies according to system type and design strategy. In any case, the most common and relevant aspect is the proliferation of elements across several growth steps, in which each element is regenerated rather than added to another. In this process **each element and component adapts its morphology by calibrating its functional requirements with its particular sub-location in the overall system.**

- This computational generation of performative phenotypic components is driven by a feedback with different simulation and analysis tools. These tools are not only employed for cross-checking the self-forming limits of the system, but also enable iterative analyses and evaluation cycles, so that the **specific gestalt of the system unfolds from the reciprocal influences and interactions of form, material and structure within a simulated environment.**

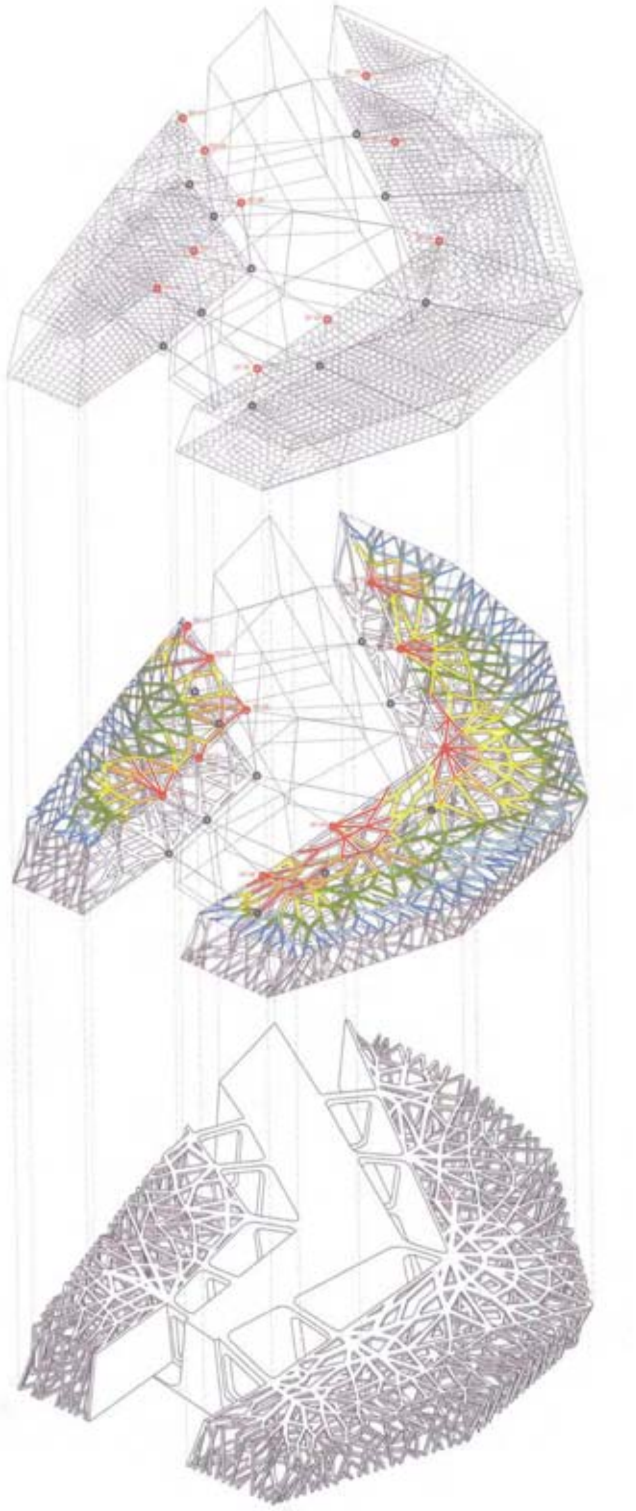


Figure 26: An analytical computational procedure indicates the stress distribution within the envelope of the new library's cantilevering volumes which is evaluated and mapped as a vector field of principle forces (top). According to this structural information, combined with other parameters such as the angle of incident sunlight, view axes and spatial characteristics, a network of merging branches is derived (centre) which is developed into a structural envelope of the volumes cantilevering from the central volume comprising the national archive (bottom). . (Source: AD Journal, Volume 78 no. 2, 2008)

- Similar to the algorithmic growth process, evolutionary computation offers different ways of implementing such generative processes and fitness evaluation techniques. What all such procedures have in common is using the evolutionary dynamics of combination, reproduction and mutation of the underlying genotypic datasets through a genetic algorithm as well as selection procedures.

Overall it is important to note that true morphological as well as performative differentiation requires the design and evaluation criteria, as well as their hierarchies and weighing, to develop alongside the evolution of material system. Rather than aiming for single-objective optimisation, computation becomes the means of integration: integration of the system-inherent constraints of materials, manufacturing and assembly, together with the system's interaction with a wide range of external influences and forces.

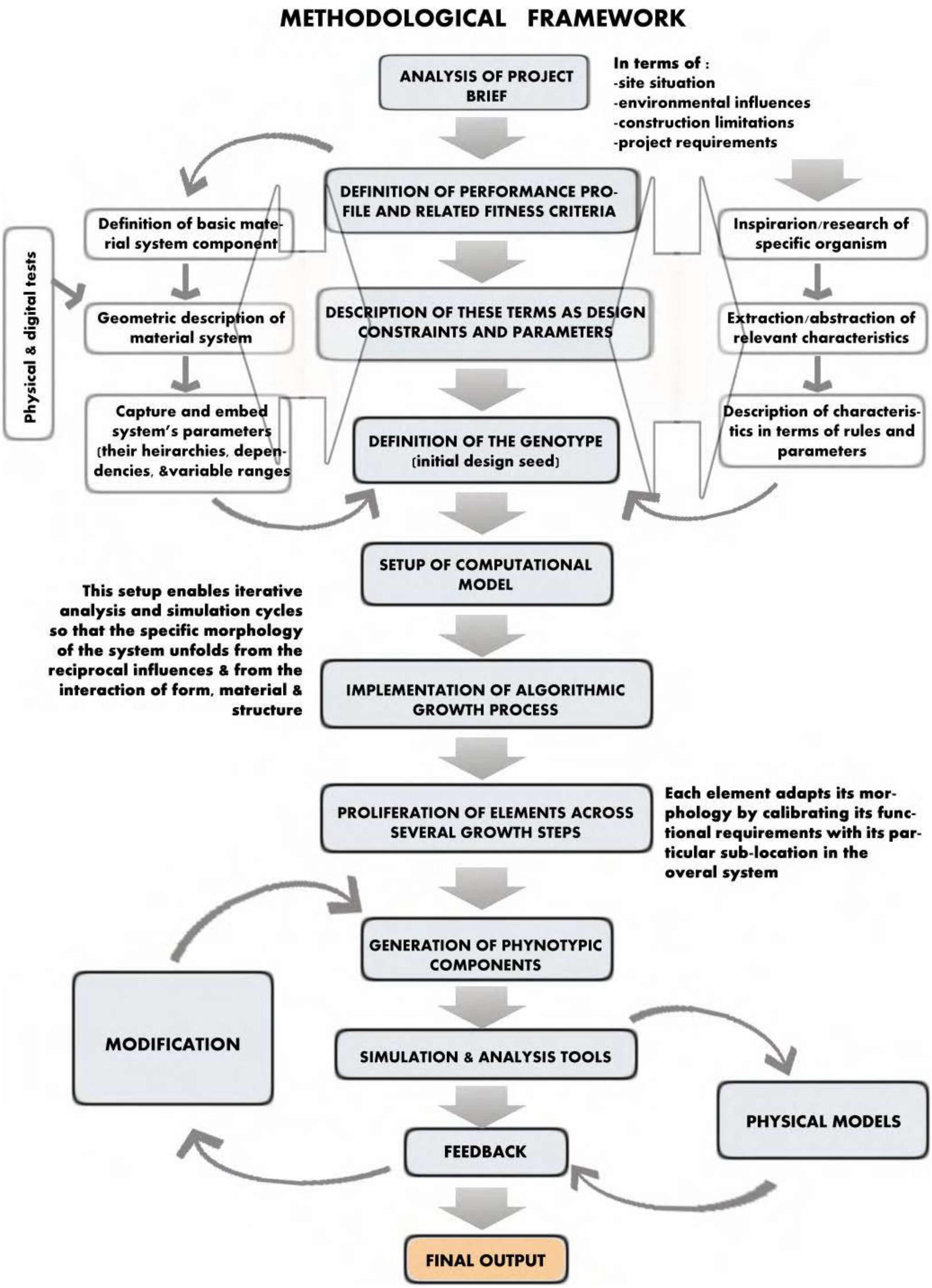


Figure 27: Diagram summarizing the presented methodological framework

3.9 Chapter Summary

This chapter has demonstrated an overview of morphogenesis, outlining the possible benefits of such an approach in architectural design. A set of general concepts relevant to morphogenesis is explained as they are needed for the comprehension of the presented approach.

A morpho-ecological design approach is presented, correlating morphogenesis and ecology, which suggests a new framework for architectural design that is firmly rooted within a biological paradigm. Both the theoretical as well as the methodological frameworks are explained for such an approach. The selected biological principles in the previous chapter are stated again, and re-explained within the context of computational design, creating a better understanding of the theoretical framework.

The morpho-ecological design approach lies at the core of this thesis, achieving a critical part of the research aim in attempting to correlate biological principles with computational design by discussing a set of selected principles twice: once within a biological context (as stated in the previous chapter) and again within the context of morphogenetic computational design.

These set of biological principles serve as analysis criteria for case studies in the following chapter, where a set of projects are analysed in order to evaluate the outcomes of such a design approach.

CHAPTER 4: CASE STUDIES: APPLICATION OF BIOLOGICAL PRICIPLES IN COMPUTATIONAL DESIGN

4.1 Introduction

It is a broadly acknowledged fact that today the majority of people on our planet live in cities, and that two thirds to three quarters of the Earth’s ecosystems are interfered with by humans. These interferences affect a great deal of change of the Earth’s biosphere, including the local and global climate. It seems obvious that the vast amount of local interlinked material and energetic modifications of any context amount to significant regional and global changes.

These local modifications are to a large extent affected by the built environment, and it is this realm that deserves greater attention and a broader scope of approaches than currently pursued. The research presented by the Emergent Technologies and Design Group at the Architectural Association in London, presents an approach towards this thematic that does not compete with the current paradigm of the preservation of the natural environment or prevailing takes on sustainability, but that examines instead the capacity of material interventions in modulating environments within specific contexts and empirically established ranges, while considering a continuum between the inside and outside across the material threshold.

Insights into how to approach this line of research derived from studies in natural systems and their interaction with the environment. This entailed, for instance, detailed studies of plant morphologies and the way in which any particular morphology contributes to the physiology of a plant and its exchange with its environment. One line of inquiry investigated the way in which morphological features of specific cacti contribute to self-shading and airflow modulation close to the surface of a selected plant, such that loss of water through evaporation and transpiration can remain within a permissible range.
However, listing such singular examples can be misleading. It would be a misconception to reduce the morphology of living systems to subsets with singular functions. This would just re-assert the prevailing prejudice based on which architecture and engineering strategizes material assemblies as mono-functional building subsystems or elements that are optimised towards single objectives. Instead, a succinct attempt was made to conduct the inquiry into the morphology and material characteristics of living systems as performative systems that cannot be reduced to mono-functional elements. (Hensel M., Menges A. and Weinstock M. 2010)

This chapter presents a number of research projects, performed at the Architectural Association School of Architecture, London, which serve as case-studies for the design approach discussed in chapter 3. The biological principles selected in the previous chapters are utilised here as analysis criteria for these projects. Each project is analysed according to these principles and then evaluated to demonstrate the main advantages of such a design approach by comparing it with conventional design means.

The projects explained in this chapter present the development of an evolutionary design tool for architecture and its application in an investigation that abstracts principles from biological structures in order to develop a new approach for sustainable architectural design.

The following case-studies will attempt to investigate the potential of different design ideas, all sharing the same general theoretical and methodological framework previously mentioned in chapter 3, but differ in their approach to solve the design problem, either solution-based or problem-based approaches. Three projects will be presented for each type.

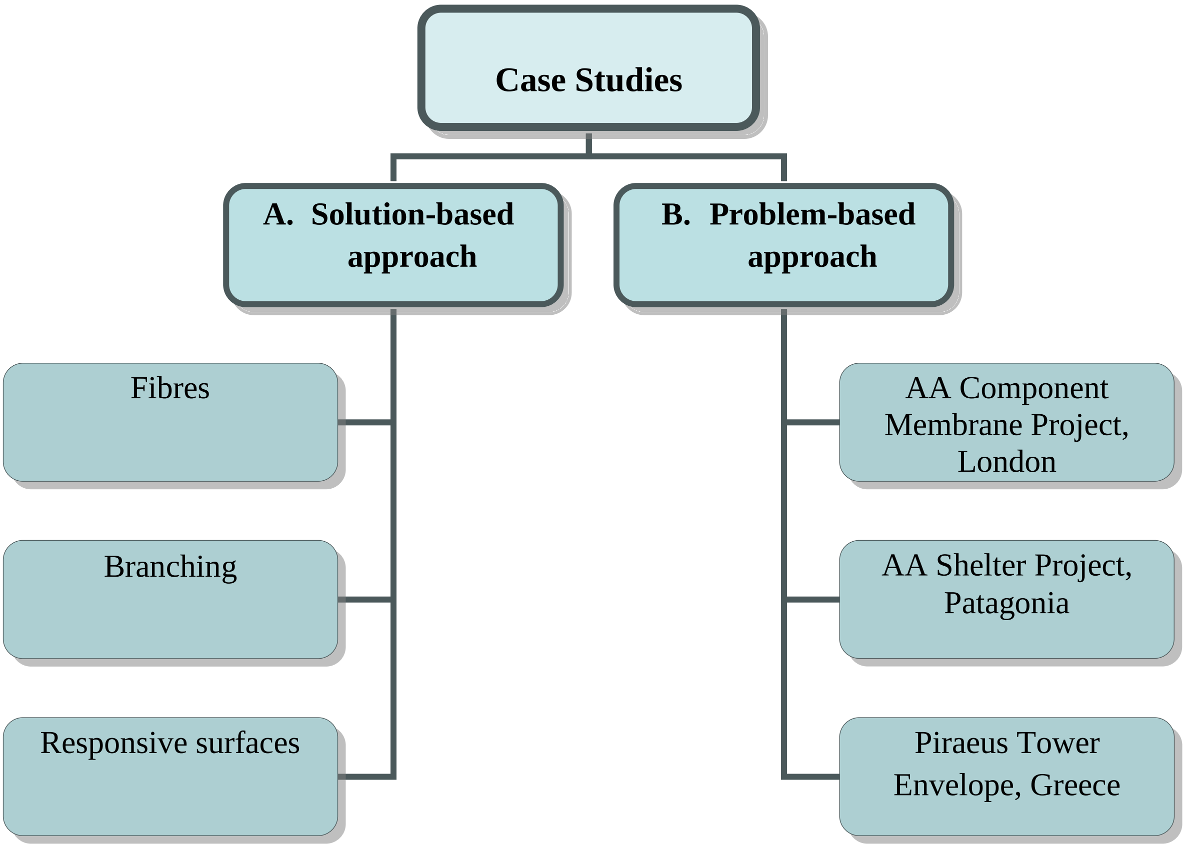


Figure 28: Types of case-studies

4.2 Solution-Based Case Studies

4.2.1 Fibres

The high integration of form, structure and function inherent to living nature very often results from the astonishing versatility of fibrous systems. This is even more remarkable if one considers that most of these biological systems consist of a small range of materials only, as it suggests that nature organises material in a highly effective manner.

The basic materials of biology are so successful not so much because for what they are, but because of the way in which they are put together. The geometrical and hierarchical organisation of the fibre architecture is significant. The same collagen fibres are used in low modulus, highly extensible structures such as blood vessels, intermediate modulus tissues such as tendons and high modulus, rigid materials such as bone.

(Hensel M., Menges A. and Weinstock M. 2010)

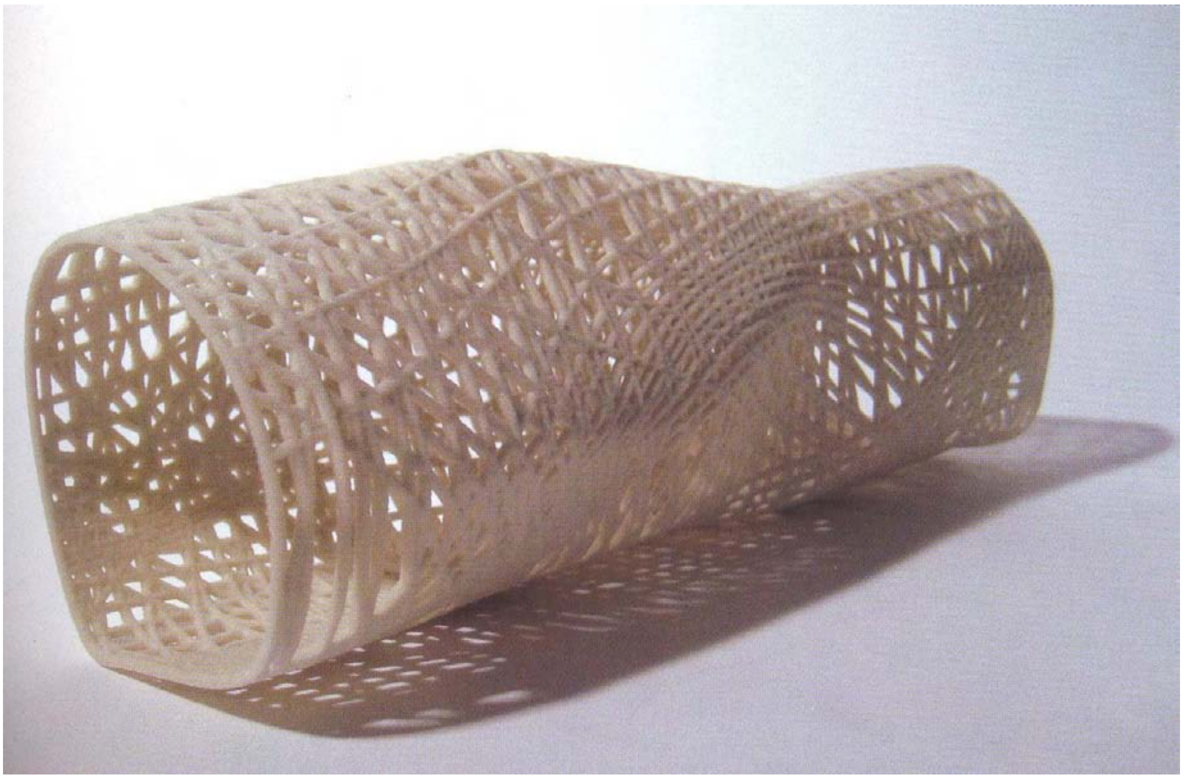


Figure 29: 3-dimentionally printed model of the fibre bridge project. March Dissertation of Christina Doumpioti, 2008. (Source: Hensel M. et al 2010)

Variations in the section and material properties of biological ‘structural members’ offer very considerable advantages over the constant section usually adopted in conventional engineered structures. The differentiated distribution of cells, fibres and bundles, according to height and slenderness, offers a very interesting model for the production of fibre-composite materials systems. Sectional variations produce anisotropy, a gradation of values between stiffness and elasticity along the length of the stem in plants that is particularly useful for resisting dynamic and unpredictable loadings.

(Hensel M., Menges A. and Weinstock M. 2006)

As a result of their highly differentiated material make up, fibre composites possess a number of properties that enable a highly specific and adaptable material distribution in response to the forces acting on them:

- Contrary to materials with homogeneous internal structures and isotropic behaviour (which means the same behaviour regardless of the direction of the forces applied), **natural composite are anisotropic**. As a consequence, the material’s structural capacity can be adapted in response to the force’s direction and magnitude.

- Natural fibre composite structures emerge from processes of adaptive growth. It is a process of growth under stress that enables the remarkable versatility of natural fibre composites by the selective deposition of new material at the position and in the direction where it is needed. It is driven by the forces the organism experiences.

- Therefore the most critical aspect in most complex natural composites is the fibre organisation and layout, rather than their materiality. The same small number of material constituents, fibres and matrix, can display a wide range of properties and serve multiple functions.

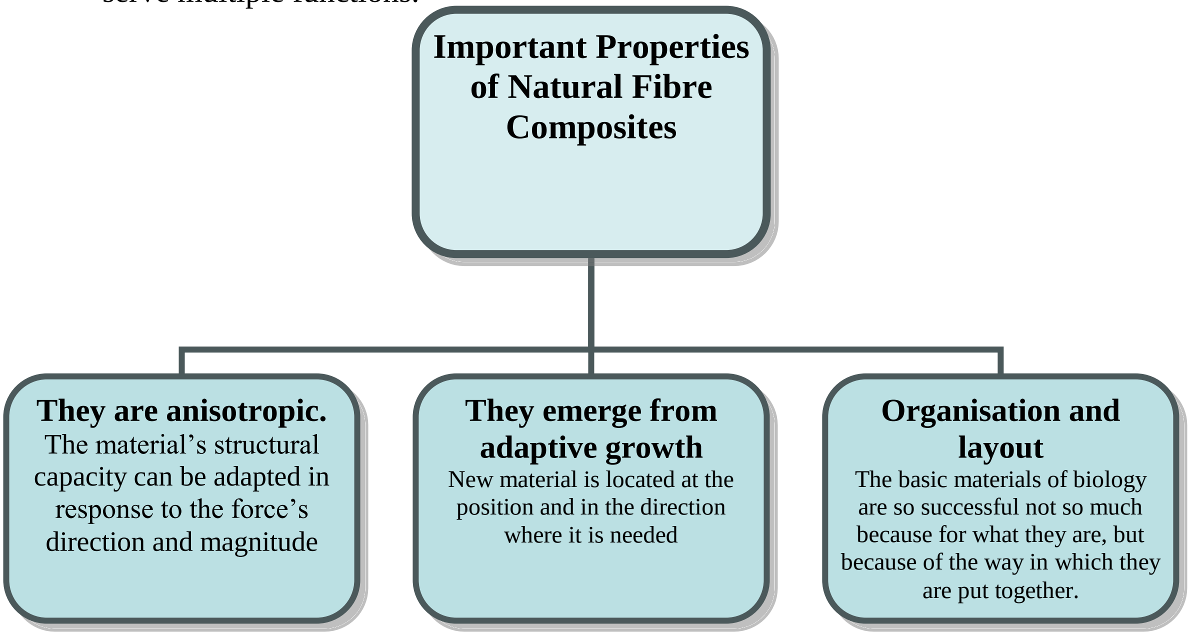


Figure 30: Properties of natural fibre composites

Christina Doumpioti’s March dissertation at the AA School of Architecture, London, investigates these resourceful fibre structures, by not only investigating the organisation and layout of fibres, but also developing and employing a computational process of growth under stress for manmade fibre composite structures. The project aimed at developing a shape-finding and fibre-path generation method for tow-steered composite structures by transferring the underlying principles of natural adaptive growth into a computational design process.

The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

4.2.1.1 Adaptation

The project was to adapt to a number of influences such as:

Project requirements:
The project’s design intention is bridging between 2 existing buildings 10 metres apart by constructing a long-span fibre composite shell that functions as a passageway as well as an exhibition space.

Structural requirements:
The objective of the system’s structural development is improving the load-bearing behaviour, minimising strain energy, levelling the magnitude of stress across the system and achieving a reduction of weight while meeting essential criteria of directional strength and stiffness.

Environmental influences
The fibre organisation must also respond to environmental influences such as solar exposure and prevailing winds.

Figure 31: Primary form generation steps of the fibre bridge. March Dissertation of Christina Doumpioti, 2008. (Source: Hensel M. et al 2010)

In an attempt to adapt to these requirements and influences, the project aimed at developing a shape-finding and fibre-path generation method for tow-steered composite structures by transferring the underlying principles of adaptive growth into a computational design process.

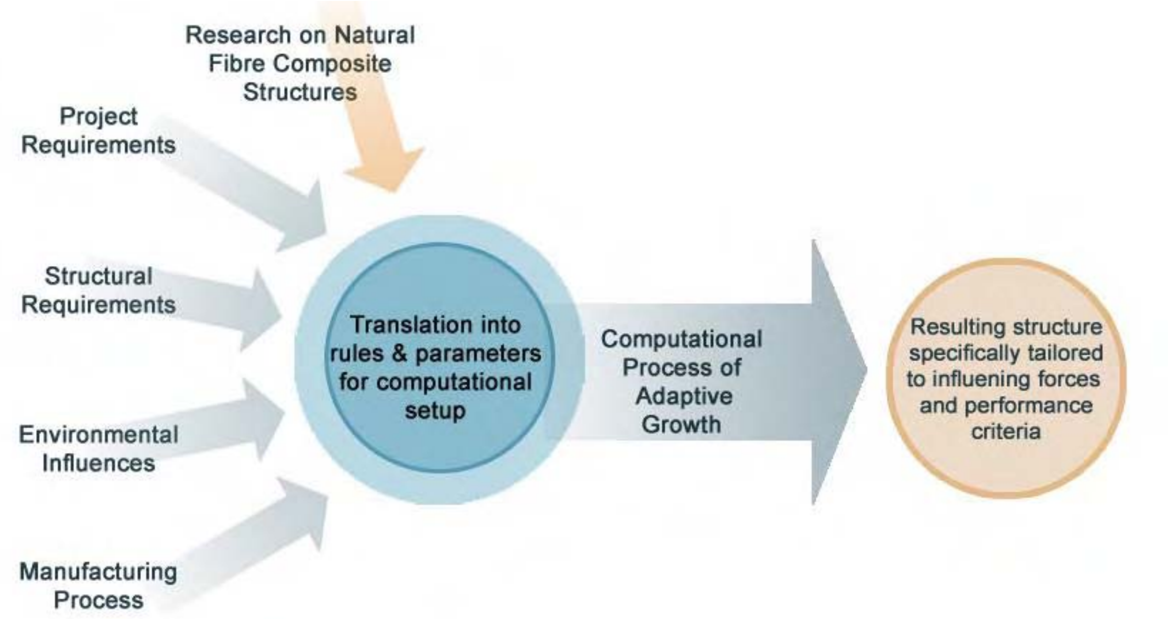


Figure 32: Adaptation process for fibre-based project

4.2.1.2 Material System

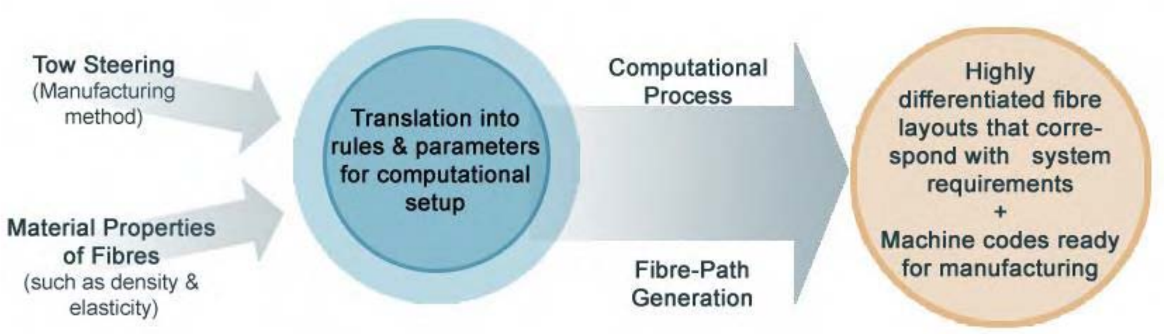


Figure 33: Material system development for fibre-based project

The manufacturing process played a major role in the development of the system. **Tow steering** is a manufacturing technique for high-end composite structures and is currently used in aerospace engineering and sailing technology. This production technology allows fabricating large-scale fibre composite structures, whereby each laminate is produced by combining layers of different fibre orientations, materiality and thickness. Most importantly, it allows for laying each fibre along an individual, digitally defined path.

The fibre tows are fed off spools through a tensioning system to the tow placement head, which travels numerically controlled along a very thin layer of fibre mats laid onto a mould. The mats provide the base surface for individually laid fibres deposited by the fibre head.

This manufacturing possibility enables the conception of large-scale, architectural fibre systems with highly differentiated fibre layouts that correspond with the structural and functional requirement of the system.

The process is directly informed by this manufacturing method, as well as material properties such as density and elasticity. The splines derived during the fibre path generation process can be directly employed to establish the related machine code for laying up the fibres.

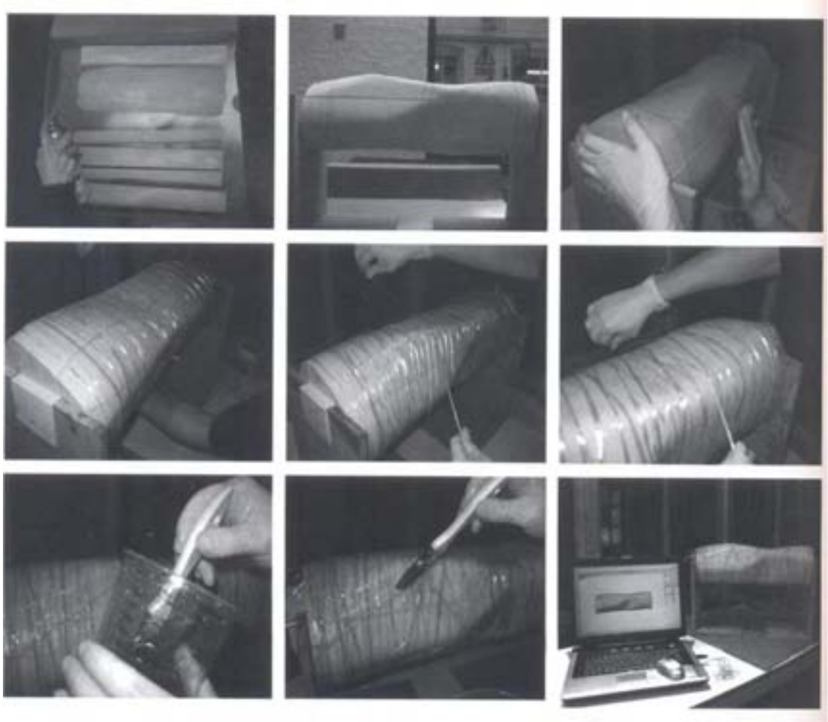


Figure 34: Testing computationally derived data by creating a model using a CNC-milled mould. March Dissertation of Christina Doumpioti, 2008. (Source: Hensel M. et al 2010)

4.2.1.3 Evolutionary Form Finding

A computational process of adaptive growth was developed in order to exploit the potential of tow steering manufacturing. This process consists of two interrelated sub-processes: one generates the overall system, and the other derives the fibre layout as fibre reference pass for tow-steering manufacturing.

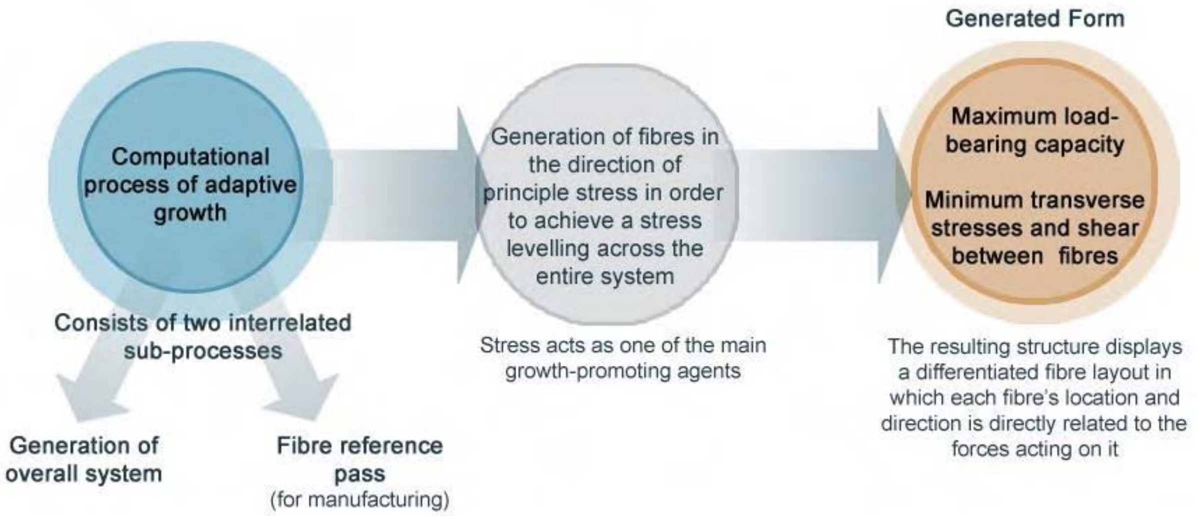


Figure 35: Form finding process for fibre-based project

Both processes are interlinked and informed by external forces and environmental influences acting on the system. Stress acts as one of the main growth-promoting agents. In the process of generating the overall shape, points act as cells and as are driven by an iterative algorithmic procedure, they self-organise into a particular pattern of point distribution. This serves as a base for defining a surface, from which new nodes are extracted that act as fibroblast cells during the path generation process. Triggered by stress concentrations, they generate fibres in the direction of principle stress in order to achieve a stress levelling across the entire system.

For each vertex point a specific load and support condition is specified according to its location within the overall system. Subsequently the overall structure is evaluated through a finite element analysis.

The vertices points with the lowest values of stress begin to act as attractors triggering the surrounding point to migrate towards them. In search of equilibrium of forces, the algorithm iterates through various cycles of structural analysis and point reconfiguration until a relatively equal distribution of forces is obtained.

For the fibre path generation, the generated overall shape is analysed by means of finite element analysis, the stress type, direction and magnitude are investigated. The nodes displaying the highest stress concentrations are defined as agents that organise the fibre structure between the nodes so that the fibres are laid in the direction of the largest principle stresses. They aim at maximizing the system's load-bearing capacity through a fibre arrangement that at the same time minimises transverse stresses and shear between the fibres. The resulting structure displays a differentiated fibre layout in which each fibre's location and direction is directly related to the forces acting on it.

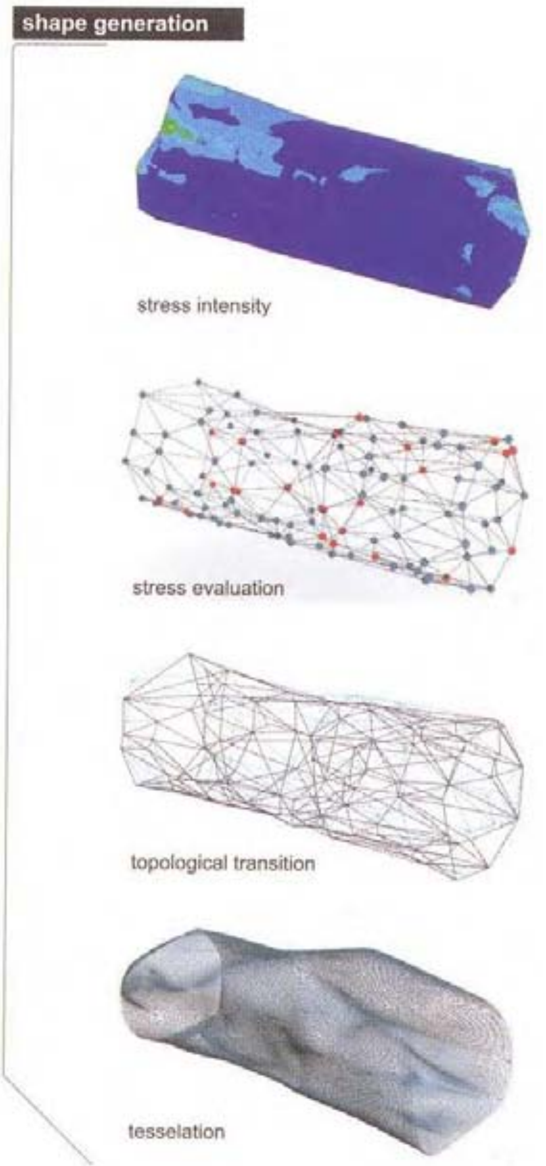


Figure 36: Form development of the fibre bridge project. March Dissertation of Christina Doumpioti, 2008. (Source: Hensel M. et al 2010)

4.2.1.4 Emergence

This case study demonstrates the enormous potential of combining the versatility of fibrous systems with new computational design and computer-controlled manufacturing processes. An interrelated development of form, material and structure in concert with novel design methods moves one step closer to the higher functionality displayed by natural systems.

In this process differentiation emerges through the intricate reciprocity between material make-up and environmental forces and influences that result in a structural articulation that cannot be reduced to its load-bearing capacity, but rather provides a robust and multifaceted range of performance capacities.

This becomes very clear for example in the process of achieving the required porosity levels. Approaching a surface assigned to form an opening, the fibre paths are locally altered so that the fibres are not disrupted or cut. Rather than terminating abruptly, as is common in other fibre lay-up technologies, here the fibres follow the contours of the openings, which allow the forces to flow around the voids.

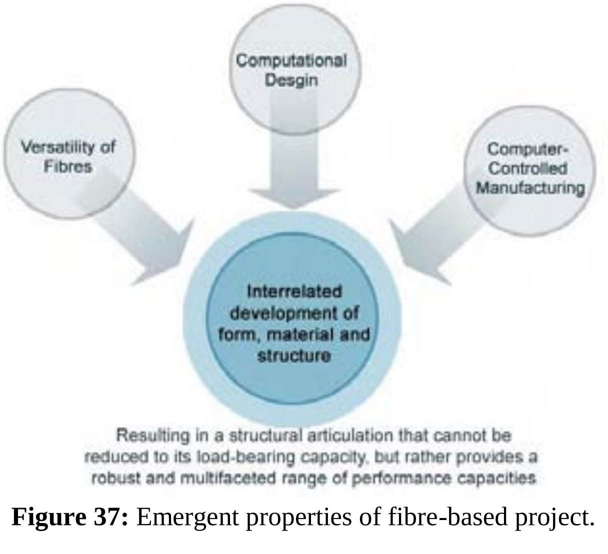


Figure 37: Emergent properties of fibre-based project.

4.2.1.5 Environmental Modulation

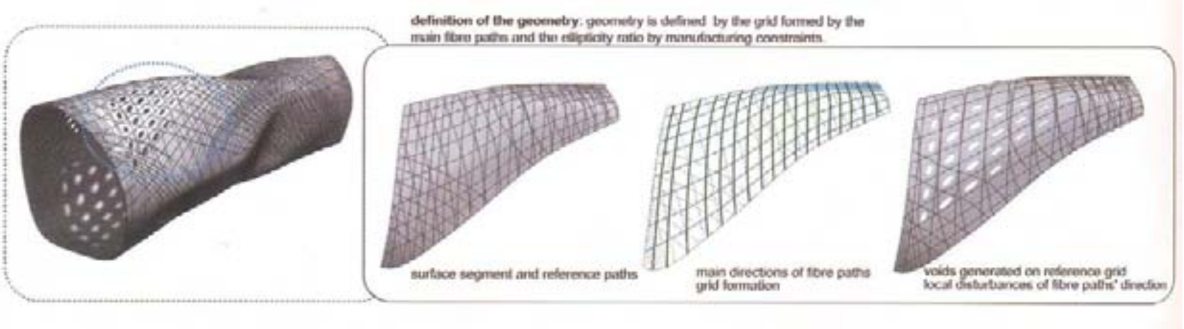


Figure 38: Distribution of surface openings. March Dissertation of Christina Doumpioti, 2008. (Source: Hensel M. et al 2010)

In addition to the structural requirements, another critical factor was included in the computational process of deriving the system’s morphology.

In order to achieve locally differentiated levels of porosity of the composite skin, the generation process is further elaborated by including environmental evaluation cycles in dialogue with the structural analysis.

Structural analysis of the fibre path system allows for identifying skin areas with the least stress concentrations, that is to say areas where material can be removed without having a major impact on the overall load-bearing behaviour. Simultaneously a fibre volume fraction analysis indicates areas of little fibre density. Where the 2 areas overlap, there are possible locations for surface openings.

In order to select which of these locations should be used to create openings, solar exposure analysis was employed to investigate the distribution and magnitude of incident solar radiation and light transmission to the system’s interior. Furthermore, computational fluid dynamics enabled testing the impact of prevailing winds on the interior airflow patterns in relation to different distributions of surface openings.

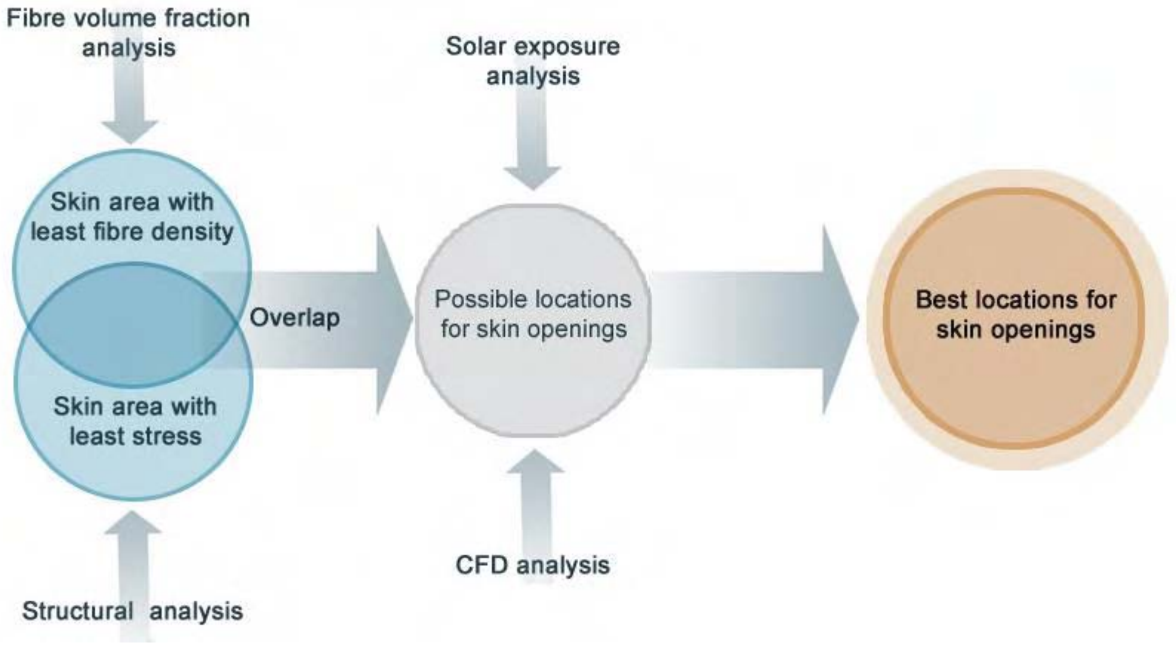


Figure 39: Fibre Bridge interfacing several analysis applications.

4.2.1.6 Form & Behaviour

This iterative computationally driven negotiation of design criteria such as structure, space, light and ventilation results in a highly differentiated fibre composite structural form integrating a wide range of performance criteria, thus radically affecting its behaviour and enabling it to successfully achieve the project requirements.

4.2.1.7 Fibre Bridge Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Comparison with conventional design methods

Achievement of goals and objectives

Required goals	How were they achieved
▪ Bridging 2 existing buildings, 10m apart. ▪ Improving load-bearing capacity. ▪ Minimizing strain. ▪ Levelling stress across the system. ▪ Reduction of weight. ▪ Directional strength and stiffness. ▪ Providing a suitable level of porosity for solar exposure and ventilation	▪ Investigating the organisation and layout of fibres in natural systems ▪ Exploring the manufacturing possibility of tow steering as a means of producing fibrous systems with highly differentiated layouts that correspond to the system's functional requirements. ▪ Employing a computational process of growth under stress for the generation of both the overall shape as well as the fibre layout. This process is directly informed by the required performance criteria as well as the manufacturing method and material properties. ▪ Recurrent analysis of the resulting system in terms of structural and environmental performance

Table 2: Fibre Bridge evaluation according to achievement of goals

Comparison between the presented design approach and conventional design methods	
Presented Approach	**Conventional Approach**
The presented design approach successfully achieved the required goals and objectives, in addition to the following aspects: ▪ **The form is a product of all affecting factors interacting with a simulated environment:** This setup enables iterative analyses and evaluation cycles, so that the specific form of the system unfolds from the reciprocal influences and interaction of form, material and structure within a simulated environment. ▪ **Advanced structural performance and versatility:** the fibres aim at maximizing the system's load-bearing capacity through a fibre arrangement that at the same time minimises transverse stresses and shear between the fibres. This resulted in a highly versatile structure, where the fibre layouts correspond to the system's structural and functional requirements. ▪ **Adaptation:** the structure displays a differentiated fibre layout in which each fibre's location and direction is directly related and adapted to the forces and influences acting on it. ▪ **High efficiency:** the computationally driven negotiation of multiple design criteria such as structure, space, light and ventilation results in a highly differentiated fibre composite structure integrating a wide range of performance criteria.	If a conventional design and construction method was to be applied, some goals and objectives will be difficult to achieve such as: ▪ Directional strength and stiffness. ▪ Difficulty of coordinating conflicting design criteria. ▪ Means of construction and fabrication might not directly affect the resultant form.

Table 3: Fibre Bridge evaluation through comparison with conventional design

4.2.2 Branching

Figure 40: X-ray of Coleus leaf showing branching system of venation.
(Source: AD Journal volume 78 No. 2, 2008)

Figure 41: Branching network of pulmonary arteries and bronchi. Resin cast of the system supplying blood and air to the lungs.
(Source: AD Journal volume 78 No. 2, 2008)

Branching patterns appear in great abundance in natural systems, ranging from overall plant morphologies, to respiratory and vascular systems of organisms, to rivers and climatic phenomena such as lightning strikes. Natural branching systems generally provide for energy efficiency in the distribution of other materials.

Such patterns are self-similar, which implies that ‘each piece of a shape is geometrically similar to the whole’ (Mandelbrot 1982:32), whether they are dispersive or convergent. Nevertheless, there are also differences in the specific patterns that occur in natural systems. Both self-similarity and differences between different branching patterns derive from the rate and ratio of bifurcations that characterize a particular branching pattern.

“In recent years, scientists have developed tools for assessing in mathematically precise way the generic features of different branching patterns, and by doing so, have been able to provide clear criteria for distinguishing one such form from another. These tools have played a crucial role in allowing us to understand how branched forms grow, because only through them do we have a definite quantifiable means of determining how close a given physical or biological model comes to reproducing the form observed in reality” (Ball 1999:111)

For the visualisation and simulation of plant growth, developmental algorithms are frequently utilised. Lindenmayer-systems or so-called L-systems, are a specific variant of a formal grammar-iterative parallel rewriting systems that are utilised for the purpose of plant growth modelling in theoretical biology, developed by the Hungarian biologist Aristid Lindenmayer (1952-89). They are particularly suited to model the growth of branching geometries.

In context-specific L-systems, this process can incorporate a variety of influences, such as the simulation of the response to gravity (gravitropism) and the response to light (phototropism), opening these processes to potentially be informed by performance criteria. (Hensel M., Menges A. and Weinstock M. 2010)

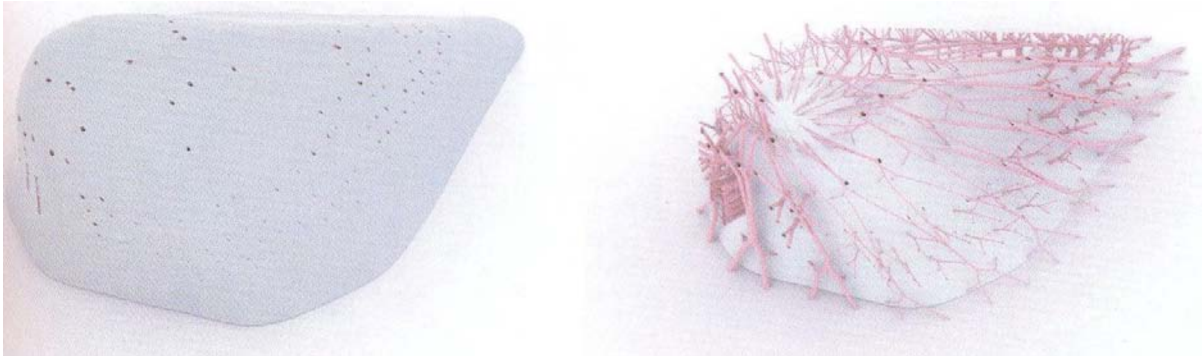


Figure 42: Digital model of branching morphology. March Dissertation of Yukio Minobe, 2008.
(Source: Hensel M. et el 2010)

The following project presents the March dissertation project of Yukio Minobe (2008), at the AA School of Architecture, where he investigated the design of a complex branching system for ventilation embedded within a cast dome-shaped envelope. In order to evolve a branching ventilation system between the inside and outside of a cast shell structure, and between determined start and end points, he developed different types of algorithms to serve each purpose.

The project embarked from a detailed analysis of the environment-related shape of termite mounds reducing thermal impact, and the complex ventilation systems of such mounds. The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

4.2.2.1 Adaptation

The project was to adapt to a number of influences such as:

- Sun path
- Prevailing winds

There was no specific program in this research project since its main objective was investigating the ventilation system through branching networks.

Figure 43: Plaster cast of ventilation chambers of a termite mound.
(Source: http://www.lboro.ac.uk/service/publicity/newsreleases/2004/04_100(a)_termites_update.html)

4.2.2.2 Material System

Due to the nature of this research project which focused on branching networks for ventilation systems, material systems were not addressed.

Further research questions will need to address material characteristics and their resulting impact on the thermal behaviour of a material construct, followed by physical tests on a construction scale.

4.2.2.3 Evolutionary Form Finding

Following the study and analysis of termite mounds, 2 algorithms were developed that articulate a branching ventilation network within the thickness of the material envelope of the volume; which are a centroid branching algorithm, and a close sphere packing algorithm. These 2 algorithms differ in their logic and in the branching pattern to serve different functions.

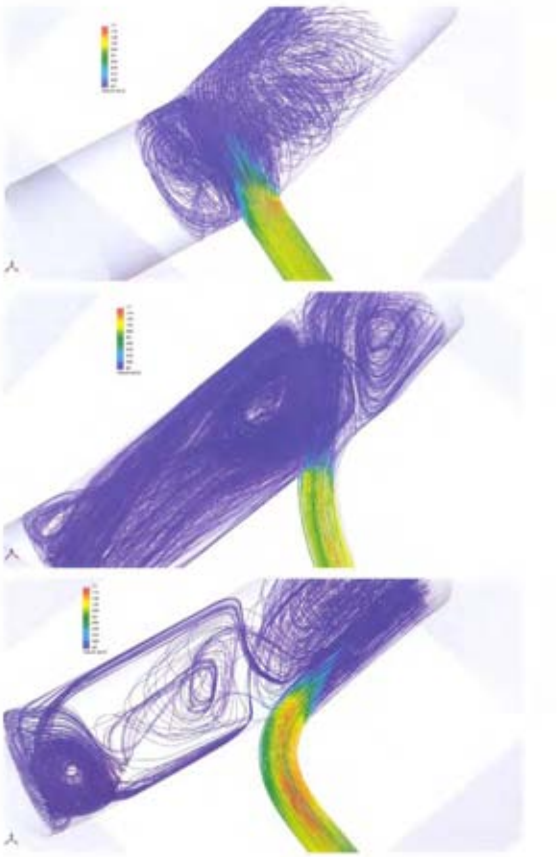


Figure 44: CFD tests of conduit bifurcation morphologies. MArch Dissertation of Yukio Minobe, 2008. (Source: Hensel M. et el 2010)

Centroid branching algorithms are deployed to adjust the growth direction of each growth step. Predefined endpoints act as attractors, attracting a tip point of new branches, so that the branches can eventually reach the attractor. In this approach, the branch length needs to be defined and, depending on that length, the branch angle will be defined too. The branch length can be adjusted in each growth step and for each cluster. This makes it possible to modify the branch length according to required airflow

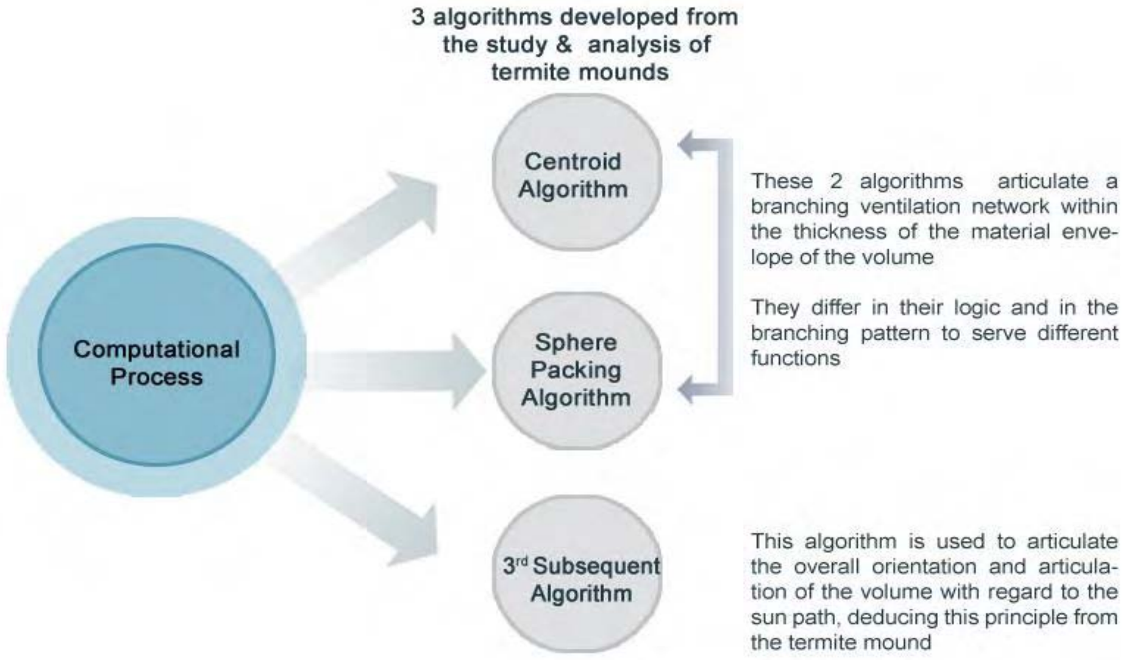


Figure 45: Branches evolved through the utilisation of 3 algorithms

conditions within the branching network. The density of branching networks and the angles between branches were analysed for resultant airflow pattern.

Subsequently an algorithm was developed that articulated the overall orientation and articulation of the volume with regard to the sun path, deducing this principle from the termite mound.

A specific site was selected to provide context-specific input such as the sun path and prevailing wind direction. For this site a series of geometries for the global volume were derived. These volumes were analysed with regard to airflow utilising different branching ventilation patterns.

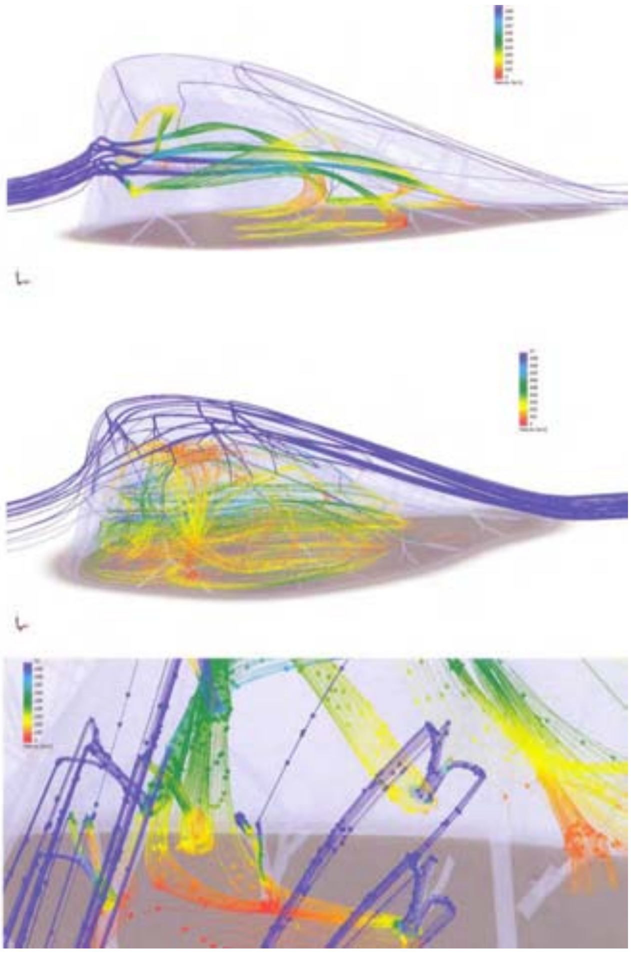


Figure 46: CFD of airflow in evolving system. MArch Dissertation of Yukio Minobe, 2008.
(Source: Hensel M. et el 2010)

4.2.2.4 Environmental Modulation

Through the analysis of termite mounds, several environmental aspects were observed:

- Upward airflows from the nest through the buoyancy effect
- The lateral air distribution from the mound chimney via lateral connections towards surface conduits.
- Airflow towards the negative pressure zone of the mound due to pressure differentials.
- Suction from the negative pressure side of the mound.

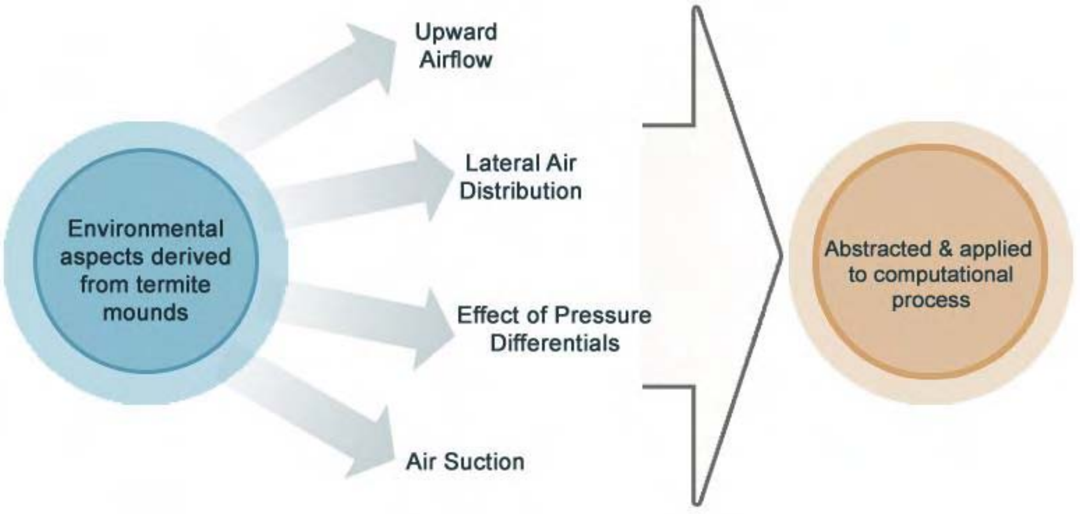


Figure 47: Principles abstracted from termite mounds

These observations were abstracted and applied in computational process in order to create a highly effective ventilation system.

4.2.2.5 Form & Behaviour

A context-sensitive iterative process of global form generation, branching pattern generation, and airflow analysis was established.

This can be explained as the overall form was developed with regard to the sun path and prevailing winds, deducing this principle from the termite mound. The form affected the behaviour of the ventilation system, as the locations of inlet and outlet point for ventilation were positioned according to the prevailing winds. CFD analyses provided continuous feedback to the process, ensuring maximum efficiency.

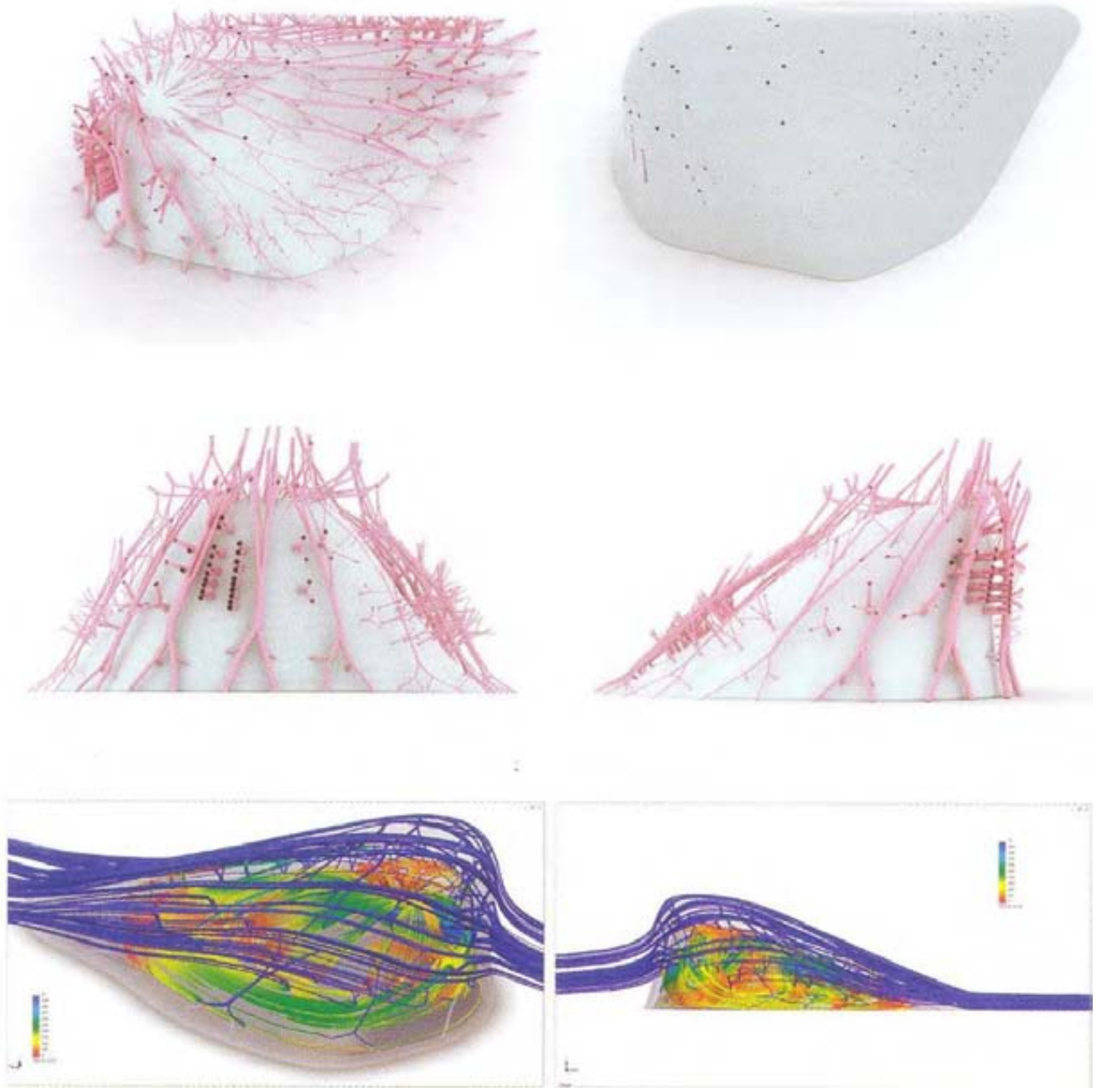


Figure 48: Models of branching morphology & associate CFD analysis. MArch Dissertation of Yukio Minobe, 2008. (Source: Hensel M. et el 2010)

4.2.2.6 Branching Project Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Comparison with conventional design methods

Achievement of goals and objectives

Required goals	How were they achieved
▪ Creating a ventilation system based on that existing in termite mounds ▪ Creating a ventilation system without the use of electrical or mechanical means.	▪ Investigating the design of complex branching systems through the study and analysis of termite mounds ▪ 2 algorithms were developed that articulate a branching ventilation network ▪ Another algorithm was developed to articulate the overall morphology ▪ Resultant airflow patterns were recurrently analysed to provide feedback

Table 4: Branching project evaluation according to achievement of goals

Comparison between the presented design approach and conventional design methods

Presented Approach	Conventional Approach
The presented design approach successfully achieved the required goals and objectives.	If a conventional design method was to be applied in order to achieve the same goals and objectives stated above, it would not be successful because of the following reasons: ▪ It is extremely difficult and complicated to accurately mimic ventilation systems in termite mounds and apply its underlying principles without the means of suitable software and computational design processes. ▪ Difficulty of manually adjusting the length and angle of every single branch to achieve the required performance.

Table 5: Branching project evaluation through comparison with conventional design means

4.2.3 Responsive Surface Structures

Figure 49: Functional Prototype of responsive surface (left) with Responsive Veneer Skin (right). (Source: Hensel M. 2009).

The response of a given material to changes in environmental conditions presents interesting opportunities for performance-oriented design. This research conducted by Steffen Reichert of the Department of Form Generation and Materialization at the Hochschule fur Gestaltung (HfG) in Offenbach, Germany in 2006/07, explores the possibility of utilising the dimensional changes of wood induced by changes in relative humidity in the environment.

Architecture is a material practice. Materials make up our built environment, and their interaction with the dynamics of the environment they are embedded within results in the specific conditions we live in. Throughout architectural history, materialization was predominantly to do with reducing change and neutralising its effect through some way of stabilisation. For example, the dimensional changes of materials due to changes in environmental conditions, such as thermal expansion. This was seen undesirable, problematic and to be avoided at all costs. This is seen as missed opportunity in the history of architecture as a material practice.

According to Phillip Ball [3]: ‘today we still do not have a material that rivals wood in its subtlety of structure and property’. This implies that we may not have understood and deployed its full capacity given that we have largely subdued or eliminated that capacity of wood with regard of its mutability in response to extrinsic influences.

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[3] Philip Ball (born 1962) is an English science writer. He holds a degree in chemistry from Oxford and a doctorate in physics from Bristol University. He was an editor for the journal Nature for over 10 years. He now writes a regular column in Chemistry World. Ball's most-popular book is the 2004 Critical Mass: How One Things Leads to Another, winner of the 2005 Aventis Prize for Science Books.

Biological materials such as wood, display inherent directionality in their material make-up: they are anisotropic. They display different characteristics in different directions, resulting also in different behaviour in different directions. It is its specific anisotropic make-up that enables wood to change dimensions due to fluctuations in extrinsic conditions. Wood is also hygroscopic; meaning that due to its complex capillary structure it absorbs moisture from its environment and yields it back so as to reach equilibrium between moisture content and the relative humidity of the environment.
(Hensel M., Menges A. and Weinstock M. 2010)

One biological system operating on this principle is the spruce cone. The initially moist, closed cone gradually dries and this leads to a differential dimensional change of the upper and lower tissues of the cone scales where they are connected to the cone stem. During the drying process this dimensional change triggers a shape change of the scales and the cone opens and the seeds are subsequently released. What is particularly interesting is that, because the behavioural response is latent in the material, this system works without any contact with the tree, and the opening and closure can be repeated over a large number of cycles without any material fatigue. (Menges A., 2009)

The project aimed for the development of a surface system made up of environmentally responsive elements that embed climate sensor, actuator, and regulating element all in one very simple component without the need for any additional kinetic mechanisms or central information control.

Figure 50: Pine cones open & close when relative humidity changes to release seeds.
(Source: AD Journal volume 78 No. 2, 2008)

The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

4.2.3.1 Adaptation

The main focus of this project is utilizing the hygroscopic characteristics of wood in the development of a surface structure capable of **adapting its porosity to changing humidity levels.** The research is still at its infancy and therefore has not been applied to an actual building project.

4.2.3.2 Material System

Initial experiments focused on the behaviour of simple veneer elements. Key design parameters were tested in relation with the element's response time to changes in moisture content and resulting shape. These parameters include:

- Fibre orientation
- Ratio of thickness
- Length and width
- Constraints of manufacturing and construction deriving necessary cutting patterns and assembly protocols

The tests resulted in the definition of a component based on material performance and anticipating the assembly of a larger system. The overall surface consists of about 600 different components; each component consists of 2 critical parts:

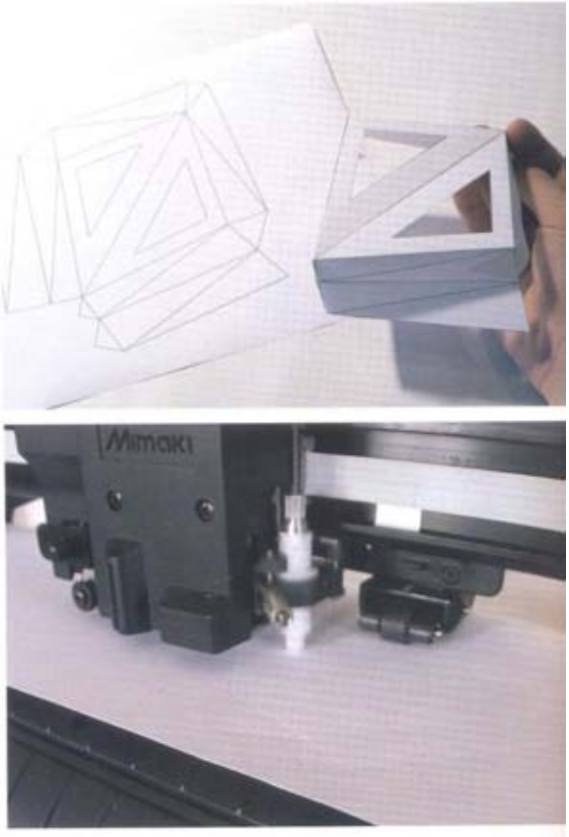

Figure 51: Development of the folded component system through paper models fabricated by cutting plotters. (Source: Hensel M. et al 2010)

Load-bearing structure: parametrically defined as a folded system with planar faces that can be manufacture from sheet material and easily connected to the adjacent component as well as the veneer on top of it.

Triangular veneer patches: in which the cutting pattern is related to the veneer grain, where the fibre direction is always parallel to the long edge of the triangle, which is then firmly connected to the substructure.

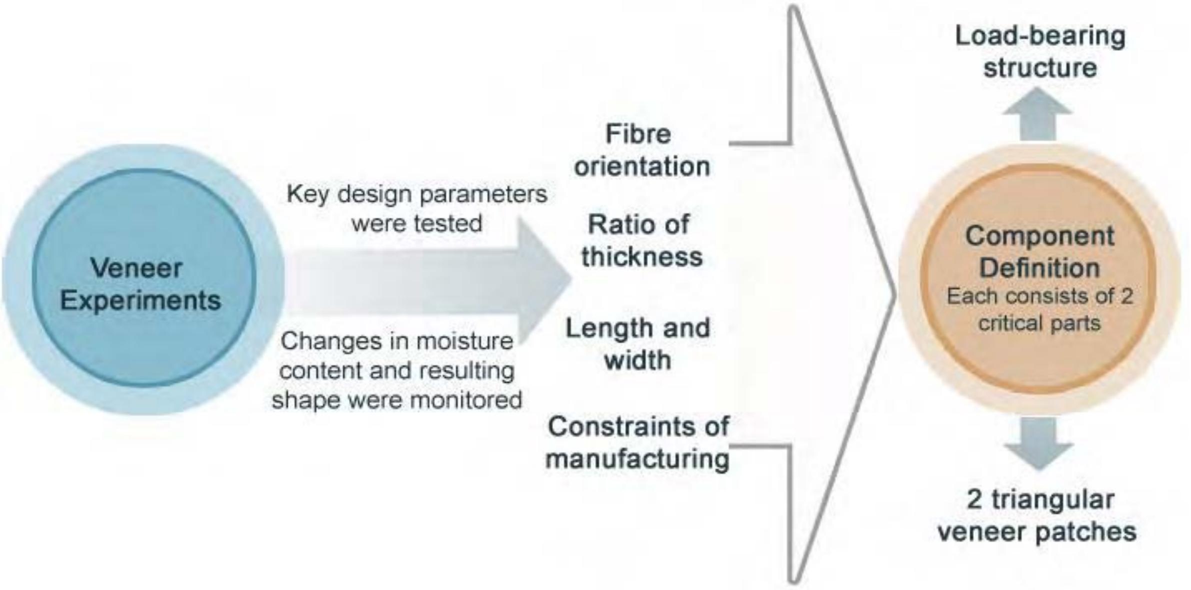

Figure 52: Development of veneer components

4.2.3.3 Evolutionary Form Finding

The complex dynamics of the mutual modulation of environmental influences, material responses and the system's behaviour needed to be taken into account during the design process.

In order to account for the relationship between individual components, their location within a larger system and the resultant micro and macro-thermodynamic modulations, the development of the global surface is based on a mathematical definition through an equation with a number of variables.

Iterative changes to these variables provide a robust yet simple base for the hygromorphic evolution of the surface geometry. This process is driven by the stochastic alteration of the mathematical surface, the subsequent associative component generation and the related Computer Fluid Dynamics analysis of each system instance's behaviour. The relevant data is continuously fed back and informs the next system generation. This enables a computational, hygromorphic evolution in which manipulation in the local element setup, regional component assemblies or the overall system are directly related to environmental modulations and vice versa.

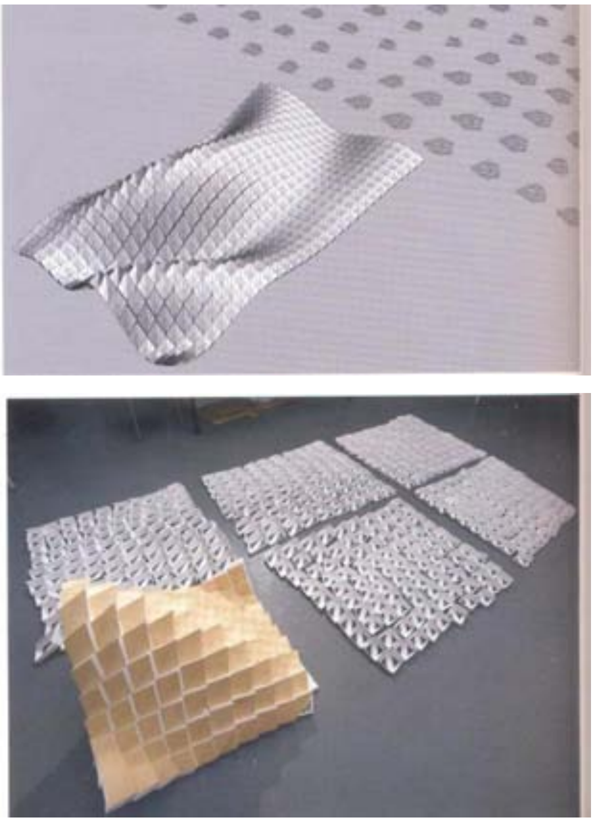

Figure 53: Development of responsive surface structure.
(Source: AD Journal volume 78 No. 2, 2008)

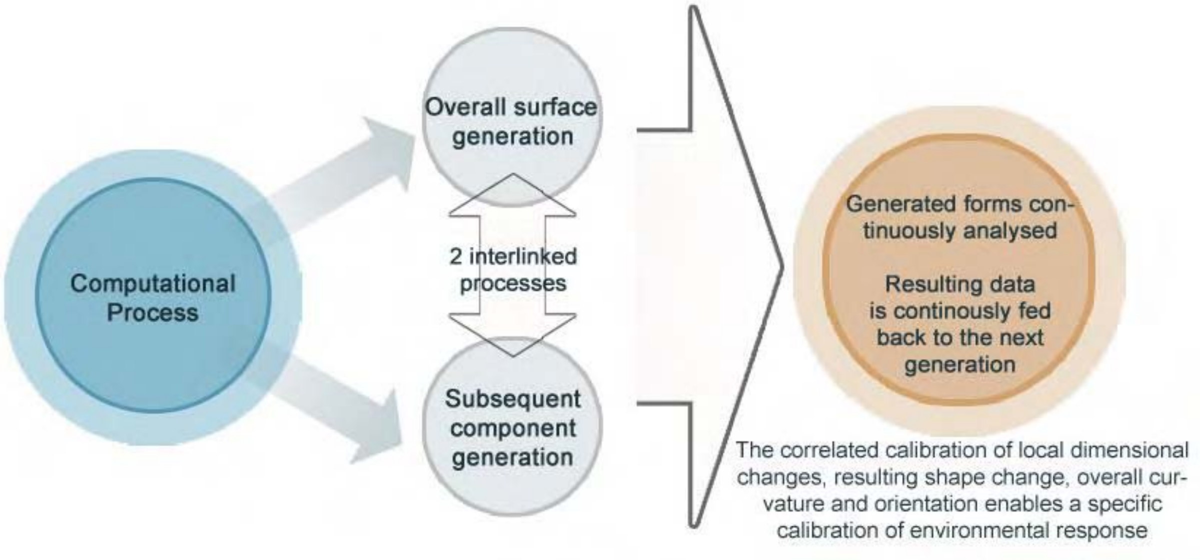

Figure 54: Responsive surface computational process

This feedback and relevant data provides for continuous parametric alterations of the computational model. In the resultant system morphology, the double curvature of the load-bearing structure orients the veneer elements towards or away from specific environmental input. In this way, the elements can either be exposed to or removed from the impact of critical influence of humid airstreams such as sunlight, thermal energy and global airflow. The fine calibration of local dimensional changes, resulting shape change, overall curvature and orientation enables an equally specific calibration of environmental response and modulation. The parametric setup of this computational differentiation process also incorporates the constraints of manufacturing and construction and derives the necessary cutting patterns and assembly protocols at the same time.

4.2.3.4 Emergence

A functional full scale prototype consisting of more than 600 geometrically variant components was constructed and tested. Once exposed to changes in relative humidity, the veneer composite patches swell or shrink and thus facilitate the opening and closure of each local component resulting in different degrees of porosity across the surface, which is both a structure and responsive skin.

This high level of integration and interaction of form, structure and material performance enables a direct response to environmental influences without the need for additional electronic or mechanical control.

4.2.3.5 Environmental Modulation

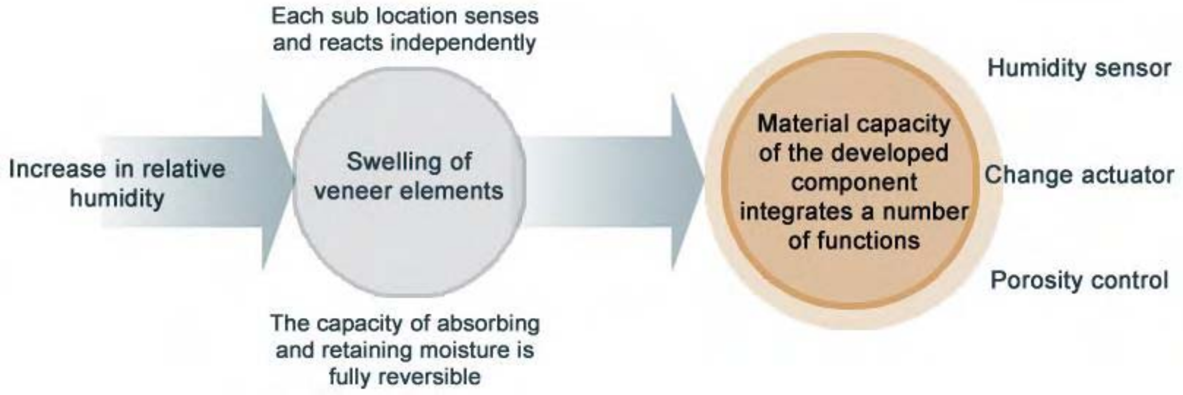

Figure 55: Environmental modulation of responsive surface

The veneer elements used in the material system swell when an increase in relative humidity and related moisture content occurs. As a result, and due to the fibrous restrictions, the surface expands mainly orthogonally to the main fibre direction. The ensuing gradual shape opens a gap between the curving element and the substructure and thus increases the component’s degree of opening.

The material’s hygroscopic capacity of absorbing and retaining moisture is fully reversible and, given an extreme change in relative humidity, is also pretty rapid with the shift from a closed to a fully opened state taking less than 20 seconds. The material capacity of the developed component integrates a humidity sensor, change actuator and porosity control element. The component’s direct responses to environmental changes suggest a locally controlled system in which each sub location senses and reacts independently as part of an emergent overall environmental modulation.

The resultant calibration of overall curvature and local component morphology in different opening states enables a highly specific modulation of airflow and related humidity levels across and along the system.

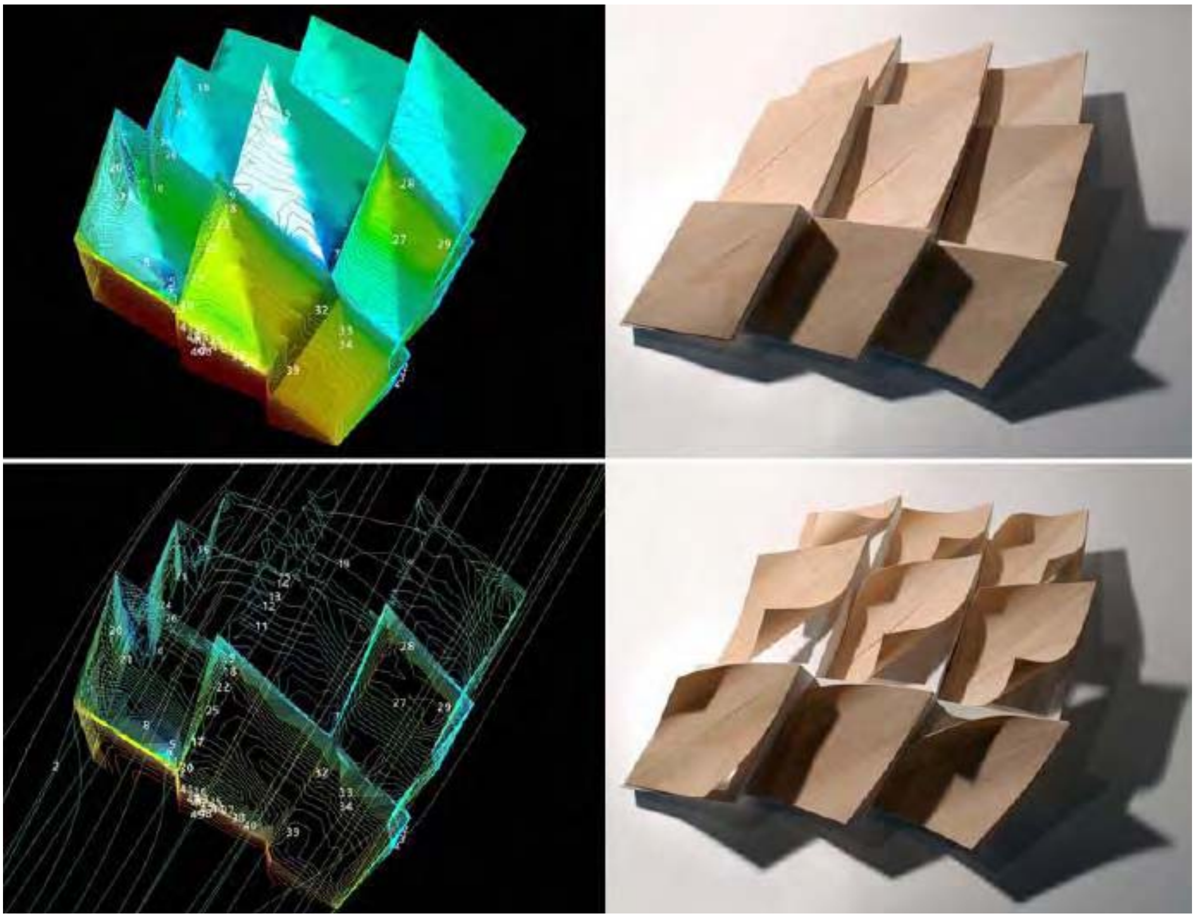

Figure 56: CFD Analysis (left) / Components in Closed and Opened State (right).
(Source: AD Journal volume 78 No. 2, 2008)

4.2.3.6 Form & Behaviour

The overall surface curvature plays an important role in the intricate interaction between system and environment. It contributes to structural capacity, as well as providing different orientation and exposure of each element to relevant environmental influences, thus affecting the behaviour of the system.

4.2.3.7 Responsive Surface Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Comparison with conventional design methods

Achievement of goals and objectives

Required goals	How were they achieved
▪ Developing a surface structure that adapts the porosity of its skin, and related cross-ventilation in response to relative humidity ▪ No electrical or mechanical devices are to be used.	▪ Analysis of wood veneer through physical tests to extract relevant performance capacities according to the performance criteria. ▪ The tests resulted in the definition of a component based on material performance and anticipating the assembly of a larger system. ▪ Underlying constraints of fabrication are embedded in the system ▪ Development of the global surface is based on a mathematical definition through an equation with a number of variables. ▪ Evolving of various designs and analysis and evaluation of their environmental performance ▪ Feedback of the findings into the next run of the procedure ▪ Selection of the evolved surface with desired environmental performance

Table 6: Evaluation of responsive surface according to achievement of goals

Comparison between the presented design approach and conventional design methods	
Presented Approach	**Conventional Approach**
The presented design approach successfully achieved the required goals and objectives.	If a conventional design method was to be applied in order to achieve the same goals and objectives stated above, it would probably be unsuccessful due to the following reasons: ▪ Difficulty of applying the relevant characteristics of the selected wood veneer without computational means ▪ Difficulty of manually calibrating each component to respond to various conditions and orientation within the envelope ▪ Difficulty of coordinating the articulation of each single element with that of the overall form.

Table 7: Evaluation of responsive surface through comparison with conventional design means.

4.3 Problem-Based Case Studies

4.3.1 AA Membrane Canopy

Figure 57: AA Membrane Canopy.
(Source: http://www.membranespaces.net/?page_id=806)

The project aimed at accomplishing both, being an experiment that allows exploring and synthesising a number of research topics, while at the same time completing a **commissioned project**, which required the construction of a canopy for the Architectural Association terrace. The project was developed, designed and construction by the Emergent Technology & Design master students at the Architectural Association School of Architecture, London, in collaboration with structural engineers from the London branch of Buro Happold[4].

The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour

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[4] **Buro Happold** is a professional services firm providing engineering consultancy, design, planning, project management and consulting services for all aspects of buildings, infrastructure and the environment. It was founded in 1976, by Sir Edmund Happold in Bath in the southwest of England.

- Environmental modulation

4.3.1.1 Adaptation

The canopy was to adapt to a number of existing influences and constraints such as:

Site situation:
The contact points between the canopy to be constructed and the surrounding building were limited to three existing columns, which could only withstand minimum bending moments.

Environmental influences
Such as wind pressure, precipitation loads of rain and snow, sunlight and shading.

Construction limitations

- Weak existing sub-structure.
- The entire canopy was to be assembled without cranes or scaffolds. (This greatly limited the overall weight and size of the individual components)
- Manufacturing and assembly processes : Due to significant budget constraints, the material system to be developed needed to consist of common, inexpensive stock material and only to rely on fabrication processes operable in the school's workshop by unskilled labour.
- Only the membranes needed to be cut and the steel elements needed to be nickel plated by specialised manufacturers

Project requirements

- The canopy needed to protect the terrace from crosswinds and horizontally-driven rain.
- On the other hand, a high degree of porosity was necessary in order to minimize wind impact pressure and to avoid blocking the view towards a specific landmark building.

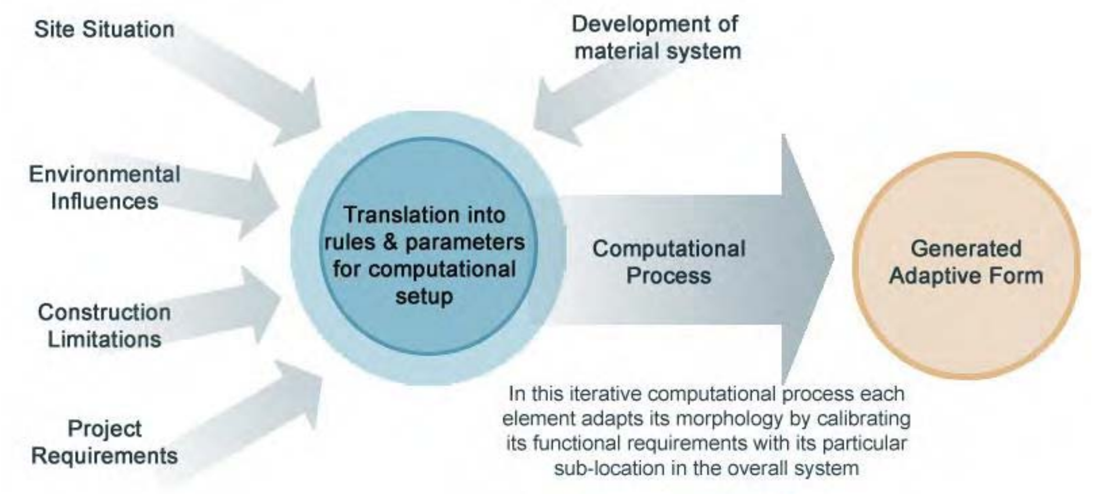

Figure 58: Adaptation process for the AA Membrane Canopy

Defining the material system’s inherent parameters and their influence in the design process and the development of the overall system allowed for each individual component to be differentiated in response to the specific requirements of the overall system’s sub location in which it is placed.

In this iterative computational process each element adapts its morphology by calibrating its functional requirements with its particular sub-location in the overall system.

4.3.1.2 Material System

Because of the aforementioned constraints, the basic component of the material system developed for this project comprises:

- A framework of compression elements, simple galvanised steel tubes;
- Steel wires as tension elements on the perimeter;
- The membrane assembly

In the overall structure the membrane patches contribute considerably to the structure’s load-bearing capacity as the main tension elements and at the same time provide the system’s skin.

For the development of the membrane component system, it was important to define the material system’s inherent parameters and in particular their variable bandwidth determined by the constraints of individual elements.

This generic definition allowed for each component to be differentiated in response to the specific requirements of the overall system’s sub location in which it is placed.

The parameterisation of the component was based on a large number of physical tests exploring the system’s inherent constraints. First the self-forming behaviour of the membrane element was investigated in relation to the location of the points where it attaches to the compression framework. The variation of the coordinates of the anchor points leads to variant equilibrium states of the acting forces and related membrane shapes.

Figure 59: Full Scale mock-up of the canopy.
(Source: Hensel M. et al 2010)

Figure 60: Close up view of steel and membrane elements.
(Source: http://www.membranespaces.net/?page_id=806)

The parametric description of the tubular steel frame is hierarchically dependant on the membranes, in that its geometric variance is limited by the constraints of their self-forming processes to prevent wrinkles or more generally to ensure proper tensioning so that the membranes can become structurally active.

In addition, the compression elements have their own inherent limits, for example the maximum deviation of joint angles on both ends. Furthermore, in order to prevent local buckling, the relative maximum length of each tube is limited in relation to the compressive force acting on it as the tubes' diameter range was restricted to 16 to 22mm owing to manufacturing and weight constraints.

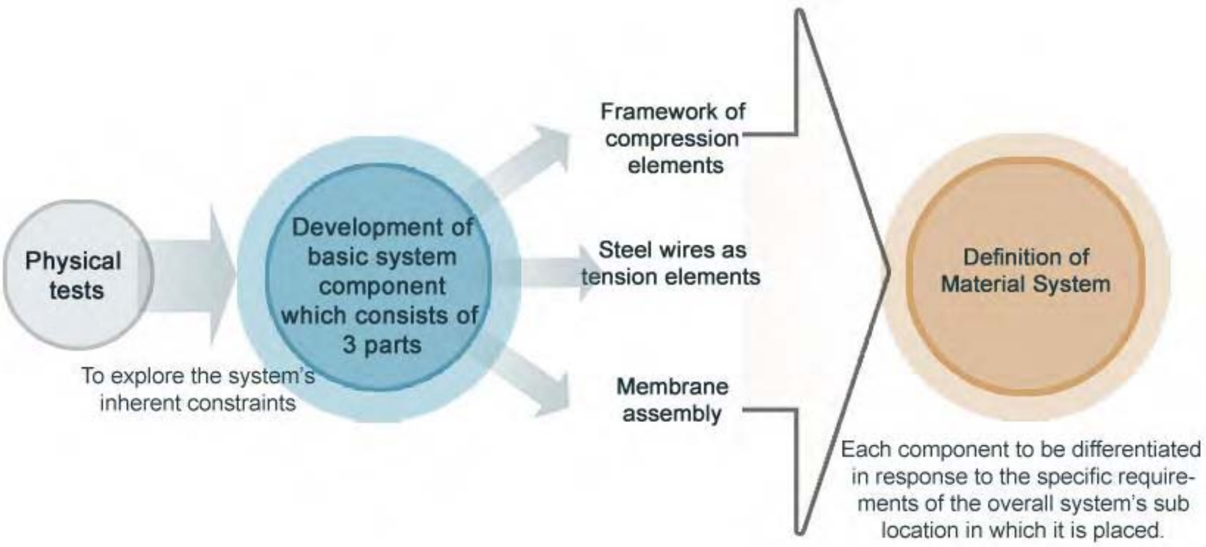

Figure 61: Development of the canopy's material system

4.3.1.3 Evolutionary Form Finding

The technical implementation of algorithmic growth processes is mainly characterized by the proliferation of elements across several growth steps, in which each element is regenerated rather than one added to another.

The computational differentiation operates on three different levels in this project:

- The component level and its dependent elements
- The level of the multi-component subsystems
- The overall system configuration

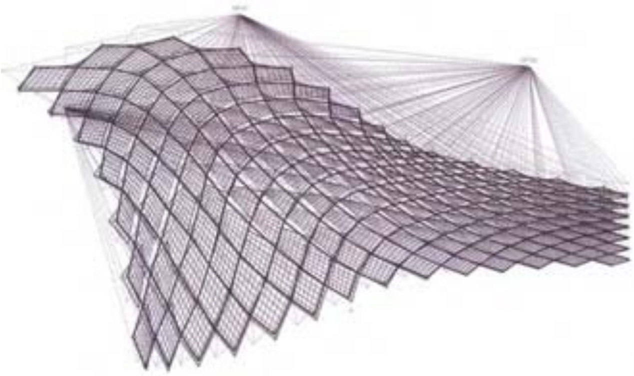

Figure 62: Computational model of the canopy.
(Source: Hensel M. et al 2010)

Each level is generated in direct feedback with different analytical tools and continual cross-checks with the given constraint space. Thus the morphogenetic process enables the balancing and calibration of multiple or even conflicting design criteria and the unfolding of the material system's inherent performative capacity.

The full exploration of the design space as defined by the variables and evolving margins of the phenotypic plasticity, as well as the related development of a system's specific performative capacity, is possible in an evolutionary process.

Similar to the algorithmic growth process, evolutionary computation offers different ways of implementing such generative processes and fitness evaluation techniques. What all such procedures generally have in common is using the evolutionary dynamics of combination, reproduction and mutation of the underlying genotypic datasets through a genetic algorithm as well as selection procedures.

The continuous differentiation of the system and all its elements is driven by the open-ended, stochastic search of the morphogenetic process, in combination with the selective nature of fitness rankings at the interval of each generation.

Similar to the definition of the material system through physical models and prototypes, the analysis and evaluation of the system's performative capacity may equally be cross-checked through empirical tests. The findings of analytical modes oscillating between the analogue and computational realm can lead to alterations in the weighing of evaluation criteria or even the system's underlying definition itself.

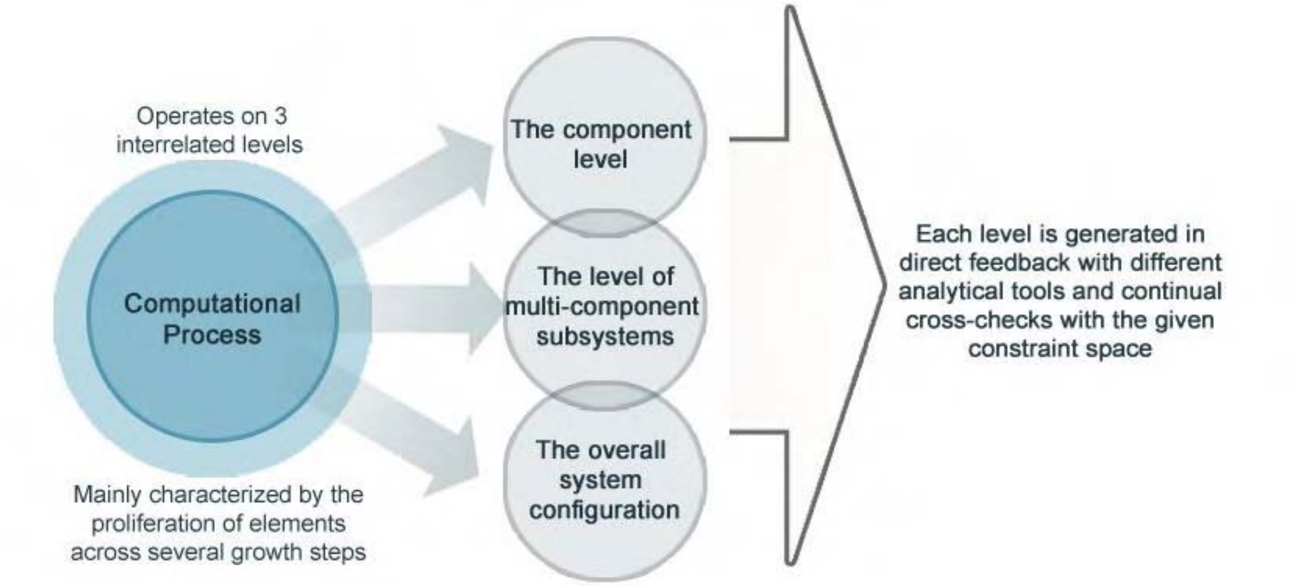

Figure 63: The canopy was developed through a multi-levelled computational process

4.3.1.4 Emergence

In this iterative growth and proliferation process each element adapts its morphology by calibrating its functional requirements with its particular sub-location in the overall system.

This computational generation of the performative phenotypic components is driven by a feedback with different simulation and analysis tools. These tools are not only employed for cross-checking the self-forming limits of the system. This setup enables iterative analyses and evaluation cycles, so that the specific gestalt of the system unfolds from the reciprocal influences and interactions of form, material and structure within a simulated environment.

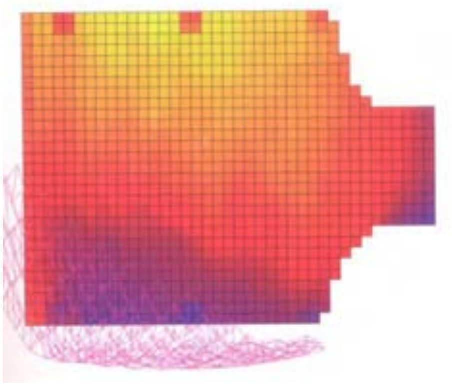

Figure 64: Shading analysis of the canopy

For example a sequence of finite element analyses conducted by the engineers from Buro Happold during the design phase evolved the structure in such a way that the pre-tensioned membrane elements became an integral load-bearing part of the system, not just a cladding on a space frame.

4.3.1.5 Environmental Modulation[5]

Depending on the system’s intended environmental modulation capacity, the morphogenetic development process needs to recurrently interface with appropriate analysis applications. For example, multi-physics computer fluid dynamics for the investigation of thermodynamic relations, light and acoustic analysis.

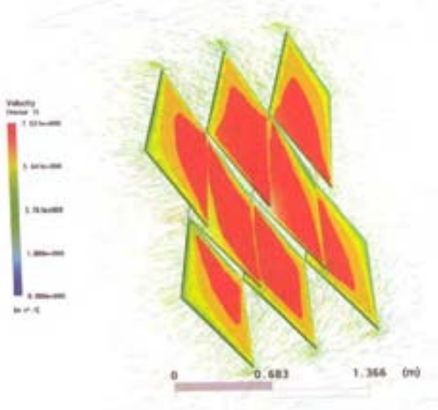

Figure 65: CFD analysis investigating pressure differentials

Concurrently iterative CFD tests of the system’s aerodynamic behaviour were conducted on both the level of the overall system and local components assemblies. In feedback with analytical tools simulating the system’s interaction with precipitation and its related drainage behaviour, this multi-criteria evaluation derived a finely calibrated level of permeability of the porous membrane skin that minimises wind pressure and simultaneously prevents local accelerations of airflow due to channelling gaps between the membrane elements.

A further important factor that influenced the system’s development was the shading behaviour of

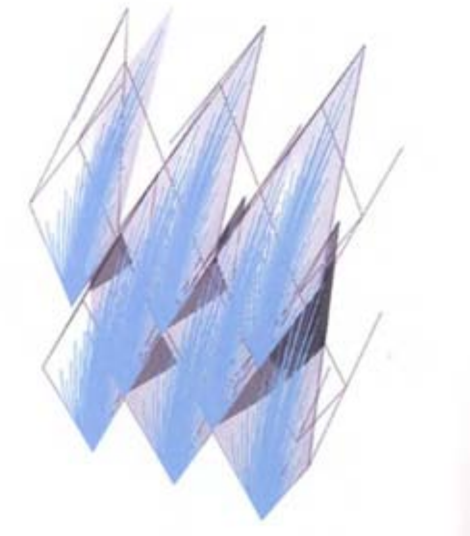

Figure 66: Rainwater runoff analysis

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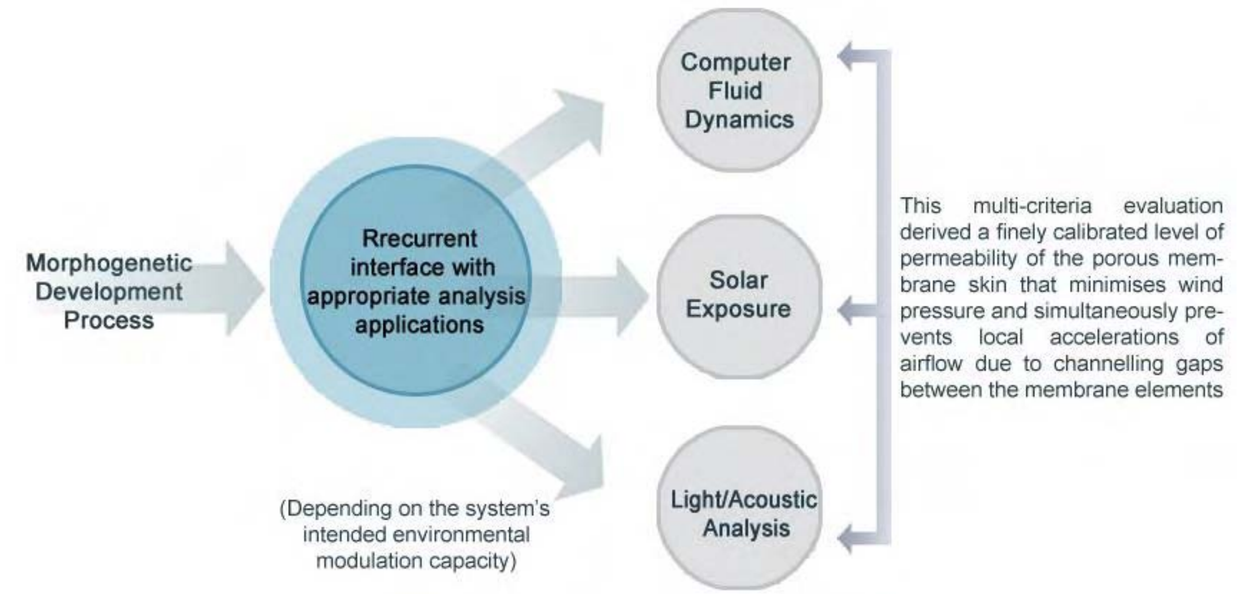
[5] Source of images in this page: Hensel M. et al 2010.

the canopy in different seasons and at different times of day, aiming for a mix of shaded and exposed terrace zones that change from winter to summer.



This multi-criteria evaluation derived a finely calibrated level of permeability of the porous membrane skin that minimises wind pressure and simultaneously prevents local accelerations of airflow due to channelling gaps between the membrane elements

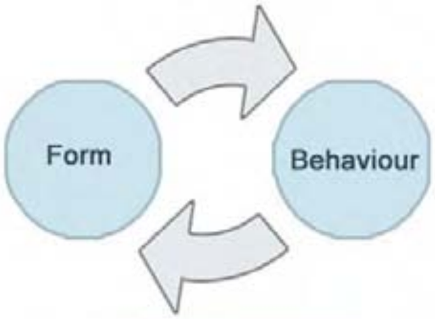
Figure 67: Environmental modulation of the AA canopy

4.3.1.6 Form & Behaviour

The form of the membrane canopy was a result of the required behaviour, which was fed into the system as a number of constraints or parameters, such as protection from wind and rain, allowing the view towards a specific landmark, in addition to the required structural behaviour. This approach enhances the intricate link between form and behaviour, such as that present in natural organisms. The form of an organism affects it behaviour in the environment, and a particular behaviour *will produce* different results in different environments.

Figure 68: AA Canopy exposed to severe snow loads.
(Source: Hensel M. et al 2010)

The resulting membrane shelters the terrace while at the same time remaining porous enough to avoid excessive winds or blocking the view across London's roofscape. In addition, the integrative nature of the morphogenetic process derived a high level of



The form of the membrane canopy was a result of the required behaviour robustness as compared to design processes aiming for single-criteria optimisation. Since its construction, it has withstood gale force winds and excessive snow loads, both were not originally designed for.

4.3.1.7 AA Membrane Canopy Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Comparison with conventional design methods

Achievement of goals and objectives

Required goals	How were they achieved
▪ Protection from wind & rain ▪ High degree of porosity ▪ Use inexpensive materials-operable in school's workshop ▪ Canopy is to be as lightweight as possible due to weak existing substructure	▪ The summation of all defining factors derived through and verified by a multitude of digital and physical test models leads to the definition of the genotype of the system's basic component. This genotype is the initial design seed which constitutes the unchanging genetic information. ▪ The relevant material properties, self-forming capacities, geometric characteristics, manufacturing constraints and assembly logics are described as reciprocal interdependencies operating within specific margins. ▪ In computational morphogenesis the genotypic information unfolds a performative phenotype through implementation of algorithmic growth processes, and the evolutionary development of system populations across many generations. The phenotype is the actual form emerging from its interaction with a specific environment. ▪ Depending on the system's intended environmental modulation capacity, the morphogenetic process recurrently interfaces with appropriate analysis applications such as computer fluid dynamics for the investigation of thermodynamic relations, light, acoustic and aerodynamic behaviour. ▪ In feedback with analytical tools simulating the system's interaction with precipitation and its related drainage behaviour, this multi-criteria evaluation derived a finely calibrated level of permeability of the porous membrane skin that minimises wind impact and simultaneously prevents local accelerations of airflow due to channelling gaps between the elements.

Table 8: Evaluation of the AA Membrane Canopy by achievement of required goals.

Comparison between the presented design approach and conventional design methods

Presented Approach	Conventional Approach
The presented design approach successfully achieved the required goals and objectives, in addition to the following aspects: ▪ **The form is a product of all affecting factors interacting with a simulated environment:** This setup enables iterative analyses and evaluation cycles, so that the specific form of the system unfolds from the reciprocal influences and interaction of form, material and structure within a simulated environment. ▪ **Balancing multiple and conflicting criteria:** This morphogenetic process enables the balancing and calibration of multiple, or even conflicting, design criteria and the unfolding of the material system's inherent performative capacity. ▪ **Adaptation:** In this iterative computational process each element adapts its morphology by calibrating its functional requirements with its particular sub-location in the overall system. ▪ **Higher robustness:** the integrative nature of the morphogenetic process derived a high level of robustness as compared to design processes aiming for single-criteria optimisation. Since its construction, it has withstood gale force winds and excessive snow loads, both were not originally designed for. ▪ **Relatively short timeframe:** considering that the entire structure was developed, designed, manufactured and erected in 7 weeks, it demonstrates the potential inherent to the integral approach of computational morphogenesis. ▪ **Higher efficiency/multi-functional components:** In the overall structure the membrane patches contribute considerably to the structure's load-bearing capacity as the main tension elements and at the same time provide the system's skin.	If a conventional design method was to be applied in order to achieve the same goals and objectives stated above, it would probably be successful. The difference will be in the following aspects: ▪ Difficulty of precisely calibrating every single element to the specific forces and conditions acting upon it, leading to less efficiency. ▪ Difficulty of coordinating conflicting design criteria. ▪ Means of construction and fabrication might not directly affect the resultant form.

Table 9: Evaluation of the AA Membrane Canopy through comparison with conventional design means

4.3.2 AA Shelter

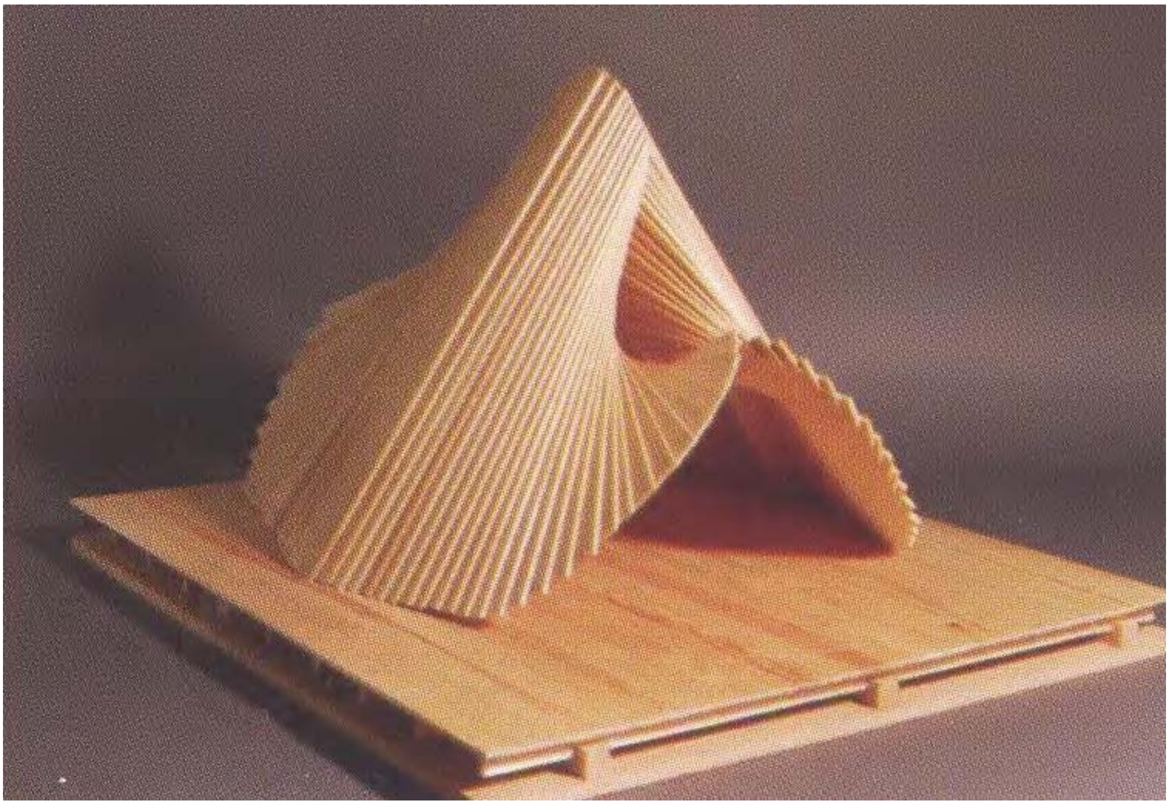


Figure 69: 1:10 model of the AA shelter. (Source: Hensel M. et al 2010)

Despite the fact that the presented design approach required a serious engagement with technology, it is certainly not limited to exotic materials, expensive manufacturing processes and vast budgets. The opposite is demonstrated through the following project, which is also based on the previously explained computational approach, yet utilises more mundane building materials and the extremely limited manufacturing technology available in one of the world's most remote areas, Patagonia.

Here complexity, and related performance capacity, unfolds from the continuous evolution and differentiation of initially simple material elements and construction procedures. The project was designed by a team of the Emergent Technology & Design Group students in the land of Hacienda Quitralco in Chilean Patagonia within one week.

The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

4.3.2.1 Adaptation

The shelter was to adapt to a number of existing influences and constraints such as:

Site situation:

The site was in a remote area on the land of Hacienda Quintralco in Chilean Patagonia, imposing stringent constraints on the development of the material system.

Environmental influences

Such as wind pressure, rain, sunlight and shading. Structural capacity in regard to frequent earthquakes was of critical importance.

Construction limitations

- Only one kind of locally cut timber was available.
- The only tool for fabrication was the chainsaw.

Project requirements

The project entailed the design of a viewing platform and shelter.

Figure 70: Site location, Chilean Patagonia. (Source: Hensel M. et al 2010)

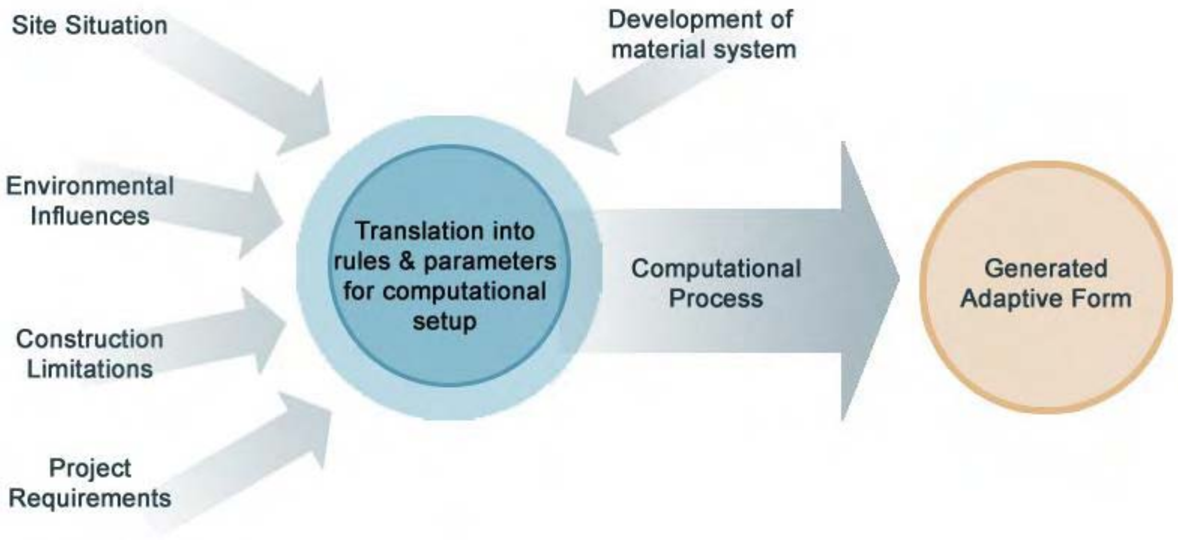


Figure 71: AA shelter adaptation process

4.3.2.2 Material Systems

The project comprised a generic platform on a raft foundation, and a shelter that consisted of two ruled surfaces made from straight equal-width timber planks.

The decision of constraining the basic computational definition of the system was made in response to:

- Pre-manufacturing constraints of timber on site.
- The available construction means.
- The local knowledge of timber construction.

Wood has variable stiffness in relation to grain orientation. The considerable difference in modulus of elasticity in relation to fibre direction is particularly useful here, with the modulus of elasticity parallel to the main fibre direction generally being approximately 15 times higher than that perpendicular to the fibres.

This enables the ruled surface to be constructed from planks that are not all situated within parallel construction planes. Depending on the overlap and joint points with the adjacent element, each plank can bend slightly along its longitudinal axis. The degree of deviation from coplanar plank assembly enables a specific curvature in the overall structure that is given as a function of each local plank joint.

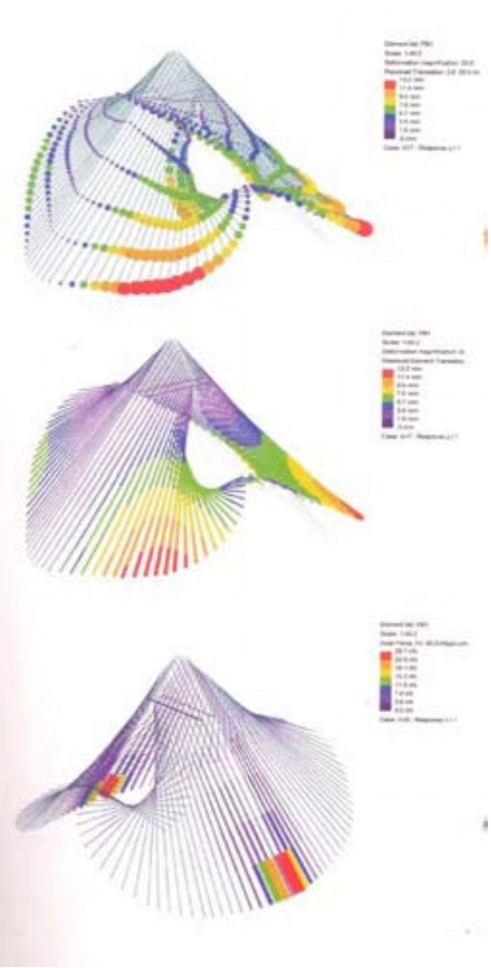


Figure 72: Structural analysis of the shelter. (Source: Hensel M. et al 2010)

The design space for the subsequent exploration of the system's capacity was defined by the possibility of varying the guide curves in space, the length and the maximum angle between planks.

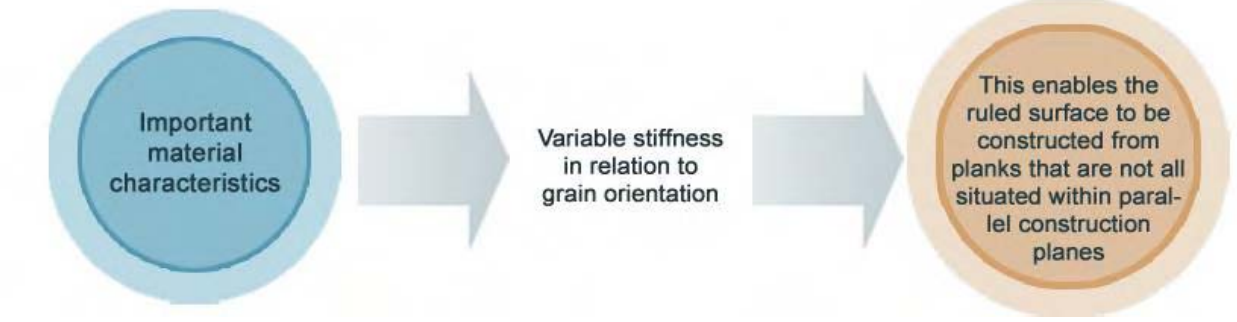
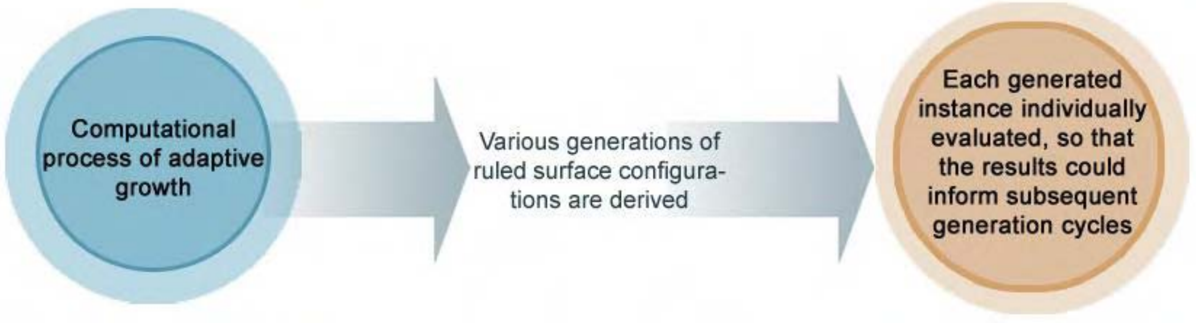


Figure 73: Important characteristic of wood

4.3.2.3 Evolutionary Form Finding

Key design criteria for the evolutionary design process were basic functional requirements such as the enclosed volume in relation to envelope surface, minimum ceiling height and the view axis towards the fjord. Structural capacity as well as climate conditions was also key criteria.

The considerable constraints determined by the availability of just one material element in addition to the mentioned design criteria provided the key constituents of the computational design process. Various generations of ruled surface configurations were derived and each generated instance individually evaluated, so that the results could inform subsequent generation cycles.



Computational process of adaptive growth

Various generations of ruled surface configurations are derived

Each generated instance individually evaluated, so that the results could inform subsequent generation cycles

Figure 74: AA shelter Computational process

4.3.2.4 Emergence

The final form of the shelter was a result of the material system's characteristics and properties, and both the form and the material system interacted to produce a structure that successfully fulfilled the proposed functional requirements.

Figure 75: Final form of the shelter as result of the complex interaction between form, material and structure. (Source: Hensel M. et al 2010)

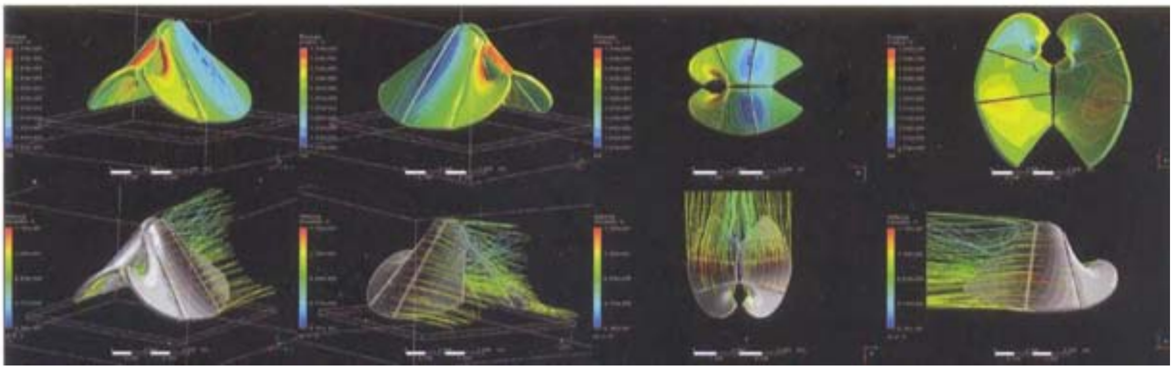


Figure 76: CFD of the shelter project. (Source: Hensel M. et al 2010)

4.3.2.5 Environmental Modulation

The design process repeatedly interfaced with environmental analysis applications, testing the model's performance and providing important feedback to the system. Such applications included structural and displacement analysis of the shelter exposed to seismic forces, in addition to computer fluid dynamics analysis which served to determine horizontal loads and airflow conditions within the shelter as a design input.

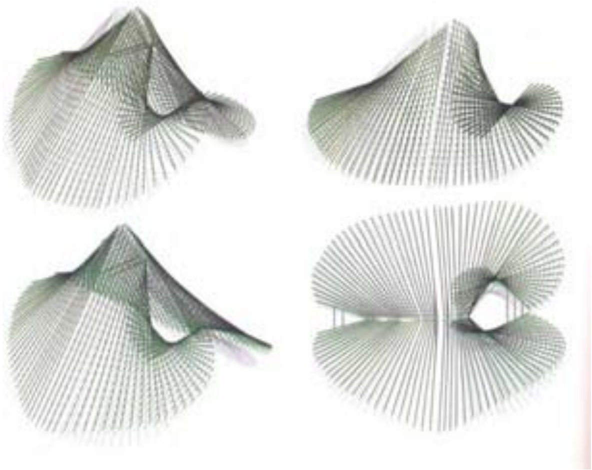


Figure 77: Displacement analysis of the shelter project. (Source: Hensel M. et al 2010)

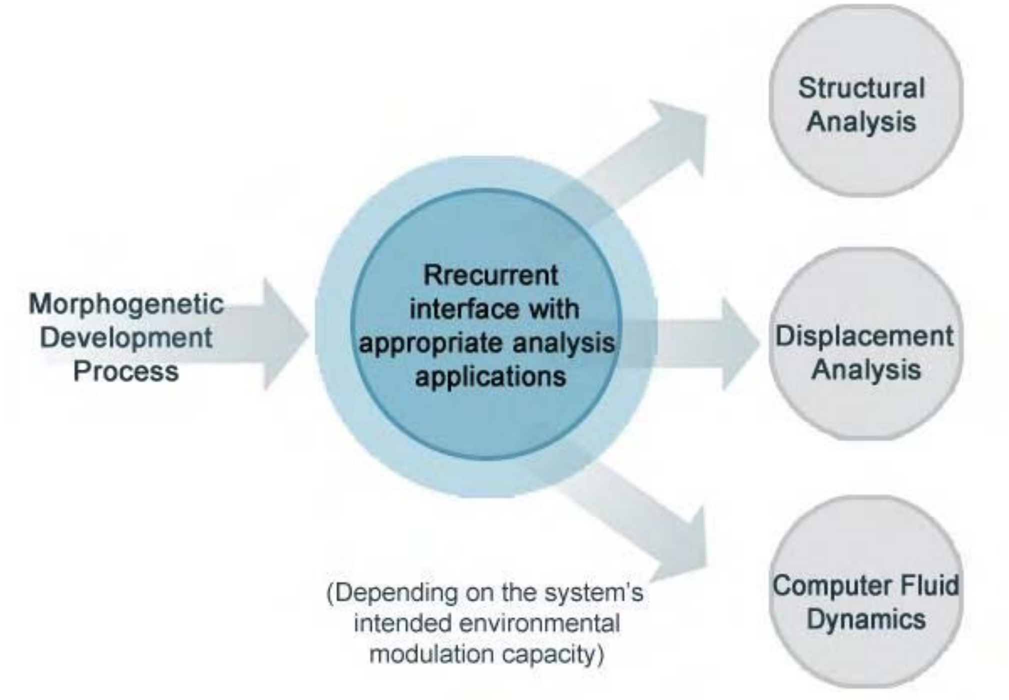


Figure 78: Environmental modulation of the shelter project

4.3.2.6 Form & Behaviour

Figure 79: Construction process of shelter & viewing platform. (Source: Hensel M. et al 2010)

The entire structure is supported by an A-shaped frame constructed from 8 planks, which form an integral part of the shelter's surface. This allows minimising contact points between platform and surface in order to avoid moisture damaging the roof planks. The two surfaces that make up the shelter are symmetrical and lean against each other. The combination of the weight of the surfaces, their flexible connection and slightly bendable planks, enabled the resistance of the completed structure to the impact of strong earthquakes of the region. The resultant form radically affected the behaviour of the structure's behaviour and its achievement of required design objectives.

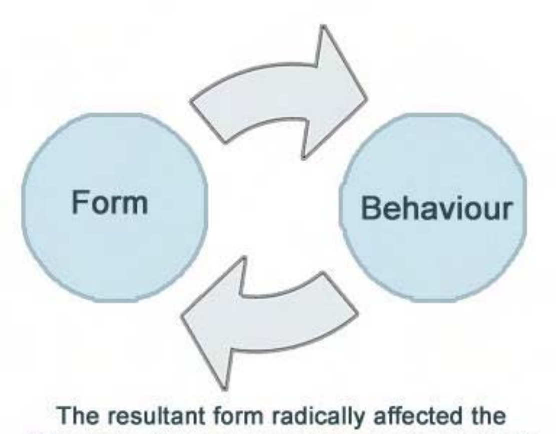


Figure 80: Interlinked relationship between form & behaviour

This was put to the test the night after completion, which witnessed a number of earthquakes; it survived this first test without damage and has withstood a number of severe earthquakes and storms since its construction was finished in spring 2007.

4.3.2.7 AA Shelter Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Main advantages of this design approach

Achievement of goals and objectives

Required goals	How were they achieved
▪ Protection from wind & rain ▪ Create a viewing platform ▪ Resistance to seismic activity ▪ Use only local construction materials and means	▪ The summation of all defining factors derived through and verified by a multitude of digital and physical test models leads to the definition of the genotype of the system's basic component. This genotype is the initial design seed which constitutes the unchanging genetic information. ▪ The relevant material properties, self-forming capacities, geometric characteristics, manufacturing constraints and assembly logics are described as reciprocal interdependencies operating within specific margins. ▪ In computational morphogenesis the genotypic information unfolds a performative phenotype through implementation of algorithmic growth processes, and the evolutionary development of system populations across many generations. The phenotype is the actual form emerging from its interaction with a specific environment. ▪ Depending on the system's intended environmental modulation capacity, the morphogenetic process recurrently interfaces with appropriate analysis applications such as computer fluid dynamics for the investigation of thermodynamic relations, light, acoustic and aerodynamic behaviour. ▪ In feedback with analytical tools simulating the system's interaction with precipitation and its related drainage behaviour, this multi-criteria evaluation derived a finely calibrated level of permeability of the porous membrane skin that minimises wind impact and simultaneously prevents local accelerations of airflow due to channelling gaps between the elements.

Table 10: Evaluation of the AA shelter project through achievement of goals

Comparison between the presented design approach and conventional design methods	
Presented Approach	**Conventional Approach**
The presented design approach successfully achieved the required goals and objectives, in addition to the following aspect: **High level of complexity** and performance even in a situation where only the simplest means of construction are available. It proves to be particularly relevant **in contexts with very limited resources.**	If a conventional design method was to be applied in order to achieve the same goals and objectives stated above, it would also probably be successful. The difference will be in the following aspects: Difficulty of creating complex forms with a single material and simple means of construction.

Table 11: Evaluation of the AA shelter project by comparison with conventional design means

4.3.3 Piraeus Tower, Athens

Ioannis Douridas' MSc dissertation(2006) at the AA School of Architecture, focused on how a new envelope for a climatically deficient 1970s mid-rise office building with a glass curtain wall, located in Athens, Greece, can make this building inhabitable without introducing any electrical or mechanical devices for climatisation.

The following aspects will be analysed in order to evaluate the application of the previously mentioned biomimetic principles in morphogenetic computational design:

Figure 81: Image of existing Piraeus Tower, Athens, Greece

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

4.3.3.1 Adaptation

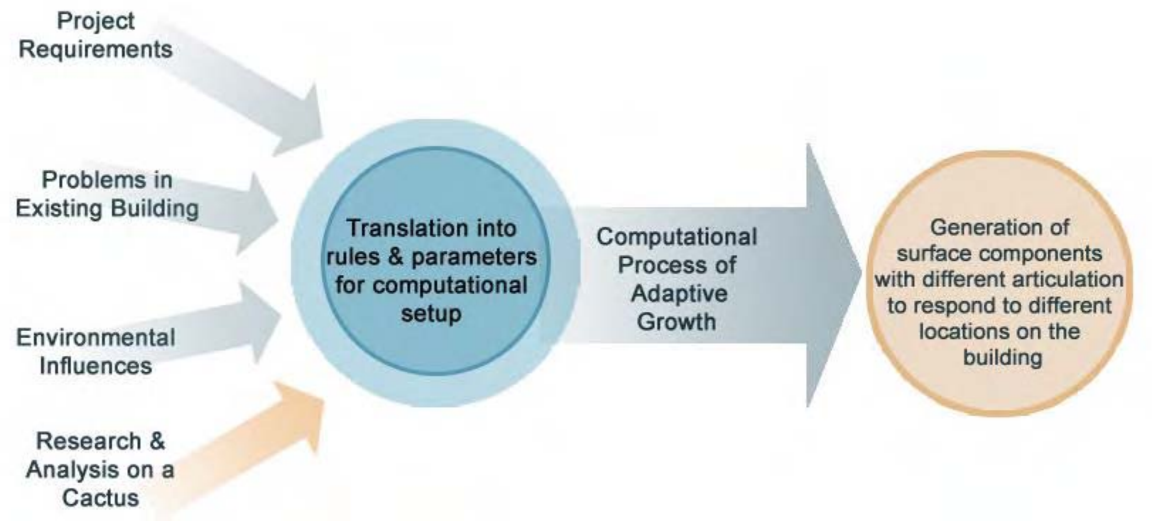


Figure 82: Piraeus Tower adaptation process

The project was to adapt to a number of influences such as:

Project requirements:
Designing a new envelope for an existing mid-rise building, overcoming excessive heating and cooling loads.

Environmental influences
- Sun path
- Prevailing winds
-

Existing building suffers from the following:
- Intense overheating of the interior space in the summer months and the inverse during the cold winter months.
- As a result cooling and heating loads are very high
- The building is consequently inhabited.

These acting influences and constraints were translated into a set of rules, parameters and variable ranges and implemented in the computational process. The generated forms are consequently radically affected by them.

4.3.3.2 Material System

Due to the nature of this research project which focused on the envelope's morphology and design, material systems were not addressed.

The actual material characteristics of the component require elaboration, and its performative impact would need to be embedded in the system.

4.3.3.3 Evolutionary Form Finding

Research and analysis of a cactus (Echinocactus grusonii) revealed certain morphological features that help in reducing thermal gain.

Based on this study, an initial surface component was established to serve as the base element for an articulated surface for the selected building.

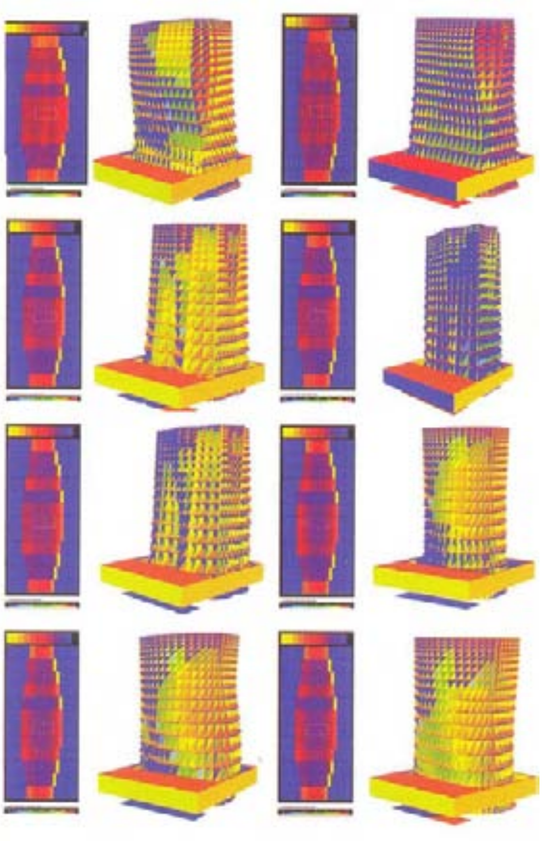


Figure 83: Multiples generations of Piraeus Tower envelop, MSc dissertation of Ionannis Douridas 2005. (Source: Hensel M. et al 2010)

Subsequently the different logics driving the articulation of the global form of the envelope, the meso-scale of the component regions and the local scale of the singular component needed to be established.

On each scale criteria of aerodynamic performance, self-shading and light penetration are affected. Together the entire system fulfils its performative capacity with regard to these three criteria.

Following this a process for evolving the system needed to be established. A hill climbing algorithm based on multi-objective optimisation that is typically used in artificial intelligence applications that evolve from a starting condition towards an articulated global state in a non-linear process.

A large number of system configurations were evolved, analysed and evaluated with regard to local and global performance, gradually approaching a set of valid solutions to the multi-objective optimization.

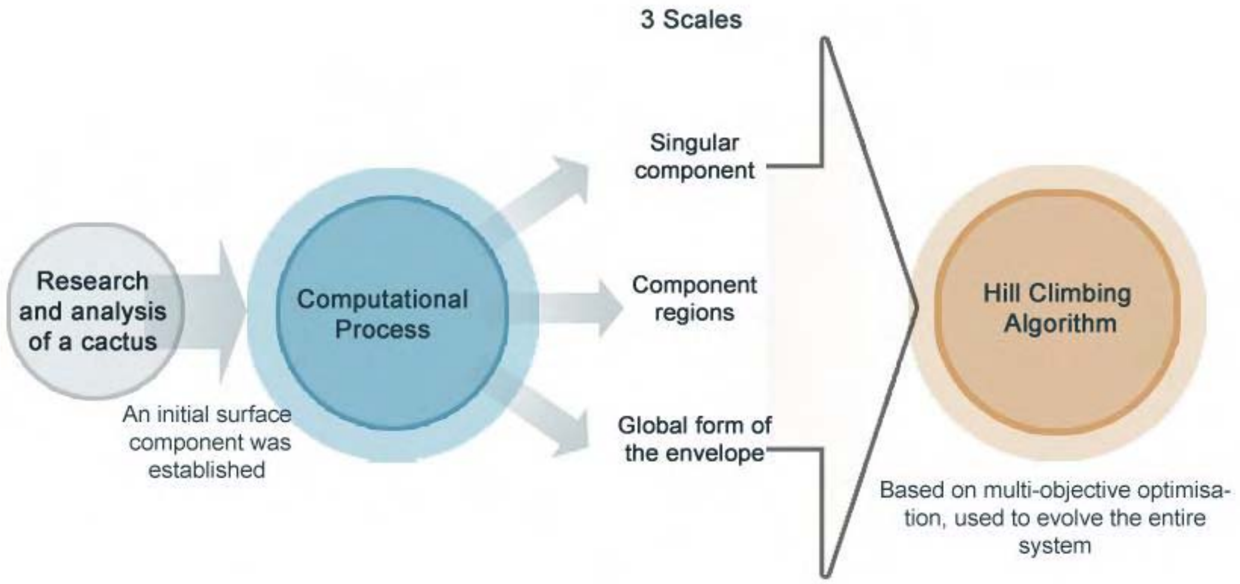


Figure 84: Computational process of Piraeus Tower

4.3.3.4 Emergence

This research project focused on the environmental performance of the new building envelope with regard to its aerodynamic performance, light penetration and self-shading in an attempt to minimize thermal gain. The actual material and the necessary structure of this envelope are key areas for further research.

4.3.3.5 Environmental Modulation

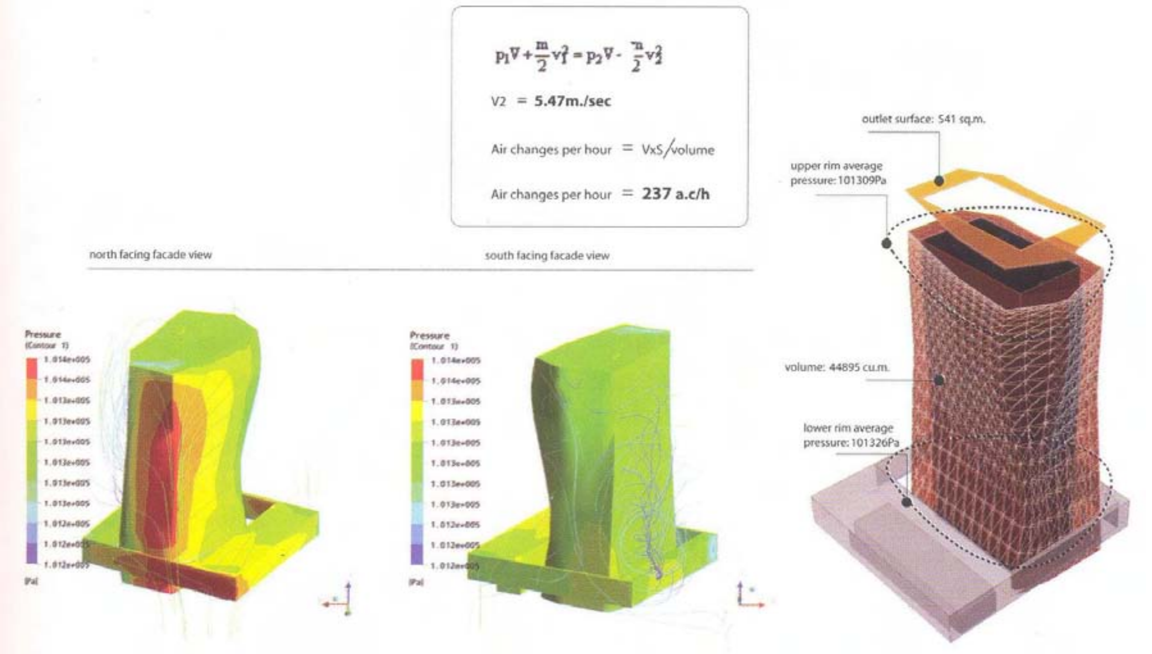


Figure 85: Iterative algorithmic procedure of Piraeus Tower based on solar exposure analysis, MSc dissertation of Ionannis Douridas 2005. (Source: Hensel M. et al 2010)

Figure 86: Picture of the studied cactus (Echinocactus grusonii)

Research into the environmental performance of a cactus (Echinocactus grusonii) revealed that the combined morphological features-hydrostatic and ribbed body- help in reducing thermal heat gain through a combination of self shading and utilising air flow.

Airflow was investigated through extensive computer fluid dynamics analysis.

Based on this study, an initial surface component was established to serve as the base element for an articulated surface for the selected building.

The geometry of this initial component was analysed and modified based on its self-shading capacity and the light penetration with regard to the interior, leading to a set of components with different articulation to respond to different locations on the building envelope with respect to their orientation to the sun path.

A second step aperture is introduced to the component in a similar process as the one before and elaborated through airflow analyses of homogeneous and heterogeneous regions of components, including acceleration and deceleration of airflow velocity and pressure zone distribution.

On the north side, the differentiated components serve only ventilation purposes, while on the other sides the combined effect of self-shading and ventilation must be operative.

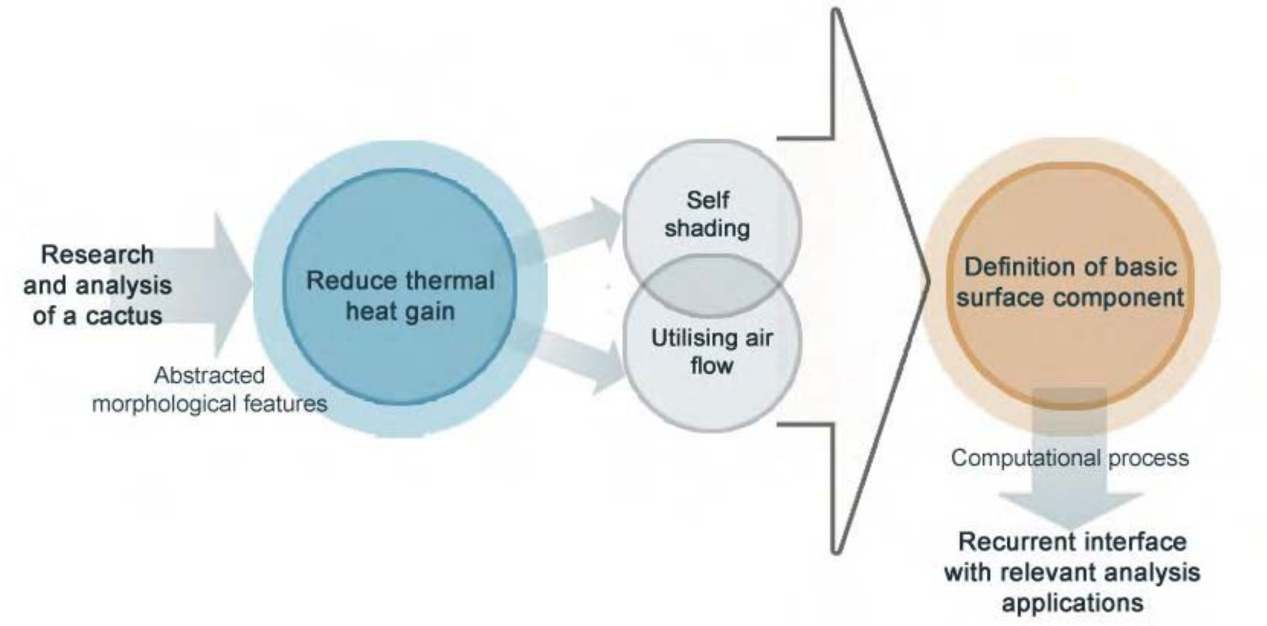


Figure 87: Environmental modulation of Piraeus Tower

4.3.3.6 Form & Behaviour

The overall form of the envelope has a significant impact on its behaviour regarding its aerodynamic performance, light penetration and self-shading that together create a system that minimizes thermal gain.

4.3.3.7 Piraeus Tower Evaluation

The suggested design approach is evaluated according to the following criteria:

- Achievement of goals and objectives
- Comparison with conventional design methods

Achievement of goals and objectives

Required goals	How were they achieved
▪ Minimizing thermal gain through 3 important criteria: 1. Aerodynamic performance 2. Self-shading 3. Light penetration ▪ No electrical and mechanical means are to be used.	▪ Architectural analysis of the selected building: type, location, use, etc... ▪ Analysis of the environmental building performance ▪ Analysis of specific plant morphology to extract relevant performance capacities according to the performance criteria established in 2. ▪ Setup of algorithmic design procedure ▪ Evolving of various designs and analysis and evaluation of their environmental performance ▪ Feedback of the findings into the next run of the algorithmic procedure ▪ Selection of the evolved envelope with desired environmental performance

Table 12: Piraeus Tower evaluation through achievement of required goals

Comparison between the presented design approach and conventional design methods

Presented Approach	Conventional Approach
The presented design approach successfully achieved the required goals and objectives.	If a conventional design method was to be applied in order to achieve the same goals and objectives stated above, it would probably be partially successful due to the following reasons: ▪ Difficulty of applying the relevant characteristics of the selected plant morphology without computational means ▪ Difficulty of manually modifying the geometry of the envelope's component to respond to various conditions and orientation within the envelope ▪ Difficulty of coordinating the articulation of each single element with that of the overall form.

Table 13: Piraeus Tower evaluation through comparison with conventional design means

4.4 General Advantages of the Presented Design Approach

The presented research projects all share a set of common advantages that significantly imply the importance and potential of the suggested design approach. Through the analysis and evaluation of these projects, the following issues were observed:

- **The form is a product of all affecting factors interacting with a simulated environment:** This setup enables iterative analyses and evaluation cycles, so that the specific form of the system unfolds from the reciprocal influences and interaction of form, material and structure within a simulated environment.

- **Adaptation:** In this iterative computational process each element adapts its morphology by calibrating its functional requirements with its particular sub-location in the overall system.

- **Higher efficiency/multi-functional components**

- **Balancing multiple and conflicting criteria:** This morphogenetic process enables the balancing and calibration of multiple, or even conflicting, design criteria and the unfolding of the material system’s inherent performative capacity.

- **Integration:** Rather than aiming for rationalization or single-objective optimisation, computation becomes the means of integration: integration of system-inherent constraints of materials, manufacturing and assembly, and a wide range of external influences and forces.

4.5 Chapter Summary

This chapter has presented a set of research projects demonstrating the main characteristics of the ‘Morpho-Ecological’ design approach discussed in chapter three. Six projects were analysed, three represented the ‘Solution-Based’ approach and three for the ‘Problem-Based’ approach. Both approaches were discussed in chapter two.

Analysis criteria for these projects were the abstracted biological principles:

- Adaptation
- Material Systems
- Evolutionary form finding/growth process
- Emergence: interaction of form, material and structure
- Form and behaviour
- Environmental modulation

These principles were presented in both chapters; two and three. Each project was evaluated in two ways; first according to its achievement of required goals and objectives and second by comparing it with conventional design means.

CHAPTER 5: CONCLUSION

5.1 Summary

This thesis is an investigation into biomimicry (on the behaviour and ecosystem level) and presents the development of a design method based on biological principles that are applied and correlated with morphogenetic computational design.

Architecture and biology at first glance do not appear to be so different—both are materially and organizationally based, both are concerned with morphology and structuring. Both are wound together by multiple simultaneous systems and drives, and probably most important for us, both are constructed out of parts operating as collectives. Recent bio-theories on complex adaptive systems and especially the phenomena of emergence have begun to open up territory that architecture can no longer ignore if it is to have any relevance, and indeed resilience, in the future.

A truly biomimetic approach to architectural design requires the development of novel design methods that integrate both the modelling of behaviour and the constraints of materialization processes, in addition to environmental factors and influences. This requires an understanding of form, material and structure not as separate elements, but rather as complex interrelations that are embedded in and explored through integral computational design processes. Correlating and combining morphogenesis and ecology, suggests a new framework developed for architectural design that is firmly rooted within a biological paradigm. This morpho-ecological approach aims for a more integral design approach to correlate object, environment and subject into a synergetic dynamic relationship.

Nature’s design process utilizes a number of feedback systems to direct the growth and formation of an organism based on the internal and external forces acting on and within it. All systems are continually updated and act in concert with each other to provide optimum functionality at all levels of development. If this is applied to architecture, then it becomes possible to develop buildings that are strongly related to and affected by their surrounding environment, and are much more advanced in terms of environmental and sustainable performance.

This thesis started by exploring the application of biomimicry in current architectural design, resulting in a set of design approaches, levels and principles as presented in chapter two. Computational design and morphogenesis are then discussed in chapter three, introducing the ‘Morpho-Ecological Approach’ which correlates morphogenesis with ecology. A theoretical and methodological framework is presented for this approach, outlining its main characteristics. The same biological principles discussed in chapter two are stated again within the context of computational design, and serve as analysis criteria for case studies to evaluate the outcomes of the presented design approach.

Case studies in chapter four demonstrated the huge potential of integrating biological principles with current computation, analysis and simulation software. They present the possible implications of such a design approach in future sustainable and regenerative architectural design.

5.2 Benefits & Drawbacks

Through the analysis and evaluation of the selected case-studies, it can be concluded that the suggested theoretical and methodological frameworks enable the designer to:

- Develop an architecture that is produced as a result of the existing environmental, materialization, and special requirements, and therefore specifically tailored to its location and conditions.

- Produce a more advanced architecture in terms of sustainability.

- Create a variable structural prototype unit that is able to conform to a variety of complex surfaces and whose form is derived from natural spatial and structural morphologies, the physical limitations and benefits of the intended construction materials, and the desired construction methods.

- Develop a design process and documentation system that allows the architecture, engineering, and construction community to work more effectively as a cohesive unit with regard to the digital design and physical construction of architectural projects.

- Reduce the complexity of the translation from digital design to built form.

- Support for extra complexity. For the structures to become more flexibly adaptable, their complexity will have to increase.

- Amplified imagination. Benefits of this approach in the context of creative practice include algorithmic visual creation, potentially leading to unusual results.

- Procedural integration with environmental simulation, evaluation and design tools. Flexibility given by a fully generative, dynamic approach that can inform the development of form at multiple levels of the hierarchy can help to derive structures able to respond to needs for comfort, amenity, energy, climate responsiveness and environmental impact. Environmentally efficient design solutions can be counterintuitive, especially in situations where there are complex patterns of usage and unusual building forms. Integration of analysis with the flexibility of a generative approach to form-making can help to explore the benefits of configurations that would otherwise be overlooked.

Although this approach has radical benefits to architecture and future sustainable building and design, it must be stated that currently there are a number of obstacles that face this approach:

- The way to explain a real space in a digital space might be regarded as the most problematic factor in the developments of emergent technologies and sustainable design. In a virtual space of 3D visualisation software, drawn objects do not have any meanings, and they are the brief output of binary data on a screen. On the other hand, users regard such objects as buildings, rooms, parts of architecture, etc. This gap of recognition between computers and human beings is one of the factors that obstruct combinations of digital and sustainable design.

- Accurate realistic iterations of enormous calculations are obstacles. Accuracies and practicalities including spatiality, materiality and so on are exceedingly significant factors for environmental simulations. It is impossible to simulate environmental performance in any case without these elements. In fact, a great deal of data must be determined for calculations in environmental simulation software like ECOTECT, TAS, etc to produce meaningful results.

- User preference is another obstacle in terms of not only environmental optimization, but also design aspects of architecture. It might be easy to achieve targets only numerically. For example, the purpose to gain maximum sunlight is simply solved with the largest window or glass box. However, these solutions are, needless to say, not acceptable for designers or architects. Environmental solutions produced by computers are only useful when they are satisfied with these solutions. Moreover, projects are more complicated due to the existence of clients. Therefore, optimized solutions are necessary to be generated in accordance with user preferences.

5.3 Criticism

Three critical concerns are related to the research presented in this thesis. The first concern related to the manufacturing and assembly costs of buildings made from parts that are all different in dimension. However, by and large it is now accepted that feasible production is possible owing to contemporary computer-aided manufacturing techniques. Because of the financial crisis of 2008-2009, however, this concern has been repositioned; now, highly differentiated architectures are more often than not seen to stand for an exuberant capitalism out of control that does not consider expenditure or the lack of resources. Yet, the approach presented here may well be accomplished in a context of sparse material or technological resources (except those that derive the design process itself).

The second criticism, which is frequently voiced, is that the approach introduced here relies heavily on very specific knowledge, skills and tools. True as this may be, it needs to be seen within the context of the insufficiency of current answers to the problem of local and eventually global climate change. The question is whether architectural education and practice needs serious rethinking and repositioning. With this also comes the necessity of re-skilling and re-tooling. When seen in this context it may become more evident why first-principle knowledge in physics, computation and engineering is indispensible as a first step.

The final criticism regarding this design approach is the role of the designer. Some might claim that the increasing software development in computational design gradually diminishes the human role in design. Although the presented design approach heavily depends on computer software and technology, the architect's role remains significant and is summarized in the following points:

- Analysis of project requirements and constraints
- Definition of the material system component according to these requirements and constraints and its geometric description and properties (through a large number of physical tests)
- Definition of the relation between these components
- Description of the aforementioned points as design parameters in the computational model
- Definition of the genotype (initial design seed) as a result of the summation of all defining factors through and verified by a number of physical and digital test models
- Selection of suitable algorithmic growth processes
- Recurrently interfacing with appropriate analysis applications
- Continuous evaluation and feedback

As Christopher Alexander[6] has stated 'A digital computer is essentially a huge army of clerks, equipped with rule books, pencil and paper, all stupid and entirely without initiative, but able to follow millions of precisely defined operations. The difficulty lies in handing over the rule book.'

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[6] Christopher Alexander (born October 4, 1936 in Vienna, Austria) is an architect noted for his theories about design. He is professor emeritus at the University of California, Berkeley. Now retired (though ceaselessly active), he is based in Arundel, Sussex, UK.

5.4 Future Research

- The presented projects in this thesis are all still within the context of research and exploration. It would be important for future research projects to fully implement such a design approach within the context of actual building projects, with all its associate complex spacial and functional requirements.

- Another important line of research is the application of such a design approach on an urban scale. This was outlined by Professor Michael Weinstock, who explains that we should recognise architectural constructions not as singular and fixed bodies, but as complex energy and material systems that have a finite lifespan, exist as part of the environment of other active systems. He continues to elaborate:

‘A metabolic model abstracted from natural systems can be developed to enhance the performance of individual buildings so that their metabolic systems are responsive to their internal and external environment. Groups or clusters of environmentally intelligent buildings can be interlinked with systems for material and energy flows, organised to generate oxygen, sequester carbon, fix nitrogen, collect and purify water, acquire solar, ground source and wind energy, and respond intelligently to the dynamical changes in local weather systems. As energy plays a critical role in all biological scales, from the cell to the ecosystem, so energy flows and metabolic systems for buildings and cities with be central the adaptation of contemporary urban culture to climate change.’
(Weinstock, M. 2010)

REFERENCES

Alberti, M., Marzluff, J. M., Shulenberger, E., Bradley, G., Ryan, C., & Zumbrunnen, C. (2003). Integrating Humans into Ecology. *Bioscience*, 53, 1169-1179.

Alderesy-Williams, H. (2003). *Zoomorphic-New Animal Architecture.* London: Laurence King Publishing.

Allen, J. (2005). Global Winner, Biolytix is Taking on Effluent Society. *ECOS*, 5, 127.

Allen, T. F. (2002). Applying the principle of ecological emergence to building design and construction. In S. &. C. J. Kebert, *Construction Ecology.* London: Spon Press.

Allenby, B. R., & Cooper, W. E. (2007). Understanding industrial ecology from a biological systems perspective. In M. P. Zari, *An ecosystem based biomimicry theory for a regenerative built environment.* Lisbon: Lisbon Sustainable Building Conference. [Personal Communication].

Baumeister, D. (2007a). Biomimicry Presentation at the University of Washington College of Architecture. Seattle.

Baumeister, D. (2007b). Evolution of the Life's Principles Butterfly Diagram. In M. P. Zari, *Biomimetic Approaches to Architecutral Design for Increased Sustainability.* [Personal Communication].

Benyus, J. M. (1998). *Biomimicry: Innovation Inspired by Nature.* Perennial (HarperCollins).

Berkibile, B., & McLennan, J. (2004). The living building. Biomimicry in architecture, integrating technology with nature. *BioInspire 18.*

Charest, S. (2007). Ecosystem Priciples Research. In M. P. Zari, *Biomimetic Aproaches to Architecural Design for Increased Sustainability.* Sustainable Buildings Conference, Auckland. [Personal Comuunication].

De Groot, R., Wilson, M. A., & Boumans, R. M. (2002). Typology for the Classification, Description and Valuation of Ecosystem Function, Goods and Services. *Ecological Economics*, 41, 393-408.

De Wolf, T., & Holvoet, T. (2010). Emergence versus Self-Organisation: Different Concepts but Promising when combined. In M. Hensel, A. Menges, & M. & Weinstock, *Emergent Technologies & Design: Towards a Biological Paradigm for Architecture.* New York: Routledge.

Dollens, D. (2006). Digital Biomimetic Architecture [Online]. *Art and Architecture in Digital Social-Contemporary City and Genetic City Conference.* Barcelona: Available from: http://www.artyarqdigital.com/fileadmin/user_upload/PDF/Publicaciones_Jornada_II/18-Jornadas_II._DennisDollens.pdf [Accessed: April 2010].

Faludi, J. (2007). Biomimicry for green design. In M. P. Zari, *An ecosystem based biomimetic theory for a regenerative built environment.* Lisbon: Lisbon Sustainable Building Conference. [Personal Communication].

Feuerstein, G. (2002). *Biomorphic Architecture- Human and Animal Forms in Architecture.* Stuttgart: Edition Axel Menges.

Frazer, J. (1995). *An Evolutionary Architecture.* London: E.G. Bond Ltd.

Garrod, R. P., Harris, L. G., Schofield , W. E., McGettrick, J., Ward, L. J., Teare, D. H., et al. (2007). Mimimcking a Stenocara Beetle's Back for Microcondensation Using Plasmachemical Patterned Superhydrophobic-Superhydrophilic Surfaces. *Langmuir*, 23, 689-693.

Graham, P. (2003). *Building Ecology-First Principles for a Sustainable Built Environment.* Oxford: Blackwell Publishing.

Guild, B. (2007). *Innovation inspired by nature work book.* Biomimicry Guild.

Harding, S. (2001). Complexity and stability in a Gaian ecosystem model. *Paper presented at the International School Earth Planetary Sciences, Earth Science system*. Siena.

Hastrich, C. (2006). The Biomimicry Design Spiral. *Biomimcry Newsletter*, pp. 4.1, 5-6.

Helms, M., Swaroop, S. V., & Goel, A. K. (2009). Biologically inspired design: process and products. *Elsevier*, 606-622.

Hensel, M. (2006a). Towards Self-Organisational. *AD- Techniques & Technologies in Morphogenetic Design*, 5-11.

Hensel, M. (2006b). Computing Self-Organisation:Environmentally Sensitive Growth Modelling. *AD Techniques and Technologies in Morphogenetic Design*, 12-17.

Hensel, M. (2006c). (Synthetic) Life Architectures:Ramifications and Potentials of a Literal Biological Paradigm for Architecural Design. *AD Techniques & Technologies in Morphogenetic Design*, 18-25.

Hensel, M., & Menges, A. (2007). *Morpho-Ecologies: Towards Heterogeneous Space In Architecture Design.* AA Publications.

Hensel, M., & Menges, A. (2008). Designing Morpho-Ecologies. *AD-Versatility & Vicissitude: Performance in Morpho-Ecological Design*, 102-111.

Hensel, M., & Menges, A. (2008). Inclusive Performance: Efficiency Versus Effectiveness. *AD Versatility & Vicissitude-Performance in Morpho-Ecological Design*, 54-57.

Hensel, M., Menges, A., & Weinstock, M. (2010). *Emergent Technologies & Design: Towards a biological paradigm for architecture.* New York: Routledge.

Jeronimidis, G. (2009). Bio-inspired Material Structure-Integration for Functional Designs in Construction. *International Biona Symposium.* Stuttgart: [Personal communication].

Jones, C. G., & Lawton, J. H. (1995). *Linking Species & Ecosystems.* New York: Chapman and Hall.

Kay, J., & Schneider, E. (1994). Embracing Complexity: The challenge of the ecosystem approach. In L. Westra & J. Lemons (Eds.). *Perspectives on Ecological Integrity*, 49-59.

Kelly, K. (1994). *Out of control- the new biology of machines.* London: Fourth Estate.

Kibert, C. J. (2006). Revisiting & Reorienting Ecological Design. *Construction Ecology Symposium.* MIT, Cambridge, MA.

Kibert, C. J., Sendzimir, J., & Guy, G. B. (2002). *Construction Ecology.* New York: Spon Press.

Killeen, M. (2002, May). Water Web. *Metropolis Magazine*.

Knight, W. (2001). Beetle fog cather inspires engineers. *New Scientist*, pp. 13, 38.

Knippers, J. (2009). Building & Construction as a Potential Field for the Application of Modern Biomimetic Principles. *International Biona Symposium.* Stuttgart: [Personal communication].

Kolarevic, B. (2000). Digital Morphogenesis and Computational Architectures [online]. *4th SIGRADI Conference* (pp. 98-103). Rio de Janeiro: Available from: http://cumincades.scix.net/data/works/att/fbc9.content.pdf [Accessed June 2010].

Korhonen, J. (2001). Four Ecosystem Principles for an Industrial Ecosystem. *Journal of Cleaner Production*, 9, 253-259.

Laurenci, A., Zuffo, J. A., & Gualberto, L. (2004). Incipient Energy Expresses the Self-Organisation Generative Activity of Man-Made Ecomimetic Systems. *4th Biennial International Workshop. Advances in Energy Studies.* Compinas, Brazil.

Mayr, E. (2002). *Die Entwicklung der biologischen Gedankenwelt.* Berlin, London, New York: Springer.

McDonough, W., & Braungart, M. (2002). *Cradle to Cradle-Remaking the Way We Make Thigs.* New York: North Point Press.

Menges, A. (2006). Instrumental Geometry. *AD Techniques and Technologies in Morphogenetic Design*, 42-53.

Menges, A. (2006). Polymorphism. *AD Techniques & Technologies in Morphogenetic Design*, 78-87.

Menges, A. (2009). Integral Computational Design. *International Biona Symposium.* Stuttgart: [Personal communication].

Odum, E. P. (1969). The strategy of ecosystem development. *Science*, 164, 262-270.

O'Reilly U., Hemberg M., Menges A. (2004, May/June). Evolutionary Computation & Artificial Life in Architecture. *Architecural Design*, 49-50.

Pakrer, A. R., & Lawrence, C. R. (2001). Water Capture by a Desert Beetle. *Nature*, 414,33.

Panchuk, N. (2006). *An Exploration into Biomimicry and its Application in Digital & Parametric Architectural Design.* Msc Thesis, University of Waterloo, Ontario.

Ravilious, K. (2007, July 31). Borrowing from Nature's Best Ideas. *The Guardian*.

Reap, J., Baumeister, D., & Bras, B. (2005). Holism, Biomimicry & Sustainable Engineering. *ASME International Mechanical Engineering Conference & Exposition.* Orlando, FL, USA.

Reed, B. (2006). Shifting our Mental Model- 'Sustainability'to Regeneration. *Rethinking Sustainable Construction 2006: Next Generation Green Buildings.* Sarasota, Florida.

Rosemond, A. D., & Anderson, C. B. (2003). Engineering Role Models: Do Non-Human Species have the Answers? *Ecological Engineering*, 20, 397-387.

Roudavski, S. (2009). Towards Morphogenesis in Architecture [Online]. *International Journal of Architectural Computing*, 345-374 Available from: http://dtl.unimelb.edu.au/R/H6V9SANDEJRNDYQ8FQ85I2AL3NAQF8TQ3TSLA1M5FXILP2YM5K-00585?func=dbin-jump-full&object_id=116799&pds_handle=GUEST [Accessed April 2010].

Russell, J. A. (2004). *Evaluating the Sustainability of an Economic Energy System: An Energy Flow Assessment of South Carolina.* Department of Mechanical Engineering, University of South Carolina.

Shear McCann, K. (2000). The diversity-stability debate. *Nature*, 405, 228-233.

Steadman, P. (2008). *The Evolution of Designs-Biological Analogy in Architecture & Applied Arts.* Oxon: Routledge.

Tezridis, K. (2006). Algorithmic Architecture. In A. Menges, *Integral Computational Design- International Biona Symposium (2009).* Stuttgart: [Personal Communication].

Thomson, D. W. (1942). *On Growth and Form (2nd Edition).* Cambridge: Cambridge University Press.

Todd, J. (2004). Restorer Eco-Machines for The Culture of Aquatic Animals and the Restoration of Poluuted Aquatic Environments. *BioInspire 19*.

Todd, J., & Josephon, B. (1996). The Design of Living Technologies for Waste Treatment. *Ecological Engineering*, 6, 109-136.

Van der Ryn, S. (1996). *Design for Life- The Architecture of Sim Van der Ryn.* Salt Lake City: Gibbs Smith.

Vincent, J. (2007). Re: Designing around existing patents through TRIZ . In M. P. Zari, *Biomimetic Approaches to Architectural Design for Increased Sustainability.* Sustainable Building Conference, Aukland. [Personal Communication].

Vincent, J. F., Bogatyrev, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. (April 2006). Biomimetics-Its Practice & Theory. *Journal of the Royal Science Interface*.

Vincent, J. F., Bogatyrev, O., Pahl, A., Bogatyrev, N. R., & Bowyer, A. (2005). Putting Biology into TRIZ: A Database of Biological Effects. *Creativity and Innovation Management*, 14, 66-72.

Vogel, S. (1998). *Cat's Paws and Catapults.* New York: Norton and Company.

Von Frisch, K., & Von Frisch, O. (1974). *Animal Architecture.* New York: Helen & Kurt Wolff Books.

Weinstock, M. (2004). Morphogenesis & The Mathematics of Emergence. *AD Emergence: Morphogenetic Design Strategies*, 10-17.

Weinstock, M. (2010). *The Architecure of Emergence.* John Wiley & Sons Ltd.

Weinstock, M., & Stathopoulos, N. (2006). Advanced Simulaiton in Design. *AD Techniques & Technologies in Morphogenetic Design*, 54-59.

Weinstock, M., Jeronimidis, G., & Stathopoulos, N. (2006). Self-Organisation and. *AD-Techniques & Technologies in Morphogenetic Design*, 26-33.

Wiscombe, T. (2005). Emergent Processes [online]. *OZ Journal*, Available from: http://www.emergenttomwiscombellc.com/publications.php?more=0&id=1 [Accessed July 2010].

Wiscombe, T. (2006). Emergent Models of Architectural Practice. *Yale Perspecta*.

Zari, M. P. (2007). An ecosystem based biomimetic theory for a regenrative built environment. *Sustainable Building Conference.* Lisbon: [Personal communication].

Zari, M. P. (2007). Biomimetic Approaches to Architectural Design for Increased Sustainability. *Sustainable Building Conference.* Auckland: [Personal communication].

APPENDIX

List of Definitions

(Source: Merriam-Webster online dictionary)

- **Algorithm:** [noun]

A procedure for solving a mathematical problem (as of finding the greatest common divisor) in a finite number of steps that frequently involves repetition of an operation; *broadly* **:** a step-by-step procedure for solving a problem or accomplishing some end especially by a computer.

- **Anisotropic:** [adjective]

Exhibiting properties with different values when measured in different directions.

- **Bifurcate:** [verb]

Transitive verb**:** to cause to divide into two branches or parts.

- **Biomimetics:** [noun]

The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones.

- **Computation:** [noun]

a: the act or action of computing **:** calculation .
b: the use or operation of a computer .

- **Differentiation:** [noun]

1: the act or process of differentiating.
2**:** development from the one to the many, the simple to the complex, or the homogeneous to the heterogeneous.
3 *a*: modification of body parts for performance of particular functions
b: the sum of the processes whereby apparently indifferent or unspecialized cells, tissues, and structures attain their adult form and function .

- **Emergent Evolution:**[noun]

Evolution that according to some theories involves the appearance of new characters and qualities at complex levels of organization (as the cell or organism) which cannot be predicted solely from the study of less complex levels (as the atom or molecule)

- **Evolution :** [noun]

A process of continuous change from a lower, simpler, or worse to a higher, more complex, or better state: growth.

- **Genotype:** [noun]

[International Scientific Vocabulary *gene*]: all or part of the genetic constitution of an individual or group.

- **Gestalt:** [noun]

A structure, configuration, or pattern of physical, biological, or psychological phenomena so integrated as to constitute a functional unit with properties not derivable by summation of its parts.

- **Hygroscopic:** [adjective]

1**:** readily taking up and retaining moisture.
2**:** taken up and retained under some conditions of humidity and temperature.

- **Integration:** [noun]

1**:** the act or process or an instance of integrating: as
a: incorporation as equals into society or an organization of individuals of different groups (as races)
b: coordination of mental processes into a normal effective personality or with the individual's environment.

2 *a*: the operation of finding a function whose differential is known.
b: the operation of solving a differential equation.

- **Iteration:** [noun]

The action or a process of iterating or repeating: as
a: a procedure in which repetition of a sequence of operations yields results successively closer to a desired result.
b: the repetition of a sequence of computer instructions a specified number of times or until a condition is met.

- **Isotropic:** [adjective]

Exhibiting properties (as velocity of light transmission) with the same values when measured along axes in all directions.

- **Modulation:** [noun]

A regulating according to measure or proportion: tempering.

- **Morphogenesis:** [noun]

The formation and differentiation of tissues and organs.

- **Phenotype:** [noun]

The observable properties of an organism that are produced by the interaction of the genotype and the environment.

- **Reciprocal:** [adjective]

1**:** serving to reciprocate: consisting of or functioning as a return in kind <the *reciprocal* devastation of nuclear war>

2**:** mutually corresponding <agreed to extend *reciprocal* privileges to each other's citizens>

- **Regeneration:** [noun]

1: an act or the process of regenerating: the state of being regenerated.
2: spiritual renewal or revival.
3: renewal or restoration of a body, bodily part, or biological system (as a forest) after injury or as a normal process.

- **Stochastic:** [adjective]

1**:** random; *specifically*: involving a random variable <a *stochastic* process>
2**:** involving chance or probability: probabilistic <a *stochastic* model of radiation-induced mutation>

برغم الفوائد العظيمة لهذا المدخل التصميمي و ما يتيحه من إمكانيات للممارسة المعمارية و تصميم المباني المستدامة, إلا أنه هناك بعض المعوقات لهذه الممارسة و منها:

- طريقة وصف الفراغات الحقيقية في الفراغ الرقمي يمكن اعتبارها أكبر المشاكل أو العوامل المؤثرة على تطور التكنولوجيات القائمة على مبدأ الظهور (Emergence) و التصميم المستدام بصفة عامة. في الفراغ التخيلي لأي برنامج إظهار ثلاثي الأبعاد, الأجسام المرسومة لا يكون لها أي معنى و لا تمثل أكثر من مخرج مختصر للمدخلات الرقمية ثنائية التكوين (Binary data) على الشاشة. على النقيض من ذلك, ينظر المستخدم لهذه الأجسام على اعتبارها مباني أو فراغات معمارية. هذه الفجوة في الإدراك بين الحاسب الآلي و الإنسان تمثل أحد المعوقات التي تعطل اندماج التصميم الرقمي و التصميم المستدام.

- الحسابات المعقدة المتكررة في برامج الحاسب الآلي تمثل عقبة كبيرة نسبيا حيث لا يمكن محاكاة الطبيعة باستخدام البرامج المتخصصة مثل (Ecotect) و (TAS) بدون الاحتياج لمثل هذه الحسابات .

- حق الاختيار الشخصي أو التفضيل يمثل عقبة أخرى لهذه النوعية من التصميم ليس فقط على المستوى البيئي و لكن النواحي المعمارية أيضا. المثال على ذلك, إذا افترضنا أن الهدف هو الحصول على أقصى آشعة شمس فبطبيعة الحال يكون من السهل استنتاج أن ذلك يعني مسطح زجاجي أكبر, و لكن هذا قد لا يرضي المعماري المصمم. الحلول البيئية التي ينتجها الحاسب الآلي تكون فقط مفيدة عندما يرضى عنها المصمم. على جانب آخر , المشاريع تتعقد أكثر بوجود العملاء و تدخلهم و مستوى رضاهم عن التصميم و بالتالي يجب الرجوع للأذواق الشخصية في مرحلة ما.

مزايا عامة للحالات الدراسية من حيث الاستدامة:

تشترك المشاريع البحثية المقدمة في مجموعة من المزايا التي تشير بوضوح لأهمية و إمكانيات المدخل التصميمي المقترح. من خلال التحليل و التقييم لهذه المشروعات تم ملاحظة الآتي:

1- الكتلة هي نتاج كل العوامل المؤثرة المتفاعلة في بيئة المحاكاة: هذه الفرضية تتيح تحاليل و تقييمات دائمة تضمن أن الكتلة المصممة نتجت من القوى المتجاذبة و التفاعل بين الكتلة و المادة و الهيكل و ذلك داخل بيئة المحاكاة.

2- التكيف: في عملية التصميم الحسابية المتكررة, كل عنصر يقوم بتكييف تكوينه المورفولوجي عن طريق ضبط و معايرة احتياجاته الوظيفية بموقعه الدقيق في المنظومة المتكاملة.

3- المكونات متعددة الوظيفة / ذات كفاءة أعلى.

4- توازن المعايير المتعددة و أحيانا المتضادة : العملية المورفولوجية تتيح توازن و معايرة العديد من المعايير التصميمية المتضادة إلى جانب إظهار قدرة و سعة أنظمة المواد.

5- التكامل (Integration): بدلا من السعي إلى تطوير أحادي الاتجاه لأحد عناصر التصميم, يفيد التصميم الحسابي (Computational design) كأسلوب أو وسيلة للتكامل بين العديد من القوى و المؤثرات الخارجية و الداخلية المتفاعلة.

و أخيرًا ينتهى البحث فى الفصل الخامس بمناقشة نتائج تم استنتاجها من تحليل و تقييم حالات الدراسة، حيث يقوم بعرض أهم الميزات و العقبات لهذا الأسلوب التصميمى كما يعرض نقدا لمدى إمكانية تطبيق هذا الأسلوب فى الواقع الحالى.

مزايا و عيوب عامة للمدخل التصميمي المقترح:

من خلال دراسة و تحليل الحالات الدراسية, يمكن استنتاج أن الإطار النظري و المنهجي المقترح يتيح للمصمم الآتي:

- تطوير عمارة ناتجة من ظروف محيطها و متطلباته و نابعة منها.
- إنتاج عمارة أكثر تقدما من حيث الاستدامة.
- تطوير منظومة تصميمية و توثيقية تسمح للعمارة و الهندسة و مجتمع البناء بصفة عامة بالعمل بطريقة أكثر فاعلية و كفاءة كوحدة واحدة و ذلك عن طريق استخدام التصميم الرقمي و ما يستتبعه من تنفيذ مادي للمشروعات المعمارية.
- تقليل التعقيد فيما يخص الانتقال من الصورة الرقمية للبناء الفعلي.
- زيادة التعقيد بمعنى أن الهياكل لكي تكون أكثر تكيفا مع محيطها يجب أن يزداد تعقيدها من حيث التركيب.
- تطوير القدرة على التخيل حيث يعطي التمثيل البصري للوغاريتمات بعض النتائج التي قد لا يمكن الوصول لها بدون الأطر النظرية و المنهجية السابق ذكرها.

كما يقوم هذا الفصل بعرض المستويات المختلفة الممكنة لمحاكاة الطبيعة و هى متمثلة فى مستوى الكائن، مستوى السلوك و مستوى النظام الإيكولوجى مع عرض مميزات و عيوب كل مستوى و إلقاء الضوء على إمكانيات كل منهم في عملية التصميم المستدام. تم تحديد مستوى النظام الإيكولوجى و اختصاصه بالدراسة حيث أنه الأكثر عمقا و إفادة. هذا النظام له مبادئه البيولوجية الخاصة به، تم ذكرها و دراستها حيث أن بعض منها سوف يمثل معايير لتقييم مجموعة من حالات الدراسة فى الفصل الرابع من هذا البحث. اختيار هذه المبادئ دون غيرها مبني على ما هو متاح من معلومات و دراسات قائمة لمحاولة ربطها بالمبادئ و الأبحاث الجارية في مجال التصميم المورفولوجي باستخدام الحاسب الآلي.

التكنولوجيا و البرمجيات الحسابية في التصميم يقدمان أدوات جديدة و مفيدة لدراسة و تحليل المبادئ البيولوجية السابق ذكرها. الانبهار الحالي الواسع بالطبيعة هو انعكاس لوجود سبل و وسائل جديدة لتصوير التكوين الداخلي و البناء للحيوانات و النباتات بالميكروسكوب الاليكتروني إلى جانب دراسة رياضيات العمليات البيولوجية. كما أن أساليب العمل الجديدة في التصميم المعماري و التنفيذ التى تستخدم الحاسب الآلى تنتشر بسرعة كبيرة في الأوساط المعمارية و الهندسية حيث أحدثت هذه الأساليب تغييرا جذريا في تقنيات التنفيذ و البناء. التعامل مع المواد أو الخامات في العمارة المعاصرة لا يمكن فصله عن النقلة النوعية في الإطار العام الذي يتم فيه إدراك و ممارسة العمارة.

ينتقل الفصل الثالث لدراسة علم المورفولوجيا و تحديد كيفية تطبيقه فى عملية التصميم بواسطة الحاسب الآلى للإستفادة منه عن طريق عرض أسلوب جديد للتصميم يسمى بالأسلوب الـ "مورفو- إيكولوجي" الذى يربط بين مبادئ النظام الإيكولوجى و علم المورفولوجيا. يتم في هذا الفصل أيضا دراسة الإطار النظرى و المنهجى لهذا الأسلوب بالإضافة إلى إعادة دراسة المبادئ البيولوجية التى تم ذكرها فى الفصل الثانى و لكن فى إطار البرمجيات و استخدام الحاسب الآلى فى عملية التصميم. يقع المدخل التصميمي المورفو- إيكولوجي في قلب هذه الرسالة لتحقيق الجزء الأكبر من هدف البحث و هو محاولة ربط المفاهيم البيولوجية بالتصميم المعماري عن طريق استخدام الحاسب الآلي.

بعد ذلك ينتقل البحث للفصل الرابع الذى يتعرض لمجموعة من حالات الدراسة و المشاريع البحثية التى تمثل نماذج للأسلوب التصميمى المقترح. ثلاثة منها يتبع المدخل التصميمي المبني على البحث و التطبيق و ثلاثة آخرين يتبع كل منهم المدخل التصميمي القائم على حل المشكلة. تم تحليل هذه المشاريع وفقًا للمعايير التى ذكرت فى كل من الفصل الثانى و الثالث و هم:

- التكيف
- أنظمة المواد
- عملية النشوء و التطور
- عملية التفاعل بين الكتلة و الهيكل و الخامة
- العلاقة بيت الكتلة و السلوك

بنهاية الفصل الرابع يتم تقييم هذه المشاريع عن طريق تحديد مدى نجاحها فى تحقيق الأهداف المطلوبة، بالإضافة إلى مقارنتها بالأساليب التقليدية المستخدمة فى عملية التصميم. ثم ينتهى الفصل بتحديد مجموعة من المميزات الرئيسية لهذا الأسلوب التصميمى.

ملخص البحث

فى ظل ما يواجهه العالم من نقص للموارد و التغيرات الجوية و العديد من المظاهر الاخرى التى نتجت عن سوء استخدام و استغلال الانسان لبيئته، تقوم هذه الرسالة بعرض اسلوب مختلف لعملية التصميم المعمارى يعتمد على اتخاذ الطبيعة كنموذج و معلم و مقياس . هذا الاسلوب يقوم باستخراج مجموعة من المبادئ البيولوجية و تحليلها ثم تجريدها لتصبح قواعد و بيانات يمكن تطبيقها باستخدام الحاسب الآلى فى عملية التصميم. العمارة و علوم الاحياء لا يوجد بينهما اختلاف كبير. كلاهما يعتمد على أساس تنظيمى و مادى، و كلاهما يهتم بالإنشاء و المورفولوجيا. تمثل الطبيعة مصدر غنى من الحلول لكثير من مشاكل الإنسان مما يمثل دافع قوى لتأمل و دراسة الكائنات الحية و الأنظمة الطبيعية للتحرى من مدى الاستفادة المحتملة فى مجال الدراسة المعمارية و التنمية المستدامة.

فى ظل ما يواجهه العالم من نقص للموارد و التغيرات الجوية و العديد من المظاهر الأخرى التى نتجت عن سوء استخدام و استغلال الإنسان لبيئته، تقوم هذه الرسالة بعرض مدخل مختلف لعملية التصميم المعمارى يعتمد على اتخاذ الطبيعة كنموذج و معلم و مقياس . العمارة و علوم الأحياء لا يوجد بينهما اختلاف كبير. كلاهما يعتمد على أساس تنظيمى و مادى، و كلاهما يهتم بالإنشاء و المورفولوجيا. من أهم نقاط الإلتقاء بين المجالين أن كلاهما يعمل كمنظومة متكاملة من مجموعة من المكونات المتفرقة. النظريات الحديثة في علوم الطبيعة و التي تخص بالدراسة و البحث النظم المتكيفة المعقدة و خاصة ظاهرة الظهور (Emergence) فتحت المجال أمام العمارة لاستخدام هذه المفاهيم و عدم تجاهلها في المستقبل. تمثل الطبيعة مصدر غنى من الحلول لكثير من مشاكل الإنسان مما يمثل دافع قوى لتأمل و دراسة الكائنات الحية و الأنظمة الطبيعية للتحرى من مدى الإستفادة المحتملة فى مجال الدراسة المعمارية و التنمية المستدامة.

عملية التصميم في الطبيعة تستخدم عدد من أنظمة التغذية المرتدة (Feedback) لتوجيه عملية النمو و تكوين البناء بناءا على القوى الداخلية و الخارجية التي تؤثر عليه أو تعمل من خلاله. كل الأنظمة تتطور باستمرار و تعمل بتوافق كامل فيما بينها لتحقيق أفضل كفاءة أداء وظيفي على كل المستويات. إذا تم تطبيق ذلك على العمارة, فيصبح من الممكن تطوير مباني مرتبطة بقوة بمحيطها و متأثرة به و تكون في نفس الوقت أكثر تطورا من حيث الأداء البيئي و المستدام.

التطور الحالى فى مجال البرمجيات و الحاسب الآلى بالإضافة إلى أنظمة المحاكاة و التحليل الجديدة التى توفرها التكنولوجيا الحديثة يزيد من إحتمالية تطبيق و الإستفادة من المبادئ البيولوجية و الحلول التى تقدمها لنا الطبيعة حيث يقوم هذا المدخل التصميمي باستخراج مجموعة من المبادئ البيولوجية و تحليلها ثم تجريدها لتصبح قواعد و بيانات يمكن تطبيقها باستخدام الحاسب الآلى فى عملية التصميم. لهذا فإن هذا البحث يهدف إلى دراسة كل من علم محاكاة الطبيعة و علوم البرمجيات المورفولوجية الحديثة فى التصميم المعمارى و الربط بينهما للحصول على عمارة أكثر تطورًا فى مجال الإستدامة.

يبدأ هذا البحث باستكشاف التطبيق الحالى لعلوم محاكاة الطبيعة فى التصميم المعمارى حيث يتناول الفصل الثانى أهم التوجهات التصميمية فى هذا المجال متمثلة فى مدخلين أساسيين للتصميم المحاكي للطبيعة و هما:

أولا: التصميم المبني على تحديد المشكلة التصميمية و بالتالي دراسة الحلول الممكنة لها

ثانيا: التصميم المبني على البحث و الدراسة المستمرة للأنظمة الطبيعية ثم إيجاد التطبيقات الممكنة لها في مجال العمارة.

لجنة الاشراف

أ.د. / محمد عاصم حنفى ....

د. / زياد طارق الصياد ....

محاكاة الطبيعة كأداة للتنمية المستدامة فى التصميم المعمارى

نحو العمارة المورفولوجية

مقدمة من

سلمى أشرف سعد الأحمر

للحصول على درجة

الماجستير فى العلوم الهندسية

المبانى و البيئة

لجنة المناقشة والحكم على الرسالة	موافقون
أ.د./ محمد عبد العال ابراهيم	....
أ.د./ محمد ابراهيم جمعة	....
أ.د./ محمد عاصم حنفى	....

وكيل الكلية للدراسات العليا والبحوث

كلية الهندسة – جامعة الاسكندرية

أ.د. / إبتهال يوسف البسطويسى

....

محاكاة الطبيعة كأداة للتنمية المستدامة فى التصميم المعمارى

نحو العمارة المورفولوجية

رسالة علمية

مقدمة الى الدرسات العليا بكلية الهندسة – جامعه الاسكندرية

استيفاء للدراسات المقررة للحصول على درجة

الماجستير فى العلوم الهندسية

فى

المبانى و البيئة

مقدمة من

سلمى أشرف سعد الأحمر

يناير 2011