



RESPONSIVE CLIMATE DESIGN:

A BIOMIMETIC APPROACH

Marcello Soeleman

MSc-3 Research Report | Architectural Engineering
TU Delft | Faculty of Architecture

RESPONSIVE CLIMATE DESIGN: A BIOMIMETIC APPROACH

MSc-3 Research Report

TU Delft | Faculty of Architecture

Architectural Engineering Lab 7

Tutors: Jan Engels, Suzanne Groenewold, Andy van den Dobbelsteen

Marcello Soeleman

Student nr.: 1212060

m.soeleman@gmail.com

September 2012

TABLE OF CONTENTS

Preface	6
Introduction	7
Technology versus nature: madness versus elegance	7
The 'human' vs. the 'natural' way	8
Designing for a changing world	9
Biomimicry: a sustainable solution?	
PART 1 A BIOMIMICRY MANUAL	
Chapter 1	12
Research framework and outline	
1.1 Background and boundary conditions	12
1.1.1 Climate bionics and lightness	12
1.1.2 Position within biomimetic research	13
1.1.3 Boundary conditions	13
1.2 Research: Problem statement, objectives and research question	14
1.2.1 Problem statement and hypothesis	14
1.2.2 Objectives	14
1.2.3 Research question	14
1.3 Approach and methodology	15
Chapter 2	16
Responsive climate biomimetics: fundamentals	
2.1 Four interlocking fields of research	16
2.2 Factors and scales of climate biomimetics	17
Chapter 3	19
Turning to biology	
3.1 Biologize the question	19
3.1.1 The biological energy and material cycle	19
3.1.2 Energy and organisms: flows	20
3.2 Thermoregulation in animals	21
3.3 Responsive thermoregulation of animals: a toolbox	22
Chapter 4	35
Thermal comfort: the human factor	
4.1 Thermal comfort: a short research history	35
4.1.1 Elements of thermal comfort	35
4.1.2 Psychometrics: the static model	36
4.1.3 Thermal comfort perception	36
4.2 Alfa and Beta buildings	39
4.3 Thermal comfort and the human body	39
4.3.1 Local differences in comfort conditions	39
4.3.2 Comfort and physiology	40
4.3.3 Six basic factors... or more?	40
Chapter 5	41
Conclusions of part 1	
Literature	43

PREFACE

The report before you is the concept thesis that is part of the graduation exam of the 7th lab of Architectural Engineering, hosted at the Faculty of Architecture, Delft University of Technology; aE7 for short.

The aim of this studio is to design a work of architecture, based on a technical fascination. In this studio, technological research and analysis becomes leading for the design of a building. This thesis then is the result of this technological research. My own fascination lies in biotechnology: technology based on biology. The scientific field that entails this subject is dubbed *biomimicry*.

This thesis describes the technical (and in my case, biological) research conducted as part of the first period of the graduation process. As such, the results derived from this research are meant to form a context and inspiration for architectural starting points, concepts and principles, culminating into a building design that is one of the final products of this graduation project.

This thesis is subdivided into several parts. After an introductory chapter that describes the problems, challenges and potentials that this research aims to tackle, Part 1 comprises a *biomimicry manual*. Part 1 describes a methodology that can be applied to biomimicry, and taking my own specific fascination as an example, it examines a case of biomimetic research that is then translated into technology. The biological examples and their technological analogies are summarized in a toolbox. This toolbox then serves as a reference during architectural design: to fall back on and as inspiration. As a second part of biomimetic research, the findings are put further into context by analyzing human needs from first principles. This provides criteria to which biomimetic solutions can be evaluated. A final step is to propose possible innovations into existing technologies, or new technologies. The viability of these innovations are worked out in the design of the building.

Part 2 describes the steps taken designing a building and its geographical context using biomimetic principles. The biological analogy is put forward for every step, indicating to what degree biology has played a role in the design process. An analysis of the intended location as well as analyzing precedents sheds light on the final assignment, after which several designed and tested solutions are put forward. The final design forms the conclusion of this part.

Finally, part 3 is a reflection on the application of biomimetics into architecture. Research results and conclusions are presented and compared to existing biomimetic buildings (these buildings have a different approach to biomimetics than my fascination but they do illustrate the concepts of the research field).

TECHNOLOGY VERSUS NATURE: MADNESS VERSUS ELEGANCE

When looking at nature, its principles, its design and engineering, one thing that stands out time and time again is the elegance of its solutions. The differences between nature's approach to problems and human-made approaches are so large that this discrepancy could be one of the most important reasons why human technology today more often has a destructive effect on the natural environment than it is conducive to it. This chapter aims to point out these discrepancies, while putting them into the larger context of a changing world: the Anthropocene is well on its way into becoming a reality, and whether this is a good thing or a bad thing is entirely up to us.

The 'human' vs. the 'natural' way

To get us started, consider the story of spider silk. With the back of their legs, spiders 'spin' an aligned stream of polymers into a thread as main material for their intricate webs. When dry, this silk is stronger than Kevlar. This fact becomes even more striking when it is considered how Kevlar, a brand of aramid fibre is made: petroleum is boiled in sulphuric acid at around 750 °C, after which the mixture is subjected to enormous pressure to get the polymers into place, producing large amounts of toxic waste in the process. Compare this to the spider, which achieves the same relative strength at ambient temperatures and pressures, with nothing but consumed flies and water as raw materials. (Pawlyn, 2011)



Fig. 0.1 Spider silk is relatively stronger than aramid...

And spider silk is by no means an exception. Consider trees. They need huge quantities of water and nutrients for their leaves, dozens of metres up. After sucking in water at the roots via capillary action, the most important way trees get water to their leaves is transpiration: trees only use a small part of the water for their own purposes; the rest is evaporated at the leaves. By evaporation of water from the leaves, this water is replaced by water coming up from the roots via an intricate network of parallel sets of "pipes". And on top of this, trees evaporate so much water that it has a large cooling effect: one tree cools as much as ten room-size, residential air conditioners operating 20 hours a day. (Canopy.org, 2012) Compare this to heavy-duty, energy slurping pumps that mechanical engineers deploy to get water up no further than 10 metres and to the aforementioned room-size air conditioners.



Fig. 0.2 An array of air conditioners: these cool less than a tree...

These examples vividly demonstrate some key differences between the 'natural' and the 'human' way of dealing with quite similar problems. Where humanity tackles a problem head-on and seeks specific solutions for specific problems, nature seeks a way around a problem and the process of evolution by natural selection ruthlessly favours more effective solutions; which more often than not have several unexpected effects that can have added benefits for an organism.

And the way we solve things are, in the long run, shown to be destructive for our own development. In several ways, we as a species are affecting the world in previously unseen ways: we have begun to influence it in such a way that humanity is becoming a driving force for the global climate.

Designing for a changing world

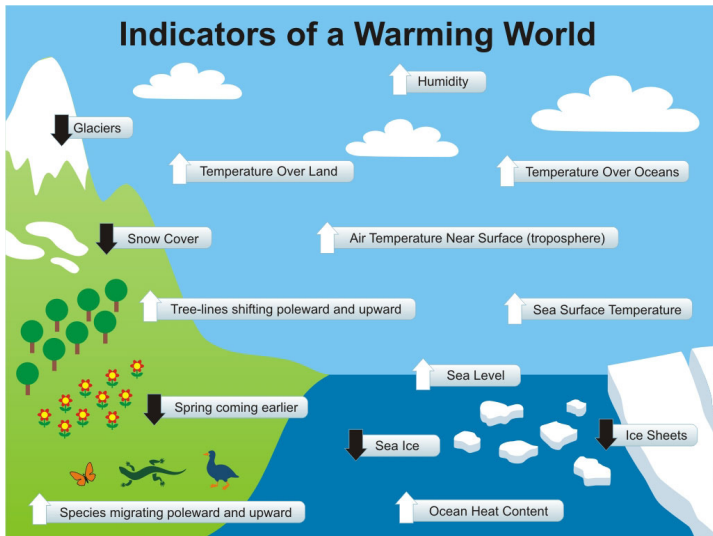


Fig. 0.3 This drawing shows the many different indicators, that together show how global climate is changing. White arrows indicate an increase in the factor, black arrows indicate a decrease. (Skeptical Science, 2010)

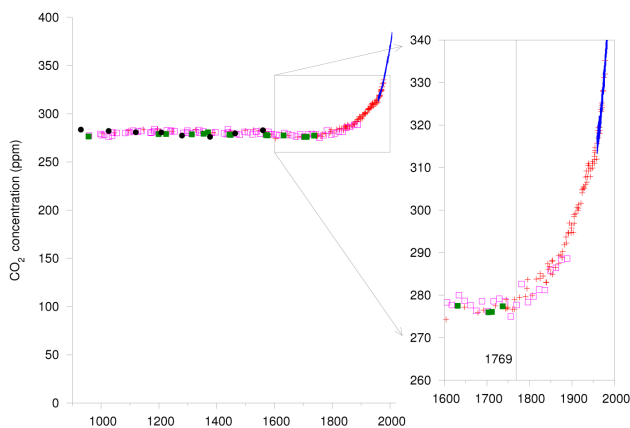


Fig. 0.4 Historic CO₂ levels from about 1000 years ago until now. The zoomed area displays levels from 1600: the vertical line drawn at 1769 is the year that James Watt patented his steam engine. (MacKay, 2009)

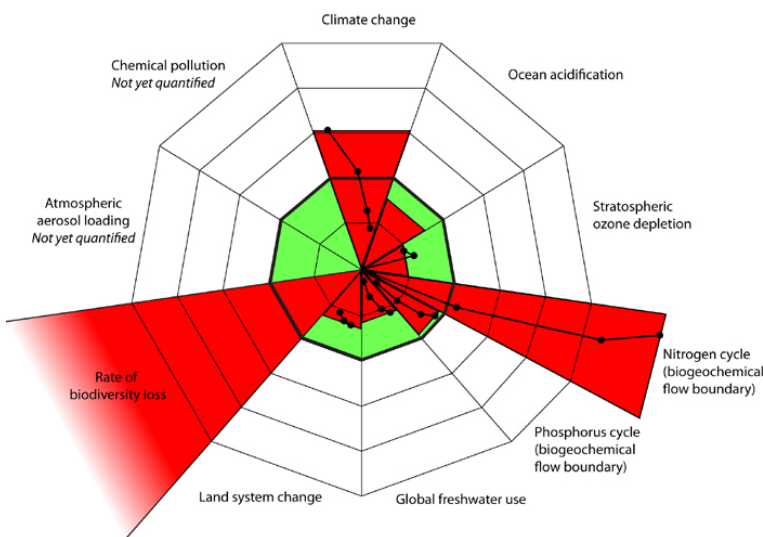


Fig. 0.5 Nine planetary boundaries, conceived by Rockström et al.

Slowly but surely, the global climate is changing. Average global temperatures are rising, the compositions of top soil and river minerals are changing and biodiversity is diminishing at an increasing rate, which in itself has consequences for the global climate as well. Humanity at large is a big contributing factor in the afore described changes, given the extra CO₂, NH₄, NO_x and other gases humans put out into the atmosphere via industrial processes, while deforestation and desertification are other contributing factors. While in some societal circles anthropogenic climate change is still under heavy dispute (politics being a notoriously stubborn one), just one glance at the scientific evidence paints a very clear picture. How are we as architects expected to respond to these developments?

Evidence of climate change

There are numerous organizations and scientific institutions that research climate change. One of these is the Intergovernmental Panel on Climate Change, or IPCC. This panel keeps track of global temperatures, concentrations of CO₂ in the atmosphere, solar irradiance and other climatic factors (or 'forcings'), while it also constructs predictive models for future global temperatures and other parameters. The drawing on the left shows the many different indicators, that together paint a picture of how the climate is changing. White arrows indicate an increase in the mentioned factor, while black arrows indicate a decrease. Supported by decades of scientific research, the picture's conclusion is straight and simple: the climate is changing, and we are responsible. (Skeptical Science, 2010) Much to the same conclusion comes professor of natural philosophy in the department of Physics at the University of Cambridge, David MacKay, in his seminal book *Sustainable Energy – without the hot air* (2009). This book, which looks at "numbers, not adjectives", is a sober – and sobering – account of the status quo in (British) energy production and consumption, offset against our influence on global climate: what Britain can achieve with sustainable energy versus what the country needs, motivated by the notion of anthropogenic climate change. Studies like these give much valuable insights in the situation we're in.

Another take on the conclusion of humanity's influence on the state of the planet is presented by the Swedish researcher Johan Rockström, executive director of the Stockholm Environment Institute and the Stockholm Resilience Centre. His group of scientists has developed the concept of 'planetary boundaries'. These boundaries – nine in total – go beyond the notion of climate change, to determine boundaries "within which we expect that humanity can operate safely. (...) Planetary boundaries define, as it were, the boundaries of the "planetary playing field" for humanity if we want to be sure of avoiding major human-induced environmental change on a global scale." (Rockström, 2009) Of these nine boundaries, seven are currently quantified by the team while research is continuing to quantify the remaining two. While the outcome is broader than the conclusions of the IPCC and even MacKay, the general conclusion is the same: as a species, we are extorting an enormous influence on the global characteristics. Rockström then rightfully calls the times we are in as the "anthropocene". (Rockström, 2009)

Biomimicry: a sustainable solution?

Given the fact that our climate is changing, plus the fact that human technology is more often than not destructive of our living world than it is conducive to it, taking in lessons of 3.8 billion years of evolution by natural selection seems a valid source of information and inspiration to vastly improve upon our technologies. Biomimicry / biomimetics is not a new field of study. In fact, the field has been in development for centuries; Leonardo da Vinci was of course a pioneer in looking at natural forms to emulate them to develop into technology. Only in recent decades has biomimicry been designated as a separate scientific field, amongst others by the standard book by Janine Benyus, aptly named *Biomimicry*.

The core concept of biomimetic design seems simple. Benyus defines it as follows: “Biomimicry is learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs.” (Benyus, 2012) The goal, thus, of biomimicry is clear: achieving sustainable designs, for a changing world. For life has been on this planet for 3.8 billion years, sustaining itself while surviving the greatest disasters; albeit barely following some mass extinction events. Benyus captures the essence of the objective of biomimicry in the statement that “life creates conditions conducive to life,” (Benyus, 2012) so therefore it’s only natural (pun intended) that human design should try to emulate living systems. The building industry is one of the fields where biomimetic research is especially applicable to. As one of the biggest polluters of all human activities, the world of construction has a lot to learn from how nature ‘designs’ (evolves) and constructs its life forms, from the forms to the inner workings of organisms.

Of course, biomimicry is not the only approach towards biological integration into technology. Benyus distinguishes three approaches that can be taken when looking at nature for technology: apart from biomimicry, she has named ‘bio-utilization’ and ‘bio-assisted technology’. Where biomimicry seeks to emulate natural processes and solutions in technology, bio-utilization “harvest[s] a product or producer, e.g. carving wood for floors or harvesting medicinal plants”, while bio-assisted technology “involves domesticating an organism to accomplish a function, e.g. bacterial purification of water or cows bred to produce milk.” (Benyus, 2012) This is of course not to say that bio-utilization and bio-assisted technology are somehow less sophisticated than biomimicry, but it’s good to be aware of the differences; it’s fairly easy to fall into the trap of thinking you are doing one when in reality you’re doing the other.

One thing that can be added to this distinction is what especially architects are ‘guilty’ of: something that can be dubbed as “bio-morphic architecture”. This entails taking biological form as inspiration for architectural form: plant shapes as inspiration for a handrail, or a human twisted torso as inspiration for a similarly named tower (the ‘turning torso’). While very evocative, this of course needs not have anything to do with biomimicry.

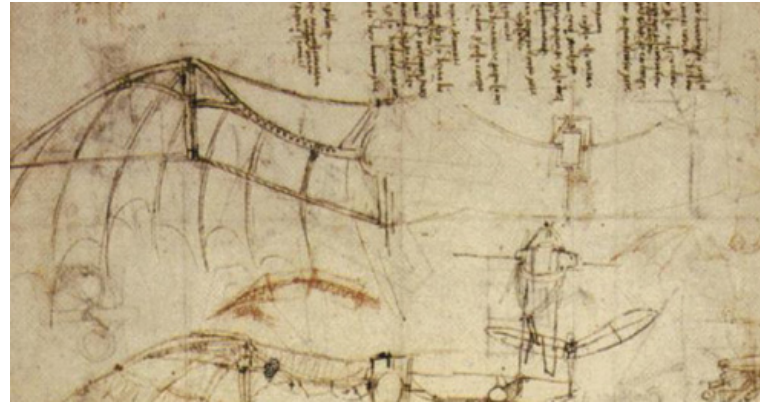


Fig. 0.6 Sketches by Leonardo da Vinci, arguably the first biomimetic designer.

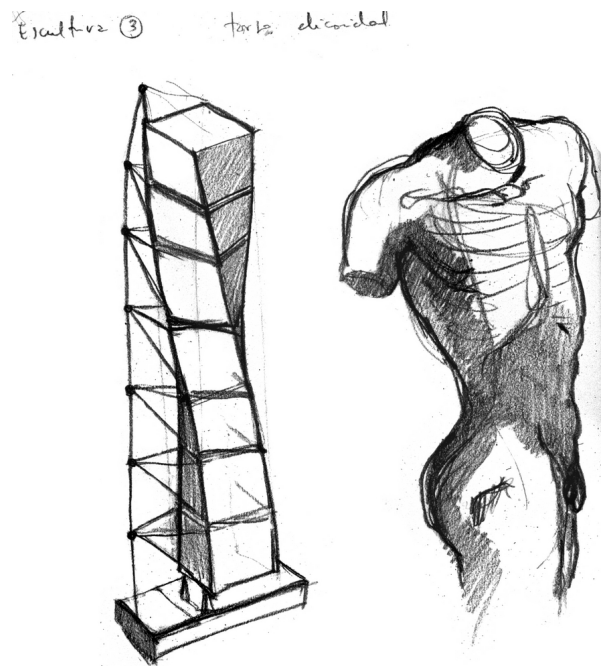


Fig. 0.7 Sketch by Santiago Calatrava for the Turning Torso, a tower in Malmö.



Fig. 0.8 Modern examples of biomimicry: ventilation inspired by termite mounds, a high speed train's nose inspired by a kingfisher's beak. (AskNature, 2011)

Biomimicry has thus championed sustainability as one of its central tenets. However Benyus herself acknowledges that sustainability doesn't necessarily need to be the outcome of biomimetics. She distinguishes "three levels" of biomimicry: the mimicking of natural form as the first level, exemplified by the nose of the Japanese high-speed bullet train, the shape of which was modelled to the kingfisher's beak to decrease its noise output. The second level is emulating a natural process: "how a thing is made". An example is the fabrication of said kingfisher's beak, with natural, re-used materials and chemicals, at ambient temperatures. The third and deepest level of biomimicry then is mimicking natural ecosystems. The kingfisher's beak is part of a kingfisher that is part of a biome that in turn is part of the biosphere. (Benyus, 2012)

Architect Michael Pawlyn, former partner of Grimshaw Architects, focuses Benyus' premise to a more building- and product-design oriented view, summarizing his view in three "major changes" that need to occur "if the grand project of humanity is to endure: achieving radical increases in resource efficiency, shifting from a fossil-fuel economy to a solar economy and transforming from a linear, wasteful and polluting way of using resources to a completely closed-loop model in which all resources are stewarded in cycles and nothing is lost as waste." (Pawlyn, 2011) These visions are important in pointing towards a direction for biomimetic research. These are ultimate goals: very difficult to achieve, but important, dare I say necessary goals nonetheless. This research paper serves as one case of biomimetic research that ultimately has to lead towards innovative technology in architecture; part 1, the "biomimicry manual" describes how said research might come about.

	bio-utilization: acquire the product or producer	bio-assisted: domesticate the producer	biomimicry: emulate the producer
well- adapted	sustainable harvest	natural breeding	mimicking form, process AND ecosystem
mal- adapted	unsustainable harvest	transgenics	mimicking form alone; heat, beat, and treat processes

EXAMPLES:

	bio-utilization	bio-assisted	biomimicry
example 1: abalone nacre			
well- adapted	sustainable harvest of wild abalone for nacre	natural breeding of abalone for farming	mimicry of nacre self- assembly processes
mal- adapted	over-harvesting of wild abalone for nacre	using genetic engineering of abalone to create "better" nacre	production of high-tech ceramics using heat, beat, and treat
example 2: spider/silkworm silk			
well- adapted	sustainable harvest of silkworm silk	natural breeding to maximize silk production	mimicry of spider's manufacturing process
mal- adapted	over-harvesting of silkworm silk	splicing "silk" gene into goats to produce silk proteins in milk	nylon and kevlar manufacturing

Fig. 0.9 The differences between several bio-approaches. (Benyus, 2012)

PART 1

A BIOMIMICRY MANUAL

RESEARCH FRAMEWORK AND OUTLINE

This chapter will describe more specifically the outline of the technological research of this thesis. After describing some boundary conditions, the main objectives, the research question and problem statement are put forward. Finally, the chapter describes the approach and methodology of this research.

1.1 Background and boundary conditions

In the introduction, the concept and main principles of biomimetics are described. How could these principles be applied to my own research?

Two particular subfields within biomimetics particularly are of interest. These subfields can be designated as 'Climate Bionics' and 'Bio-lightness'. Drawing upon the realization that life does the most it can with the fewest possible resources, as has been demonstrated in the intro, Climate Biomimetics and the concept of lightness are two very promising concepts in my mind. These are further elaborated upon below.

1.1.1 Climate bionics and lightness

Already a well-established field of research, looking at biology for climatic solutions has delivered some practical and built solutions. The most famous example of course is the intelligent ventilation of termite mounds, applied in building design to passively cool buildings in hot (desert) climates. As termites don't have access to air conditioning, they must invent passive ways to keep temperature and humidity in their nests stable. The ingenious system of tunnels and canals in their mounds, connected to an elaborate system of tunnels underground, ensures a constant temperature and humidity throughout the year by means of passive ventilation. Some buildings have incorporated the termite mound principles into their architecture. The Eastgate Centre in Zimbabwe for example cools the incoming hot air by the concrete mass of the building, entirely eliminating the need for an air condition system.

What the Eastgate Centre also has however, is mass. A lot of it. Thermal mass has many advantages: accumulating heat can be stored in thermal mass, and when temperatures drop this mass gives off its heat to the space. However, thermal mass takes up a lot of material. And while animal builders know their way with building materials (termites process earth and change its composition before depositing it on their nest structures), animals themselves have their own sophisticated ways to thermoregulate. And since animals need to move around, they need to be lightweight; and in building, reducing material use is just as important as reducing energy use. For these reasons, this research concentrates on how animals employ thermoregulation, in order to find inspiration for technology that behaves more intelligently; taking nature as a mentor.



Fig. 1.1 The spinosaurus uses its gigantic sail to cool itself, while it also acts as courtship display and intimidation device.

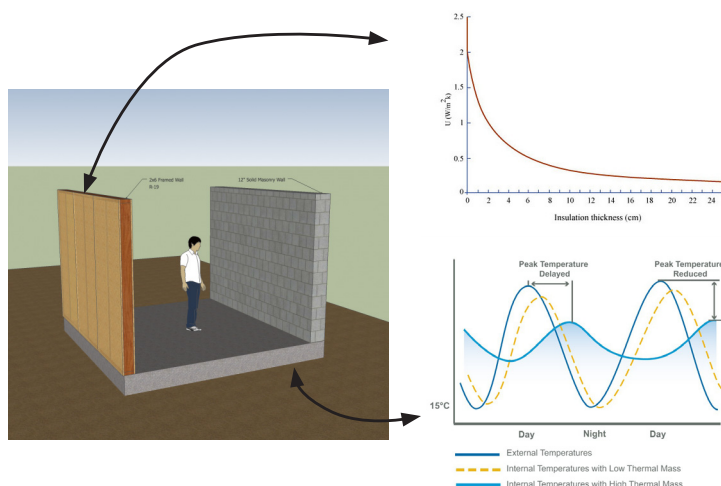


Fig. 1.2 Thermal mass compared to insulation. The two means of heat insulation have very different ways of dealing with heat: thermal mass accumulates heat from a source (mostly the sun) while insulation shields heat transfer off.

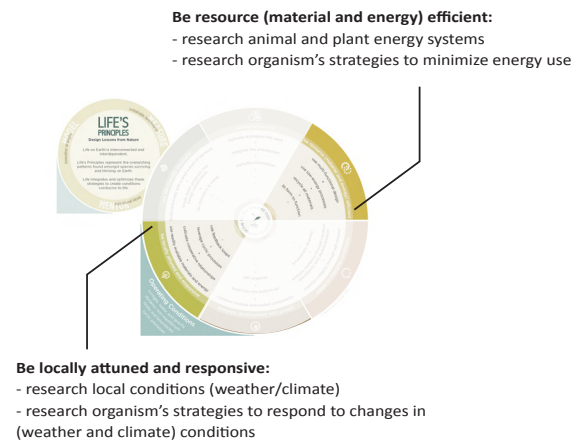
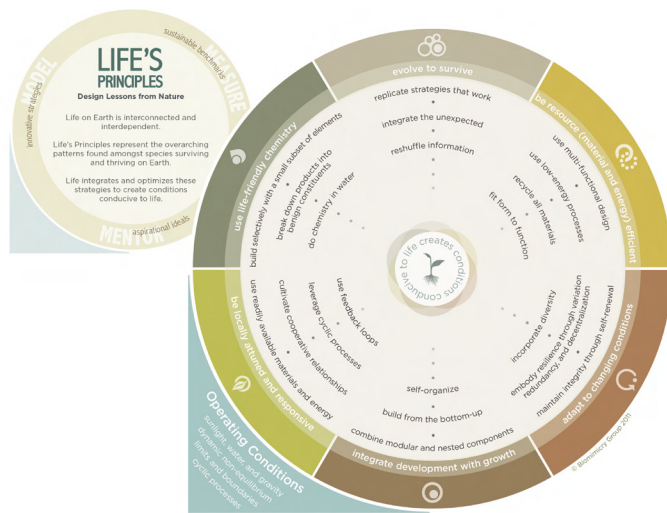


Fig. 1.3 The wheel of 'Life's principles', and the two focus points of this research paper.

1.1.2 Position within biomimetic research

The two subfields that are introduced above, can be put within the wider framework of biomimetic research using the research wheel by the Biomimicry Institute on the right. As a wheel of 'Life's principles', it illustrates the varying conditions biomimicry should adhere to; of course, one biomimetic research has different focus points from the next, so one or a few of these items should be highlighted for each case of biomimicry. For my own research, the diagram below illustrates the focus points of this research paper: 'be resource (material and energy) efficient' and 'be locally attuned and responsive'. While at first glance it might seem that this research only looks at the former 'piece of the pie', when it comes to climate design, there's no other option than be locally attuned: which solutions are to be explored are heavily determined by the local climate. More on this is explained in the next section.

1.1.3 Boundary conditions

As this research is done for the MSc-3 semester of the seventh Architectural Engineering graduation lab, this research should result in technological inspirations and principles for the design of a building. This building is to be designed in the area of Scheveningen Harbour, located on the West coast of The Netherlands. The maps on the right illustrate Scheveningen's location in The Netherlands. This suggests some boundary conditions for the research. We now know that it is a temperate, oceanic climate that is being tackled: temperatures generally don't fall below -10 °C in winter, while rarely exceeding 25 °C in summer. Only a few days a year can be seen as a 'tropical day', where temperatures reach or exceed 30 °C.

World map of Köppen-Geiger climate classification

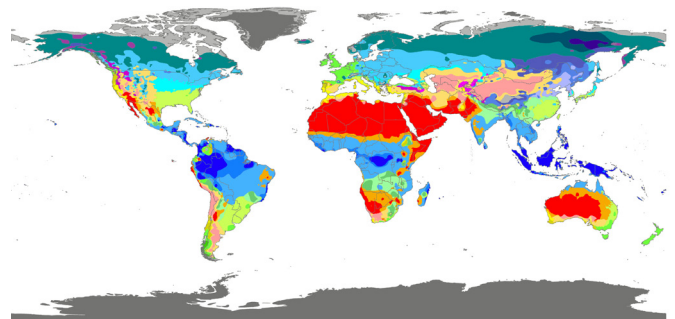


Fig. 1.4 According to this climate classification by Köppen, The Netherlands is situated in the 'oceanic climate' (Cfb).



Fig. 1.5 The coastal system of The Netherlands is part of a large coastal region, stretching from northern Germany into Belgium and France. The Dutch coast can be subdivided into three regions: the 'Wadden', the 'Holland coast' and the 'Zeeland coast'.



Fig. 1.6 As part of the Holland coast, Scheveningen is the only relatively large-scale urban development that reaches all the way to the waterline of The Netherlands.

1.2 Research: Problem statement, objectives and research question

1.2.1 Problem statement and hypothesis

Given all of the information from the previous chapter, we now arrive at the problem statement of this technical research, followed by the main hypothesis:

Architectural design today has to deal with great changes in climate and increasing frequency and amplitudes of extremes in weather, however the built solutions today are either ill-suited to cope with said changes and extremes, or are very limited in their ways to address them, still consuming very large amounts of mass and energy to operate.

As one of the laws of life is to minimize energy and material use to perform its functions, while responding to environmental conditions, building solutions based upon life's principles have the potential to drastically enhance their (energetic and material) performance.

1.2.2 Objectives

This study and research has one main objective and two sub-objectives. The main objective of this research is to find and engineer solutions for a building to minimize its energy and material use, by means of form (meaning overall shape, orientation and spatial layout) and by means of responsive design: the ability of a building to change its (skin) configuration or even its overall shape and/or orientation (and in the most extreme case, its position), in response to outside weather and climatic conditions. In order to develop engineering solutions, all of these parameters will have to be more exactly specified, however each solution will require (slightly) different parameters and considerations, so this will be dealt with in the relevant paragraphs.

The subfield mentioned in the previous paragraph are reformed here to sub-objectives of the research. The first sub-objective is to find intelligent ways for a building to respond to weather and climate, inspired by solutions found in the animal (or plant) kingdom. As solutions from biology are researched, technological implications are developed as well.

1.2.3 Research question

From the problem statement and the objectives stated above, the main research question can be formulated:

How can architectural technologies based on life's principles, e.g. minimizing material and energy use and responding to environmental conditions, minimize material and energy consumption?

1.3 Approach and methodology

Biomimetics has many methodologies. Remarking that “[b]iomimetic design in architecture still lacks an underlying design theory” (Gruber, 2011), Petra Gruber makes clear that a real generic methodology has not (yet) been proposed. Applying biomimetics as a tool in architectural design does however suggest a specific methodology. Gruber distinguishes several steps in architectural biomimetic research:

Start of research: in architecture (Gruber gives traditional architecture as an example) and in life sciences, according to personal interest, supposed transfer and/or functional analogy;
Abstraction: abstraction of the start-of-research results. Crucial for the process, according to Gruber;
Application: searching an application field of the research and abstraction formulated above.

Gruber also describes a more detailed and specific methodology for the development of deployable structures for lunar missions, inspired by biological solutions and traditional architecture. Research for this seemingly rather far-fetched case study served as a basis for the aforementioned more general methodology.

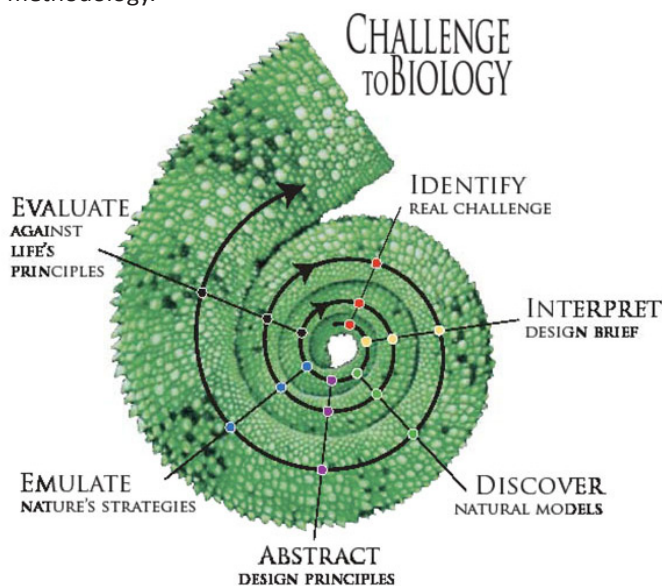


Fig. 1.8 The 'design spiral', pointing to a methodology for biomimetic research.

The Biomimicry Guild developed a more detailed general methodology, described by their very own 'design spiral':

- Identify: develop a design brief of the human need;
- Interpret: biologize the question; ask the design brief from nature's perspective;
- Discover: look for the champions in nature who answer/resolve your challenges;
- Abstract: find the repeating patterns and processes within nature that achieve success;
- Emulate: develop ideas and solutions based on the natural models;
- Evaluate: how do your ideas compare to life's principles, the successful principles of nature?

For the scope of the MSc-3 research project, one can say that the first point that Gruber brings up, as well as the first two points of the Biomimicry Guild, are covered in this document. For the determination of the further steps to take from this point, the methodology of the Biomimicry Guild provides an adequate template to follow. For the MSc-3 research, the following, more specific methodology is proposed:

1. Propose a problem statement and a research question;
2. define the scope of the project;
3. Biologize the question: in order to define a 'search space' within the biological world, find which biological functions perform (and which functions do NOT perform) what the research question and problem statement define, in the boundaries of the research scope;
4. Discover: search in the defined 'search space' for organisms that are 'champions that answer/resolve the questions', and find how exactly they address the problems posed in step 1;
5. Abstract: find repeating patterns shared by the found organisms, come to conclusions on the results and model generic patterns that address the problems in step 1;
6. Emulate: develop engineering solutions and ideas based on the developed models in step 4.
7. Test: developing the found engineering solutions further, testing their performance, should provide a basis from which the solutions can be compared to their natural counterparts.
8. Evaluate: from the results of the tests, a comparison can be made between the engineered solutions and the natural solutions. This comparison can be a conclusion of the research.

In steps 2 and 3, literature research would be the core of the research activities. Getting out in the field, finding intriguing organisms that address the posed problems, could be part of the research, but as I am not a biologist, literature research should definitely follow this up. Opening up discussions with biologists or other experts on the found organisms also could add valuable information to the results of steps 2 and 3.

Steps 4, 5 and 6 would entail mostly modelling and putting the models to the test. Modelling solutions in the computer via 3D visualization programs such as Rhino or Revit and making physical (scale) models are key research activities. During these steps, the research focus should shift from a mainly climate oriented focus to a mainly biotensegrity oriented focus; the main concern after all is to come up with methods to make the found solutions. The computer models can subsequently be analyzed in finite element analysis programs such as Diana, Ecotect and/or DesignBuilder / EnergyPlus.

RESPONSIVE CLIMATE BIOMIMETICS: FUNDAMENTALS

Before delving into the world of biology, it's useful to provide some backgrounds upon which this biomimetic building technology research is based. While the biomimetic research field is introduced in chapter 1, this scope is elaborated upon in this chapter. This should provide a more exact framing of the questions at hand, not only within the biosphere, but also in the technosphere: the technology that is aimed at by learning from nature.

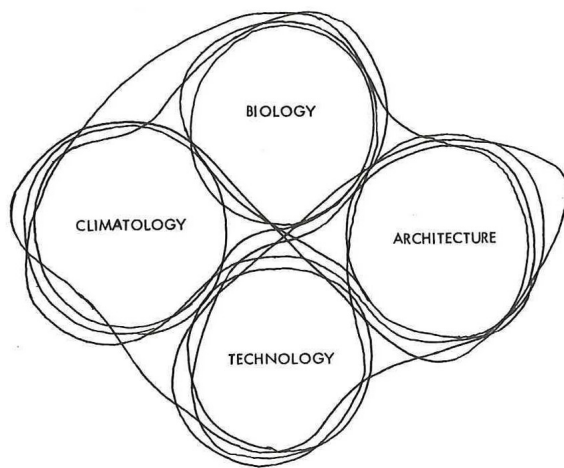


Fig. 2.1 Four interlocking fields of research. (Olgyay, 1963)

2.1 Four interlocking fields of research

In the much-encompassing book “Design with Climate: bioclimatic approach to architectural regionalism” (1963), Victor Olgyay distinguishes four fields of climatic design: climatology, biology, technology and architecture. According to Olgyay, these four fields follow each other, influencing each next step in the design methodology: “The first step toward [architectural] environmental adjustment is a survey of climatic elements at a given location. (...) Since man is the fundamental measure in architecture and the shelter is designed to fulfil his biological needs, the second step is to evaluate each climatic impact in physiological terms. As a third step the technological solutions must be applied to each climate-comfort problem. At the final stage these solutions should be combined, according to their importance, in architectural unity”. (Olgyay, 1963) In the third step, “technology”, Olgyay distinguishes another six factors: *site selection, (solar) orientation, shading calculations, housing forms and building shapes, air movements (wind and ventilation) and indoor temperature*. These factors all contribute to achieve a “balanced shelter”. (Olgyay, 1963)

These four described fields all of course influence the climatic circumstances of indoor spaces and of direct surroundings of a “shelter”. However, in the design process for a building, the four fields don’t necessarily follow linearly upon each other, a process that Olgyay seems to suggest.

What this paper aims to do as well is to provide another look upon these four elements. Other than a linear relationship, these four fields interlock, for they all influence the configuration, concept and design of works of architecture. This is, rather ironically, illustrated as well by Olgyay in his diagram. This paper first and foremost concentrates on the “biology” and the “technology” aspects of the diagram, extending the biological “bubble” by not only taking the biological requirements of *homo sapiens* as a starting point, but also the inner biological workings of other animals that serve as inspiration for technology.

2.2 Factors and scales of climate biomimetics

Professor of Sustainable Architecture at Queens University Belfast, Greg Keffe, in his philosophy on biomimicry, describes five factors of climate biomimetics, or in his words “bioclimatic architecture”: *order, energy, separation, self perpetuation* and *evolution*. Keffe expands on these factors, which were first described by John Keosian. (Keosian, 1964) On all scale levels (macro, meso and micro scale), these five factors play a role within life; and therefore, within *bioclimatic architecture*. The factors and their characteristics are described below. This should provide a philosophical basis for categorization and abstraction on the biomimetic solutions of this research paper.

Order

Living things are more ordered than nonliving things. The orderliness of living things is actually a result of a process that counters the second law of thermodynamics (entropy): which states that an isolated system will tend towards disorder. Since life is not an isolated system (as we’ll see), it evolves towards higher and higher levels of order. This notion is also known as “negative entropy”, a term coined by physicist Edward Schrödinger. (Schrödinger, 1945) In biomimetic architecture, Keffe states that it “will be ordered in a way that responds to the climatic demands of the site and the spatial and environmental needs of the brief.” (Keffe, 2007) An interpretation of this might be that biomimetic architecture employs intelligent ways in which the elements of a building respond to both inner (spatial) climatic needs and outside climatic circumstances.

Energy

Life is not an isolated system, since it continually receives energy from the sun: all life on Earth is dependent on it. Therefore, many bioclimatic strategies that living things deploy are derived from the solar characteristics of a certain area: “Living things have a metabolism, a sophisticated method of collecting, utilizing and storing energy. Those that rely directly on the Sun for energy move in a rhythm with it.” (Keffe, 2007)

Separation

In the interface of local climatic circumstances and the inner treatment of heat and energy, the skin is the modulator between inside and out. Keffe: “Most skins are multilayered and none are exclusive. Exchange is the key here; skins allow different climatic elements and energy forms to enter or be excluded at any time.” (Keffe, 2007) Basically this is arguing for a multi-layered, complex skin for buildings: a skin that responds intelligently to climatic conditions. In the examples presented in chapter 3, several modes of heat and energy transport from and to the skin are discussed.

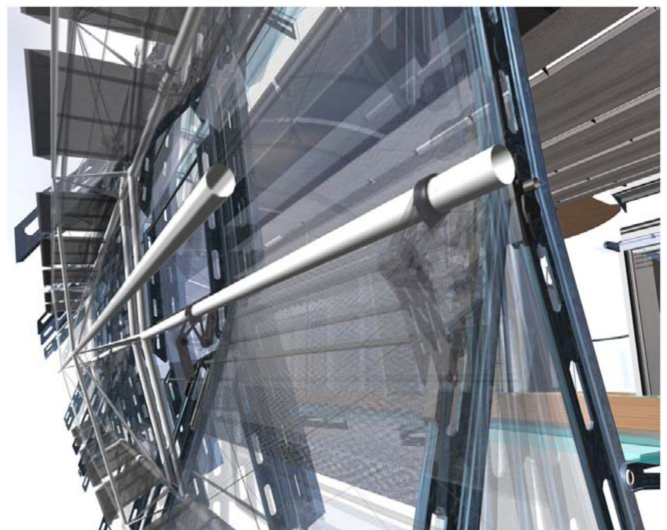
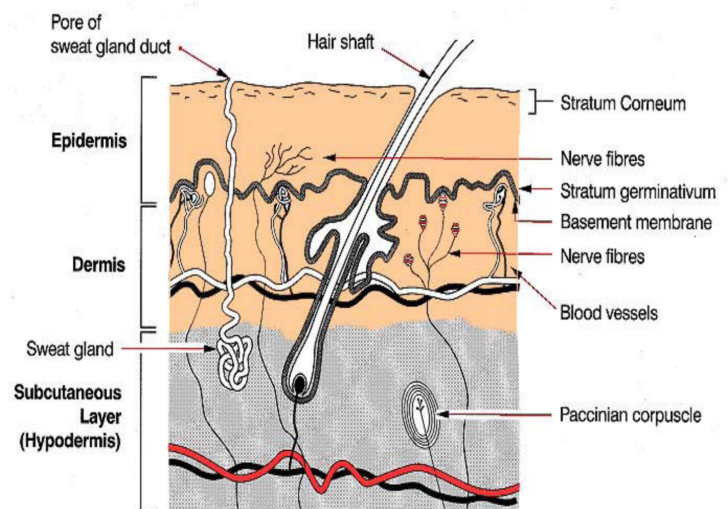


Fig. 2.2 Separation: a multi-layered, complex skin.

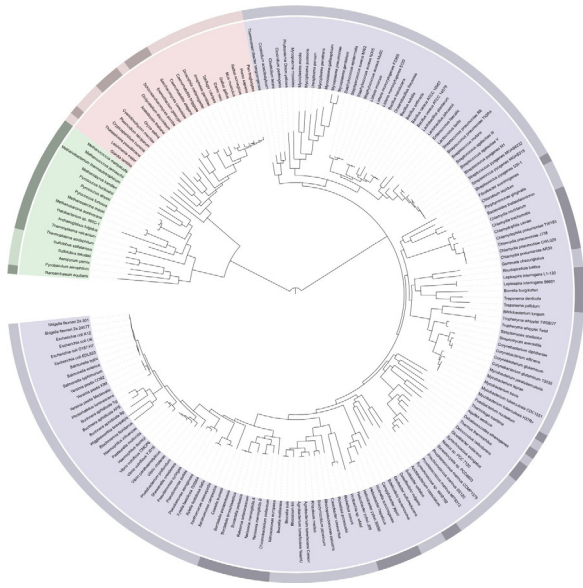


Fig. 2.3 The 'tree of life', here showing the species that have their genomes sequenced. Note Homo sapiens in the pink band, second to right.

Self perpetuation

Much akin to the idea of Cradle2Cradle, Keeffe views life here as "consisting of common elements, all of which are biodegradable. Once dead, living things directly provide key elements for the production of new creatures." (Keeffe, 2007) Applied to architecture, this translates according to him into building elements and components that can be reused and reconfigured, or at least recycled.

Evolution

Being the defining characteristic of life when viewed from a broader perspective, evolution by natural selection favours traits that are beneficial to a species. When these traits are passed on to the next generation, they become ever more prolific within a species; when many new beneficial traits accumulate, species evolve. Of course, a literal application in architecture would be problematic: buildings do not reproduce. Still, in engineering, there are many ways to optimize structures and other characteristics of a building using so-called *genetic (evolutionary) algorithms*. These computer programs mimic the process of evolution to optimize building elements before they're fabricated in the 'real' world.

Keeffe takes a different approach: he views evolving buildings to be adaptable to change; flexibility becomes a prime concern, for buildings to be able to "evolve" to suit changing needs and requirements.

On each scale level, the macro, meso and micro scale, Keeffe distinguishes several characteristics of biomimetic architecture. These characteristics are displayed in the matrix below.

	Order	Energy	Separation	Self-perpetuation	Evolution
Macro	climate derives form	rhythm - summer/winter	solar envelope	homeostasis	adaptation
Meso	planning and organization	rhythm - day/night	passive solar design		
Micro	integration in detail	rhythm - occupied/unoccupied	active solar design		

Fig. 2.4 A summary of Keeffe's schematization of architectural biomimetic design

TURNING TO BIOLOGY

After introducing the subject matter and research focuses in the previous chapters, now it is time to delve deeper into the biological world. To do this, we first have to specify the research question and deconstruct it into several sub questions: referred to in chapter 1 as “biologizing” the question. After introducing main categories in which living things are classified, the main body of this chapter is an exploration into life’s solutions to the problems asked. These solutions are then abstracted into principles, that can be translated into building principles; a built example that is compared and related to life’s solution is then put forward. This all can be summarized into a ‘toolbox’, providing inputs and inspiration for architecture.

3.1 Biologize the question

The main research question is, “How can architectural technologies based on life’s principles, e.g. minimizing material and energy use and responding to environmental conditions, minimize material and energy consumption?”. From the methodology follows that in this chapter, the research question and its sub-questions are ‘biologized’: they are reformulated into biological questions that are used to give some direction while searching the immense search space of biology. The main research question for this chapter then becomes:

How do organisms respond to environmental conditions, thereby minimizing their energy and material consumption?

3.1.1 The biological energy and material cycle

Viewed from the largest of scales, energy generation and use in organisms in relation to the environment can be summed up in a grand biological cycle.

The diagram displays the general concept of the biological energy and material cycle. Energy is taken up in plant chloroplasts, forming sugars, water and energy according to the well-known photosynthesis equation, also displayed here. The plants use the energy to synthesize sugars and other molecules from minerals taken from the earth, constituting growth and energy for other processes within plants. When the plants are eaten and digested by animals (and when animals are eaten by other animals in the infamous ‘food web’), the animals break down the ingested complex molecules, to use them in their own systems. (Campbell & Reece, 2005)

In both animals and plants, within the mitochondria in animals (through cellular respiration, a process that utilizes the sugars generated in digestion) and in chloroplasts in plants (through sunlight), energy is ‘stored’ in the versatile molecule adenosine-5′-triphosphate (ATP). This molecule, often dubbed the ‘energy currency of cells’, is responsible for all kinds of metabolic processes: synthesis of RNA, DNA and proteins, transport of molecules through the cellular membranes, maintaining cell structures by facilitating maintenance of the cytoskeleton, muscle contraction and respiration, to name a few. One of the by-products of the synthesis of ATP is heat: in humans, most heat is generated in the liver, the heart and in the brain, after

which blood circulation is largely responsible for heat transfer within the body. (Campbell & Reece, 2005)

The cycle is closed by the generation of water and carbon dioxide in animals, as other by-products of the breaking down of the sugars taken up by food (through the aforementioned cellular respiration); these molecules then leave the body through the main respiration, where they are taken up by plants again to make sugars. Other ‘waste’ materials such as phosphorus, nitrates and other carbon compounds are excreted through urine and faeces, which are subsequently processed by other organisms (among which fungi) into plant nutrients.

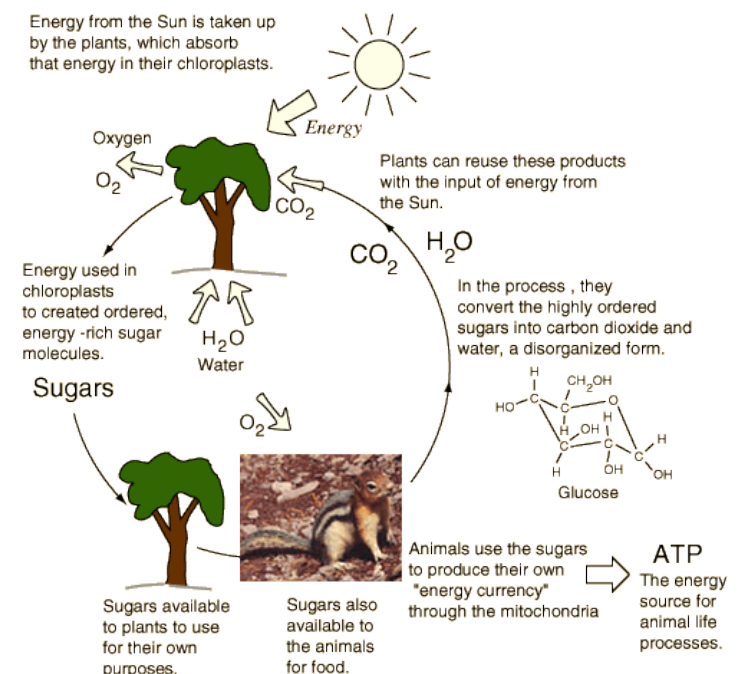


Fig. 3.1 The energy and material cycle.

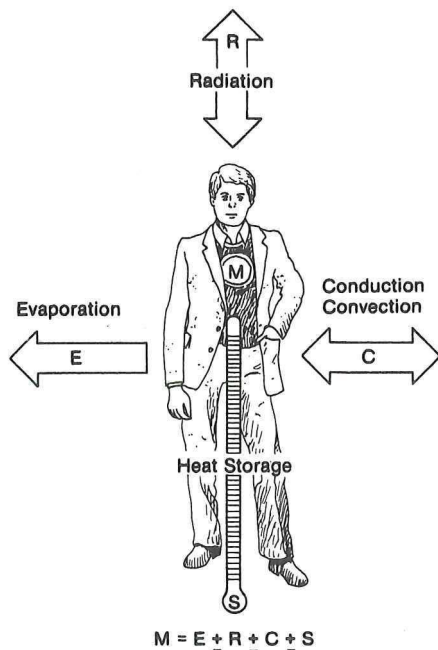


Fig. 3.2 The thermal equilibrium equation graphically explained. (Vaughn Bradshaw, 2006)

3.1.2 Energy and organisms: flows

In order to perform cellular functions properly, animals (and some plants) will almost constantly strive to maintain in thermal equilibrium with their direct surroundings; achieved when heat loss to the environment equals heat gain from the environment. The process by which these animals and plants regulate their internal temperatures is referred to as thermoregulation. Regarding the type of animal (this will be covered later), the temperature of the core body or the temperature of certain internal organs (most importantly the brain) are kept within very narrow bounds: the human core body temperature for example is kept at about 37.5 degrees centigrade, with a bandwidth of only one degree. (Campbell & Reece, 2005)

The thermal conditions of a certain habitat are of utmost importance for an organism's ability to survive there. An important explanation for the success of the human species is that we have learned to adapt to colder climates when we migrated out of Africa, by putting on layers of animal skin as clothing and 'evolving' more sophisticated means to protect ourselves from heavy temperature fluctuations throughout human history.

There are several equations describing thermal equilibrium of organisms. The simplest one regards the body as a whole in relation to the environment. While other equations delve deeper and divide the body into several compartments, the whole-body thermal equilibrium model will suffice here:

$$M = E \pm R \pm C_v \pm C_d \pm S$$

Where:

- M = metabolic rate
- E = evaporative heat loss (respiration / transpiration)
- R = radiation rate
- C_v = convection rate
- C_d = conduction rate
- S = body heat storage rate

The always positive metabolic rate M (as the body always produces heat, the metabolic rate is never zero or negative) thus equals the summation of the means of heat transfer plus or minus storage rate. The storage rate depends on the heat storage capacity of an animal, which in biology is effectively zero as heat is constantly redistributed and exchanged within the animal and to and from the environment. Radiation, convection and conduction are the three basic physical forms of heat transfer and evaporation is a more specific biological form of heat transfer that exclusively serves the purpose of cooling (it is the most effective form of cooling at that). The diagram is a graphical representation of this equation. (Vaughn Bradshaw, 2006)

3.2 Thermoregulation in animals

Now that the most general elements of thermoregulation are explored, we can take a closer look at how animals deal with their own heat treatment. In general, animals can be classified as ectotherms or endotherms; they can either be homeothermic, poikilothermic, or both. These concepts are explained below.

Ectotherms and endotherms

Also known by the somewhat outdated terms 'warm blooded' and 'cold blooded' animals, endotherms and ectotherms have different means to generate body heat. Whereas ectotherms depend on external heat sources for their body temperature such as the sun or water, endotherms produce heat via metabolism (the 'burning' of food through the process of the aforementioned ATP generation) that is regulated on the basis of negative feedback. Looking back at the equation above, it can be said that the metabolic rate M is far greater for endothermic animals than for ectothermic animals, which rely much heavier on the other terms of the equation. Even for ectotherms however, M is still not zero, as other processes (such as muscular activity) still generate heat, albeit not very much or at least not at a constant rate.

Both endothermic and ectothermic animals have their advantages and disadvantages regarding survival. Endotherms maintain a stable core temperature (the core body temperature of endotherms varies between species from 37 to 40 degrees centigrade), enabling them to survive in more extreme climates while not depending as much on the outside climate to function. Reversely, while ectothermic animals are much more confined to a certain climatic zone because their level of activity strongly depends on the outside climate, they are able to survive for far longer periods of time without food than endotherms can (even up to several months) for they don't need to keep their heat production going quite as desperately. Still, these animals display a wide variety of behavioural and physiological responses to minimize their energy needs. The following paragraph will look into these responses in more detail.

Homeotherms and poikilotherms

Where endothermy and ectothermy refers to the way in which organisms generate heat, homeothermy and poikilothermy refers to the stability of their core temperatures. Homeotherms have a stable body temperature, where the body temperature of poikilotherms varies greatly. Most endothermic animals are homeotherms, where their body temperature is often (much) higher than that of the surrounding environment. Subsequently, most ectothermic animals are poikilothermic. This however doesn't always hold up: several fish for example that are ectothermic, can also be classified as homeotherms as the temperature of the (tropical) waters they inhabit is quite stable. This is one of the main reasons why the more ambiguous terms 'warm blooded' and 'cold blooded' have come into disuse.

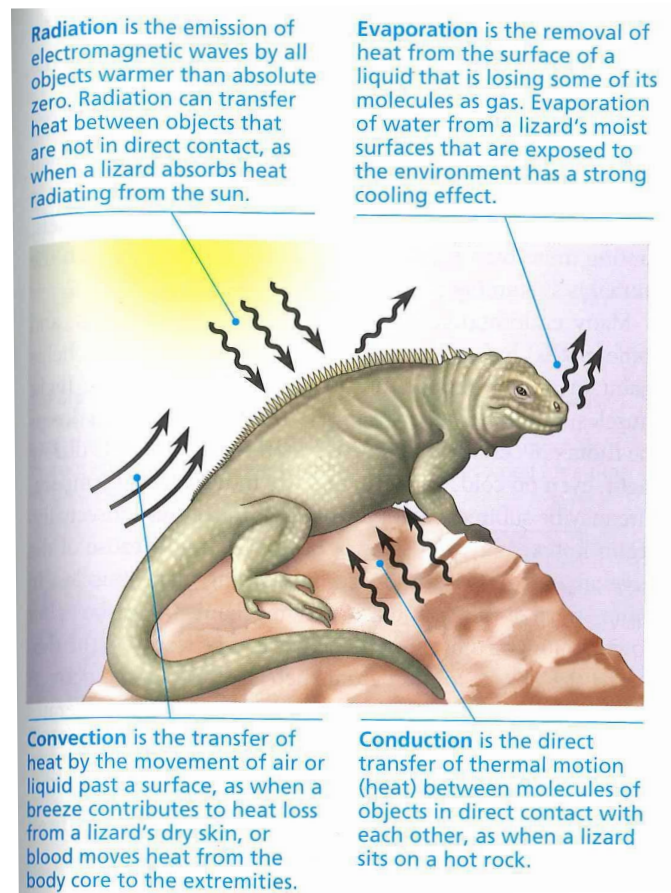


Fig. 3.3 The physical means of heat transport, utilized by organisms. (Campbell & Reece, 2005)



Fig. 3.4 an ectotherm and an endotherm; both have very different methods of thermoregulation.

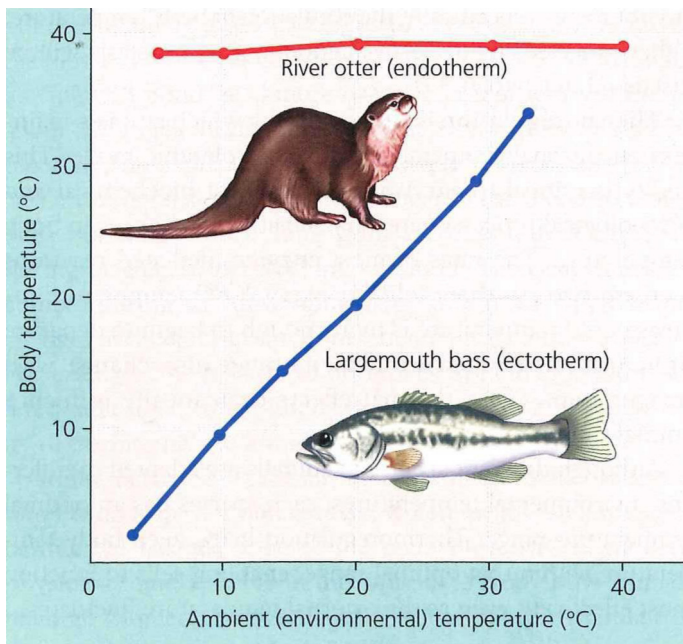


Fig. 3.5 The differences between homeotherms and poikilotherms; mostly endotherms are homeothermic and ectotherms are poikilothermic, however this isn't always the case. (Campbell & Reece, 2005)

As a special case, heterothermy refers to animals that are endotherms but can lower their metabolism such that their temperature becomes dependant of the outside climate; effectively becoming ectothermic poikilotherms. Hibernating rodents and bats are examples of this kind (lowering metabolism while resting is in biology referred to as torpor, which is different from hibernation as torpor is maintained for far shorter periods of time).

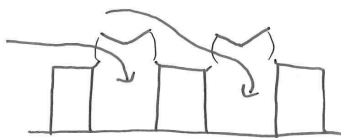
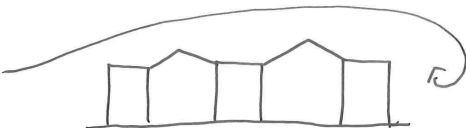
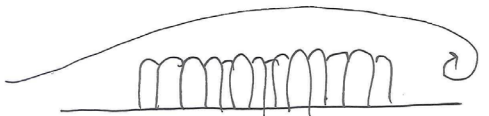
In ectothermic animals on the other hand, the core body temperature is allowed to vary as well. Still, the degree with which the core body temperatures of ectothermic animals varies is dampened in relation to the temperature variations of their extremities, and they too have some adaptations that allow their core bodies to keep temperatures quite stable.

3.3 Lightweight thermoregulation of animals: a toolbox

What follows in this paragraph from the following pages is a collection of solutions found in nature, that address the problems introduced in the previous chapters. These solutions are categorized into a 'toolbox' matrix. The toolbox consists of four items of each example: an example found in nature (typically represented by a species that is a prime example of the principle), followed by the principle that's behind the example, as an abstraction of the example. This principle is translated into a building principle, or a way in which the natural principle could be applied to buildings. The last panel shows a built example that incorporates the principle that is analogous to the natural principle.

Important to note is that the built example, the bottom item in the matrix, needs not to be directly influenced by the natural idea; many heat conservation or dissipation strategies utilized by the built and the natural world are quite comparable. The similarities and differences of each principle and solution will be discussed in the relevant section.

MACRO: COMMUNITY AND FORM



SOCIAL BEHAVIOUR

Organism: **Emperor penguin (*Aptenodytes forsteri*)**

Principle: **Sharing and conserving heat**

Technology: **IBN centre by Behnisch & Behnisch**

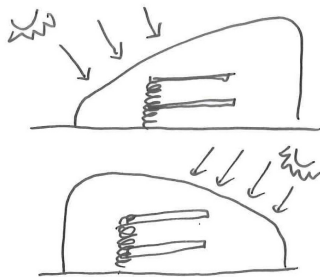
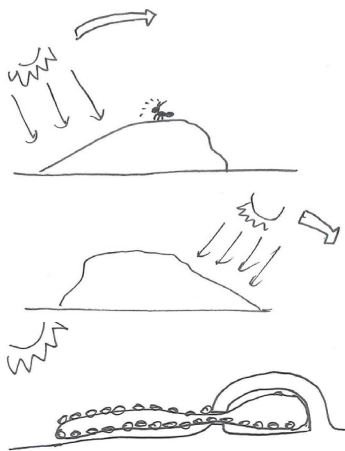
The emperor penguin is a highly specialized animal, surviving one of the harshest climates on the planet: -70°C Antarctica. The animal therefore evolved several intelligent strategies to fight the blistering cold, and thus serves as a prime example for biomimetic research. As such, the animal is featured several times in this study.

On the macro scale, the emperor penguin adopts a social strategy to retain heat: a type of behaviour dubbed 'huddling'. The emperor penguin is the only species that actually breeds during the Antarctic winter: the males incubate the eggs on land, which means (coupled with their exclusively marine diet) that they have to fast for the entire incubation period of 105-115 days (Ancel, Visser, Handrich, Masman, & Maho, 1997)

When temperatures in the Antarctic winter drop, the hundreds of breeding males in a rookery crawl together into a tightly-knit group. This behaviour has a few important consequences: one, the surface of the group compared to its volume is much lower than the surface to volume ratio of one single animal. Two, the animals in the centre of the rookery are protected against chilling gales. In fact, the penguins take turns standing on the edges of the rookery, where winds are hitting the birds full-on. Three, the heat that the animals produce is shared between them. This heat sharing greatly reduces the need for heat generation of a single animal: reducing the metabolic rate of an animal with as much as 25% (Ancel et al., 1997)

An abstraction of this example would be the notion that these animals behave according to two conditions: 'non-huddled' versus 'huddled'. Whether one condition or the other is taken, depends upon the outside temperature and on the availability of food sources: when there's no food and temperature drops, the 'huddled' condition is taken. Else, the result is a 'non-huddled' configuration. This is thus a response to climate and food availability, with the consequences that energy is saved by exposing less surface area to air, the animals are protected from strong wind and that generated body heat is shared.

One architectural 'equivalent' thermal measure would be the opening and shutting of roof canopies according to outside conditions, allowing or shunting ventilation with outside air. One building where this principle is applied is the IBN – institute for forestry and nature research in Wageningen by Behnisch Architekten. One important difference with the emperor penguin is that it is not so much sharing heat as it is cooling off the office spaces that is an important strategy in this building. During the day, shading blocks out the sun while thermal mass absorbs solar heat gain; while at night, the roof canopy is opened so trapped heat can escape. And when heat is needed, the canopy is closed, trapping heat inside the garden spaces.



SOCIAL BEHAVIOUR

Organism: **Wood ant (*Formica rufa*)**

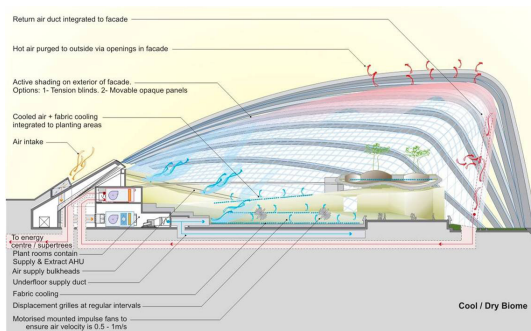
Principle: **Daily adjustment to sun and wind**

Technology: **Gardens by the Bay by WilkinsonEyre**

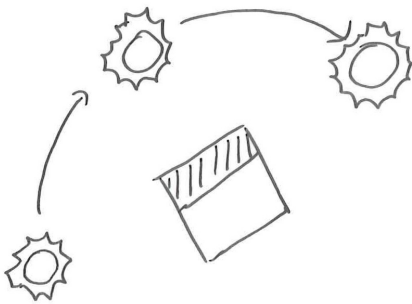
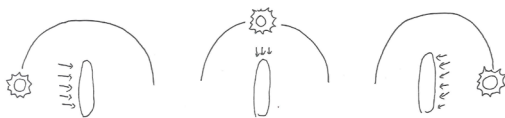
Wood ants have been studied to be constantly active regulating their nest temperatures. There are several strategies these creatures deploy: "The surface of the nest of wood ants (*Formica rufa*) has numerous holes which serve as entrances and ventilation holes; at night and in cold weather the ants plug the holes to keep heat in. The workers also keep the slope of the nest at the right angle to obtain maximum amount of solar heat. The ants bring extra warmth into their nests as live heaters by basking in the sun in large numbers and taking the heat energy collected in their bodies into the nest." (Pallasmaa, 1995)

Thus these ants are observed to utilize three main ways to mainly heat up the nest: by plugging ventilation holes in cold nights, minimizing heat loss; by optimizing solar heat gain by adjusting the nest slope; and by heating it actively with their own solar-heated body heat. This type of community behaviour, translated into a building principle, would extend the building "technology" to a more holistic viewpoint, extended to the building occupants as active parts of the "technology" employed. Taken less literally, each building element then responds to the sun and to the amount of allowed ventilation, while external elements heat the building when these elements are separately heated by the sun.

There are many buildings that use multiple strategies for heating and cooling as their primary form generator. One building that exemplifies this principle is the project for the Gardens by the Bay in Singapore, designed by WilkinsonEyre Architects. In this project, the entire master plan aids in the energy and heat treatment of the plan. Plant conservatories, placed in giant biomes much like the celebrated Eden Project, are cooled by retractable solar shading and cool displacement air that is provided from a separate "energy centre", which in turn is powered by wood chippings from the National Parks Board, an agency that cuts trees in Singapore. So while the aim is different (cooling rather than keeping heat in), this building utilizes each element to achieve this goal, much like the wood ants do.



MESO: PLANNING AND ORGANIZATION



SOALR ORIENTATION

Organism: **Compass termite** (*Amitermes meridionalis*)

Principle: **Orientation to the sun**

Technology: **Mercator 2** by Paul de Ruiter

Solar orientation is a key feature of thermoregulation in nature. The compass termite is one of the many examples of animals that use the peculiarities of solar heat gain for their own thermoregulation, or in this case, the heat regulation of the nest.

The nest of the compass termite species of northern Australia is oriented in such a way that it maximizes heat gain in the morning and in the evening, while shunting heat gain as much as possible in the hot midday: the broad, flat sides of the nest are oriented to the east and west, while the 'edges' are oriented on the north-south axis. This ensures a quick warming up of the nest in the morning, while much solar heat is captured during cooling off of the air in the evening. Maintaining a steady temperature in the dry season seems to be one of the most important reasons for this strong emphasis on nest orientation (Pallasmaa, 1995)

Of course, searching for an optimal solar orientation has been prevalent in architecture for centuries. The principle is as simple as it is effective: maximizing solar gain on oneself, a nest or a building when it's too cold, and minimizing solar gain when it's too hot. Much here depends on the requirements of indoor spaces: especially in more specialized modern societies, there often is a specific bandwidth of temperature, humidity, but also of illumination levels and the amount of permitted direct sunlight specified. This means that optimal solar orientation becomes ever more important.

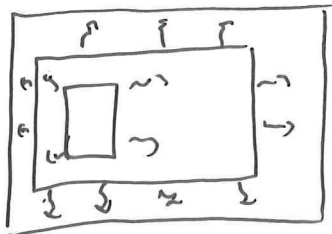
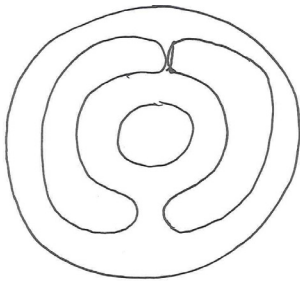
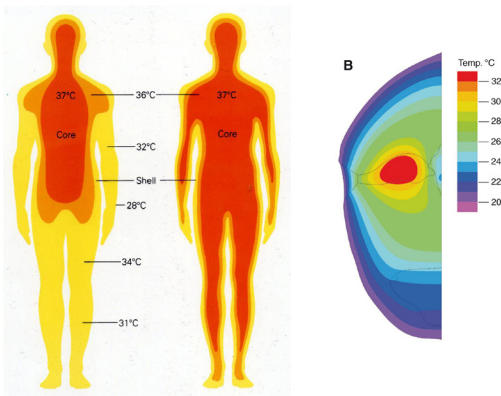
Solar angles and altitudes thus become input values for building configuration. It is not so much a response to changing conditions that is the principle, but a configuration based upon a fairly specific range of angles and altitudes that are constant from year to year. One building that is configured using solar orientation as a starting point is Mercator 2, designed by Paul de Ruiter. This 7000 m² office building, 10 floors tall, has situated the staircases, lifts and toilets on the south facade, resulting in large, north-facing office spaces. This configuration minimizes solar loads into the office spaces, minimizing energy consumption.

THERMAL PLANNING

Organism: **Ectotherms and endotherms**

Principle: **Energy saving by temperature gradients**

Technology: **Langen Foundation by Tadao Ando**



Thermal planning and organization is the key feature that differentiates between endotherms and ectotherms. As we've seen in previous paragraphs, it's far too simple to say that endotherms generate their own heat and ectotherms don't, for there are ectotherms that do generate heat (albeit far less than endotherms do) and endotherms deploy many thermoregulatory strategies that ectotherms deploy (though not quite as extensively).

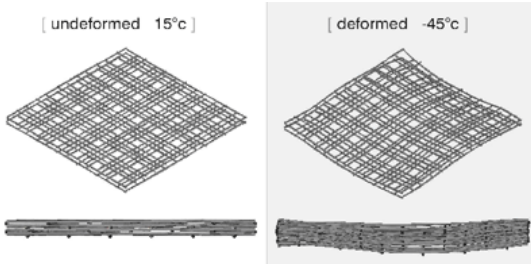
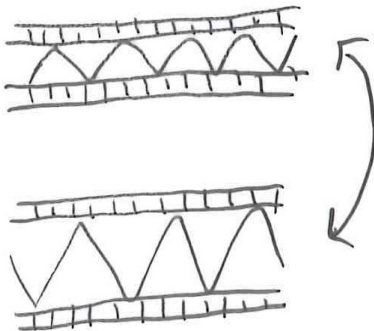
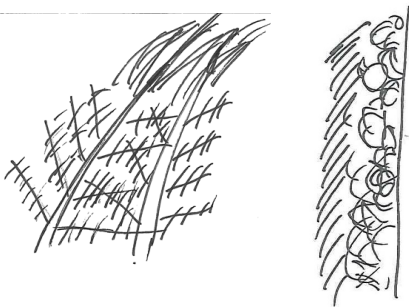
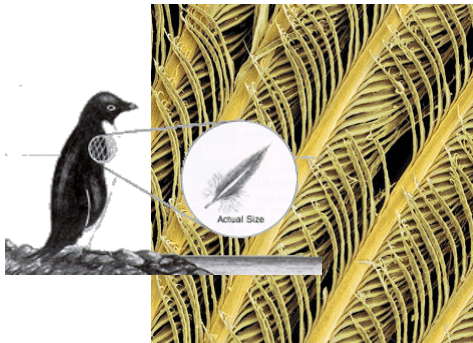
A more accurate way of differentiation between the two categories would be to define more exactly *what is being regulated*. If viewed in this light, it becomes apparent just why endotherms are so much more adaptable to different climates and why ectotherms are so much less dependent on regular food intake for their survival.

It seems that, as the vital organs have a very specific (narrow) temperature range within which they can operate effectively, endotherms have evolved their heat generation to generate enough heat to keep their core temperature at a very narrow temperature range (typically within 1°C). This means their heart, lungs, intestines and most importantly, the brain, are kept within this narrow range so they can be active for long periods of time. Where endotherms burn up much food intake in order to keep the core body temperature (and therefore that of the vital organs) as constant as possible, ectotherms go to much less trouble: in reptiles, the main regulated variable is the head and brain temperature (Tattersall, Cadena, & Skinner, 2006), while their bodies are much less regulated than in endotherms.

This notion of course has many similarities with building technology. Within buildings, there are spaces that are kept between strict temperature boundaries, be it for reasons of archive or laboratory work or otherwise; and there are spaces that are less strictly regulated. Of course the exact regulation and interplay between these spaces strongly depend on the typology and scale of the building, but the principle still holds.

One building that can serve as an example of this principle is the Langen Foundation, designed by Tadao Ando. The long gallery space of this building is encased in concrete. The climate within this concrete space is strictly regulated since it needs to hold the art collection of the Langens. The glass box that encapsulates this concrete space, is unregulated: it is a buffer, that is climatized by opening and closing parts of the glazing and by natural ventilation via the floor.

MICRO: INTEGRATION IN DETAIL



INSULATION

Organism: **Emperor penguin (*Aptenodytes forsteri*)**

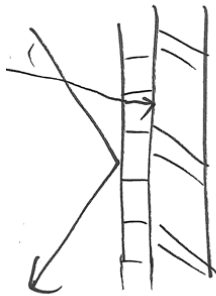
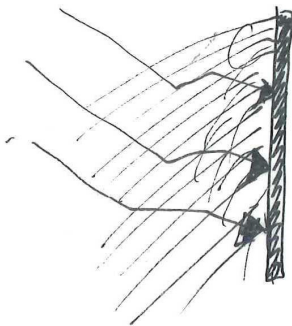
Principle: **Adaptive insulation (control conduction)**

Technology: **Expanding insulation by Variloft**

Again, the emperor penguin is featured in this study: this time describing their sophisticated plumage. This plumage has to cope with very different conditions: in air (that is, when the penguin is on land), the feathers provide a thick coat of insulation, trapping air in the fine layer of down. In water however, a layer of air would only have the effect of unwanted buoyancy; therefore when the bird enters the water, it flattens its feathers, allowing the air trapped in the down to escape. The upper part of the feather is a long, sturdy guard pen; the overlapping pattern of feathers ensures water tightness, preventing the down from getting wet. So when the penguin comes back on land, the feathers expand, allowing air to be trapped once again in the layer of down. On top of this, when temperatures rise, the feathers can expand somewhat more, allowing for the trapped air in the down layer to escape. (Dawson, Vincent, Jeronimidis, Rice, & Forshaw, 1999)

Within the penguin plumage, there are three conditions to be distinguished, depending on the whereabouts of the animal and on outside temperatures: a 'flat' condition under water, a 'raised' condition out of the water, and an 'extra raised' condition when air needs to escape in the heat. This results into a dynamic type of insulation, of which the U-value changes according to the input values (under water, cold on land and warm on land). A building principle that utilizes this principle would be a type of insulation that can change its U-value according to needs; and one that can respond to water by deploying a watertight envelope outside.

Serving as a prime example of *dynamic insulation*, similar solutions in the building industry are quite different and not at all as sophisticated. A solution that is being developed, not for the building industry but for clothing, is a type of coat insulation that thickens as temperatures drop. According to Variloft, the manufacturer of said clothing insulation, the material is made of thermally reactive bi-component fibres that change shape based on outside temperature. The penguin achieves a thickening of its plumage in a different way: by stretching and relaxing tiny muscles that are attached to the feathers (this is called pilo-erection). The layer of down then expands because the down feathers are hooked in each other by tiny barbules. So where Variloft achieves a thickening of its insulation by thermally responsive material, the penguin uses the feather structure to expand.



INSULATION 2

Organism: Polar bear (*Ursus maritimus*)

Principle: Capture sunlight for absorption in skin

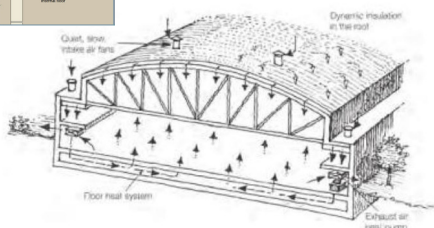
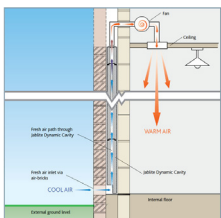
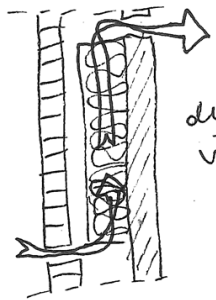
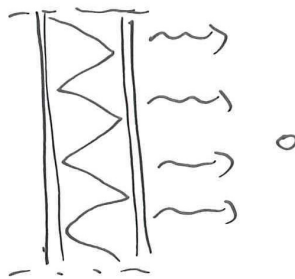
Technology: Trombe Wall

The polar bear has to cope with conditions similar to those the emperor penguin has to find an answer for. The cold Arctic sea, year-round covered with an ice sheet (though the volume of this ice sheet is diminishing year by year), forms the habitat of the polar bear, the largest bear – and with that, the largest predator – on land.

To insulate itself against the Arctic cold, the polar bear has a thick layer of fur. Contrary to what the fur's 'whiteness' might imply, the hairs are actually translucent and hollow, covering a black skin. The hollow hairs both capture and trap solar heat, and let it penetrate to the black skin, where solar heat is absorbed. Previously it was thought that the hairs act like optical fibres, guiding solar light towards the skin; though this has been disproved. (Pawlyn, 2011) Instead, the fur acts like a heat-trapping device that is so effective, that the bear is almost invisible on an infrared camera. (Preciado et al., 2002) The layer of fur consists of two distinct layers, a configuration that is found in many polar mammals: a dense layer of underfur that traps air (just like the penguin down), that is topped off by long guard hairs that protect the animal against wind. This fur doesn't change in configuration like penguin feathers do, though it does change over the seasons as the animal molts.

Rather than changing configurations, the polar bear fur has other important heat retaining abilities, namely to trap and transfer to the skin so much solar heat, that the animal becomes almost invisible for infrared cameras: the hair's emissivity is so low that it almost doesn't emit any radiation in the far infrared. The hollow, translucent hairs might not act as optical fibres, they do aid to scatter light in such a way that infrared light is absorbed by the skin while all wavelengths of visible light are reflected, causing the animal to look white.

Translated into a building principle, this would mean a building skin that absorbs virtually all infrared radiation while letting other wavelengths bounce freely. The infrared radiation would then be absorbed by a layer behind a layer that filters out other wavelengths while letting infrared through to the absorption layer. A building technology using this kind of insulation is the trombe wall: a massive wall behind a layer of glass. Heat that is caught by this wall system is trapped in the air layer between the glass and the wall, after which the massive wall absorbs the heat. Some systems even utilize hollow filaments between two layers of glazing and a black painted wall. (Pawlyn, 2011) While these system still remains rather metaphorical, they may provide directions for future solutions.



INSULATION 3

Organism: **Rorquals (family Balaenopteridae)**

Principle: **Control convective heat flow through skin**

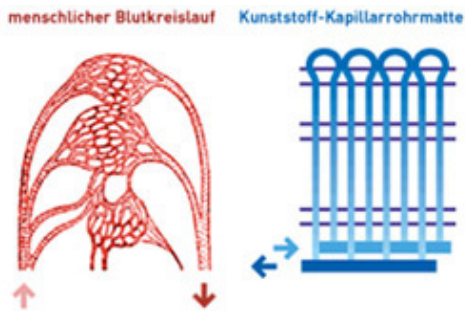
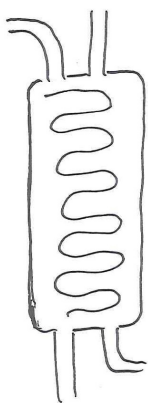
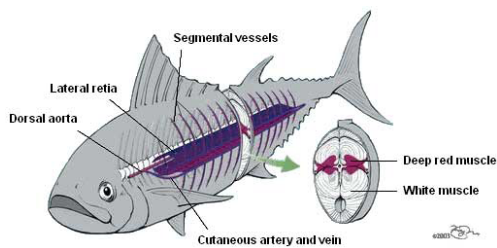
Technology: **Dynamic insulation by GAIA Architects**

Rorquals are a family of migrating whale species: twice a year they migrate from the poles to tropical waters and back. In doing so, the animals undergo a temperature difference of 25°C. And being marine mammals, the thermoregulatory systems are very different from terrestrial animals: they cannot sweat or seek shelter, or even radiate heat: they can only lose heat by forced convection to the water surrounding it. To do this, the arterioles running up to the skin through the layer of blubber are widened, forcing heat from the animal's interior to escape convectively to the surrounding water. The strategy to conserve heat however is comparable to terrestrial animals: by constricting arterioles that run to the skin, the blood flow towards the skin is diminished to almost zero. In rorquals, this system is expanded by incorporating venules that surround the arterioles, which take up heat when returning to the body. (Parry) Whale blubber is often thought of as a passive insulator, protecting the animal from cold waters. But actually blubber forms a much more complex system: actively controlling the outward passage of heat, thereby preserving the "deep body temperature despite changes in both the rate of production of heat by the animal, and in the thermal characteristics of the environment." (Parry)

Again, several conditions are to be distinguished in this animal. One 'warm', where blood arterioles towards the skin are opened, dissipating convective heat to the water; and one 'cold', where the arterioles are almost completely closed, shunting blood flow towards the skin, keeping heat inside the animal. As such it is another example of *dynamic insulation*. The amount of heat transmission that is allowed through the skin depends on the temperature difference between inside and out; regulating the exact size of capillary arterioles.

A technology that is somewhat comparable to this type of insulation is dynamic insulation deployed in some buildings. This type of insulation pre-heats incoming ventilation air by guiding it through the insulation layer, heating it with outgoing heat that is transmitted from inside the building. This type of insulation has a variable U-value, dependant on the air velocity through the insulation layer.

The McClaren Community Leisure Centre in Callander, Scotland, designed by GAIA Architects, is a building that utilizes this type of insulation. In this building, fresh air is taken in through a layer of insulation in the roof, where it is heated up by heat obtained from dehumidification by a heat pump. This heat is brought into the building via floor heating. (Bokalders & Block, 2010)



COUNTER-CURRENT

Organism: **Bigeye tuna (*Thunnus obesus*)**

Principle: **Distribute heat via counter-current**

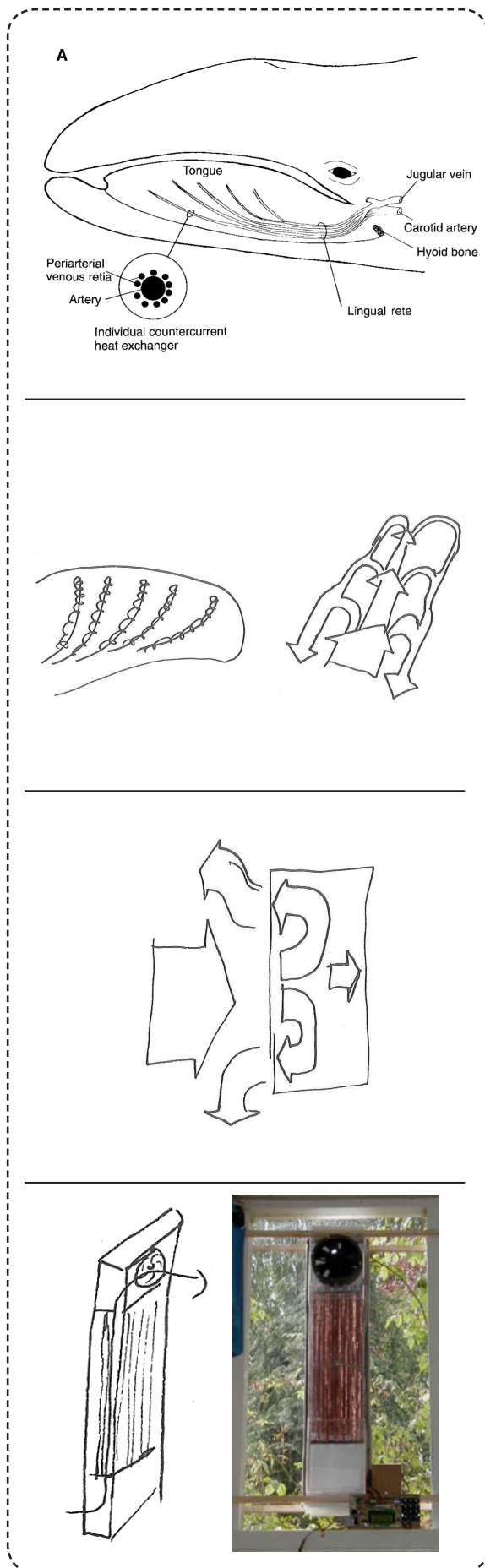
Technology: **Capillary climate mats by BioClima**

In order to keep its swimming muscles at a temperature that they can do work most effectively, the bigeye tuna is equipped with its own heat exchanger in its core. This 'rete mirabile' has the purpose of keeping the "red muscle", the swimming muscles, warm in cool waters, while it can also be bypassed when the organ is not needed. As this big predatory fish constantly moves vertically along the water column (down to depths of 500 metres), it encounters a wide range of water temperatures. The tuna's counter-current heat exchanger is a specialized organ that can modulate and distribute heat across the different categories of muscles: the "red" swimming muscles and the "white" warm muscles. This heat exchanger runs across the entire core of the fish, consisting of a very fine web of capillaries, within which blood runs slowly over a very large surface, exchanging so much heat that the swimming muscles would remain almost as cold as the waters it inhabits without this exchanger. (Boye, Musyl, Brill, & Malte, 2009)

This counter-current heat exchanger thus *distributes* generated heat, warming up the swimming muscles of the 100 kg fish. The principle is based on one input: the ambient temperature relative to the body temperature. Blood can either pass through the counter-current heat exchanger or it can bypass it, dependant on this value: if it increases a certain value, blood passes through the exchanger, giving off heat to the red swimming muscles.

Distribution of heat through a heat exchanger has many built applications as well. The principle, exchanging heat of an incoming medium with heat of an outgoing medium, has numerous examples; this particular kind of heat exchange and distribution could be likened to ultra-low temperature heating in buildings coupled with water-to-water heat exchangers.

One way to achieve this type of heat distribution is by so-called capillary climate mats: much like blood circulation, this system transports water through a fine net of "capillary" tubes along floor and wall surfaces; providing heat to rooms via radiant heating or cooling. One big advantage to this system is that the temperatures that can be used for heating and cooling don't need to differ much from the room temperatures: effective heating can already be achieved with water temperatures as low as 28-32 °C. Coupled with heat exchangers, this system could provide heating and cooling while dramatically reducing energy needs.



HEAT RECOVERY

Organism: **Gray whale (*Eschrichtius robustus*)**

Principle: **Recover heat via counter-current**

Technology: **FiWiHex thin thread heat exchanger**

Whales are famous for their thick (up to 50 cm) layer of fat, called blubber, which is also described before. However, the layer of blubber underneath the skin is not the only thermoregulatory measure whales have. As these huge mammals feed, they filter gigantic quantities of water through their mouths and baleens. Thus when feeding in cold waters, they have to prevent loss of their body heat to this water. The tongue of the gray whale provides a solution to this problem: the tongue, representing as much as 5% of the animal's total body surface, holds the largest counter-current heat exchanger yet described in biology. Called a lingual rete, the heat exchanger encompasses more than 50 sets of long, small diameter arteries, surrounded by many even smaller veins. (Heyning, 1997) This fine-grained structure ensures a slow blood flow and a large surface area, so heat from the arteries can be effectively transferred to the veins, holding blood running back into the body; and blood going to the surface of the tongue is cooled to only 0.5°C above water temperature. This 'lingual rete' is so effective, that the tongue actually loses *less* heat to water than the layer of blubber underneath the skin. (Heyning, 1997)

As heat recovery, this system is actually another type of counter-current heat exchanger. However this principle is primarily based on heat retention, while the other (the tuna rete mirabile) is aimed at heat distribution. When air temperatures differ from one side to another and heat is not to be dissipated, heat is transferred from an outgoing medium (blood in this case) to an incoming medium through a membrane. Increasing the surface of this transfer-membrane then results in a faster and more effective heat transfer.

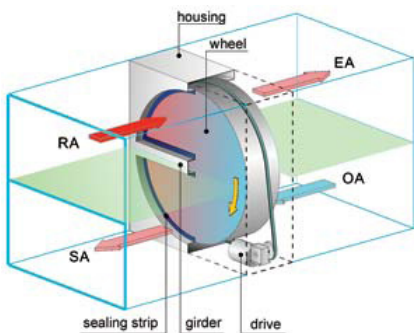
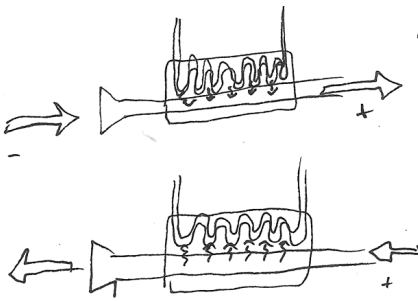
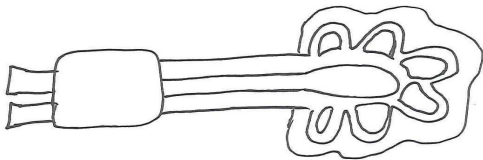
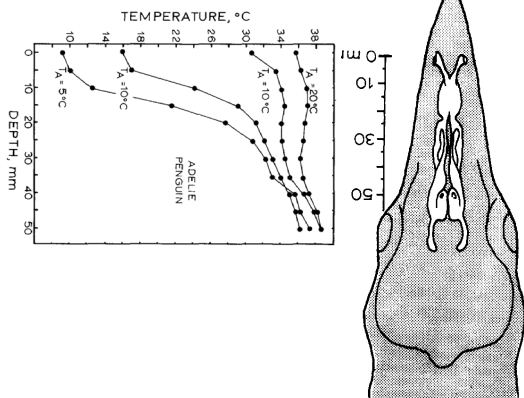
An example of a heat exchanger that uses a very large surface area to effectively exchange heat is the FiWiHex: "Fine Wire Heat Exchanger". This type of heat exchanger consists of kilometres of fine copper wire and small tubes that run water through them. This water redistributes its heat through the strongly conducting copper wires. An application of this principle that mostly resembles the gray whale tongue then is the breathing window. In this system, incoming air is blown through a network of copper wires, exchanging its heat with outgoing air. (Kristinsson, s.d.)

HEAT RECOVERY 2

Organism: **Emperor penguin (*Aptenodytes forsteri*)**

Principle: **Recover heat via evaporation/condensation**

Technology: **Heat Wheel**

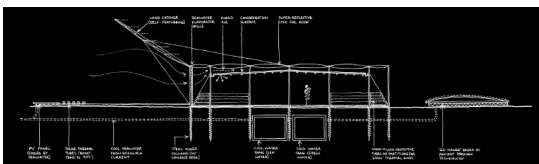
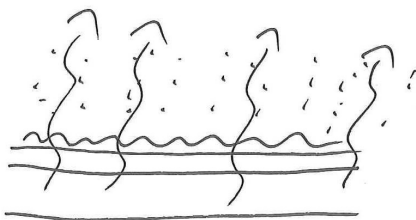
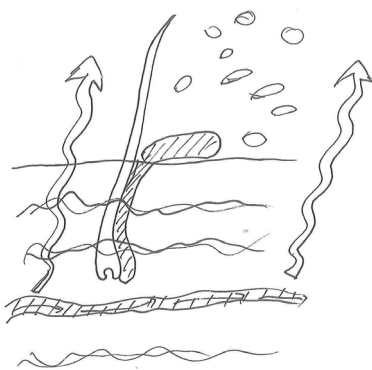


Featured for the third time now, the emperor penguin has yet another heat conserving strategy with which it stands out: its respiratory heat recovery. When breathing in cold Antarctic air, this air is preheated by evaporating mucous in the nasal cavity, saturating the air. This heat for evaporation is provided to the nasal cavity by blood vessels that run to the nasal cavity. When the animal exhales, warm air from the animal's lungs transfers its heat in the nasal cavity back to the tissues in this cavity by condensing vapour. The air leaves the body saturated but at a much lower temperature than that of the lungs. (Murrish, 1973)

This type of heat retention could also be seen as a counter-current heat exchanger; however the mediums are different (blood to mucous to air versus blood to blood), and while the afore described heat exchangers could be seen as *spatial* heat exchangers, respiratory heat recovery can be seen as a *temporal* heat exchanger. (Murrish, 1973) The principle rests on evaporation and condensation, following upon each other, transferring heat according to the direction of airflow. When the airflow is inward, moisture evaporates, transferring heat to the air; when the airflow is outward, the evaporated moisture condenses again.

Taking this principle to a built form would entail a kind of "breathing" system; while metaphorically these systems do exist, all of them (including the previously discussed "breathing window") are spatial heat exchangers rather than temporal ones. As such, the connection with the natural example is somewhat less obvious.

The heat wheel is another type of spatial heat recovery; the element that could compare this solution to the heat recovery of the penguin is the fact that this system utilizes humidification and dehumidification of outgoing and incoming air as a mean to heat up (or cool down) incoming ventilation air. As a heat recovery system, the heat wheel is one of the most effective, certainly in the context of large buildings: recovering about 60% of the exhaust air heat. (SAUCE)



EVAPORATIVE COOLING

Organism: Human (*Homo sapiens*)

Principle: Adaptive evaporation via skin

Technology: World Water Headquarters by Exploration

When it comes to evaporative heat loss, humans are actually one of only a handful of species that use sweating, or evaporative cooling through the skin, as a primary strategy to lose heat. Humans have three different kinds of sweat glands: the sebaceous glands, that are evenly distributed across the body, though they're not involved in thermally oriented sweat; the apocrine gland, concentrated in pubic regions and especially in the armpits, where it forms a 'sweat organ' that is only found in humans, gorillas and chimpanzees; and the eccrine glands, the main 'sweat glands' found on the palms and soles and also on the head, trunk and extremities. The eccrine glands are mostly responsible for thermoregulatory sweating, while also releasing sweat as a response to stress and other emotional responses.

The principle of sweating however is the same for any function of the different glands: heat is transported by blood to the highly vascular skin. By excreting fluid (sweat) upon the skin surface, this fluid evaporates; taking (latent) heat from the skin with it, thereby cooling it down. This type of cooling decreases the surface temperature of the skin as well as the temperature of (yet again) capillary blood vessels that run close to the skin, taking cooled blood to the core of the body. This strategy thus exclusively serves as cooling. There is however one very important requirement to be met in order for sweating to occur effectively: the air must be dry in order for it to carry away the excreted water vapour. When humidity increases, sweating is made more difficult; an increasing air velocity provides more convective heat loss at very high relative humidity.

A building technological strategy utilizing this type of cooling uses water as a cooling medium; by sprinkling water upon a warm surface and letting it evaporate, this surface is cooled. There are a number of more elaborate examples of this rather simplified principle. One of them is a (sadly never built) design for the World Water Headquarters, designed by Exploration (Charlie Paton) to be located in the Namibian desert. (Pawlyn, 2011) This building cools itself using evaporation of sea water as an important cooling strategy; however rather than sprinkling water upon a surface, it guides the hot desert air through a "seawater evaporation grille" before leading the cooled moist air over the roof, where condensed water would be captured and used as fresh water in the building.

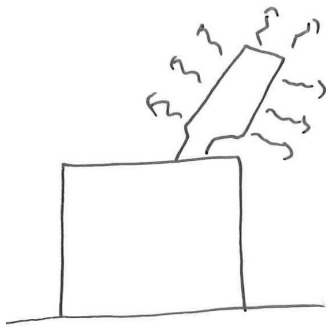
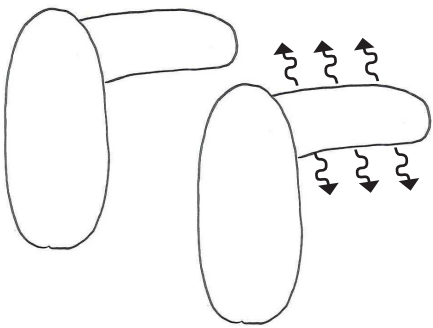


RADIATIVE COOLING

Organism: **Toco toucan (*Ramphastos toco*)**

Principle: **Adaptive heat dump organ**

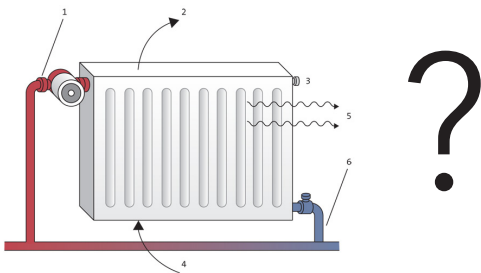
Technology: **Radiative cooling devices**



The toco toucan, home to the hot, humid Amazon rainforest, has a very distinguishable feature: the huge bill that takes up one third of the total body length of the bird. For centuries, scientists have debated its function: from a display device (much like a peacock's tail) to a device for fruit peeling. However, the thermoregulatory characteristics of this bill have been recently researched: and it seems that this bill functions quite effectively as a thermal window. The huge bill is highly vascularised. When temperatures rise, the temperature of the bill rises significantly: great quantities of heat are radiated away from the bird, as infrared cameras show vividly. It has been said that this way, the bird can radiate away up to four times the amount of heat that it produces. (Tattersall, Andrade, & Abe, 2009) The bill shows itself to be very adaptive, functioning as a giant heat dump when needed, while switching to 'heat-retention mode' in a matter of minutes. This adaptiveness is sorely needed: in flight, energy consumption of the bird is up to 12 times greater than at rest, easily leading to overheating. And when the bird goes to sleep and heat needs to be retained, it tucks the beak beneath its wings, providing extra insulation to prevent heat loss further.

As a very effective example of an adaptive organ that radiates heat, it is not so much what it does that is special, but the sophisticated way it does this. The toucan bill has many modes of operation: one as a heat dump, another as a heat retention device, which can even vary its insulation (by the bird's behaviour of tucking the bill beneath its wings). It can adjust itself to ambient temperatures and also according to the interior temperatures of the bird, becoming an essential organ in the bird's thermoregulation.

A building technology principle would entail one system that can do all the described things, while being relatively simple in its execution. It would consist of a network of "arterioles and venules" (once again), that would heat or cool a building surface, thereby changing its heat transferability. The old-fashioned radiator that heats up houses is a rather poor example for it operates at only one water temperature (90 °C, or lower temperatures in less energetically wasteful low-temperature heating systems), where only the amount of water controls the temperature of the steel surface that radiates heat (and gives off heat by convection) into rooms.



THERMAL COMFORT: THE HUMAN FACTOR

The previous chapters have dealt with biomimetic research, developing concepts for technologies from biology that ultimately are to be unified into a building design. However, no technology is sufficient when it is not being considered and developed within a human context, that is to say, human needs and requirements are an absolute necessity to form a framework for the designed technology. In this chapter, the characteristics of human comfort will be outlined. While thermal comfort (psychrometric comfort, to be more precise) is a very important issue, it is not the only one; or at least, matters are not as simple as they seem. Concentration on human needs can then result into a comprehensive philosophy regarding comfort and design, which coupled with biomimetics can form a basis for the program and starting points for architectural design. The human factor is, so to speak, the binding element between technology and architecture.

4.1 Thermal comfort: a short research history

The most general definition of indoor comfort is deceptively simple. The British Standard BS EN ISO 7730 defines thermal indoor comfort as “that condition of mind which expresses satisfaction with the thermal environment.” (Health and Safety Executive, s.d.-b) A more general definition would be “that condition of mind which expresses satisfaction with the indoor environment.” The problems we run into following these definitions are apparent. How to define ‘satisfaction’, and especially ‘satisfaction with the (thermal) environment’? How can we speak of a ‘condition of mind’ when this is perhaps one of the most subjective elements of being human? In research, much effort has been undertaken to quantify indoor comfort, in terms of psychometrics (e.g. temperature and humidity), air velocity, air quality, illumination levels and acoustical levels. This paragraph takes a closer look at these quantifications and the philosophies underlying them.

4.1.1 Elements of thermal comfort

For a more systematic approach to the judgment of comfort, it is useful to look at the several elements that define human comfort. Which physiological and climatic elements play a role in determining whether a situation is comfortable or not? Many of the elements of comfort are the same as the elements of nature described in paragraph 3.2.1: heat, air psychrometrics and air velocity. Therefore these elements are not treated again here, with the exception of air velocity: convective heat loss by wind chill is much more extreme outside than it is inside, while air velocity inside still plays a critical role in the perception of comfort.

Heat

The concept of heat – energy flow from a body with a high temperature to a body with a lower temperature – can be subdivided into two subcategories: sensible heat and latent heat. Sensible heat can be defined as the kinetic energy of molecules smashing into each other, giving rise towards the physical processes of heat transport (conduction, convection,

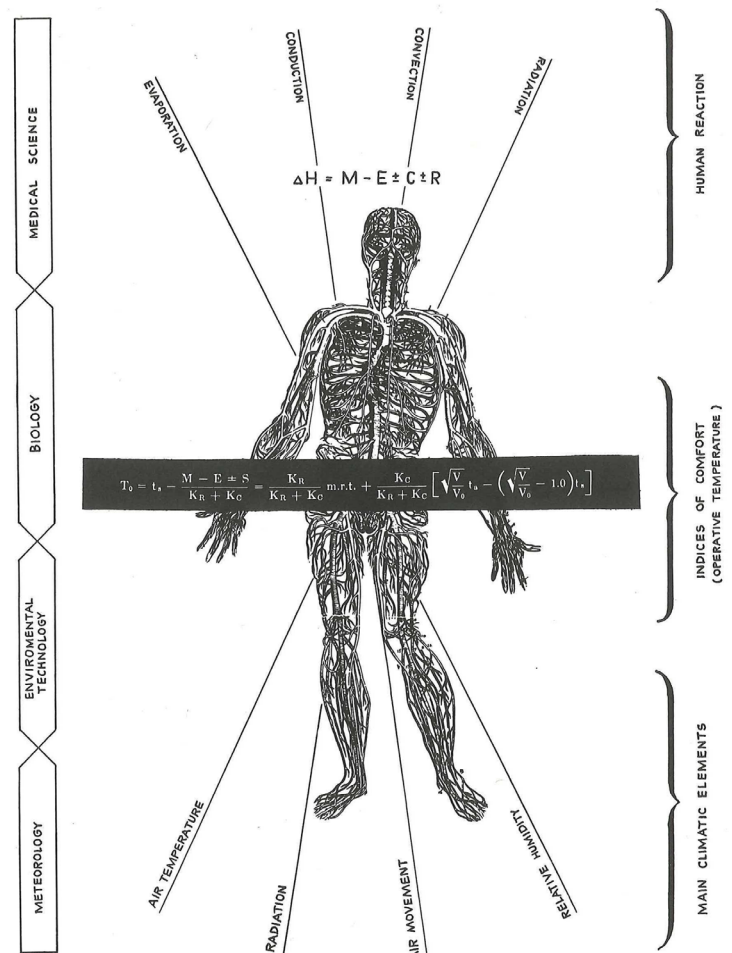


Fig. 4.1 Heat balance equation elaborated. (Olgay, 1963)

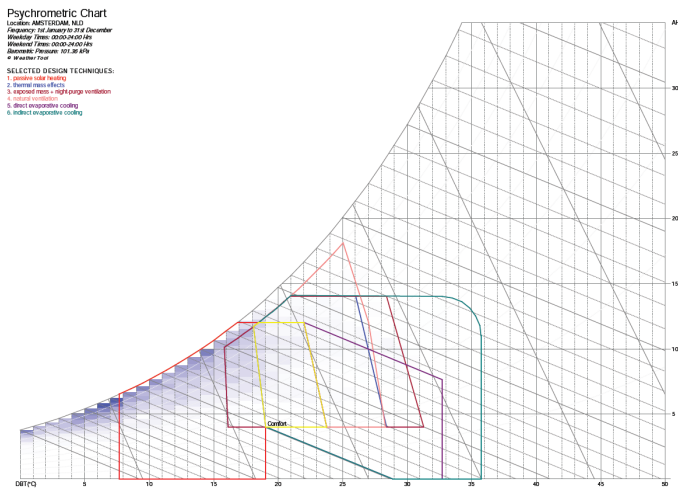


Fig. 4.2 An example of a psychrometric chart. Taken from ClimateConsultant.

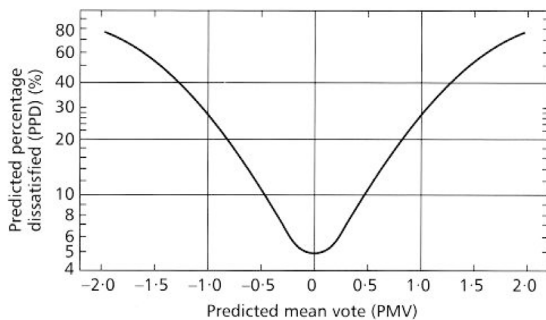


Fig. 4.3 Fanger's graph that forms the basis for his research on thermal dissatisfaction: the Predicted Mean Vote against the Predicted Percentage Dissatisfied.

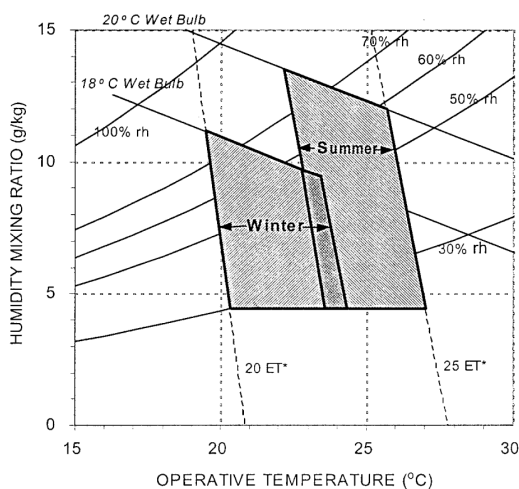


Fig. 4.4 Two temperature and humidity ranges by ASHRAE (De Dear & Brager, 2001)

radiation). Latent heat is defined as the heat needed to change the phase of a material, e.g. from liquid to gas or from solid to liquid. The sum of sensible heat and latent heat is then defined as *enthalpy*: the total *heat content* of a certain solid, liquid or gas. As the air of our ambient environment contains much water vapour, the total enthalpy that is added or removed from the air is defined by both heating (or cooling) and (de) humidification.

Temperature and Humidity: Psychrometrics

The variable 'temperature' defines *heat intensity*, and a temperature difference is the *potential* of heat to move from a relatively warm point to a relatively cold point. In comfort physiology we then further specify the *dry bulb temperature* (what we read on the standard thermometer), *wet bulb temperature* (the lowest temperature that can be achieved by evaporation of water (exchanging sensible heat for latent heat), a measure of the humidity of the air), the *dew point* (the so-called 'saturation temperature', the temperature below which condensation occurs) and the *mean radiant temperature* (the mean temperature of radiant surfaces of an enclosure surrounding the body)

Air Velocity

The speed of air particles in a space, which differs from wind speed since that is a variable of outside conditions, is an important variable that is often kept constant for purposes of determining thermal comfort.

4.1.2 Psychrometrics: The Static Model

One of the most extensively studied elements of indoor comfort is psychrometric comfort. As one of the most decisive factors in building energy use, controlling temperatures and determining comfort levels has been studied since the 1970s, when Ole Fanger first came up with his hypotheses regarding thermal comfort and his 'predicted mean vote (PMV)' remains an important source of information. Since then, the American association ASHRAE, amongst others, have further researched the concept of psychrometric comfort levels, having defined a bandwidth of temperatures and humidity levels within which 'comfort' is to be achieved.

The natural question then arises: is this the be-all end-all of psychrometric comfort? Should we design our buildings to heat up or cool down to a temperature between 22 and 28 degrees Celsius and humidity levels between 35 and 60% and be done with it? In other words, can the above graph be considered *universal*? Let's take another look at how subjective and variable body temperatures – and more importantly, the *perception* of comfort, really are.

4.1.3 Thermal comfort perception

For some decades already, the 'passively' defined comfort zone as is shown in figure 4.3, has been called into question. It is based on strictly controlled tests, putting subjects into 'climate chambers' with controlled temperatures and humidity levels, regarding the subjects as passive (hence the name) recipients of thermal stimuli.

Conversely, the *adaptive* comfort model posits that human

beings “play an *active* role in creating their own thermal preferences. Contextual factors and past thermal history are believed to influence expectations and thermal preferences. (...) In short, satisfaction occurs through appropriate adaptation to the indoor climate environment.” (De Dear & Brager, 2001) In the 2001 paper by De Dear and Brager, the duo investigates adaptive thermal comfort in relation to mean outdoor air temperature, indoor air velocity and clothing level. The researchers present an alternative to the strict comfort regions the ASHRAE diagram puts forth. The above diagram looks at the comfortable indoor temperature as a linear function of the outdoor temperatures, noting that “particularly for naturally ventilated buildings, the indoor temperatures found to be neutral (...) were significantly warmer in locations with warm outdoor climates than they were in cold climate zones. In other words, indoor thermal neutralities and preferences tended to track the patterns of outdoor climate, [which] could not be explained merely by differences in clothing levels.” (De Dear & Brager, 2001) One remark has to be made, that this graph already takes into account local as well as whole-body thermal comfort and accounts for people’s clothing adaptation in naturally conditioned spaces as well. Furthermore, the researchers note that outside the temperature limits of the graph, extrapolation might not be valid, positing instead that “In extreme climate zones, where mean monthly temperatures go beyond that range, instead of simply extrapolating the linear models, one should adopt the relevant upper or lower comfort temperatures and acceptability limits from [the graph].” (De Dear & Brager, 2001)

It thus can be said that indoor temperatures falling outside the ASHRAE graph may not be so much of a problem for buildings using natural (or hybrid) ventilation systems. And in warm conditions, air velocities can rise above 0.15 m/s (the standard ASHRAE maintains throughout its comfort models) without compromising comfort conditions. We apparently do enjoy a light breeze when it’s warm.

In general, the adaptive comfort model posits that what occupants *perceive* as a comfortable situation indoors, strongly relates to the climatic situation outdoors. One of the most important reasons for this conclusion is that when entering spaces with different climates, human beings need some time to acclimatize. This acclimatization is of course easier when the differences between the two climates are smaller. Thus, comfort not only relates to our physiological state versus that of the surroundings, but also to our relation to the *change* of the physiological state of the surroundings.

In essence, it can be said that comfort is achieved when our body doesn’t have to put too much effort to adapt to the surrounding climate. As Vaughn Bradshaw puts it: “We feel uncomfortable when our body has to work too hard to maintain thermal equilibrium. Under conditions of comfort, heat production equals heat loss without any action necessary by the heat control mechanisms.” (Vaughn Bradshaw, 2006) This heat production and heat loss may be aided by in- or decreasing air velocity that can speed up evaporation in hot conditions, or prevent too much convection in cold conditions.

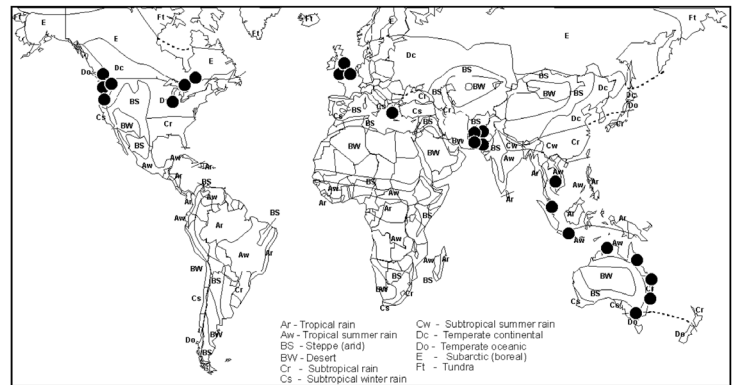


Fig. 4.5 Dots on this map indicate where thermal comfort research by Fanger et al. has been undertaken. (De Dear & Brager, 2001)

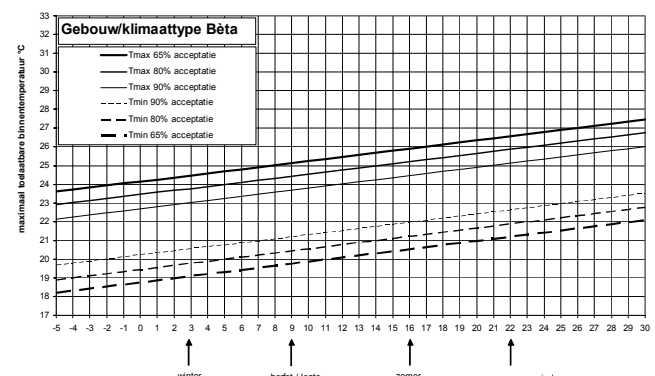


Fig. 4.6 The temperature range within which a comfortable condition is achieved. (Van der Linden)

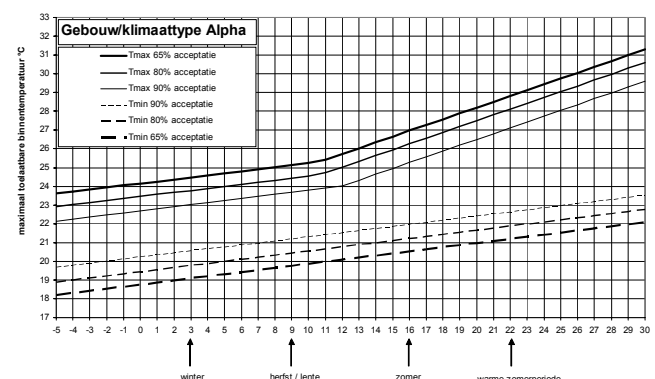


Fig. 4.7 The temperature range within which a comfortable condition is achieved, when an increased air velocity at higher temperatures is taken into account. (Van der Linden) Which graph applies depends on the building ‘type’; this will be expanded upon in paragraph 4.2.

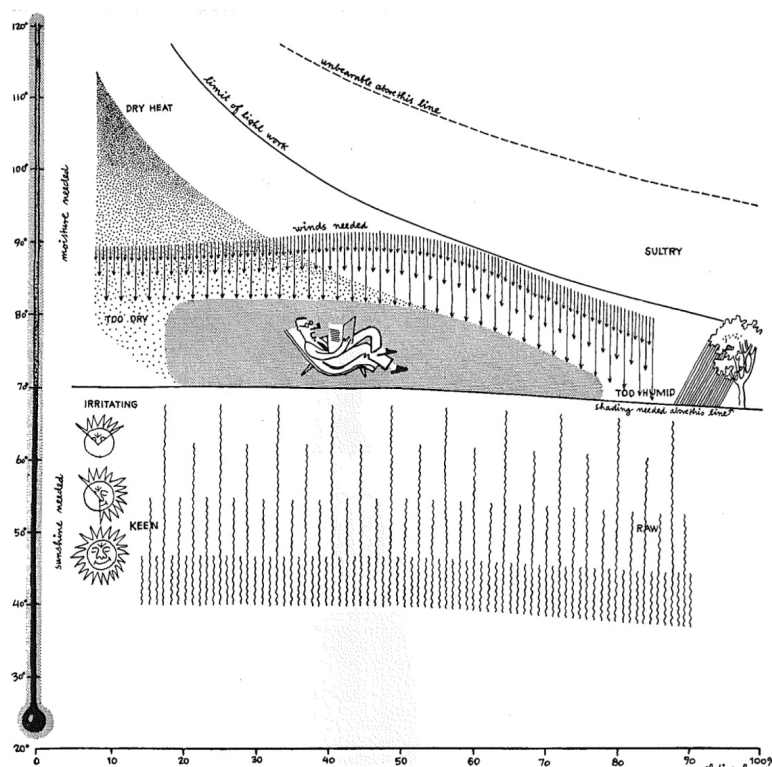


Fig. 4.8 Olgyay (1963), taking ASHRAE's research as a starting point, comprised this graph in which not only temperature ranges are displayed, but also effective means to influence climate in order to achieve a comfortable situation.

When De Dear and Brager, and later Van der Linden complemented Fanger and ASHRAE's research on thermal comfort, one can wonder what effect this ongoing research has had on the actual limits and regulations that are imposed on building practice. On first glance, the effect seems actually quite small: for low temperature ranges (below human thermal comfort levels), the limits are virtually unchanged since Fanger, while for higher temperatures, the boundaries are somewhat widened according to air velocity. As Van der Linden put it: "Comfort temperatures in the adaptive model are related to 'average outdoor temperatures'. This means for the Dutch summer situation – where the average day temperatures don't exceed 23-25 °C – that deviations with respect to the PMV model stay limited to approximately 1 °C."

While this notion might sound like a downplay of the importance of the research undertaken in this field, it's very important to note that it's not so much about the imposed limits as it is about the factors, constraints and variables that are taken in and looked at. Adaptive thermal comfort limits are very different from ASHRAE's thermal comfort limits because adaptive comfort factors in several elements: from taking outdoor temperatures as a starting point to factoring in human behaviour in response to varying thermal conditions. Van der Linden himself complements this research further by factoring in air velocity at higher temperatures. These are by no means elements to be overlooked. They can provide important ideas and notions for buildings to provide comfort, while greatly reducing energy use and demand.

4.2 Alfa and Beta buildings

The above paragraph has looked at several types of comfort models. In order of strictness with regard to the allowed temperature ranges, these are the PMV model by Fanger, the summer/winter ranges by ASHRAE, the adaptive comfort model by De Dear and Brager and the extended adaptive comfort model by Van der Linden. The latter two models have one extra requirement in order for them to be valid: the buildings designed that utilize these models are naturally ventilated, and have ways for its occupants to regulate the indoor climate; either by changing position within the building, by operable windows or by other means.

Van der Linden therefore classifies buildings climatically into “alfa” and “beta” buildings: “Type alfa are buildings with operable windows and many possibilities to influence the thermal inner climate by the individual user. Type beta buildings are buildings with completely closed facades and a centrally regulated air conditioning.” (Linden, 2006) In practice, most buildings are a mix of type alfa and beta; also classified as “hybrid”. (Kurvers, Linden, Boerstra, & Raue, s.d.) Then, the individual spaces are to be considered separately.

4.3 Thermal comfort and the human body

4.3.1 Local differences in comfort conditions

All of the previous has concentrated on a constant, uniformly distributed air temperature. Practice however shows that the air temperature is rarely evenly distributed across a room. Differences in local air temperature result mainly from differences in radiation from surrounding surfaces (asymmetrical thermal radiation) and from convection when air velocity becomes high enough. The effect of radiant asymmetry can be calculated in the *Mean Radiant Temperature* (MRT): a “weighted average of the temperatures of all the surfaces in direct line of sight of the body”. (Linden, 2006) Large differences between surfaces often occur at large glass surfaces (that are colder than wall surfaces), hot lights and other heat sources or sinks in a room.

Where the human body itself is concerned, the optimal comfortable situation arises when there is a slight vertical temperature gradient. (Linden, 2006) This principle is illustrated in the graph [on the left]: the difference in comfortable temperature between feet and head is, according to this graph, over 3 °C.

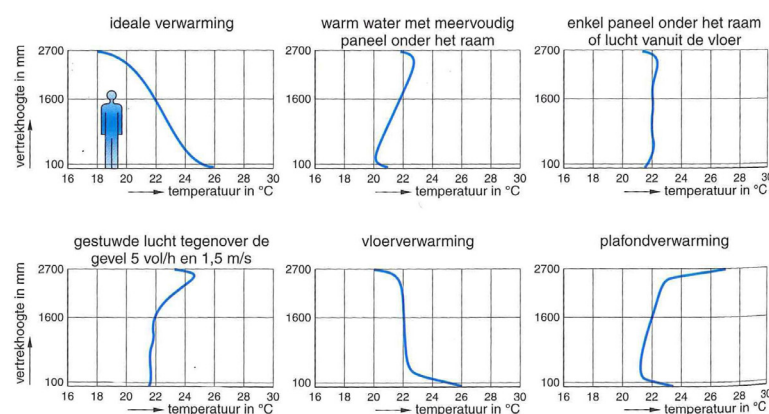


Fig. 4.9 When distributed over height, the difference between feet and head can be as much as 3 °C. In this graph, different ways of heating are compared to the ideal heat profile. (Van der Linden, 2006)

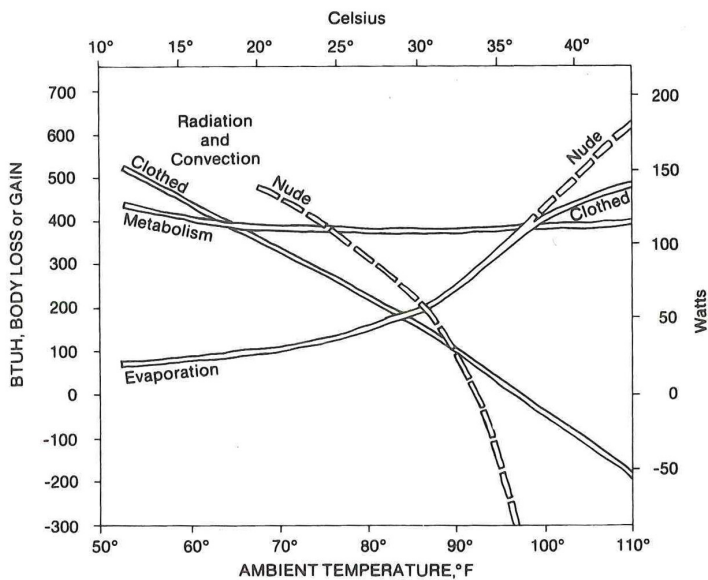


Fig. 4.10 Relative heat loss and gain via different physical processes. (Vaughn Bradshaw, 2006)

4.3.2 Comfort and physiology

Graph 4.10 displays graphically the amount of heat loss and gain by the human body from effects of radiation, convection and evaporation. Thinking back to the equation presented in chapter 3.1.2, where metabolism is put against the modes of heat transport ($M = E \pm R \pm Cv \pm Cd \pm S$), this graph is an illustration of this principle. As described by Bradshaw: "To illustrate the various modes of heat loss operating in conjunction, consider a person outdoors in 38 °C air temperature. (...) the convective heat loss is "minus" because the body is gaining heat from the air. The MRT is much higher than the body surface temperature – the sidewalk, street, building walls, sunny sky, and everything else in the range of view of the body is warmer than the body surface temperature. Thus, the radiant heat term is also "minus" because the body is gaining radiant heat. But as the person walks down the sidewalk, the metabolism produces about 200 W [walking produces more heat than the 110 W a person produces while standing], and all that heat must be lost in addition to that gained by convection and radiation in order to maintain the heat balance. The total heat the body must lose may be over 300 W, all by evaporation. The sweat glands automatically open, and the resultant moisture emitted onto the body surface then evaporates." (Vaughn Bradshaw, 2006) While the process of human perspiration has been explained in chapter 3.3, this graph shows how the different modes of heat transport contribute relatively to the human heat loss or gain.

When the comfortable temperature range is placed on top of this graph, it seems that the upper bounds of this range are about where the intersection is between heat loss by radiation and convection, and heat loss by evaporation. At higher temperatures, evaporation becomes more dominant in human thermoregulation, causing a noticeable amount of sweating. Also, below the lower bounds of the comfort range, heat loss by radiation and convection is larger than heat gain by metabolism; this then is the main reason we feel cold.

4.3.3 Six basic factors... or more?

With the previous considerations in mind, we can take another look at what the Health and Safety Executive says about the "six basic factors of comfort". According to the HSE, these are *air temperature*, *humidity*, *air velocity* and *radiant temperature* (the four 'environmental factors') and *clothing insulation* and *metabolic heat* (the two 'personal' factors). (Health and Safety Executive, s.d.-a) Most of these have been covered in the previous paragraph. As such, they describe the *most important* factors in thermal comfort; this is not to say that they are the only ones. As paragraph 4.2 and 4.3 already explain, the exact conditions under which thermal comfort is achieved is a bit more detailed and complex than those six described factors. While the mentioned refinements of the aforementioned six factors might not be enough to be themselves considered as separate "factors", they deepen our understanding of our bodily comfort and can add to the valuable research done already in this complex field.

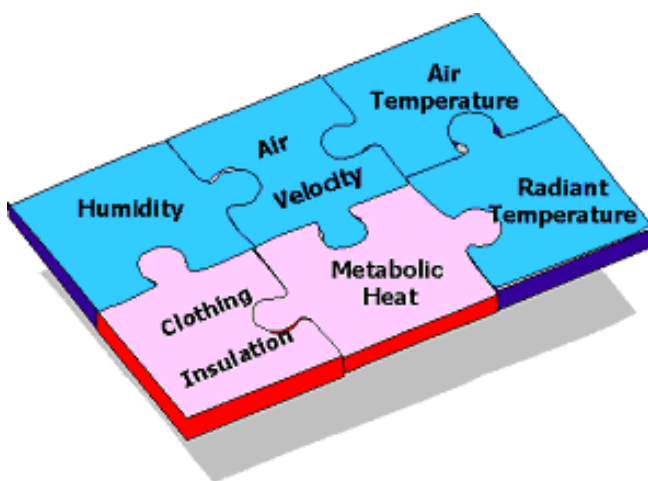


Fig. 4.11 The six 'basic factors' of thermal comfort, according to the British organization Health and Safety Executive.

CONCLUSIONS OF PART 1

So given the example of biomimetic research in this part of the graduation thesis, how can we reach conclusions at this point as a way to go forward designing a building? Echoing Petra Gruber in chapter 1, biomimetics in architecture still doesn't have an underlying design theory – and with that, not yet a cohesive, architecturally generic design methodology. However, the question is if there needs to be said methodology. The methodology put forward in this research at least attempts to be generic – however exactly how generic remains to be seen.

Reflective ponderings aside, it can be said that, following the methodology put forward in chapter 1, at this point we are at step 5: Abstract. “Find repeating patterns shared by the found organisms, come to conclusions on the results and model generic patterns that address the problems in step 1”. What follows thus are concluding findings, abstracted from the myriad of biological examples presented in chapter 3. These abstractions are put forward against the background of the three scale levels and classifications presented in chapter 2.

MACRO: COMMUNITY WORK

Rather unsurprisingly, on the Macro scale, it is the community that drives thermoregulation. Organisms are not solitary beings in an empty world. As part of a biome that is part of an ecosystem, organisms sometimes take opportunities to benefit from each other's thermoregulation, as illustrated by the huddling penguins; or work together to create optimal forms and configurations for thermoregulation, as illustrated by the wood ants. Indeed, without this community work, many organisms wouldn't have a chance to survive: penguin's eggs wouldn't incubate; ant's nests would be unable to house larvae and the ants themselves.

When abstracting community work into building principles, abundance and distribution seem to be key words. What these solutions share is that it is not much of a problem if one component stops functioning: the community as a whole survives. Indeed, this community survival seems to be an even more important driving force for evolution than the often quoted “survival of the fittest”; here it would more accurately entail “survival of the fittest group”. Distribution of a function among many agents is not the most technical of abstractions, but it does form inputs for the development of technology. We'll delve deeper into these as the scale levels get smaller.

MESO: REGULATED/UNREGULATED REGIMES

One thing that many animals share, endotherms and ectotherms alike, is the division of their bodies into ‘vital organs’ and ‘non-vital organs’; the non-vital organs being much less restrictive in temperature regime than the vital organs, temperatures of which are held within very narrow bounds. These regimes have at their core the concept of ‘conserving energy where possible, only expending energy where it's needed’. Ectotherms – and mostly reptiles, snakes and alligators – seem to be specifically adapted for this purpose, as in these animals it is the temperature of one organ – the brain – that is kept as constant as possible while the rest of the body is allowed to change temperatures according to the environment. Heating

up and cooling down then occurs when the animal needs to be active or when it can rest.

For architecture, these are valuable starting points for thermal – and energy – design. It calls for a local regulation of temperature and for a local concentration of resources, in those spaces where it's needed; when it's not needed, temperature is allowed to fluctuate. One key consideration for this type of design is the speed at which temperatures can be raised or lowered. As agents move through spaces, it's not to be expected (nor is it desirable) that very large temperature differences occur from one space to the next. Therefore another concept that most animals share is that of gradients: temperatures do not suddenly drop across a body, but gradually fall to ambient levels. This ensures more evenly distributed heat and no unnecessary large ‘jumps’ of temperature, which would themselves require large amounts of energy to maintain.

MICRO: THE COUNTER-CURRENT

One element that time and time again kept on returning in virtually all discussed examples is counter-current heat exchange. Be it from blood to blood, or from blood to air (and vice versa), or from blood to mucous to air, the principle remained constant: exchanging heat from a warm medium to a cold medium via a large surface area. One thing that is important to note is that this counter-current heat exchange is, in many of the examples, coupled with other systems: with insulation and absorption of solar heat in the polar bear, with ventilation in penguins and lizards, with evaporating sweat in humans and with the sophisticated heat dumping bill of the toucan. As such it is one of the most common and one of the most versatile principles found.

Of course, a counter-current heat exchanger with blood as heat transporting medium immediately points at a water-based heat system – one of the oldest and most elaborated upon ways of industrial heating of buildings. Again, it is not the principle that is exactly new; it is the sophisticated way with which biology has tackled its many problems that can provide a starting point for technological design. A counter-current heat exchanger, coupled with systems for insulation, radiation and evaporation, can improve drastically when natural examples are studied in detail and learned from – indeed serving as a basis for dramatic savings in energy use and overall more efficient and effective buildings.

THERMAL COMFORT: INPUT AND BENCHMARK

So where does chapter 4 come in? Research in thermal comfort, named as a basis for 'biomimetic design from first principles', becomes an important vantage point, a benchmark, to which building design can be validated and measured. Research in thermal comfort thus results in more inputs for design and a measure for the design when simulation results come in. It also shows that thermal comfort is very closely related to biomimetics; the processes and principles of human thermal comfort and biological thermal measures are very similar. Viewing a building design as some sort of 'extended organism' wouldn't even be that much of a stretch.

What conclusions can be drawn from thermal comfort research in the context of this biomimetic research paper? It could be that, seeing as biomimetic strategies are to be deployed in a cool temperate oceanic climate (see chapter 1), the discussed temperature, humidity and air velocity ranges strongly influence the choice for biomimetic strategies. In a temperate climate, where the annual range of temperatures is quite large, both heating and cooling seem to be needed. One remark needs to be made in this regard: the Dutch coastal region differs slightly from the average temperate region in that the annual temperature range is slightly narrower, while sun, wind and rain are more abundant than deeper inland. Still, the consequences for thermal comfort are obvious: for the cool temperate climate zone, large parts of the year requires heating, while cooling on 'extreme' days in summer is not to be neglected. The strategies to be deployed then can be narrowed down and refined, using the conclusions from biomimetic research discussed above.

Considering that building technology, architecture, yes technology as a whole is ultimately meant to serve mankind, perhaps it is safe to say that biomimetic design always deals with two components: with biology and with the technological problems that need tackling. Viewed in this light, all biomimetic research is incomplete when the technological component – or at the very least, the *requirements* for innovative technology – are not taken into account as well. This is what the thermal comfort component of this research aims to do: forming requirements, guidelines, and as mentioned before, a benchmark to which results can be measured.

From here on out, the goal is to design, test and emulate biomimetic technology and architecture. Steps 6 to 8 of the methodology discussed in chapter one are now the next steps to take. The results of these steps are to be discussed in the next part of this research paper.

LITERATURE

- Ancel, A., Visser, H., Handrich, Y., Masman, D., & Maho, Y. L. (1997). Energy saving in huddling penguins. *Nature*, 385(23 January), 304-305.
- Benyus, J. M. (2012). A Biomimicry Primer Retrieved 6 September 2012, from <http://biomimicry.net/about/biomimicry/a-biomimicry-primer/>
- Bokalders, V., & Block, M. (2010). *The Whole Building Handbook: How to Design Healthy, Efficient and Sustainable Buildings*. London: RIBA.
- Boye, J., Musyl, M., Brill, R., & Malte, H. (2009). Transectional heat transfer in thermoregulating bigeye tuna (*Thunnus obesus*) - a 2D heat flux model. *The Journal of Experimental Biology*, 212, 3708-3718.
- Campbell, N. A., & Reece, J. B. (2005). *Biology*. San Fransisco: Pearson.
- Canopy.org. (2012). The Benefits of Trees Retrieved 20 September 2012, from <http://www.canopy.org/pages/about-trees/the-benefits-of-trees.php>
- Dawson, C., Vincent, J. F. V., Jeronimidis, G., Rice, G., & Forshaw, P. (1999). Heat Transfer through Penguin Feathers. *Jorunal of theoretical Biology*, 199, 291-295.
- De Dear, R., & Brager, G. S. (2001). The adaptive model of thermal comfort and energy conservation in the built environment. 45(Int J Biometeorol), 100-108.
- Gruber, P. (2011). *Biomimetics in Architecture*. Vienna: Springer-Verlag.
- Health and Safety Executive. (s.d.-a). Six basic factors Retrieved 20 September 2012, from <http://www.hse.gov.uk/temperature/thermal/factors.htm>
- Health and Safety Executive. (s.d.-b). What is thermal comfort? Retrieved 20 September 2012, from <http://www.hse.gov.uk/temperature/thermal/explained.htm>
- Heyning, J. E. (1997). Thermoregulation in the Mouths of Feeding Gray Whales. *Science*, 278, 1138-1139.
- Keeffe, G. (2007). Daffodils and Polar Bears: Towards a Biomimetic Architecture Retrieved 10 september 2012, from <http://greenmodernism.blogspot.nl/2007/03/daffodils-and-polar-bears-towards.html>
- Keosian, J. (1964). *The origin of life*. London: Chapman and Hall.
- Kristinsson, J. (s.d.). A 'breathing window' for each room Retrieved 20 September 2012, from <http://www.breathingwindow.org/>
- Kurvers, S. R., Linden, A. C. v. d., Boerstra, A. C., & Raue, A. K. (s.d.). *Adaptieve Temperatuurgrenswaarden (ATG)*.
- Linden, A. C. v. d. (2006). *Bouwfysica*. Amersfoort: ThiemeMeulenhoff.
- MacKay, D. J. C. (2009). *Sustainable Energy - without the hot air*. Cambridge: UIT Cambridge Ltd.
- Murrish, D. E. (1973). Respiratory heat and water exchange in penguins. *Respiration Physiology*, 19, 262-270.
- Olgyay, V. (1963). *Design with Climate; bioclimatic approach to architectural regionalism*. Princeton: Princeton University Press.
- Pallasmaa, J. (1995). *Animal Architecture*. Helsinki: Suomen Rakennustaiteen Museo.
- Parry, D. A. The Structure of Whale Blubber, and a Discussion of its Thermal Properties.
- Pawlyn, M. (2011). *Biomimicry in Architecture*. London: RIBA.
- Preciado, J. A., Rubinsky, B., Otten, D., Nelson, B., Martin, M., & Greif, R. (2002). Radiative properties of polar bear hair. *Advances in Bioengineering*, 53, 1-2.
- Rockström, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, 14(2), 32.
- Schrödinger, E. (1945). *What is life? the physical aspect of the living cell*: Cambridge University Press.
- Skeptical Science. (2010). The Big Picture Retrieved 20 September 2012, from <http://www.skepticalscience.com/big-picture.html>
- Tattersall, G. J., Andrade, D. V., & Abe, A. S. (2009). Heat Exchange from the Toucan Bill Reveals a Controllable Vascular Thermal Radiator. *Science*, 325, 468-470.
- Tattersall, G. J., Cadena, V., & Skinner, M. C. (2006). Respiratory cooling and thermoregulatory coupling in reptiles. *Respiratory Physiology & Neurobiology*, 154, 302-318.
- Vaughn Bradshaw, P. E. (2006). *The Building Enviornment: active and passive control systems*. New York: Wiley.

